CRITICAL CATCHMENT MODEL INTERCOMPARISON AND MODEL USE GUIDANCE DEVELOPMENT

Report

to the Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND AND AIMS

Catchment hydrological modelling has become a central component of water resources management in South Africa. Models are regularly used for a range of applications, including predicting inflows to supply reservoirs, helping to delineate flood lines, and assessing the probable impacts of land cover and climate change. A plethora of modelling tools are available, each with differing approaches to representing hydrological processes. Given the reliance on modelling to inform weighty decisions, continuous research and capacity building is needed to enable the water sector to take advantage of and make wise use of the diversity of strategies and tools. This project aimed to contribute to this field by producing accessible information and guidance that can assist modellers in the process of selecting and applying modelling tools for typical use cases. This was informed by reviewing the structural differences across several commonly used modelling tools in South Africa and exploring the implications of these differences in various settings.

Project objectives

- Review and compare the structures and structural options in a selection of catchment modelling software tools commonly used in South Africa
- Apply a set of catchment modelling software tools to a set of case study catchments and change scenarios across a diversity of settings to allow for more quantitative exploration of the implications of structural differences
- Capture and document user experiences with the different tools being compared and reviewed through workshops and surveys
- Synthesise the resulting information to produce guidance materials for modellers

The modelling tools and versions selected for intercomparison in this project were as follows:

- ACRU, Agricultural Catchment Research Unit model, ACRU4 version (Schulze, 1986; 1995; Schulze and Davis, 2018)
- WRSM-Pitman, Water Resources System Model, WRSM2000 version (Bailey, 2015; Bailey and Pitman, 2015; Pitman, 1973)
- SPATSIM-Pitman, modified Pitman Model run through the SPatial And Time Series Information Modelling platform, SPATSIM v3 version (Hughes, 2013; 2019; Pitman, 1973)
- SWAT, Soil and Water Assessment Tool, SWAT2012 implemented with the ArcSWAT2012 interface (Arnold et al., 1998; Neitsch et al., 2011)
- MIKE-SHE, Système Hydrologique Européen, MIKE-SHE and MIKE-Hydro 2019–2020 versions (Abbott et al., 1986; DHI, 2019a; Refsgaard and Storm, 1995)

These tools were selected for several reasons. They are already being used in the South African water sector, with WRSM-Pitman, SPATSIM-Pitman and ACRU being used widely, and SWAT and MIKE-SHE having more limited use to date. They are all appropriate for modelling at the meso-catchment or quaternary catchment scale, and are needed for most water resource management applications. As a set, they encompass a variety of modelling approaches and structural types, and were developed both locally and overseas under both proprietary and open-access settings.

The project accomplished its primary objectives in completing an in-depth comparison of structural options for the focus tools; applying the tools to four case studies; conducting a model user survey; and synthesising learnings from these steps into a wiki website (https://hydromodel-sa-wiki.saeon.ac.za/) that can continue to be updated and improved through input from users. Methods, outcomes and suggested next steps are summarised in the sections below.

A critical issue demonstrated in this project was that different models of the same catchment, all based on the same information and input data, can predict notably different amounts of change when applied to an alternative scenario. This makes a strong case for further investigating model process representation with field data and for supporting improved practice around model uncertainty analyses.

METHODOLOGY

Model user survey

A short, anonymous, online survey was conducted to improve the understanding of how practitioners and researchers in South Africa are using catchment-scale hydrological modelling tools, which tools are commonly used, and what the user experiences have been. The questionnaire was reviewed and given ethical clearance by the Rhodes University Human Ethics Committee (RU-HEC). It was distributed via the email list of 192 members of the South African National Committee of the International Association of Hydrological Sciences (SANCIAHS) with requests for it to be forwarded to their relevant contacts. The call to participate indicated that respondents should have an interest in and some exposure to hydrological modelling, and that it was open to all experience levels.

Structure and interface review

The structural intercomparison of the focus tools covered their options for model spatial, temporal and process scales and discretisation, as well as the algorithms used in the representation of surface and subsurface processes. The review was based on modelling tool documentation, theory and user manuals, experience within the project team, and consultation with experienced and expert users. Comparable aspects of discretisation and process representation (e.g. model units used to represent the soil profile, algorithms governing storage vs percolation) were described across the set of tools side by side. When differences were noted, potential implications for use and output in different settings and use cases were highlighted. Practical aspects of tool use were also compared, such as the user interface, inputs and outputs and their formats, user documentation and support, computational burden and access cost. The initial review was done in preparation for the case study modelling and was subsequently updated based on learnings from the case studies.

All the tools afford users some flexibility in the model structures that can be built. MIKE-SHE, however, includes a relatively high diversity of options in terms of algorithms and the spatial and vertical discretisation that goes with them to represent different processes. Users can choose different combinations of approaches for different processes when building a model. To facilitate comparison across the tool set, MIKE-SHE was described for two essentialised approaches: using the more spatially lumped and more conceptual options and using the more distributed and more physical/mechanistic options. WRSM-Pitman offers different options for representation of the subsurface processes: the original Pitman model formulation (Pitman, 1973), in which the unsaturated zone and aquifers are represented as a single subsurface storage unit, the Sami ground water method (Sami, 2015) and the Hughes ground water method (Hughes, 2004). Because the Hughes method is incorporated into SPATSIM-Pitman, WRSM-Pitman is presented with the Sami method in the review.

Case study modelling

The focus tools were used to build models of four case study catchments selected to cover a variety of climate, geomorphological and land cover settings. These were the Mistley catchment in the Upper Mvoti River in KwaZulu-Natal, the Upper Berg River catchment in the Western Cape, the Upper Kromme river catchment in the Eastern Cape and the Middle Letaba catchment in Limpopo (Table 0.1). For each, one or more alternative scenarios were applied to assess how differently they predicted the responses to the change. These were land cover scenarios for the Mistley, Berg and Kromme catchments and a change in irrigation water sources in the Letaba catchment. Model outputs were compared in terms of fit to observed streamflow, magnitude and pattern of change predicted when a scenario was applied, and the modelled catchment water balances under baseline and scenario conditions.

These specific catchments were chosen in part because they had been modelled in other projects for which the input data and scenario descriptions could be made available to the project team (Cornelius et al., 2019; Haasbroek et al., 2015; Rebelo and Holden, 2020; Scott-Shaw, 2020). This reduced the time needed to obtain, vet and process input data, allowing more time to focus on model structures and outputs. The pre-existing models were used as starting references for structure and parameter decisions made in the other tools when relevant.

An effort was made to build models representing the same conceptual understanding of catchment properties and processes across all tools. All models were run with the same effective rainfall and evaporative demand at the catchment scale. Different tools require different climate inputs specified for different spatial units. The spatial distribution of climate input in the pre-existing model reference was used as the shared underlying distribution in this process. The same terrain, land cover maps, soil type maps and property data, and aquifer property data informed each model. However this necessarily took different forms across tools. For each case study, the project team held a series of online workshop sessions to introduce the catchment, pre-existing model, data and scenarios, and to discuss structures and parameterisation for models in the different tools.

Limited attempts at improving the models' output fit to observed streamflow data through parameter adjustments were conducted. In this process, parameter value ranges were kept consistent with parameter meanings, guidance documentation and the catchment property data and process conceptualisation. Adjustment focused on more conceptual parameters, such as those having less direct value derivation from the physical property data available for the catchment.

Table 0.1: Case study catchments, use-case demonstration scenarios and modelled change in mean annual runoff (MAR), and highlighted process representation issues encountered in model building

Case study catchment	**Climate type**	**Geology, geomorphology, natural vegetation**	**Scenario modelled and range of MAR change predictions across models**	**Highlighted model representation issues**
Mistley, Upper Mvoti (U40A), **KwaZulu-Natal**	Summer rain, subtropical	Shale and dolerite, rolling hills, grassland	**Scenario:** *12% of catchment, eucalyptus plantation converted to riparian wetland* **MAR change range:** +4% to +34%	Riparian zone processes
Upper Berg (G10A), Western Cape	Winter rain, sub-humid / semi-arid, Mediterranean	Table Mountain Group quartzite, steep mountain, fynbos	**Scenario:** *8% of catchment, upland invasive pines converted to fynbos* **MAR change range:** +0.1% to +7%	Interflow in steep, rocky mountains

Case study catchment	Climate type	Geology, geomorphology, natural vegetation	Scenario modelled and range of MAR change predictions across models	Highlighted model representation issues
Upper Kromme (K90A,B), Eastern Cape	Bimodal rain, semi-arid	Table Mountain Group quartzite – steep mountain + floodplain alluvium, fynbos	**Scenario:** *58% of catchment, fynbos and wetland converted to wattle and pine* **MAR change range:** -21% to -45%	Spatial rainfall distribution and flow connectivity both interacting with subcatchment delineation; valley bottom wetland representation
Middle Letaba (B82A-D), Limpopo	Summer rain, semi-arid, temperate	Gneiss and granite, relatively flat, woodland	**Scenario:** *8% of catchment, switched from surface and ground water irrigation to surface sources only* **MAR change range:** -1.7% to +0.1%	Irrigation from ground water and from multiple sources; numerous small farm dams; channel transmission loss

Guidance material: Wiki

Findings from the structural review, case study modelling experience and community survey were reviewed to create material for a wiki website focused on catchment hydrological modelling in South Africa (https://hydromodel-sa-wiki.saeon.ac.za/). The site was built using MediaWiki online software. It is freely hosted on the South African Environmental Observation Network (SAEON) servers of the National Research Foundation (NRF). The site was set up so that additional editors can have full access to edit the site. General users can comment and suggest edits and additions to the content via discussion pages rather than freely editing all the content on the site.

RESULTS

Model user survey responses

Of the 45 respondents to the model user survey, 40 indicated that they had used hydrological models for independent projects outside a class exercise. These respondents were directed to the model use questions, while the other five were directed to questions about any potential barriers to model use they had experienced. These interested respondents, who had not yet used the model, comprised students and one company employee. They indicated a lack of support and lack of time to break through the learning curve as barriers. One respondent indicated the lack of computing power.

The 40 model user respondents covered a range of experience levels: two (5%) had only used a modelling tool for one project to date, 10 (25%) had used at least one tool for multiple projects, 12 (30%) use at least one tool on a regular basis, and 16 (40%) indicated that they teach and/or work on the development of at least one tool. Respondents also came from a variety of sectors, with academics making up the majority (58%) if PhD students and postdocs are included, with consultants making up 35%.

Most respondents (95%) indicated that they had some level of exposure to multiple modelling tools, but only 11 (28%) indicated using more than one tool regularly. In total, the respondent group reported using 34 different modelling tools, with ACRU, SPATSIM-Pitman, WRSM-Pitman, MIKE-SHE, SWAT, HEC-HMS and the Water Evaluation and Planning System (WEAP) being the most frequently reported. The most frequently cited model uses in the group were land cover and climate change impact studies, followed by reservoir planning and operation. Agriculture and invasive alien vegetation were the most frequently selected focus areas of land cover change studies.

Survey participants were asked to indicate the top three factors that most strongly influence their tool selection from a given list (see factors in Figure 0.1). All ten factors listed were selected as being highly influential by multiple respondents. This demonstrates the diversity of situations under which this decision is made, balancing practicalities and idealised priorities. The three factors most frequently chosen were prior use of the tool, specific tool capabilities and the data available for the project. The least frequently selected factors were literature on the use case using the tool, the tool’s calculation approach and ease of use. This project placed a significant focus on the calculation approach and ease of use. There is an overlap between the capabilities and calculation approaches, and between prior use and ease of use, although these are not quite the same. If calculation approaches have been less of a focus for users, this may be because of the complexity of engaging with it across different tools. This is something that this project directly aims to address.

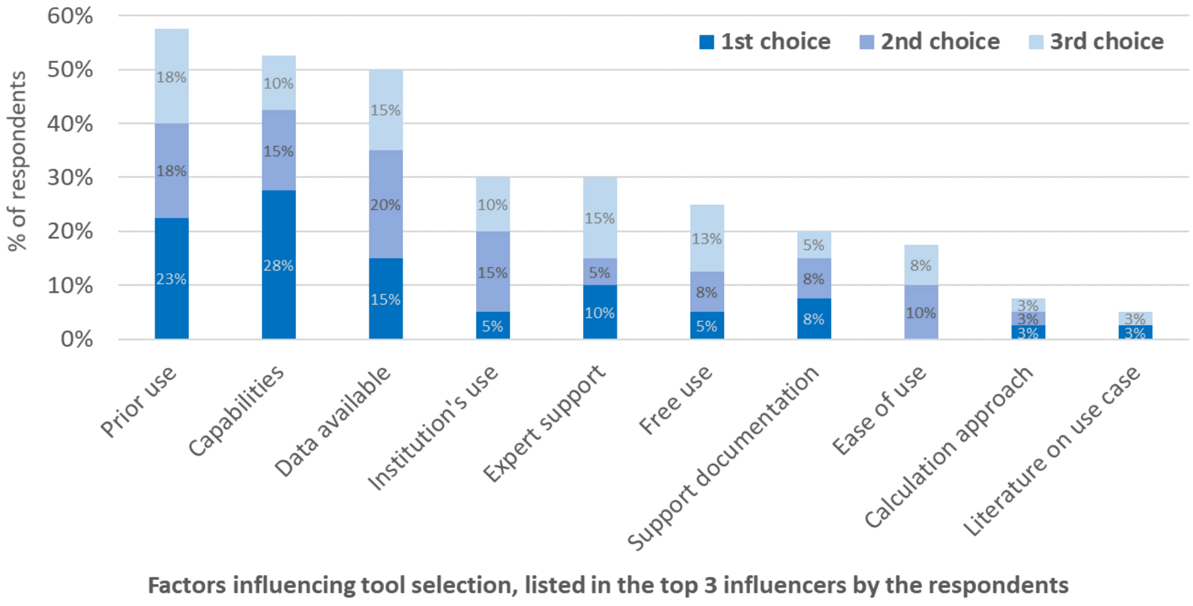

Figure 0.1: Factors influencing modelling tool selection: Proportions of survey respondents selecting a factor as one of the top three factors influencing their decision of which tool to use

Participants were also asked to score the ease of use for tools with which they are familiar in terms of the tool’s interface, documentation and support. Scores were on a scale of 1 (poor) to 5 (excellent), with 3 being satisfactory. On average, the frequently used tools received relatively similar above satisfactory scores (between 3 and 4). However, MIKE-SHE received the lowest user scores across this set with 3 for interface and 2.1 for documentation.

Model structure intercomparison

Viewed at a very basic level, the five catchment modelling tools under review are similar in the following notable ways:

- **Catchments divided into subcatchments:** All the tools can represent a larger catchment as an accumulative flow network of smaller subcatchments. In this way they are all 'semi-distributed' to a certain extent, allowing the spatial distribution of climate and catchment properties to be explicit in a model. MIKE-SHE also offers a 'fully distributed' (3D grid) representation as an option.
- **Same major vertical layers:** All tools represent hydrological processes for the same broad set of vertical layers – vegetation canopy and land surface, soils/unsaturated zone, and aquifer materials – that are then linked to a channel network.
- **Multiple land cover types per subcatchment:** All the tools allow different land cover types to be explicitly represented across different subcatchments and within them. At a minimum (with some tools allowing more), within each subcatchment, all the tools can explicitly represent the following:
  - A dominant generalised vegetation type per subcatchment (i.e. local indigenous veld, non-irrigated grazing land)
  - A separate tree-dominated vegetation type per subcatchment (e.g. forest, commercial tree plantations, invasive alien tree stands)
  - An area of irrigated crops
  - Impervious cover (urban area, bare rock).
- **Reservoirs, dams or water bodies:** All tools can include reservoirs, dams or water bodies fed by the channel network.

Table 0.2: Structure overview across the modelling tools

Structure characteristic	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE Semi-distributed, more conceptual**	**MIKE-SHE Distributed, more physical**
Timestep	Monthly* *(daily versions exist; limited use to date)*		Daily	Daily, subdaily	Daily, subdaily* *(dynamic timesteps by process; outputs saved for selected step)*	
Spatial discretisation	Modules connected by routes *(runoff modules' + special area modules + channel modules create subcatchments)*	Subcatchments + limited internal sub-area types	HRUs within subcatchments		Gridded surface and soils + zones within subcatchments: overland flow, interflow, baseflow reservoirs	Gridded (3D), no subcatchments *(topography is explicit: flow is dictated by gradients)*
Spatial model units for:						
Climate input	Modules	Subcatchments	Subcatchments or HRUs* **laborious*	Subcatchments	Grid cells or zones	Grid cells or zones
Surface and shallow subsurface processes	Runoff modules + special area modules	Subcatchments (+ internal special sub-areas)	HRUs		Grid cells + overland flow zones + interflow reservoir zones	Grid cells

Structure characteristic	WRSM-Pitman	SPATSIM-Pitman	ACRU4	SWAT2012	MIKE-SHE Semi-distributed, more conceptual	MIKE-SHE Distributed, more physical
Ground water processes	Runoff modules	Subcatchments	HRUs	Subcatchments	Baseflow reservoir zones	Grid cells
Channel processes	Channel modules, flexible connections to other modules	Single channel unit within a subcatchment	Channel units with flexible connections to HRUs and dams within a subcatchment	Single channel unit within a subcatchment	Spatially and topographically explicit channel reaches between nodes, connects to bordering landscape units (surface and subsurface), flexible spatial layout	
Waterbodies (optionally added)	Reservoir modules, flexible connections to other modules	Single reservoir at outlet of subcatchment channel (not for irrigation) + single/lumped dam internal to subcatchment (can irrigate)	Dam units with flexible connections to HRUs and channels within a subcatchment	Single reservoir at outlet of subcatchment channel (can irrigate) + pond and depression units internal to subcatchment (not for irrigation)	Storage created with explicit bathymetry cross-sections in channel reach set-up (can irrigate) OR Simple storage unit attached to reach (not for irrigation)	

HRU = hydrological response unit

However, despite their high-level similarities, there are numerous differences in how the tools allow users to discretise and represent various components of catchments, in terms of scales, unit types and connections (see overview in Table 0.2), as well as in the process algorithms used to calculate flows in and out of the different modelled units. These differences have implications for what a model can represent explicitly and for how model-building decisions, such as discretisation into subcatchments and other model units, parameterisation, etc., influence process representation.

SPATSIM-Pitman and WRSM-Pitman run monthly timestep models. The subcatchment is the primary unit for representing processes. In both tools, a subcatchment is represented with one basic land cover type onto which a restricted set of additional cover type sub-areas can be added. In SPATSIM, these are input as portions of the subcatchment. In WRSM, most additional cover types are established with special modules tied to a runoff module. Alone, the runoff module represents the subcatchment as if these additional cover types were not present. An exception is impervious cover, which is specified within the runoff module. In both tools, the additional sub-areas or modules serve to modify the subcatchment-scale process calculations, i.e. subcatchment-scale soil and ground water storages with thresholds controlling surface runoff, interflow and ground water flow. A partial exception is the WRSM's irrigated area module, for which surface and shallow sub-surface runoff are calculated more independently. A significant difference between these two tools is the modular structure of WRSM, which allows more flexible representation of landscape linkages to channel and reservoir units and more differentiated irrigated areas tied to different water sources.

Both ACRU4 and SWAT2012 calculate surface and shallow subsurface processes at the scale of a hydrological response unit (HRU), each HRU having land cover and soil properties. However, they differ in subsurface representation. Each ACRU4 HRU has its own baseflow store, while SWAT2012 models aquifers at the subcatchment scale. Percolation from SWAT HRUs is routed to the subcatchment's aquifer units (shallow and deep).

Both tools generally route lateral HRU outflows directly to a linked channel unit in parallel. This applies to ‘quickflow’ and ‘baseflow’ in ACRU4 and ‘surface flow’ and ‘lateral flow’ (interflow) in SWAT2012. Purely parallel routing would mean that upslope areas would not influence lowlands if these were separate HRUs. However, both tools have optional routines and settings to represent aspects of hillslope connectivity. In ACRU4, special riparian HRUs can be established. The ‘baseflow’ output produced by non-riparian HRUs can be routed to the soil of the riparian HRU. In SWAT2012, access to the subcatchment aquifer for evapotranspiration (ET), representing capillary rise, can be specified differently by HRU. Lowlands can be set to access more, while uplands provide recharge. Neither tool includes the explicit routing of surface flows across a hillslope series of HRUs. Both generally calculate all processes for a daily timestep, although SWAT2012 models can use subdaily timesteps given subdaily climate input.

MIKE-SHE has notably different structural approaches to the other tools. The catchment area is broken up into uniformly sized grid cells, which have explicit surface elevations and thicknesses of underlying material. Climate, cover and subsurface properties are input for mapped zones that do not need to align. Each cell can have a unique combination. Infiltration, ET, soil storage and percolation are calculated for each cell. There are different options for representing surface and subsurface flows. When fully distributed, surface and subsurface water can move from a cell to a neighbouring cell based on relative water elevation or ground water head. Cells bordering a channel can exchange water with it. No subcatchment boundaries are needed. Alternatively, surface flow can be routed across a series of mapped hillslope zones within a subcatchment. Surface water generated by cells in a zone is lumped and routed to the next zone or channel. Detention and infiltration can occur on the path. For subsurface flows, interflow and aquifer storage and outflow can optionally be represented using linear reservoir units within subcatchments. Interflow reservoirs and baseflow reservoirs have explicit and potentially different spatial extents. Interflow reservoirs receive percolation from grid cells that overlie them and can recharge the baseflow reservoir below. Interflow is routed through a hillslope series of interflow reservoirs, while baseflow reservoir outflows are routed in parallel. Processes can be calculated for different timesteps for the overland, unsaturated zone and saturated zone processes with steps becoming shorter when there is more flow. If daily climate inputs are used, the model will subdivide this internally.

In addition to these obvious differences in the basic spatial structure of a catchment model, the tools were also found to differ in their options for the following:

- The spatial scales at which climate inputs can be specified
- The vertical discretisation of soils, other unsaturated zone material and aquifers into layers
- Connections between landscape and channel units (e.g. overbank flooding, transmission loss)
- The explicit representation of ground water flow between subcatchments
- The inclusion of ground water withdrawals and where this water can be routed
- The positions and hydrological linkages of waterbodies and wetlands
- The storages from which irrigation water can be drawn
- The ability to change land cover and reservoir parameters over time during a model run

These differences across the tools are described in section 4.4 of this report.

Process algorithm and parameter intercomparison

Linked to the differences in scale (temporal, spatial and vertical), the algorithms for calculating various hydrological processes differ across tools. The functions applied determine the input parameters needed, their meanings and how appropriate values can be determined. Algorithms for different processes were presented side by side across the tools using common terminology, and are compared in section 4.5 of this report. In general, for this set of tools, the MIKE-SHE algorithms for the fully distributed options required the greatest number of input parameters. However, these were mostly properties that, in theory, could be measured in the field (e.g. soil-saturated hydraulic conductivity, leaf area index).

WRSM and SPATSIM-Pitman required the fewest parameters, but, for the most part, these were more conceptual and so based on regionalisation and/or local calibration. SWAT2012 and ACRU4 fell in between, with both measurable physical property parameters and several important conceptual parameters, such as the SCS-Curve Number parameter in SWAT2012 or the quickflow response coefficient (QFRESP) in ACRU4.

Viewed broadly, many of the algorithms have similar forms and input types across the tools, simply because the same physical process is being approximated. For example, in all tools, the calculation of infiltration versus surface runoff generation for a landscape unit (a subcatchment, HRU or grid cell) requires the calculation of maximum potential infiltration for the timestep, which is then compared to the water reaching the soil surface in the timestep. Excess becomes surface flow (infiltration excess runoff). In all tools, this maximum potential infiltration is linked to the unit's soil moisture at the time and becomes zero at saturation (saturation excess runoff). However, the relevant input value for saturation soil moisture, and the means of calculating the maximum potential infiltration, is necessarily different for a subcatchment-scale soil storage unit and a monthly timestep (Pitman tools) compared to the upper layer of a grid cell's soil profile and an hourly timestep (MIKE-SHE). Process algorithms to represent interflow and ground water flow diverged more across the tools than surface processes, linked to the greater differences in subsurface layers, units and connections across the tools.

When different tools call for the same physical property parameter, but the parameter is applied at different spatial and/or temporal scales, one would expect appropriate values to differ. Further to this, however, it was noted that a few common physical property parameters are used in different ways and in algorithms with different mathematical forms across tools using potentially similar scales. For example, MIKE-SHE uses soil-saturated hydraulic conductivity to calculate infiltration and percolation, while SWAT2012 uses it to calculate percolation and interflow, but not infiltration. MIKE-SHE uses Leaf Area Index (LAI) to calculate canopy interception and ET, with the Kristensen-Jensen equation (Kristensen and Jensen, 1975). SWAT2012 uses LAI to calculate ET either in the Penman-Monteith equation (Monteith, 1965; Penman, 1948) or in estimating a crop factor with which to adjust a reference potential evapotranspiration (PET). This means that using the same property value at the same scale will not necessarily produce the same predicted flux across tools. However, each modelled process is linked to other processes, which also have different algorithms across the tools, and so the calculation of a flux seldom hinges on a single parameter. Nevertheless, the algorithm differences can mean that, for the same physical property and scale, different parameter values might produce more realistic outcomes in different tools.

In a few cases, it was noted that a process explicitly represented by most tools reviewed was not directly included in a particular tool (details presented in section 4.5 of the report). For example, ACRU4 does not directly represent channel transmission loss: water in a channel cannot move directly into soil or ground water in the model. SWAT2012, when run at a daily timestep, does not explicitly represent canopy interception. Interception is implicitly represented in the application of the Soil Conservation Service-Curve Number (SCS-CN) approach (USDA, 1954) to estimating runoff generation. However, all water that does not become runoff is assumed to infiltrate the soil in the model. If a process that is not explicitly represented is significant in a catchment, it would need to be implicitly represented, most likely in the parameterisation of other processes.

Implications of structural and process representation differences

Some of the structural differences across the tools manifest as differing capabilities in terms of what processes or aspects of spatial or temporal variability can be explicitly represented. A summary of capabilities across tools is presented in Table 0.3. All the tools had most of the capabilities listed, while no one tool had all of them. In many cases, differences between tools were in how a process was represented, rather than whether it could be explicitly represented or not.

Table 0.3: Modelling tool capabilities overview

Capability	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE**
Climate (rain and PET)					
Spatially variable across model domain	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Spatially variable within subcatchment	*(limited)*	No	*(limited)*	No	**Yes**
Inter-annual variability in PET	No	**Yes**	**Yes**	**Yes**	**Yes**
Land cover and change					
Processes explicitly linked to land cover	*(limited)*	*(limited)*	**Yes**	**Yes**	**Yes**
Multiple land cover types included	*(limited)*	*(limited)*	**Yes**	**Yes**	**Yes**
Cover has explicit location in subcatchment	*(limited)*	No	*(limited)*	*(limited)*	**Yes**
Cover can vary over model run timespan	**Yes**	No	*(limited)*	**Yes**	*(limited)*
Irrigation + dynamic demand and supply	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Potential direct ET from ground water (deep root)	**Yes**	**Yes**	*(limited)*	*(limited)*	**Yes**
Peak flows and flooding					
Maximum daily or subdaily peak flow estimation	No	No	**Yes**	**Yes**	**Yes**
Explicit impacts of channel capacity on flow	*(limited)*	*(limited)*	*(limited)*	*(limited)*	**Yes**
Calculation of flooded area extent	*(limited)*	No	*(limited)*	*(limited)*	**Yes**
Flood water subject to infiltration, ET, etc	*(limited)*	No	**Yes**	No	**Yes**
Reservoirs, dams and channel flow modification					
Reservoirs explicitly modelled	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Facility to represent many small dams	**Yes**	**Yes**	*(limited)*	*(limited)*	No
Abstractions and external inputs	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Internal transfers between model units	**Yes**	No	**Yes**	**Yes**	*(limited)*
Ground water representation and ground water-surface water interactions					
Dynamic, two-way, ground water-surface water exchange	**Yes**	**Yes**	No	*(limited)*	**Yes**
Ground water table elevation predicted	*(limited)*	*(limited)*	No	*(limited)*	**Yes**
Ground water pumping included	**Yes**	**Yes**	No	**Yes**	**Yes**
Wetlands and riparian zones					
Wetland processes included	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
On-channel wetlands	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Off-channel wetlands (fed by channel spill)	**Yes**	**Yes**	**Yes**	No	**Yes**
Ground water fed (receive fround water from surroundings)	*(limited)*	*(limited)*	*(limited)*	*(limited)*	**Yes**

Capability	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE**
Other catchment and vegetation processes					
Sediment movement	No	No	**Yes**	**Yes**	**Yes**
Water quality	No	No	**Yes**	**Yes**	**Yes**
Crop yield	No	No	**Yes**	**Yes**	No
Uncertainty and parameter calibration					
Tools for uncertainty, parameter sensitivity and auto-calibration (batch runs)	No	**Yes**	No	No	**Yes**

The specific implications of the differences across tools and their real importance for a modelling project will differ across use cases. These will be dependent on the combination of the type of catchment, the changes that are to be modelled, the data available and the types and scales of model outputs that are needed. This makes it challenging make generalisations about the relative importance of particular differences. However, the case study modelling exercises helped highlight some issues that may come to the fore in common use cases.

In the case study modelling exercise, for each catchment modelled, various process representation issues became salient when trying to decide on appropriate model structures for each tool. For some of these highlighted issues, the concern was not that the tools did not represent the desired processes, but rather that their approaches were so different that it was difficult to determine how to set them up comparatively. This was the case for representing water access by riparian zone vegetation, which was relevant in several case studies, and how interflow is represented and how subsurface layers are defined, which is particularly relevant in the steep, rocky Upper Berg case study. On the other hand, the Letaba case study highlighted some straightforward differences in capability, i.e. only SWAT2012 and MIKE-SHE directly represented irrigation from ground water. However, SWAT2012 and MIKE-SHE made it more difficult than the other tools to represent many small farm dams and to have these used as irrigation sources.

A cross-cutting issue brought to light during the exercise was that trade-offs in process representation may need to be considered when deciding how to delineate subcatchments. This came to the fore for the Kromme, a larger catchment with both mountainous and lowland areas and a rainfall gradient. With the exception of MIKE-SHE, the tools generally specify climate inputs by subcatchment. At the same time, different tools limit the modelled surface and subsurface flow connections between subcatchments in different ways. In the Kromme, the valley aquifer and soils are fed by both surface and subsurface flows from the mountains (Cornelius et al., 2019; Tanner et al., 2019). When model subcatchments were delineated to explicitly include the climate gradient between mountains and lowlands, modelled flow connections in the landscape became limited and various purposeful tool-specific adjustments were needed for the lowland vegetation to have realistic access to water.

Looking at model performance across the case studies, there was no consistent pattern of over- or underprediction of streamflow with the different tools across the different case studies. Model performance by tool varied by case. This demonstrated that model performance is not only a function of the capabilities of the tool to represent local processes, but also input data, performance evaluation data and the many decisions made by modellers.

An important finding was that models with comparable performance against observed streamflow could potentially be built using any of these tools, but their modelled water balances and the magnitudes of change they predict when applied to different scenarios could differ substantially. Despite predicting relatively similar runoff generation for the baseline case, the modelled contributions from surface and subsurface sources differed across models. Modelled contributions to total ET, from canopy interception and ET drawn from soil and ground water, also differed. Figure 0.2 demonstrates this for the Upper Berg models.

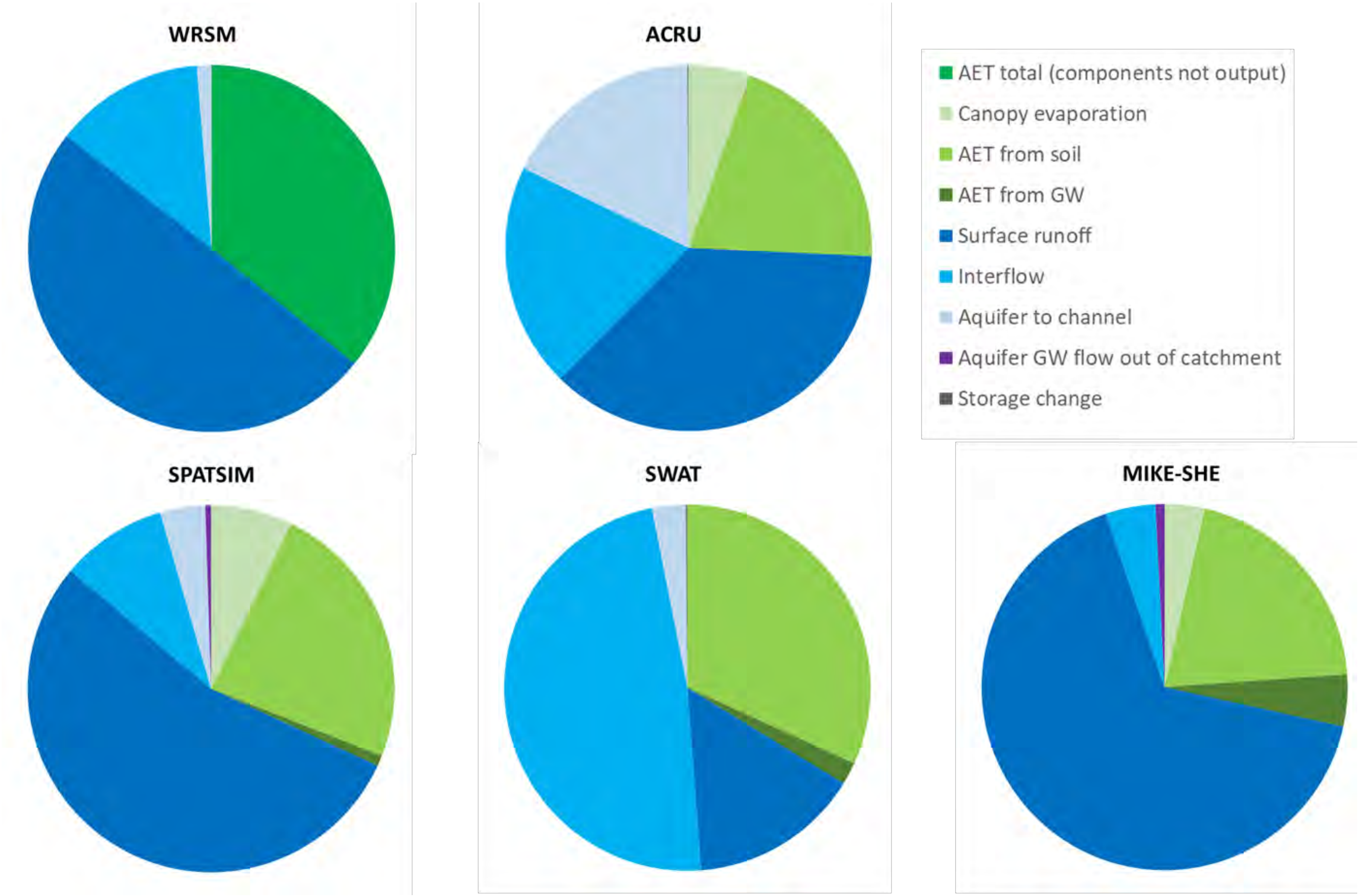

Figure 0.2: Modelled mean annual fluxes for the Upper Berg catchment for 2006-10-01 to 2018-09-30, predicted using five different modelling tools shown as proportions of catchment mean annual precipitation

NB: Not all fluxes are explicitly modelled by all tools.

This occurred for multiple case studies, even though the model set-ups were all informed by the same set of catchment property data and information. Differences in process representation in the baseline models meant that the streamflow predictions became more divergent when the alternative scenarios were applied. In the most extreme example, modelling the impact of clearing eucalyptus from 12% of the Mistley catchment to restore the wetland, predicted that increases in mean yield would range from 4% to 34% across different models (Table 0.1). This variability in prediction was found across models built using different tools in this exercise. This could also occur across different models built using the same modelling tool, but with different structures due to different set-up choices made by the user.

The practical challenges in extracting and processing various water balance outputs meant that water balances were only compared across these models post-hoc, not during calibration in this exercise. The results highlighted the importance of assessing modelled water balances, ideally using information sources beyond catchment outlet streamflow, such as ground water, soil moisture, evapotranspiration, and/or water chemistry data, to validate its realism during the model building and calibration process. This is currently difficult to do in practice in many cases, both because there is generally limited auxiliary data available to assess the water balance, but also because obtaining these model outputs is very time consuming in several of the tools. However, without this, it is hard to discern which of the divergent modelled outcomes is more realistic. The uncertainty of the modelling exercise remains high.

Modelling tool interface differences and implications

The user interfaces of modelling software tools can notably influence the overall approach of the modeller and the resulting structure of the model. Cumbersome model set-up processes reduce what can be achieved in a given time and can more easily result in user error in the set-up. They also incentivise the simplification of the model structure. This can have some benefits: prompting more careful consideration of the level of detail necessary and reducing the potential for over-parameterisation. However, it could also lead to the simplification of details that might assist model performance, such as limiting the number of areas with differentiated climate inputs. The ease with which parameter values can be adjusted and batches of models run can facilitate sensitivity analyses, uncertainty analyses and calibration. The ease with which water balance outputs can be obtained can facilitate more sense-checking of the process representation.

The process of setting up models was found to differ significantly across the tools. ACRU4 and WRSM-Pitman have the most manual and laborious set-up processes of those reviewed: every modelled unit (HRU or module) and connection is individually set up by the user, moving through a series of menu windows for each one. This provides control and flexibility in design, but is time consuming, and can be error-prone in complex set-ups. Neither tool makes it simple to specify or edit parameter values in batches, e.g. for all units of a given cover type. In contrast, SWAT and MIKE-SHE use spatially explicit map inputs of topography, land cover and soil types, and for MIKE-SHE, aquifer types, to drive an automated set-up of units, connections and parameter assignments. Parameters are entered by land cover type and soil type, and are automatically assigned to all relevant model units. The automated derivation of the structure from map inputs increases efficiency and reduces the opportunity for certain kinds of user errors. It can also limit possibilities for some structural decisions and simplifications that may be helpful, like lumping many small farm dams or lumping several parallel tributaries into one conceptual subcatchment. SPATSIM subcatchment parameters are perhaps the most efficient to both input and alter as they are input as series of externally prepared tables.

ACRU4 and SWAT2012 both have built-in vegetation and soil type parameter databases that users can opt to use. This can significantly speed up model set-up, although it can lead to the use of inappropriate parameter values if database values are used without local evaluation. The SWAT databases were developed primarily in the USA, while the ACRU Compoveg and Autosoils databases were developed for South African vegetation and soil types.

MIKE-SHE does not include an in-built parameter database. However, its input file structure allows users to build their own databases across models. Users can also add entries to the SWAT2012 database, which can be used in different models, although the mechanism of adding this to new models is less obvious. The ACRU4 databases are not easily editable for general users.

Batch-run facilities and autocalibration routines are available for MIKE-SHE, ArcSWAT2012, and SPATSIM, while they are not available for ACRU4 and WRSM. For SWAT, this is an independently produced software: SWAT-Calibration and Uncertainty Program (SWAT-CUP) (Abbaspour, 2015). For all three tools, the user can select which parameters to vary across a set of runs, the value ranges over which to test them (and value probability distributions if desired) and the objective functions with which to calculate or evaluate the performance of each parameter set. There are also facilities to run a batch of user-specified parameter sets to test specific values or combinations of interest, rather than having the tool generate sets across the ranges provided. For MIKE-SHE AutoCal and SWAT-CUP, the process of setting up the tool with its links to the base model is relatively intensive and has a fairly big learning curve at the outset, whereas the SPATSIM tool is more simply and easily integrated.

The tools also differed in terms of how easy it is to export certain water balance outputs for different scales. All tools make it simple to obtain the catchment outlet streamflow. However, obtaining catchment-scale-modelled ET or interflow contributions, for example, was less straightforward. This was found to be most challenging for WRSM-Pitman and ACRU4, with WRSM-Pitman being the most laborious per module. For ACRU4, WRSM-Pitman and SPATSIM-Pitman, most modelled outputs need to be exported for each model unit, i.e. HRU or subcatchment, and externally processed to get catchment-scale estimates for various fluxes. SWAT2012 and MIKE-SHE make water balance export at different scales somewhat simpler, although some outside processing is generally required. Depending on the tool and the complexity of the model set-up, it can be an intensive process to check whether a model is predicting the water balance in agreement with one's conceptual model of the catchment's processes or with any auxillary data when available. The implication of the time and effort needed is that it is not likely to be common practice to do so.

GUIDANCE WIKI INITIAL CONTENT

The overall structure of the wiki website (HydroModel SA wiki: https://hydromodel-sa-wiki.saeon.ac.za/) has been built and much of the envisioned initial content has been put on the site. The initial content will be finalised after review by the project reference group and additional project advisors to be ready for public launch in October 2021. It is intended to be a living resource to which the model user community can contribute.

Pages are organised into general content types, linking to pages on more specific topics. The site has a search function to aid navigation. The main topic groupings and pages are as follows:

- Site introduction: Main page, wiki scope, content team, discussion page instructions
- Modelling background: Terminology, modelling process overview, model types and tools
- Tool intercomparison: Capabilities overview, units and connections, process representation, water balance outputs, user interfaces, documentation and support, specific use cases
- Resource links: Tool documentation, data sources, intercomparison study project report

The site has discussion pages, automatically associated with each content page, where any user who creates a log-in can post suggestions or participate in a discussion thread. A site administration team will update content pages in response to user input. Some project team members will likely stay engaged in this, but the site would benefit from having tool developers and curators in the group. The process of content management would be developed by this initial group with a strategy for rotating team membership over time. The revived SANCIAHS and hydrology community of practice group are growing communication channels and fora that will assist in spreading awareness of the site and finding potential content management volunteers in future.

KNOWLEDGE DISSEMINATION AND CAPACITY BUILDING

The hydrological modelling wiki website initiated by this project is intended to facilitate capacity building for both new and experienced modellers, and those who use model outputs. It provides a platform to learn and exchange knowledge around modelling and the use of different modelling tools. It is a resource that can have ongoing improvement directed by its users and so has a potential long-term capacity-building impact in the sector.

The project has also significantly built the capacity of the project team. This project was initiated by a team of early career hydrologists. The team consisted of five postdoctoral researchers, an early career researcher and two postgraduate students. This group gained exposure to all the modelling tools reviewed, engaged in modelling process workshops and learnt to create content on the wiki website. The team is spread out geographically and across institutions, with representatives from SAEON, the University of KwaZulu-Natal, Rhodes University, the University of the Western Cape, the University of Cape Town and Stellenbosch University. Each member interacts with different students, researchers, organisations and stakeholders who can benefit from what has been learnt. Beyond academia, expert advisors in the consulting sphere were also involved in the learning process.

CONCLUSIONS AND THE WAY FORWARD

This study is the first of its kind to compare the structures, process representation options and interfaces of these catchment modelling tools side by side. The comparison demonstrated that the tools have high-level similarities in basic capabilities, but also many notable differences in model spatial units and subsurface layers, flows between layers and units, the scale at which climate inputs are specified, algorithms that calculate flows and timesteps used. These result in differences in what can explicitly be modelled and result in differences in modelling results, particularly when applied to scenarios of change. Tool interfaces differ significantly, influencing set-up efficiency and transparency, the ease with which the range of plausible parameter values can be explored for calibration and uncertainty analyses, and the ease with which different water balance outputs can be obtained to assess model realism. Each tool was found to have some type of advantage over others for specific applications or aims. Using the information brought together in this project and made accessible through the wiki website, modellers can more easily and objectively assess the tools in light of the needs of their modelling projects: the type of catchment, the questions to be answered, the outputs needed, the data and the time available.

The intercomparisons and case study modelling highlighted the need to not only consider parameter uncertainty, but also model structural uncertainty, and the need to not only assess modelled streamflow outputs, but also evaluate the modelled water balance before extending models to scenarios. This exercise demonstrated that, with the levels of data commonly available in South Africa, various different model structures and parameterisations can be reasonably justified, all of which may produce baseline streamflow outputs that would be deemed acceptable in practice, but which could predict significantly different amounts of change when applied to alternative scenarios. This uncertainty in prediction generally goes unaccounted for if only one model structure is tested and applied. This can have important implications for decision making in water resources management.

Resolving which models represent processes realistically, and so reduce prediction uncertainty, often requires additional process data, such as ET, soil moisture and/or ground water levels. Remote-sensing products can assist, but these require extensive calibration with field data. As such, the project findings strongly show the need for more long-term climate and streamflow data and more field data on various catchment processes. Meteorological and hydrological monitoring has declined in recent decades in South Africa and the water sector relies on modelling to fill the gaps. However, there is likely much more uncertainty in this approach than is generally accounted for.

The project identified further activities to continue exploring and improving the use of hydrological modelling in South Africa. These include outreach and dialogues across the sector, and tool and method developments.

This project looked at differences between modelling tools, but not differences in how one tool may be applied by different individual users. Modeller experience may significantly impact outputs. Variability across tools and users could be explored in a participatory modelathon activity, which would also be a catalyst for reflection and discussion on practice in the sector.

Looking at tool and method development, the South African modelling tools were found to be the most frequently used and – with the exception of SPATSIM – have the most time-consuming interfaces for implementing parameter sensitivity analyses, and accessing and analysing water balance outputs. To improve their applied use, their software interfaces require investment to make these critical assessments easier and quicker to implement. In addition, research on operationalising water balance and process representation assessments for commonly used tools is needed. Different approaches would be necessary to compare model outputs to different auxiliary data types across different tools given their structures, scales and outputs.

It is hoped that this project, and the HydroModel SA wiki site, will contribute to grow the number of well-equipped modellers by helping people engage with modelling tools and foster the practice of “looking under the hood” of the models to ensure that they are put to appropriate use. This will help improve decision making around the management of water, an extremely scarce and over-exploited resource in South Africa.

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ACRONYMS AND ABBREVIATIONS

2LWB	Two-layer water balance
3Di	Delft University of Technology, Deltares, Nelen and Schuurmans
ACRU	Agricultural Catchment Research Unit
AET	Actual evapotranspiration
ARC	Agricultural Research Council
AWBM	Australian Water Balance Model
AWC	Available water holding capacity
CF	Capillary fringe
CI	Canopy interception
CSC-CN	Soil Conservation Service-Curve Number
CUP	Calibration and Uncertainty Program
CWRR	Centre for Water Resources Research
DEM	Digital Elevation Model
DHI	Danish Hydrologic Institute
DUL	Drained upper limit
DWS	Department of Water and Sanitation
E	Evaporation
E_m	Maximum evaporation
E_r	Reverence potential evaporation
E_t	Plant transpiration
ET	Evapotranspiration
ET_{rate}	Evapotranspiration rate
ET_{ref}	Reference evapotranspiration
FAO	United Nations Food and Agriculture Organisation
FC	Field capacity
FDC	Flow duration curve
FF	Full forestry
FT	Interflow rate

GF	Gravity flow
GIS	Geographic Information Systems
GRA	Groundwater Resource Assessment
GW	Ground water
GW-SW	Ground water-surface water
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modelling System
HEC-RAS	Hydrologic Engineering Center – River Analyses System
HRU	Hydrological Response Unit
HSPF	Hydrological Simulation Program – FORTRAN
Ia	Initial abstraction
IAP	Invasive alien plants
IAPx	Extreme IAP coverage
IFR	Interflow reservoir
IR	Infiltration rate
IWR	Institute of Water Resources
K_c	Crop coefficient
LAI	Leaf Area Index
LL	Lower layer
MAE	Mean absolute error
MAP	Mean annual precipitation
MAR	Mean annual runoff
MPF	Macropore flow
NLC	National Land Cover
NRF	National Research Foundation
NSE	Nash-Sutcliffe Efficiency
PE	Pan evaporation
PET	Potential evapotranspiration
Q	Streamflow
QFRESP	Quickflow response coefficient
R	Shape parameter

R^2	Correlation
RE	Recharge
RHESSys	Regional Hydro-Ecological Simulation System
RM	Runoff Module
RMSE	Root mean square error
RO	Runoff
RU-HEC	Rhodes University Human Ethics Committee
RWL	Resting water level
SAEON	South African Environmental Observation Network
SANCIAHS	South African National Committee of the International Association of Hydrological Sciences
SAT	Saturation
Sat SM	Saturation soil moisture
SAWS	South African Weather Service
SEBEI	Socio-economic Benefits of Ecological Infrastructure
SHE	Système Hydrologique Européen
SL	Drainage limit
SM	Soil moisture
SMHI	Swedish Meteorological and Hydrological Institute
S-pan	Symon’s pan
SPATSIM	Spatial and Time Series Information Modelling
SRO	Surface runoff
ST	Saturation moisture
SW	Surface water
SWAT	Soil and Water Assessment Tool
SWL	Static water level
SZ	Saturated zone
TMG	Table Mountain Group
ToC	Time of concentration
TU-Delft	Delft University of Technology

UKZN	University of KwaZulu-Natal
UL	Upper layer
USACE	United States Corps of Engineers
USDA-ARS	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UZ	Unsaturated zone
VIC	Variable infiltration capacity
VPD	Vapour pressure deficit
VZ	Vadose zone
WARMS	Water Use Authorisation and Registration Management System
WB	Wetland buffer
WCT	Water Quality Tool
WEAP	Water Evaluation and Planning System
WF	Wetting front
WP	Wilting point
WR2012	Water Resources 2012
WRC	Water Research Commission
WRPM	Water Resource Planning Model
WRSM	Water Resources System Model
WRYM	Water Resource Yield Model

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Catchment hydrological modelling has become a critical component of water resource management in South Africa. Modelling is used to predict catchment inputs to water supply reservoirs, estimate flows in ungauged catchments, and assess the likely impacts of land cover and climate changes, among other applications. A plethora of modelling tools is available, with different approaches and structures for representing hydrological processes. Given the existing and growing reliance on modelling to inform catchment and water management decisions, there is a need for continued research and capacity building that enables the water sector to take full advantage and make wise use of the diversity of modelling strategies and tools.

Different catchment hydrological modelling tools, such as WRSM-Pitman (Bailey and Pitman, 2015; Pitman, 1973), ACRU (Schulze, 1986; 1995; Schulze and Davis, 2018) or SWAT (Arnold et al., 1998; Neitsch et al., 2011), have different structural options, algorithms and formats. These differences have implications on the input data and assumptions needed in model set-up, the model's outputs for different variables and scales of interest, the types of scenarios and changes that can be explicitly considered using the tool, the quantification of uncertainty and the computing resources needed. The modeller must determine what type of model structure to use for a given setting and modelling question and which modelling tool to use to achieve this. All modelling tools have different advantages and disadvantages. While there will not be a single best choice of tool for a given use case, there will be more or less appropriate and advantageous ways of applying a selected tool. A comparison of structural options of different modelling software tools, and an exploration of the implications of these when applied, would be of use in the modelling process, particularly for newer modellers entering the water research and management sectors. Such analyses would provide the basis for giving guidance on determining suitable model structures and using modelling tools to achieve these.

This project emerged from the shared experience of several early-career researchers involved in catchment-scale hydrological modelling and faced with the task of selecting modelling approaches and tools. It was timed to take advantage of modelling work being done for the Socio-Economic Benefits of Ecological Infrastructure (SEBEI) project, focused on the uMngeni, Berg and Breede catchments, and various initiatives in the Kromme catchment: the Algoa Water Fund, recent Water Research Commission (WRC) projects (K5-2527 (Cornelius et al., 2019) and K5-2548 (Tanner et al., 2019)) and other ongoing academic and applied research in the area. These projects provided a useful opportunity to explore multiple modelling tools in practice by applying them to case study catchments for which the project team has developed an understanding and a database. Additional areas will be added to diversify the application settings considered. Experiences and learning from the modelling tool application process will be supplemented by consultation with modelling experts, particularly those curating and developing the modelling tools, and a systematic structural review based on model documentation and literature regarding these tools.

1.2 PROJECT AIMS AND OBJECTIVES

Aim

Provide informed and accessible guidance that can assist modellers selecting and applying commonly used catchment modelling tools in South Africa for typical use cases.

Objectives

- Review and compare the structures and structural options in a selection of commonly used catchment modelling software tools in South Africa

- Apply a set of catchment modelling tools to a diverse set of case study catchments and scenarios of change to allow for more quantitative exploration of the implications of structural differences
- Document user experiences with the tools through application to the case studies, workshops and other interactions
- Synthesise the resulting data and information to produce guidance material for modellers

1.3 PROJECT APPROACH OVERVIEW

The modelling tools and versions selected for intercomparison in this project were as follows:

- **ACRU**, Agricultural Catchment Research Unit model, ACRU4 version (Schulze, 1986; 1995; Schulze and Davis, 2018)
- **WRSM-Pitman**, Water Resources System Model, WRSM2000 version (Bailey, 2015; Bailey and Pitman, 2015; Pitman, 1973)
- **SPATSIM-Pitman**, modified Pitman Model run through the SPatial And Time Series Information Modelling platform, SPATSIM v3 version (Hughes, 2013; 2019; Pitman, 1973)
- **SWAT**, Soil and Water Assessment Tool, SWAT2012 implemented with the ArcSWAT2012 interface (Arnold et al., 1998; Neitsch et al., 2011)
- **MIKE-SHE**, Système Hydrologique Européen, MIKE-SHE and MIKE-Hydro River 2019–2020 versions (Abbott et al., 1986; DHI, 2019a; Refsgaard and Storm, 1995)

Note: The coupled hydrologic-hydraulic system is together referred to as MIKE-SHE in this report for simplicity.

The number of tools included was limited to allow for depth in review and to make case study modelling across the set of tools tractable. These specific tools were selected for several reasons. They are already being used in the South African water sector, with WRSM-Pitman, SPATSIM-Pitman and ACRU being used widely, and SWAT and MIKE-SHE having more limited use to date. They are all appropriate for modelling at the meso-catchment or quaternary catchment scale, and are needed for most water resource management applications (Uhlenbrook et al., 2004). As a set, they encompass a variety of modelling approaches and structural types, and were developed locally and overseas under proprietary and open-access settings. Tool familiarity in the project team and the availability of local advising experts weer also considered. The versions of the software tools used were generally the most recent versions and/or the most public facing.

These tools were reviewed and compared using multiple approaches in this project:

- Going through theory and user documentation to look at their structural options and algorithms side by side
- Applying them to the same set of case studies to better understand practical and quantitative implications of their differences, including the software interfaces
- Surveying other model users about their use and experience with the tools

The review was an iterative process. Not all implications of the differences in model structure between the modelling tools were obvious from looking at their spatial structure and algorithms, particularly given their complexity and the range of settings, and hence parameterisations for which they would be applied. The modelling tools were applied to four case study catchments with a range of geomorphological and climatic settings to help elucidate potential differences in process representation in different conditions.

The findings of the review were synthesised into the initial content of a wiki website, HydroModel wiki SA (https://hydromodel-sa-wiki.saeon.ac.za/). The site is intended to be a living resource that the modelling community can continually update. It is aimed at both those relatively new to modelling and those who are already experienced, but may be interested in trying different tools for different applications and/or developing tools.

The material covers similarities and differences between the tools in terms of process representation and user experience, with a focus on implications for common use cases or use settings. Many factors influence what tool a modeller may use and the learning curves that prevent users from jumping between many. As such, part of the intent of the site is to provide suggestions for using any of the common tools in a given context: things to consider in model set-up, ways of implicitly representing processes that a tool cannot represent explicitly, etc. With the diversity of applications, scales and settings across which catchment-scale models are used, the goal was not to be exhaustive during the current project, but rather to establish a framework and platform for sharing this information.

It was recognised in the inception of this project that the user's model set-up decisions are as important, if not more important, than the choice of modelling software tool. For this reason, a 'modelathon' activity, in which several people independently model the same case-study catchment with a given tool, was proposed as an additional activity in this project. Unfortunately, there was insufficient time in the project to organise and host this. However, it would be an important addition to this effort.

1.4 BACKGROUND: MODEL TYPES AND MODEL INTERCOMPARISON

1.4.1 Catchment modelling approaches, structures and software tools

Different catchment model structures have arisen from differing approaches to model development. Models are often classified as physical, conceptual or empirical, which reflects the strategy applied when trying to numerically represent and predict the hydrological behaviour of a catchment. These general strategies, used individually or in combination, lead to different ways of breaking a catchment up into modelled units, representing hydrological processes with algorithms and parameters, and determining appropriate values for parameters. Modelling software tools encode modelling strategies, allowing users to build catchment models using a specified set of methods and algorithms (structural options) with varying degrees of flexibility. A wide variety of catchment modelling software tools is available with different built-in structural options and capabilities. A sample of relatively well-used models with some basic descriptors of structure and capability is given in Table 1.1 to demonstrate this diversity.

What are referred to as physical, mechanistic or process-based models aim to estimate water flows using as much physics, biology or chemistry-based understanding of individual processes as possible, developed from field and laboratory experiments. In this approach a catchment-scale model is built from the bottom up from individual smaller-scale processes: using algorithms that describe the current understanding of how the transpiration of an individual tree works, or how water moves in porous media, and linking all these finer-scale process descriptions together to predict the behaviour of the catchment as a whole. As understanding of individual processes becomes more detailed, so too can the models. In a pure form, all input parameters to the model algorithms would be measurable properties of different aspects of the catchment. In reality, the feasibility of measuring these properties at the scales they are sometimes applied can become infeasible. This makes the algorithms somewhat conceptual in practice and parameter values somewhat empirical in that appropriate values for given cases are found through model testing and calibration.

Another approach is to develop a catchment model from the top down (Sivapalan et al., 2003). As an empirical extreme, this can start with an attempt to find equations that approximate the outflow hydrograph given rainfall alone. Parameters, other inputs and compartmentalised representations are added, generally guided by conceptual understanding of hydrological processes when the additions improve model performance at the catchment scale. The resulting conceptual models are conceptualisations of dominant, emergent processes. The parameters and equations are not necessarily directly linked to individually measured or measurable physical properties and processes in a way that has been described because they were not derived in this way. They may be representing amalgamations of multiple processes and properties together that tend to co-occur: emergent properties of catchment systems at the scale being modelled. As such, numerically definable links between conceptual model equations and combinations of measured processes and/or between conceptual model parameters and combinations of individually measurable properties may be discovered post-hoc.

Table 1.1: Examples of commonly used and emerging catchment-scale hydrological modelling software tools and/or code (highlighted rows are tools selected for detailed review in this project)

Modelling tool	Current curator, developer or owner	Proprietary	Time-step	Spatial discretisation options*	Explicit impacts of land cover change	SW-GW: Two-way dynamic^
ACRU *Agricultural Catchment Research Unit model* (Schulze, 1986; 1995; Schulze and Davis, 2018)	University of KwaZulu-Natal (UKZN) Centre for Water Resources Research (CWRR)	No	Daily	Semi-distributed: HRUs (not catena) in subcatchments	Yes	No
FLEX – Topo (Savenije, 2010)	Delft University of Technology, Water Resources (TU-Delft)	No	Daily and sub-daily	Semi-distributed: HRUs (catena or not) in subcatchments	Yes	No
HBV *Hydrologiska Byråns Vattenbalansavdelning* (Bergström, 1976; 1995)	Swedish Meteorological and Hydrological Institute (SMHI)	No	Daily and sub-daily	Lumped/semi-distributed: subcatchment (zone option for snow and soil moisture)	Yes	No
HEC-HMS + HEC-RAS *Hydrologic Engineering Center – Hydrologic Modelling System and River Analyses System* (USACE-HEC, 2000; 2010; 2018)	US Army Corps of Engineers (USACE)	No	Daily and sub-daily	Semi-distributed: HRUs (not catena) in subcatchments	Yes	No
HSPF *Hydrological Simulation Program – FORTRAN* (Bicknell et al., 1993; Johanson et al., 1980)	US Environmental Protection Agency (USEPA) and US Geological Survey (USGS)	No	Daily and sub-daily	Lumped/semi-distributed: subcatchment or HRUs in subcatchments	Yes	No
HYPE *Hydrological Predictions for the Environment* (Arheimer et al., 2008; Lindström et al., 2010)	SMHI	No	Daily	Semi-distributed: HRUs (not catena) in subcatchments	Yes	No

Modelling tool	Current curator, developer or owner	Proprietary	Time-step	Spatial discretisation options*	Explicit impacts of land cover change	SW-GW: Two-way dynamic^
MIKE-SHE + MIKE-Hydro *Système Hydrologique Européen* (Abbott et al., 1986; DHI, 2019a; Refsgaard and Storm, 1995)	Danish Hydrologic Institute (DHI)	Yes	Daily and sub-daily	Distributed/semi-distributed: gridded or HRUs (catena or not) in subcatchments	Yes	Yes
WRSM-Pitman *Water Resources System Model* (Bailey, 2015; Pitman, 1973)	Water Research Commission (WRC)	No	Monthly (daily version exists)	Lumped/semi-distributed: subcatchments (internal subdivision options: irrigated, invasive alien plants, impervious)	limited direct (irrigated, invasive alien plants, wetland, impervious); other via indirect parameterisation	Yes
SPATSIM-Pitman *SPatial And Time Series Information Modelling platform* (Hughes, 2004; 2013; Pitman, 1973)	Rhodes University Institute of Water Resources (IWR), WRC	No	Monthly (daily version exists)	Lumped/semi-distributed: subcatchments (internal subdivision options: irrigated, invasive alien plants, impervious)	limited direct (irrigated, invasive alien plants, wetland, impervious); other via indirect parameterisation	Yes
RHESSys *Regional Hydro-Ecological Simulation System* (Running and Coughlan, 1988; Tague and Band, 2004)	University of California Santa Barbara	No	Daily	Semi-distributed: HRUs (catena routing) in subcatchments (patches in hillslopes in basins)	Yes	No
SWAT *Soil and Water Assessment Tool* (Arnold et al., 1998; Neitsch et al., 2011)	Texas A&M University and US Department of Agriculture (USDA-ARS)	No	Daily and sub-daily	Semi-distributed: HRUs (not catena) in subcatchments	Yes	no (some module exceptions)
TOPMODEL (Beven and Kirkby, 1979)	Lancaster University	No	Daily and sub-daily	Distributed: gridded	Yes	No
VIC *Variable Infiltration Capacity model* (Liang et al., 1994)	University of Washington	No	Daily and sub-daily	Distributed: gridded	Yes	No

Modelling tool	Current curator, developer or owner	Proprietary	Time-step	Spatial discretisation options*	Explicit impacts of land cover change	SW-GW: Two-way dynamic^
WEAP *Water Evaluation and Planning System* (Sieber, 2019; Yates et al., 2005)	Stockholm Environment Institute's US Center	No	Monthly	Semi-distributed: HRUs (not catena) in subcatchments	Yes	No
3Di (3Di Foundation, 2015)	3Di Foundation (Delft University of Technology, Deltares, Nelen and Schuurmans)	Yes	Daily and sub-daily	Distributed: gridded	Yes	Yes

***HRU:** Hydrological Response Unit*
***Catena routing:** Runoff passed between HRUs in a hillslope sequence to reach the channel network*
*^**SW-GW:** Surface water-ground water exchanges*
***Two-way:** Water can flow in either direction*
***Dynamic:** Direction of the exchange can change over time – model continually calculates the direction of the exchange)*

It should be noted that the term “conceptual model” is used in multiple ways in literature. In some cases, it refers to a conceptual numerical catchment model, i.e. a set of conceptual algorithms that calculate streamflow predictions. In other cases, it describes process understanding more broadly than has been put into words and diagrams, rather than a connected set of algorithms that produces a numerical output.

Catchment models apply different levels of spatial discretisation of the catchment area linked to the scale and discretisation of the process representation. A “lumped” model calculates flows and processes at the scale of the entire catchment. Algorithms and parameter values apply to the catchment as a whole and are necessarily more conceptual. More physical-mechanistic and more complex conceptual models require the catchment to be broken up into smaller compartments, such as areas of different vegetation types thought to have different transpiration patterns, to calculate individual processes being represented separately. This can be done in different ways. When the catchment area is broken up into grid cells, and processes are calculated for each cell individually, along with flows between cells, the model is classified as “distributed.” This can allow for each cell to have its own set of properties, parameters, and inputs. However this is not always the case in application. For example, a simple set of conceptual process algorithms could be used to calculate runoff for each grid cell in a distributed catchment model. The same parameter values could be applied to each cell. The only difference between cells is in the elevation and topographic position, allowing routing and potentially spatially defined individualised rainfall input. This would be a spatially distributed, lumped-parameter, conceptual model. Between lumped and distributed approaches are semi-distributed approaches in which the user defines, maps and separately conceptualises and parameterises areas considered to be similar in their hydrological response (HRUs). Processes are calculated for each one, as are the potential flows between them.

Models also vary in the vertical discretisation of surface, soil, and rock layers. The terms “lumped” and “distributed” typically refer to horizontal or surface discretisation as terminology that emerged when catchment models were more predominantly surface-water focused in their process description.

However, a “lumped” catchment model can have multiple vertical compartments or storages. A “distributed” model could discretise both the land surface and the subsurface using regular horizontal and vertical grids, creating a 3D grid for the subsurface in which every subsurface cube (or volume if not cubic) has a separate calculation of inputs and outputs, and could theoretically have its own parameters. Subsurface processes could also be modelled in “lumped” columns extending below the defined surface units, or with input layers of given depths defining different storage types, with separate algorithms describing them (“semi-distributed” in the vertical direction).

Model type classification provides some information about structure, but it should be noted that many models and tools do not fall cleanly into a particular class. A single model can employ multiple approaches internally. For example, one could use more physical algorithms to estimate infiltration and actual evapotranspiration (AET) in a spatially distributed way, while also using conceptual, simple, lumped linear reservoirs to represent ground water flow at the catchment scale. There is also a grey area as to when a process representation is deemed “physical” or “conceptual.” Furthermore, many modelling software tools now include several options for spatial discretisation or for algorithms to represent different processes. This makes the term “model”, when applied to a modelling software tool, somewhat ambiguous. For example, MIKE-SHE can be used to build a model that is spatially distributed using primarily physical mechanistic algorithms, but it can also be used to build a semi-distributed, more conceptual model for the same catchment area, depending on the choices made by the user. A modelling tool that is seen as more lumped and conceptual, such as WRSM-Pitman, can be used to build a model of a catchment area conceptualised with many individually parameterised subcatchments, making it essentially semi-distributed.

Different model structures have been developed to meet the needs of a variety of applications. There are context-specific advantages and disadvantages of each. More physical models tend to be more complex, needing more input data and parameters than more conceptual models. When the required input data is not readily available, many assumptions need to be made to generate inputs and parameter values. Assumptions can be assessed and improved upon through model testing and calibration if there is sufficient observed data to which to compare model outputs. However, when the number of uncertain parameters is high compared to the amount of observed data for assessment, the risk of equifinality grows (Beven and Binley, 1992; Beven and Freer, 2001). Multiple parameter value sets have the potential to provide equally accurate model outputs against the existing observations. With a greater number of uncertain parameters, a model may have a good fit for the wrong reasons, i.e. a combination of parameter values that are incorrect in reality, but compensate for one another.

These issues complicate uncertainty analyses for complex models and are especially problematic when the model is applied beyond the calibration period and/or is altered to represent scenarios of change. However, less detailed and/or more conceptual representations of a catchment also pose challenges. It is less straightforward to assign parameter values based only on information about the catchment’s characteristics when parameters have less direct connections to measurable properties. This is generally addressed through calibration, but becomes problematic for ungauged catchments and when looking at scenarios of change. In addition, for certain applications, internal catchment processes and states, such as soil moisture, ground water levels or flooding, are also of key interest in addition to catchment outflow, necessitating the use of a more discretised and mechanistic model that explicitly quantifies these at the scale of interest.

The choice of model structure for a particular application should balance the goals of the modelling exercise and the information available (Vaché and McDonnell, 2006; Wagener et al., 2001; Young et al., 1996). In an ideal world, modellers could address this by designing a use case-specific model. Time and capacity constraints generally mean making use of existing modelling tools and structural options, although these are becoming more flexible, allowing more case-specific adjustment. Several modelling software tools may be able to build similar and/or equally suitable structures for a use case, potentially with different sets of compromises.

Compromises and assumptions will be made in all cases, and the modeller should understand them and make them explicit to the end users of the information through uncertainty analyses, for example. If these uncertainties and compromises are assessed and understood, there may be certain cases in which a high-impact decision is deferred to gather additional data and/or improve models to allow for sufficiently informative predictions.

1.4.2 Catchment model structure intercomparison studies

The published literature on model structure intercomparison through application to case studies covers a wide variety of approaches with mostly case-specific results. Studies have applied multiple modelling tools with differing structures to a single case-study catchment (De Boer-Euser et al., 2017; Borah et al., 2007; Butts et al., 2004; El-Nasr et al., 2005; Golmohammadi et al., 2014; Singh et al., 2012; Yang et al., 2000; Zhang et al., 2013), or to a set of case study catchments (Chahinian et al., 2006; Clark et al., 2008; Krysanova et al., 2017; Perrin et al., 2001; Refsgaard and Knudsen, 1996; Tegegne et al., 2017; Yew Gan et al., 1997). Others have used the same modelling tool with different levels of spatial discretisation (Caldeira et al., 2019; Garavaglia et al., 2017; Pignotti et al., 2017). In this case, the process algorithms remain constant across trials, but the parameter values may change depending on the set-up and calibration. Another approach to structural comparison has been to start with a simple lumped conceptual model and progressively add complexities, such as adding more explicit process representations, testing for performance improvement with each addition (Fenicia et al., 2008).

Calibration approaches varied substantially across these studies. Some applied the same automated calibration procedure across models tested, attempting to maximise an objective function using a search algorithm to explore the parameter space with a specified level of search effort (De Boer-Euser et al., 2017; Caldeira et al., 2019; Garavaglia et al., 2017; Krysanova et al., 2017; Tegegne et al., 2017; Yew Gan et al., 1997). Others applied manual calibration procedures (Golmohammadi et al., 2014) or did no calibration, using their initial parameter estimates for each model. Some compared models both with and without calibration (Refsgaard and Knudsen, 1996).

These studies compared the models based on their goodness-of-fit metrics against observed data, typically only looking at catchment outlet streamflow, but using more than one statistic to look at both high and low flows, as well as overall average fit. Few comparison studies evaluated model outputs against other observations, such as ground water levels, AET or snow coverage, although commenting that it would be desirable (Garavaglia et al., 2017). Very few have gone further to also compare the models' predictions of change, as was done by Krysanova et al. (2017), who applied nine modelling tools to 12 catchments using 20 future climate predictions.

Although studies varied in settings and approaches, there are some emerging messages from the body of existing model intercomparison studies. Firstly no one modelling tool or approach emerges as superior in performance across studies and their differing contexts. For example, two studies applying SWAT and the Hydrological Simulation Program – FORTRAN (HSPF) to different catchments in the USA had opposing results in terms of relative performance of the two models (Im et al., 2003; Singh et al., 2005). Some studies found that simpler models performed as well as or better than more complex models in certain settings (Garavaglia et al., 2017; Perrin et al., 2001), while others found that more distributed or complex models performed better (El-Nasr et al., 2005; Refsgaard and Knudsen, 1996; Singh et al., 2012). Performance rankings between models could also differ for low versus high flows (de Boer-Euser et al., 2017). In multi-site studies, models generally achieved poorer performance in drier than wetter catchments and in lower flow time periods (Clark et al., 2008; Krysanova et al., 2017). However, a recurring finding across several studies was that more spatially distributed and/or process discretised models tended to achieve higher performance results than lower resolution models for larger and/or drier catchments due to the greater complexity and greater spatial variability in hydrologic response in these settings (Clark et al., 2008; Garavaglia et al., 2017; Krysanova et al., 2017; Maneta et al., 2008; Tegegne et al., 2017; Yew Gan et al., 1997).

There have been studies assessing the South African modelling tools (the ACRU and Pitman versions) across a variety of local conditions and typical applications (Hughes, 2013; Jewitt and Schulze, 1999; Kapangaziwiri and Hughes, 2008; Tanner and Hughes, 2015; Warburton et al., 2010). However, these studies have not looked systematically across multiple tools and have not produced accessible guidance for selecting across tools and structures for applied cases. This project aims to fill this gap.

CHAPTER 2: MODEL USER SURVEY

An online survey was conducted to gain a better understanding of how practitioners and researchers in South Africa are using catchment-scale hydrological modelling tools, which tools are commonly used, and what the experiences of the users has been. The survey was kept short with the aim of getting more respondents. Participants were given the opportunity to comment further on all the topics covered, as well as to provide broader comments at the end of the survey. Participants responded anonymously and the questionnaire was reviewed and given ethical clearance by the Rhodes University Human Ethics Committee. It was distributed via the email list of 192 members of SANCIAHS with requests for it to be forwarded to their relevant contacts. The call to participate indicated that respondents should have an interest in and some exposure to hydrological modelling, and that it was open to all experience levels. Of the 45 respondents, 40 indicated that they had used hydrological modelling tools outside a course exercise. These respondents were directed to further questions regarding their model use. Respondents who had not used a modelling tool independently were directed to questions regarding potential barriers to model use they had experienced. The questionnaire can be viewed at: https://forms.gle/ZdndJQV2LxgKDMQu7.

2.1 WHO RESPONDED TO THE SURVEY?

The 40 respondents who had used hydrological modelling in their work span a range of sectors and model-use experience levels, as shown in Figure 2.1. The two most frequently specified positions in the group were academics and consultants: each was selected by 14 people (35% of the group). If postdoctoral and doctoral researchers are included in a larger academic class, this category dominates, with 58% of respondents indicating that they work in this space. Government agency employees (three people, 8%), scientists at research facilities (three people, 8%) and members of non-profit organisations (one person, 3%) made up the smaller proportion of the group. Respondents were permitted to list more than one position if applicable. Two postdoctoral researchers and one academic also consult, and a research facility scientist is also pursuing a doctoral degree. All responses were included when looking at sectoral representation. Percentages are given as a proportion of the group of 40 respondents.

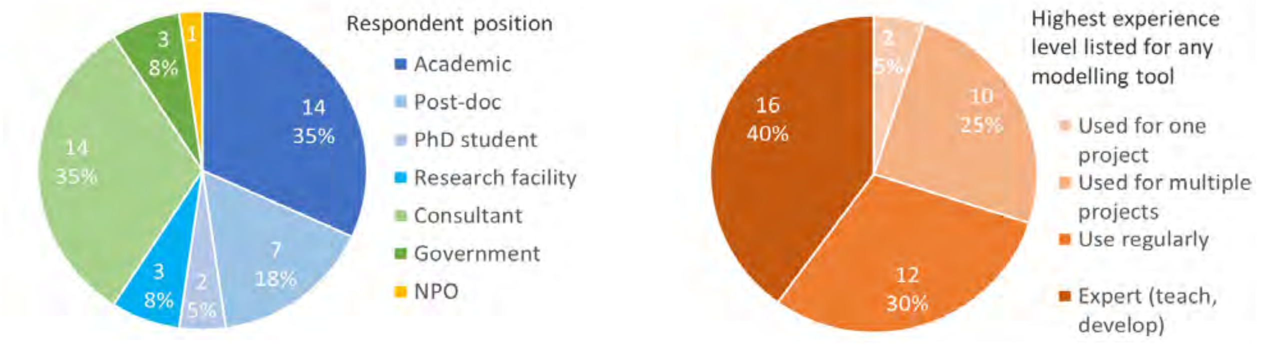


Figure 2.1: Positions (left) and experience levels (right) of the survey respondents

Note: Respondents could list multiple positions. The sum of values shown will therefore exceed the number of respondents. Percentages shown are proportions of the number of respondents. Respondents were asked to indicate experience levels by tool. The highest level specified across their listed tools was used here (one value per respondent).

There was a mix of experience levels in the respondent group, from those who had used a single modelling tool in a single project to experts who teach modelling and work on developing tools (Figure 2.1). Looking at the highest experience levels listed by each respondent across the tools they indicated having used, two (5%) had only used a modelling tool for one project to date, 10 (25%) had used at least one tool for multiple projects, 12 (30%) use at least one tool on a regular basis and 16 (40%) indicated that they teach and/or work on the development of at least one tool. Seen cumulatively, 95% of respondents had used at least one tool more than once (in more than one project) and 70% of the respondents had at least one tool that they use regularly (including expert and non-expert users).

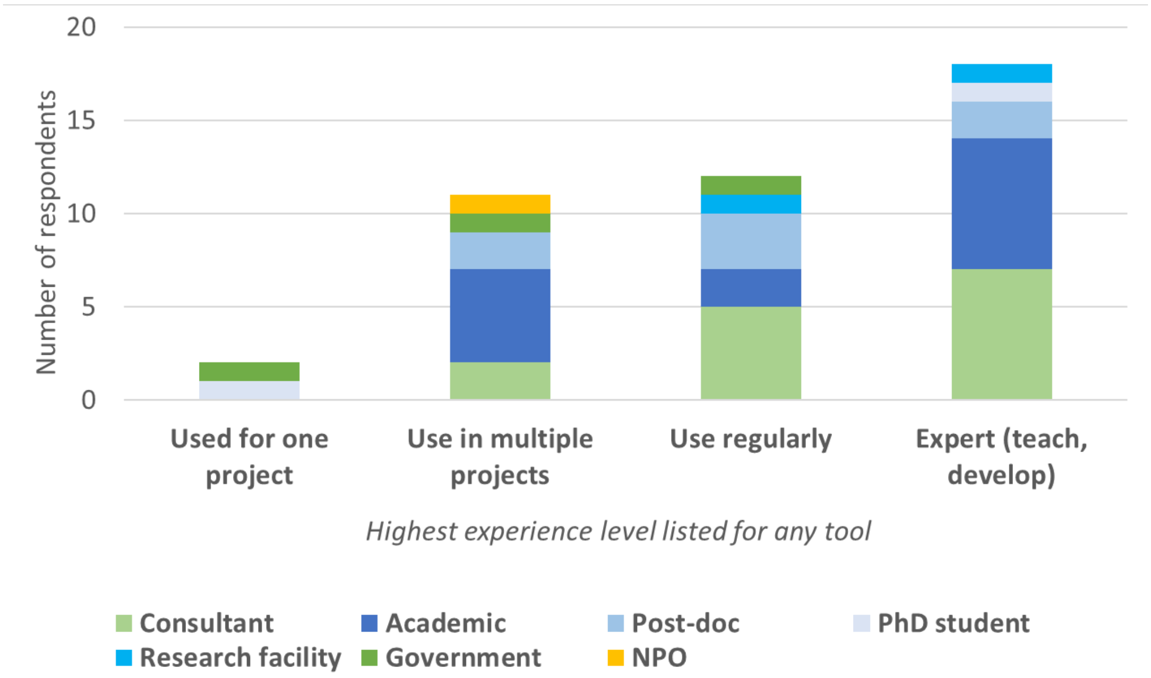


Figure 2.2: Positions listed by respondents with different model use experience levels (when multiple positions were listed, all were considered)

The intersection between experience level and position or sector in the respondent group is shown in Figure 2.2. Looking at respondents indicating expert level use of one or more modelling tools, there was equal representation in the consulting and academic sectors (seven respondents selected each), again more in academia if postdoctoral and PhD researchers are considered. Among those indicating regular, ongoing use of one or more tools, but not at an expert level, consultants made up the largest proportion (five out of 12).

This distribution of respondents across sectors may be representative of the number of people engaging directly with catchment modelling in each sector. In this case, results indicate that hydrological modelling is primarily done by academics and consultants with relatively little in-house modelling in government agencies. It should be clarified that this has not been researched thoroughly here: there was no pointed, in-depth canvassing across sectors to determine how many people use hydrological models. There were no modeller respondents from private companies, such as agribusinesses, development and construction or mining industry companies. Those operating at large scales may do some modelling in-house and it is possible that the communication channels used would not have reached them. It is also possible that these sectors rely primarily on external consultants if and when modelling is required.

Most respondents (95%) indicated that they had some level of exposure to multiple modelling tools. Exposure could range from using a tool during a course to being the developer of the tool. Two respondents (5%) had only been exposed to one modelling tool, while 28 (70%) had some level of exposure to five or more different tools (Figure 2.3). Respondents were asked to indicate their level of use for different tools. As would be expected, the number of different tools people listed decreased as the specified level of use increased: 22 (55%) indicated that they had used more than one tool for multiple projects, 11 (28%) indicated using more than one tool regularly, and four (10%) indicated that they are expert users of more than one tool.

Applying modelling to different location types and for different purposes can increase the depth of knowledge a user has with modelling and modelling tools. Survey participants were asked to indicate the provinces for which they have done relevant work, with the opportunity to list other locations (i.e. outside South Africa). Of the 40 respondents, 28 (70%) indicated having worked across multiple provinces and/or countries. Participants were also asked about the purposes for which they have used catchment models (i.e. supply planning, predicting land cover change impacts, etc.) across a range of general and more specific use-focused options (see Figure 2.4), with the opportunity to list their own. About 95% of respondents indicated that they had used models for three or more of the focused topics, and the majority (55%) expressed having worked on eight or more.

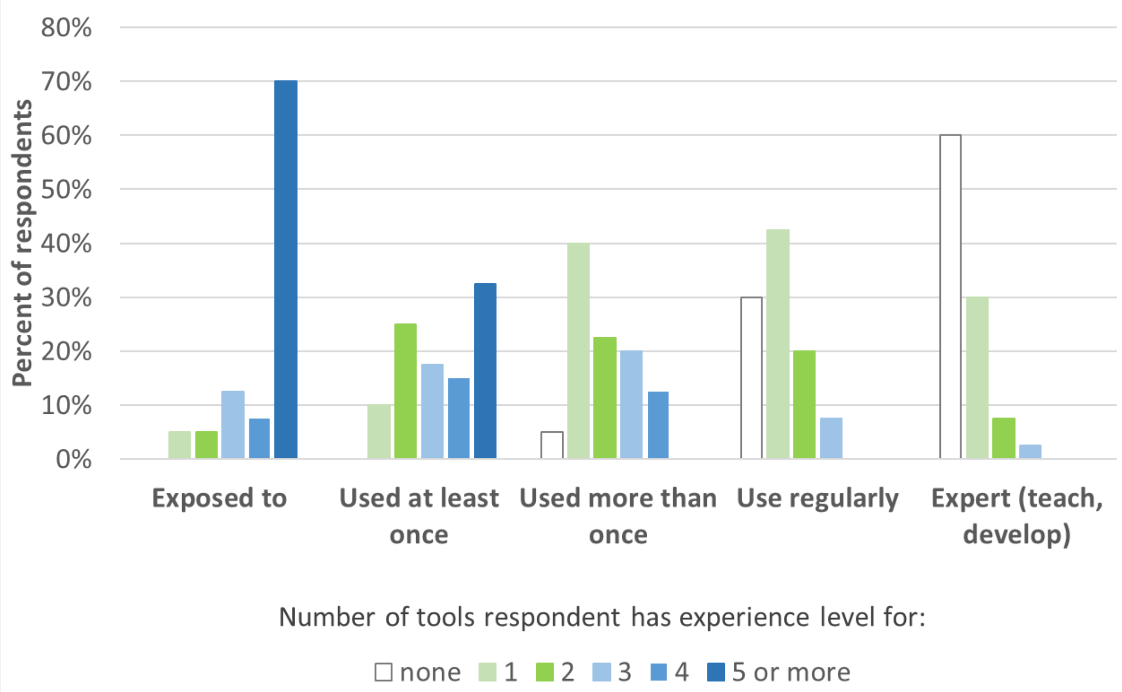


Figure 2.3: Percentage of respondents who have reached a given experience level for a number of different hydrological modelling tools

2.2 WHAT ARE CATCHMENT MODELLING TOOLS BEING USED FOR?

The survey results demonstrated the diversity of uses for which catchment modelling is being fairly widely applied, with most of the listed use focus areas being selected by 45% (18) or more of the respondents (Figure 2.4). The most frequently selected topics were land cover impacts on surface water (33, 83% of respondents), the impacts of climate change (29, 73%), the impacts of agriculture (23, 58%), reservoir planning and operation (22, 55%), general water supply planning (21, 53%), and the impacts of alien invasive vegetation (21, 53%).

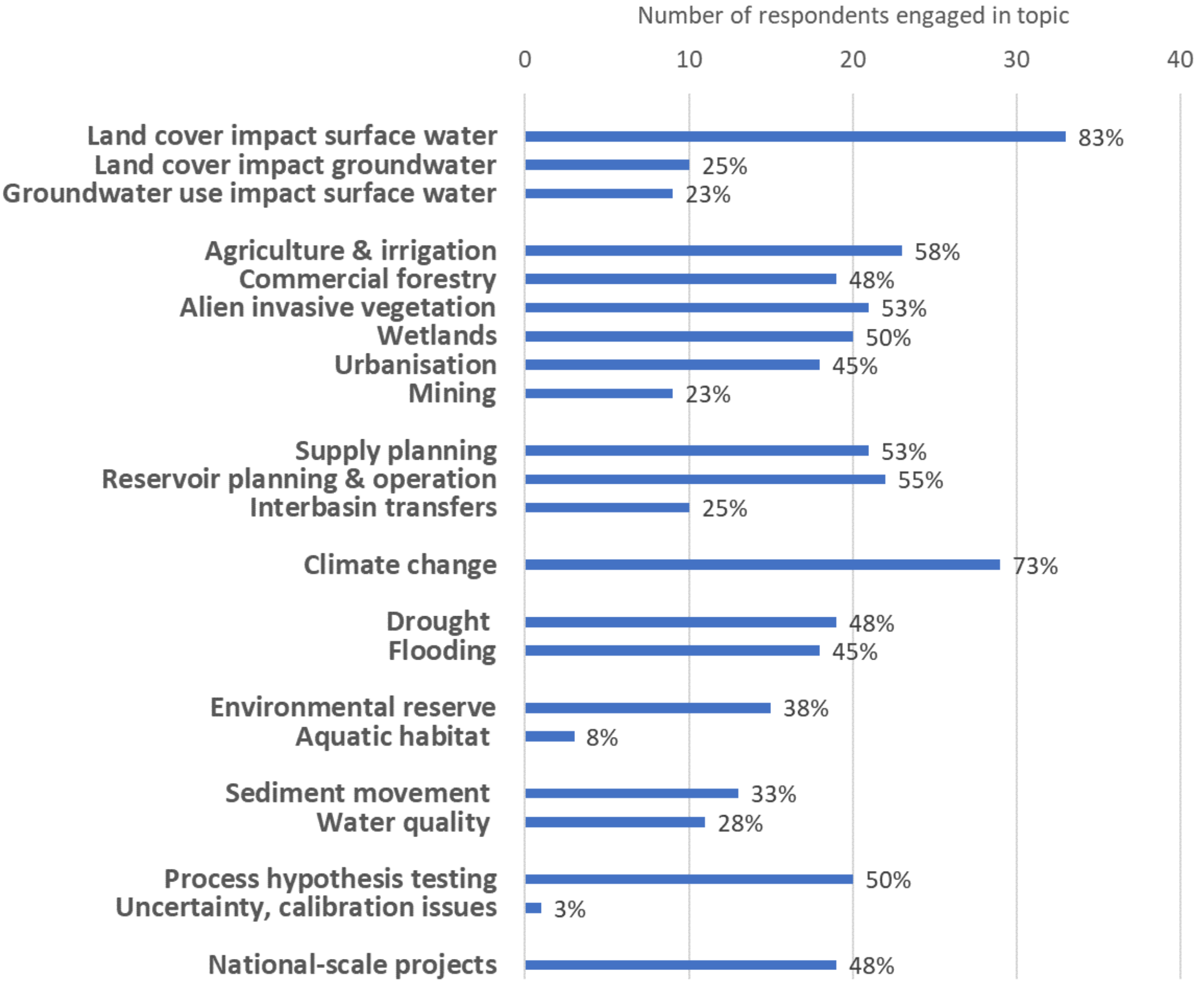


Figure 2.4: Number of respondents who have applied catchment models to different topics or for different purposes

The results also highlighted topics potentially receiving less attention across the modelling community, if the respondent group can be assumed to be representative. Notably, only one respondent indicated engaging in modelling work primarily focused on model uncertainty and calibration issues. Presumably others engage with these issues in modelling work that is focused on other topics, but have not worked on a project in which exploring model uncertainty was the express purpose. The next least frequently selected focus was an aquatic habitat (three respondents, 8%). More encouragingly, 15 respondents (38%) had used hydrological models in environmental reserve studies linked to preserving the aquatic habitat, if not studying it in detail. Also related is that 20 respondents (50%) had worked on projects that looked at the impacts of wetland loss and/or restoration.

The other topics that were less frequently selected were still worked on by more than 20% of the respondents (more than eight). These were the impacts of mining (nine, 23%), the impacts of ground water withdrawal of surface water (nine, 23%), the land cover impacts on ground water (10, 25%) and interbasin water transfer planning or operation (10, 25%). Finding fewer catchment modellers that focused on ground water-surface water interaction topics is to be expected given the historical division between ground water and surface water research and modelling. However, finding that over 20% have engaged in this space may indicate a movement towards bridging this divide. It would be interesting to see if this proportion grows in the future.

Respondents were given the opportunity to add other uses of hydrological modelling in which they had engaged. Two respondents did so, mentioning the use of catchment models in conjunction with economic models, and the use of models for water accounting.

Survey participants were asked to indicate for which provinces they had done hydrological modelling work (i.e. modelled a site or sites in that province). Not all respondents selected provinces, some giving more general responses (southern Africa in general) and/or primarily indicating international work. Of the 34 respondents who selected provinces, the most frequently selected provinces were the Western Cape (23 respondents, 68%) and KwaZulu-Natal (21, 62%), while the Free State (10, 25%) has had the fewest modelling projects from the respondent group.

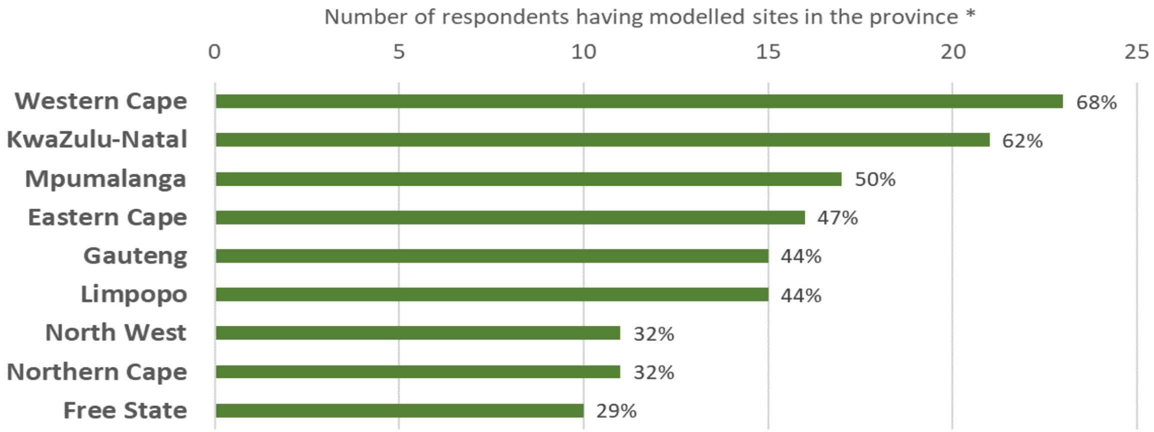


Figure 2.5: Number of survey respondents indicating they have done modelling work in a given province

* 34 respondents selected provinces in the survey. Percentages shown are out of this number rather than all 40 survey respondents

2.3 WHICH TOOLS ARE BEING USED AND BY WHOM?

Survey participants were asked to indicate their experience levels with a set of catchment hydrological modelling tools anticipated to be relatively commonly used (WRSM-Pitman, SPATSIM-Pitman, ACRU, MIKE-SHE, SWAT, HEC-HMS, WEAP). They were also asked to list any other tools they have used. In total, 38 tools were listed and several respondents indicated that they had coded their own models (Table 2.1). The tools that the respondents added do not all serve similar purposes. For example, some are specifically for event peak flow estimation (e.g. SCS-SA), while others are for the stochastic modelling of water supply systems (e.g. WRPM, WAFLEX). This means that some may have chosen to list a tool, while others, who may also use that tool, may not have listed it in the survey. As such, for these added tools, the number of respondents who listed using it cannot be assumed to reflect the actual number who have used it in the respondent group. For example, it is highly likely that more than three people in the respondent group have used WRYM.

However, this list is useful in showing the diversity of tools being used to model different aspects of catchment processes. It also shows that there was not another functionally similar tool to the set that was written into the survey that is commonly used by the members of the group. If there had been, multiple respondents should have added it.

Table 2.1: Catchment modelling tools survey respondents indicated having used

Modelling tool listed	**n respondents listing tool***	**Modelling tool listed**	**n respondents listing tool***
SPATSIM-Pitman	*34*	GLEAMS	1
WRSM-Pitman	*30*	Goldsim	1
ACRU	*28*	GWAVA	1
MIKE-SHE	*19*	HBV	1
SWAT	*18*	HDAM/Rafler	1
HEC-HMS	*13*	HYLARSMET	1
WEAP	*13*	HYPE	1
(self-coded model)	5	InfoWorks ICM	1
SCS-SA	5	LISFLOOD-FP	1
Water Resource Planning Model (WRPM)	3	ModHYDROLOG	1
Water Resource Yield Model (WRYM)	3	Panta Rhei	1
Australian Water Balance Model (AWBM)	2	Pitman – self-coded version	1
EPA-SWMM	2	PyTOPKAPI	1
HYDRUS	2	SCIMAP	1
JAMS/J2000	*2*	Utility Programme for Drainage	1
JULES-Hydro	2	VIC	1
MIKE-11+NAM2	2	WAFLEX	1
PCSWMM	2	WARMF	1
EXSMET	1	Water Quality Tool (WQT)	1
Flowmaster	1		

*The italicised tools were elicited in the survey itself. The rest of the tools were added by respondents, so the number that listed each one cannot be assumed to reflect the true number of users of the tool in the respondent group.

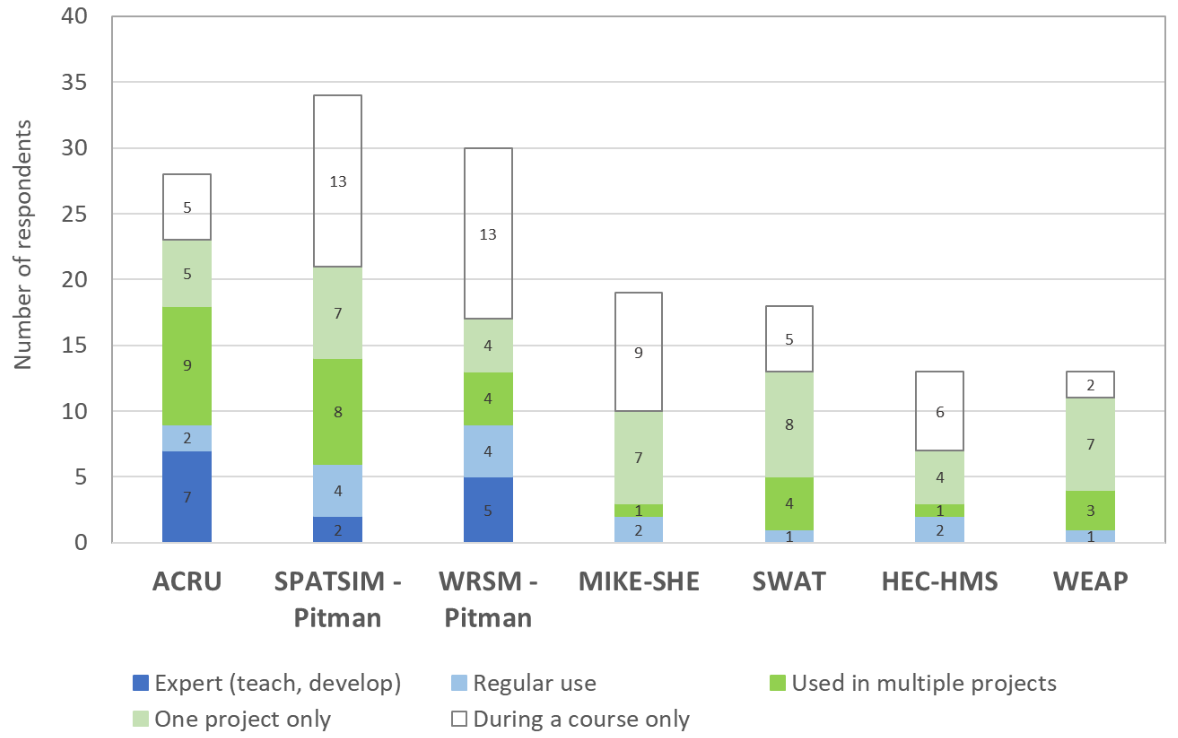


Figure 2.6: Numbers of respondents with different experience levels for the most commonly used catchment modelling tools

Of the most commonly used tools, the relative prevalence of use in the respondent group varied when looking at different levels of use. All 40 respondents had some level of experience with one or more of the tools explicitly listed in the survey: WRSM-Pitman, SPATSIM-Pitman, ACRU, MIKE-SHE, SWAT, HEC-HMS and WEAP. As would be expected, the three tools developed for South African conditions were the most frequently used. When any level of experience was considered, from using it in a course through to being an expert, SPATSIM-Pitman was the tool with the greatest total exposure across respondents, with 34 respondents (85%) indicating that they had used it (Figure 2.6). This was followed by WRSM (30, 75%), ACRU (28, 70%), MIKE-SHE (19, 48%), SWAT (18, 45%), HEC-HMS and WEAP (both 13, 33%). When only looking at respondents using a tool at least once in an independent project, outside of a course, ACRU was the most frequently cited (23, 58%), followed by SPATSIM (21, 53%) and WRSM (17, 43%). This order was retained when looking at the number of respondents who had used a tool multiple times. Looking at regular, ongoing use of a tool, ACRU and WRSM were the most frequently cited, both having nine regular users (including expert users) in the respondent group (23%). Six respondents (15%) indicated the regular use of SPATSIM. Of the expert user respondents, seven indicated they were expert users of ACRU, five were expert users of WRSM, and two were expert users of SPATSIM. This included four people who indicated expert level use for more than one of these tools.

For the more commonly used tools developed outside South Africa, MIKE-SHE, SWAT and WEAP, none of the respondents indicated use at an expert level. MIKE-SHE had a slightly higher general exposure among the respondents than the other two when including those who had only tried it in a course setting (19 respondents, 48%). This changed when higher levels of use were specified. SWAT and WEAP had more respondents indicating use in at least one independent project, 13 (33%) and 11 (28%), respectively, with 10 respondents (25%) indicating the independent use of MIKE-SHE. SWAT and WEAP also had more respondents indicating use in multiple projects. Very few respondents indicated the regular use of any of these tools: two for MIKE-SHE, two for HEC-HMS, one for SWAT and one for WEAP.

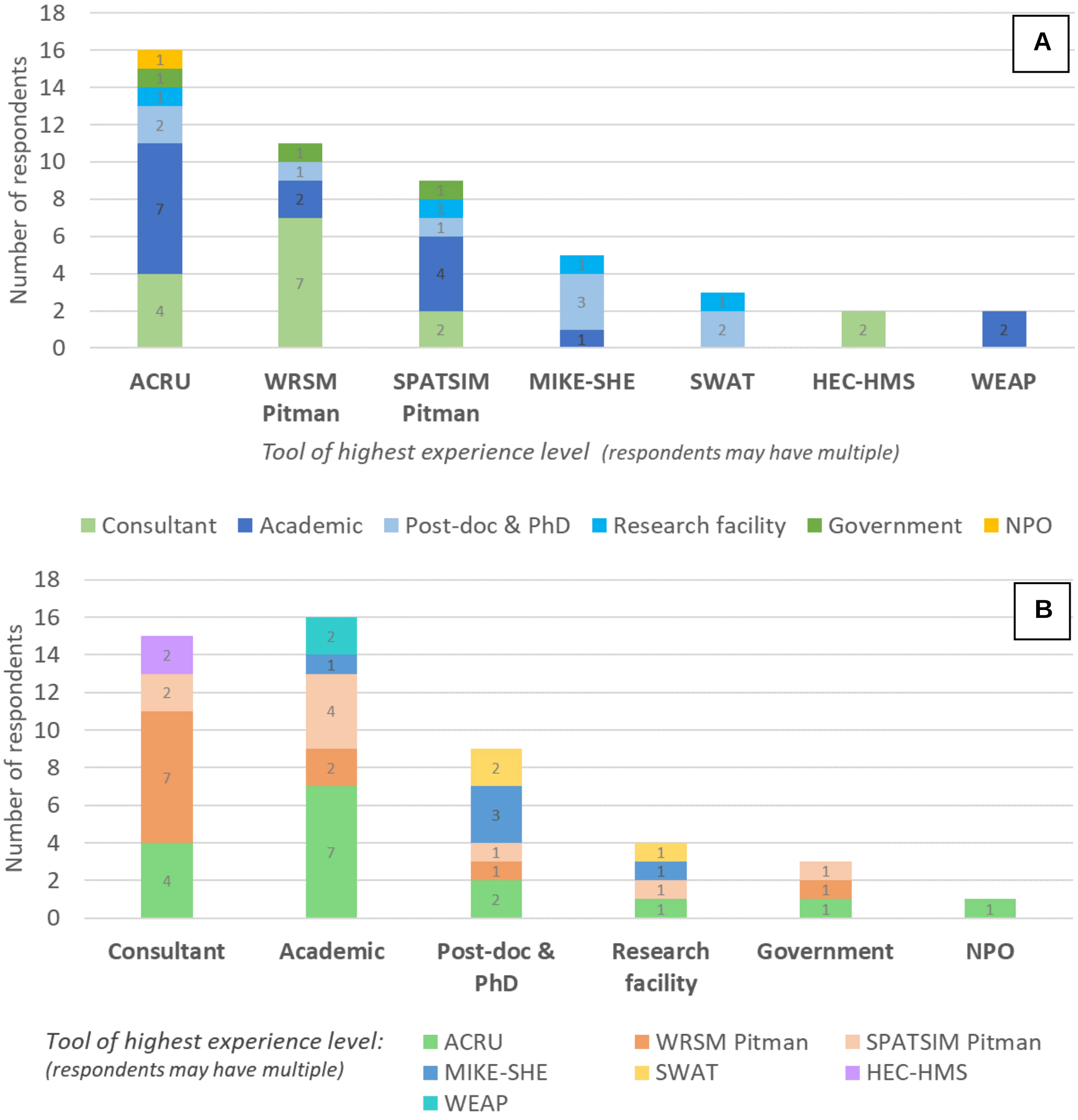


Figure 2.7: Intersections between tools of highest experience level by respondents and respondent-listed positions: (A) distribution of positions indicating primary use of a tool; and (B) distribution of tools primarily used by respondents working in a position type.

NB: Some respondents have multiple highest-level tools – all were included.

To get an indication of the use of the different tools across sectors where modelling, the tool(s) of highest experience level was determined for each respondent and the intersections of these with respondents' listed positions was assessed (Figure 2.7). These are likely to be the tool(s) the respondents primarily use. If a respondent indicated the use of multiple tools at that person's highest tool use level, all were included (i.e. multiple 'primary' tools per respondent). Some respondents indicated that their highest use level was for tools other than those commonly used in the group. This was true for four respondents who specified most experience using PyTOPKAPI, JAMS/J2000, WRYM and their own self-coded models. ACRU was the tool most frequent among respondents' highest-experience-level tools, listed by 16 respondents (40%), followed by WRSM (11, 28%) and SPATSIM (nine, 23%). If only respondents indicating regular or expert tool use were included, WRSM was the most frequent highest experience-level tool, listed by 10, closely followed by ACRU (nine) and SPATSIM (seven).

There were some differences across the tools in terms of the positions of respondents who listed them as their highest experience-level tools. Most of the respondents listing ACRU as their highest experience-level tools specified working in academia (seven academic, two postdocs or PhDs out of 16). For WRSM-Pitman, consultant was the most frequently specified position (seven out of 11), while for SPATSIM-Pitman, it was academia (four academics and one postdoc out of nine). Of those listing MIKE-SHE or SWAT as their highest experience-level tools, most were postdocs or PhDs, while for HEC-HMS all were consultants. For WEAP, all were academics.

2.4 HOW ARE MODELLERS DECIDING WHICH TOOL TO USE IN A PROJECT?

It is acknowledged that modellers decide to use a given tool for a given project for a variety of reasons. The balance of reasons can shift from project to project. Survey participants were asked to generalise about their experiences and indicate the top three factors that most strongly influence their tool selection out of a given list (see factors in Figure 2.8), with the opportunity to add and score other factors not listed. Only one respondent included a non-listed factor in their top three: the history of use and broad understanding of the tool in the wider community (i.e. beyond the modeller's own institution). Had this factor been listed in the survey, it seems likely that it would have been scored quite highly by others as well, as already suggested by the number including the use of a tool in their institution in their top three influencing factors. If the survey were repeated, this would be a helpful addition.

All the potential influencing factors listed in the survey were included in the top three factors for more than one respondent. This demonstrates the diversity of situations under which this decision is being made, balancing practicalities and idealised priorities. Some factors stood out as more frequently included in respondents' top three factors than others. These were prior use, tool capabilities and data availability. The respondent's own prior use of a tool was the most frequent factor in respondents' top three factors, included by 23 respondents, 58% of the group. It was the second-most frequent first choice, with nine respondents (18%) putting it first. The specific capabilities of a tool was the second-most frequent factor in respondents' top three factors, with 21 respondents (53%) including it. It was the factor most frequently ranked as the most important, with 11 respondents (28%) putting it first. Data availability, in terms of what is needed for a tool, was a close third for the number of times it appeared in respondents' top three factors (20, 15%) and was the third first choice (six, 15%). It was the most popular second choice, with eight respondents (20%) putting it second.

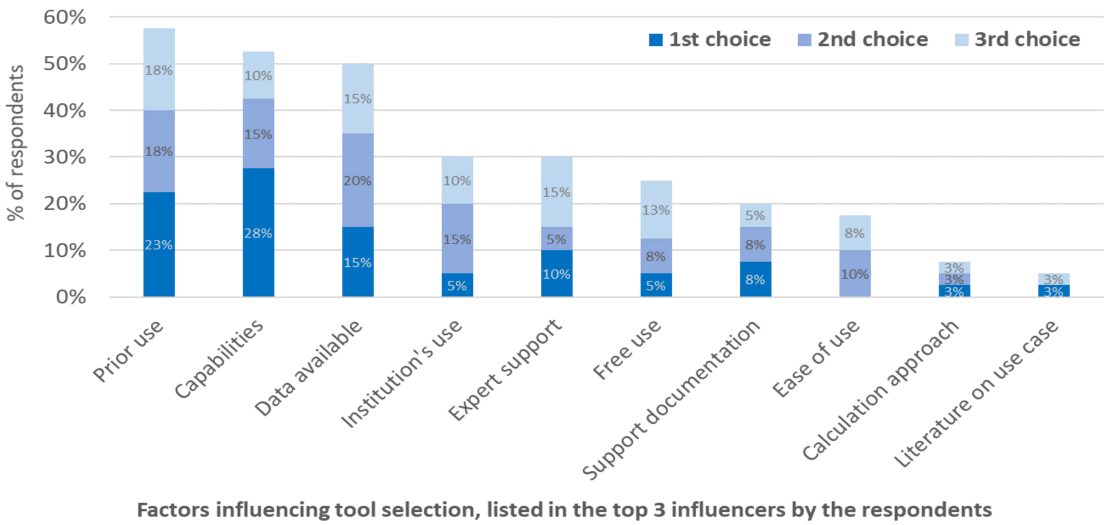


Figure 2.8: Factors influencing modelling tool selection: proportions of survey respondents selecting a factor as one of the top three factors influencing their decision of which tool to use

Among the factors listed, the tool's approach to calculating hydrological flows and storage, and having literature on the use of the tool for a similar use case, were quite clearly the least frequently selected factors in respondents' top three factors. Calculation approach was only included in the top three factors influencing tool selection for three of the 40 respondents (8%), and literature on the use case was included by two respondents (5%), although each was selected as the most important factor for a respondent. Ease of use of the tool was the third least-frequent in users' top three factors, included by seven respondents (18%). It was no one's most important factor.

2.5 USER EXPERIENCES WITH MODELLING TOOLS

The researchers tried to get a basic picture of users' experiences with different tools in terms of the ease of use of the interface, documentation and additional support available to users. Because the survey was intentionally kept short, the depth of questioning was limited. Participants were simply asked to score a tool out of five (1 being poor, 3 being satisfactory and 5 being excellent) for each of these three aspects. An individual's experience with a tool is necessarily subjective and will also be influenced by what a user is trying to do with a tool, how they have come to use it (course, mentorship, self-taught, etc.) and the resource environment in which they are using it. Nevertheless, it was hoped that this high-level scoping would give an indication of the range of user experiences with a tool. Participants were invited to score a maximum of four tools with which they have experience. A total of 34 tools were scored. Six (ACRU, SPATSIM, WRSM, SWAT, MIKE-SHE and WEAP) were scored by seven or more people (Table 2.2), while the rest were scored by fewer than five. Five respondents scored one tool each. One did not score any tools, and 34 scored two to four different tools.

For the six tools most frequently scored, all were rated as above-satisfactory (> 3) on average for all three aspects except for MIKE-SHE (Figure 2.9). MIKE-SHE had an average score of 3 (satisfactory) for its interface, and scored more poorly for documentation and support, with averages of 2.1 and 2.4, respectively. There was a range of differing scores assigned for each tool, as seen in Figure 2.9. The greatest diversity in scoring across respondents was seen for ACRU and MIKE-SHE: both had respondent ratings of both 1 (poor) and 5 (excellent) for all three aspects evaluated. Almost all tools received some scores below satisfactory (< 3) and some excellent (5) for all aspects. The exceptions were SWAT interface and documentation and WEAP document data and support, which did not receive any scores below satisfactory. Looking at average scores, SWAT had the highest average interface score (3.9) and WEAP had the highest average scores for documentation (3.9) and support (4.0). It should be noted that not all tools were scored by the same number of respondents (Table 2.2) or the same group of respondents. Having all tools scored by the same group helps to control for different individuals' interpretations of the scores – some people tend to score low and others high, but this was not possible given that different respondents had experience with different tools.

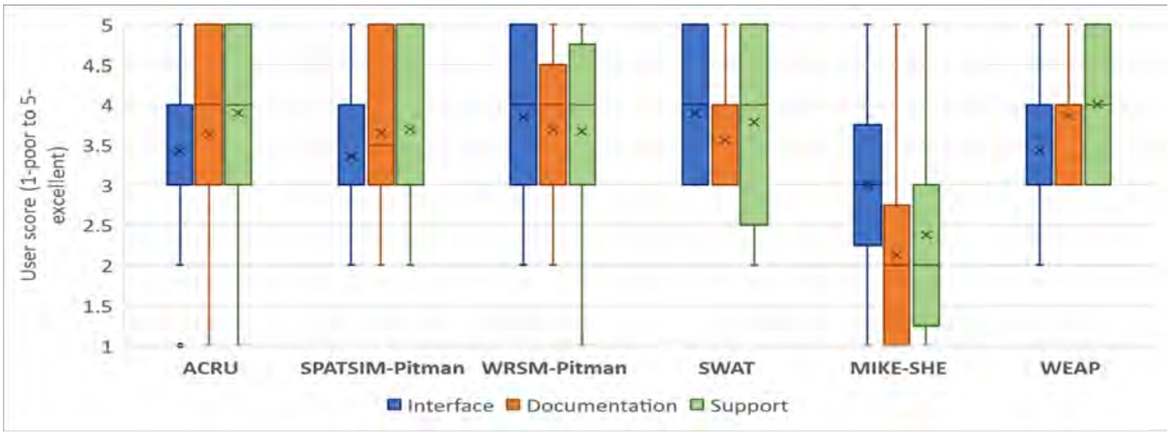


Figure 2.9: Distribution of scores given by respondents for the ease of use of the interface, ease of use of the documentation, and support offered for different modelling tools

To check whether the assessment of ease of use changes with experience level, a subset of the respondent scores for each tool was made which only included those who indicated that they had used the tool being assessed in multiple projects, were regular users or were expert users of it, and they had also used at least one other tool for multiple projects or more. Further subdivisions would have resulted in too few evaluators, as sample sizes per tool were already quite limited. Looking only at a more experienced subgroup generally did not make large differences to average scores, with most not changing or changing by about 0.1 (Table 2.2). This stability indicates a degree of reliability in the overall results. The largest changes were for MIKE-SHE, which saw average scores improve across all three usability aspects, although the sample size was down to three respondents. It brought the interface score to a par with several other tools, while documentation and support remained below par. WRSM also saw a notable increase in the average score for support, increasing from 3.7 to 4.2 with the more experienced group, the highest support score in the set.

Table 2.2: Average usability score assigned to tool by respondent groups with different minimum experience level

Tool	**Minimum experience level***	**n respondents scoring**	**Average score (1 = poor; 3 = satisfactory; 5 = excellent)**		
			Interface	**Documentation**	**Support**
ACRU	Any	19	3.4	3.6	3.9
	Multiple projects	10	3.3	3.6	3.8
SPATSIM-Pitman	Any	14	3.4	3.6	3.7
	Multiple projects	11	3.4	3.6	3.7
WRSM-Pitman	Any	13	3.8	3.7	3.7
	Multiple projects	6	3.8	3.5	4.2
SWAT	Any	9	3.9	3.6	3.8
	Multiple projects	4	3.8	3.8	3.8
MIKE-SHE	Any	8	3.0	2.1	2.4
	Multiple projects	3	3.3	2.3	2.7
WEAP	Any	7	3.4	3.9	4.0
	Multiple projects	4	3.3	4.0	3.8

*Minimum experience level refers to both the use of tool being scored and the use of at least one additional tool.

2.6 APPROACHES TO CALIBRATION AND EQUIFINALITY

Recognising that a modeller's approach to model calibration will vary from project to project, depending on data available, project scope and time, survey respondents were again asked to generalise about their experiences to select a statement that best described the calibration approach they most frequently used. The four options provided were as follows:

- Not having sufficient observational data to attempt calibration
- Having observational data, but not attempting to adjust parameters from initially selected values to improve fit
- Having observational data and manually testing parameter alternatives to try to improve model fit
- Having observational data and using automated tools to do batch-testing of potential parameter values to improve model fit

Participants were also invited to describe an alternative approach instead and/or give additional comments.

A large majority of respondents (29, 73%) indicated that they generally use a manual calibration approach, while eight (20%) indicated making use of automated calibration tools. One respondent indicated often having data, but not testing parameter adjustments, and two indicated that they typically have insufficient observational data to attempt calibration in their work. Several respondents commented that their approaches vary significantly depending on the situation. Others specified that they often apply hybrid manual and automated approaches.

Of the tools most commonly used by the respondent group, SPATSIM-Pitman, SWAT and MIKE-SHE have built-in or linked tools that automate the batch testing of models across user-specified ranges of potential parameter values. However, respondents who had these tools in their highest use-level set generally did not indicate the use of automated calibration tools as their typical approach. Of the eight respondents who indicated the general use of automated tools, one had MIKE-SHE and one had SPATSIM as a highest use-level tool, while the other six were respondents with highest use levels specified for tools outside the commonly listed set (JAMS/J2000, PyTOPKAPI, AWBM, GWAVA, WRYM and the respondent’s self-coded models). It is possible that some respondents interpreted “automated calibration tools” to mean a completely automated process, i.e. that the user does not decide what parameter ranges are reasonable to be testing. An effort was made in the phrasing to avoid this interpretation. However, it is possible that more make use of these facilities than indicated in the survey.

Survey participants were also asked whether they typically attempt to address the issue of potential equifinality in their modelling, i.e. the likelihood that multiple different sets of parameter values could produce equivalent model performance. Participants were given three generalised responses to choose from with the option to further expand on their approach. There was not a highly dominant response. The most frequently chosen response was that equifinality was an issue that they were generally not able to address, selected by 18 respondents (45% of the group), while nine (23%) indicated that equifinality generally did not apply in their work, and 13 (33%) indicated actively attempting to address it.

Respondents indicated a range of approaches to attempt to reduce potential equifinality and/or acknowledge it in the modelling processes. These included strategies to reduce the set of parameters and/or value ranges considered in calibration, such as using parameter sensitivity analyses and identifying interdependencies across parameters, and using knowledge of the catchment’s processes and the physical parameter meanings to identify those likely to be most sensitive. Several respondents also mentioned using multiple criteria and multiple data types (e.g. soil moisture, internal reservoir levels, ground water levels) where possible to more thoroughly evaluate the model’s performance. Two respondents mentioned using ensembles of models that meet the performance criteria, rather than a single parameter set, for subsequent scenario analyses and reporting on the range of output. Respondents who indicated that they did not typically attempt to address equifinality commented about time, budget and data availability constraints to be able to engage in the testing required.

2.7 INTERESTED, BUT NOT EXPERIENCED: BARRIERS TO USE

Five survey respondents indicated that they had not used catchment hydrological modelling tools independently (i.e. outside of coursework). This is a small sample from which to make generalisations. However, it can be noted that the group covered a few different potential model user groups and cited diverse barriers to model use. There were three university students, including one doctoral student, a university-employed academic and a private company employee. The company employee indicated a range of barriers to use from the time needed to learn complex tools to a perceived lack of access to support. The students expressed a perceived lack of institutional support and lack of access to adequate computing resources and sufficient data as barriers to use. The academic did not indicate that they had experienced barriers to use, but instead indicated that they engage with the outputs of hydrological models built by colleagues and that their focus is on the interpretation of outputs and links to policy development.

2.8 MODELATHON INTEREST

The survey was also used to scope potential willingness to participate in a voluntary “modelathon” activity in which participants all model the same catchment area and scenario with their tool of choice given the same starting data sets. The purpose of the activity would be to explore the ranges of approaches and ranges of outcomes across both users and tools. At a minimum, the activity would require users of several different tools to participate, and ideally multiple users of the tools would be included. Encouragingly, the majority of survey respondents (24, 60%) indicated that they would potentially be willing to participate, pending further information. This group included multiple users of each of the more commonly used tools identified in the survey (ACRU, WRSM, SPATSIM, SWAT, MIKE-SHE, WEAP and HEC-HMS), users across multiple experience levels (10 who indicated expert level use of a tool) and users active in different sectors (academia and consulting). It also included users who specified their highest use levels for the less commonly used tools, which would be very interesting to include in the exercise.

2.9 IMPLICATIONS FOR GUIDANCE MATERIAL AND FURTHER WORK

The modelling community survey results provided multiple helpful insights for the development of guidance material being initiated in this project, i.e. the wiki website. Given the short timeline of the project, the survey was conducted when the modelling tool structural review and case study modelling work was well underway. In several ways, the survey validated the focus areas of the reviews and group case study modelling. Results also clearly highlighted areas needing further coverage in future work and future development of the wiki site. It was intended to be a living resource. Survey results also provided an additional intercomparison of use-ability aspects across the tools, as experienced by the broader user community, rather than by the project team alone.

The survey results validated some of the assumptions made in designing the project:

- **Selection of modelling tools for intercomparison:** WRSM-Pitman, SPATSIM-Pitman, ACRU, SWAT and MIKE-SHE, the ones selected for review, were the most commonly used tools across the survey respondents.
- **Selection of case study modelling use cases:** The case studies modelled by the project team primarily focused on modelling different kinds of land cover impacts, specifically the impacts of invasive alien trees, commercial forestry, wetlands and irrigated agriculture. These were among the most frequently cited project focus areas for the survey respondents: over 80% have done modelling focused on land cover change, with 50% or more looking at these more specific types of projects.
- **Types of intercomparisons presented across tools:** The intercomparisons across modelling tools in the project reports and wiki material include tool capabilities, data needs and processing for input, and documentation and support, which were frequently among the top three factors respondents specified as influencing their choice of modelling tool.

The survey was intentionally kept brief, touching on a number of issues at a scoping level, rather than aiming to dig too deep. The results may give an indication of some areas in need of further development in the modelling community of practice, but further exploration would be needed to understand the degree to which this is the case. Material produced in this intercomparison project focuses on a few aspects of modelling that were less frequently highlighted in the survey responses. In so doing, they may be assisting to address some potential gaps:

- **Focus on model calculation approaches:** The similarities and differences in approaches to representing hydrological processes across modelling tools, in terms of the spatial and vertical units, linkages, timesteps, and algorithms and equations used, has been a significant focus in this project.

However, model calculation approach was one of the least frequently selected factors by survey respondents when asked what influenced their selection of a modelling tool for a project. This suggests that aspects compared in depth here are not necessarily what drives many users to select a tool. It should be noted that respondents had to select their top three factors out of many, across both theoretical and practical issues. The specific capabilities of a tool was one of the most frequently selected factors. There is certainly overlap between a modelling tool's capabilities and its calculation approaches, with capabilities referring to what is explicitly represented, what kinds of inputs can be taken and what kind of outputs can be produced, while calculation approach includes the specifics of how these processes are represented. Some calculation approaches allow or preclude certain capabilities, but there are other cases where several different calculation approaches exist for the same general process. It is likely that limitations of time and data preclude respondents from engaging with the calculation methods to some degree. Practical issues such as the modeller's prior use of a tool, which would allow them to do work of a certain level more quickly and easily, and data availability were also ranked as most important. Comparing calculation methods across tools takes time, pouring over multiple theory manuals, and the impacts of the differences may only be highly notable in certain applications. Part of the contribution of this project is to hopefully make engaging with the calculation approaches easier. Given the time and data constraints expressed, and the high rank of tool familiarity, this may not lead to more use of multiple tools, but may assist with new ways of using tools that modellers already have some familiarity with.

- **Focus on ease of use:** Interestingly ease of use of a modelling tool was also ranked quite low as an important decision factor in selecting a tool. However, prior use was very highly ranked, which speaks to how easily the user would engage with the tool, regardless of the comparative user-friendliness of its interface. Support from experts and documentation were also fairly highly ranked, which would also address difficulties in use. It is potentially the case that if tools were easier to use in general, the importance of prior use as a decision factor would decline. Most respondents reported being exposed to many tools, but using far fewer in their work. Comparing aspects of ease of use was one of the components of the current project. In the current state, this analysis may be more relevant to those working on tool development rather than influencing decisions by those applying the modelling tools.

- **Assessment of ground water-surface water interactions and ground water representation across tools:** The representation of ground water and ground water-surface water interactions across catchment modelling tools is an issue that received some focus in this project's intercomparison because differences across tools were fairly salient. Far fewer respondents indicated having worked on projects that looked at land cover impacts on ground water or ground water use impacts on surface water when compared to the number looking at land cover impacts on surface water. This may be due to the history of relatively separate research, modelling and management of surface and ground water, rather than a lack of need for such studies. Demand for this kind of work by modellers may also grow as increasing strain on water supply systems starts to make links between ground water and surface water systems more directly evident to those engaged in water supply management.

The survey responses also highlighted areas for potential future intercomparison work and further development of material for the wiki site:

- **Use-cases needing more attention:** Climate change and reservoir planning, and supply planning in general, came up as frequent focus areas of respondents' modelling work and were less thoroughly addressed in material generated in this project compared to other topics.
  - The case studies explored in this project were relevant to water supply issues in terms of modelling the impacts of cover change and issues around modelling small farm dams, irrigation supplies and flows from catchments leading into large reservoirs. However, the tools' different facilities for representing water supply systems with use and diversion constraint rules were not

  covered in any detail. Existing linkages between tools and other water supply system planning tools were mentioned, but information about how the output of other tools can be used in this context requires more attention.
  - In terms of modelling climate change impacts, material could be added about where to find relevant input data (climate change scenarios), scenario modelling approaches and means of analysing result. However, these aspects are generally handled more outside the catchment modelling tools themselves and are perhaps less within the primary scope. Links can be added to other resources on these topics. Relevant information about how climate data is input across tools has been included, but material could be added linking this to the common formats of climate prediction data. Further research on the relative sensitivities of different tools to climate inputs would also be beneficial.

- **Other tools to include:** WEAP and HEC-HMS also emerged as tools that many have used. However, few respondents indicate that these were their highest use-level tools. If there is scope to add additional tools to the intercomparison material on the wiki in future, these two may be good candidates to explore. WEAP offers a different functionality focus than the others, being specifically designed to handle various water supply system analyses.

CHAPTER 3: MODELLING AND MODELLING TOOL TERMINOLOGY

3.1 MODEL THEORY TERMS AS USED IN THIS PROJECT

Definitions of key modelling terms as they are applied in this project are provided in Table 3.1, noting that terms may be used differently outside of this project.

Various terms related to hydrological modelling are used in somewhat different ways across contexts. An important example is the word “model.” The term “model” is often used to refer to a “modelling tool”; e.g. the ACRU modelling platform is often called “the ACRU model”. This is not incorrect: the software tool enforces some aspects of process representation, so in that way ACRU is a “model” of how the real world works. However, a “model” can also refer to a particular model of a specific catchment area, which includes a certain structure, set of parameter values and input variables. Specifying the tool used gives some information about the model’s structure, but also leaves a lot of uncertainty about what a model of a specific catchment was actually like. For example, using ACRU, one could build two very different models of the same catchment: one with many subcatchments and many specific land covers considered separately, and another with a more lumped representation.

An effort was made in this project to use specific terms consistently. The term “model” is used to refer to a specific model set-up of a given catchment and “modelling tool” for the software one could use to make and run a model. “Model building” is used for setting up a specific model structure for a catchment, rather than designing a modelling software tool to be used across many applications. The latter is referred to as “modelling tool development.”

Table 3.1: Modelling theory terms and definitions applied in this project

Term	Applied definition
Model	Broadly: A physical object, diagram, or set of equations that provides a simplified representation of a more complex or larger object or system. **Used here as a “short form” for “hydrological model” – see definition below**
Hydrological model	A model that describes the flow of water through an area of land to output a prediction of its water balance. It is a structured set of equations and logic statements (collectively referred to as algorithms) along with parameter and input variable values. Given precipitation, other climate variables and parameters describing physical processes and properties, the algorithms produce estimates of how much of the precipitation will be stored in the modelled area, leave as ET or leave as surface or subsurface outflow. A “hydrological” model may or may not include a “hydraulic model” (defined below). The area represented is typically a catchment. Therefore, "catchment hydrological model" is implied. (If the modelled area is not a full catchment, additional surface and subsurface flows at its boundaries need to be specified.) The term “model” will be used to refer to the complete package required to produce the output, i.e. both the “model structure” and the “parameter values”. **Note:** Elsewhere, a “model” often refers to a “model structure” or “modelling software tool”.
Hydraulic model	A model that describes surface flow of water across a specified area. This is most often a channel network and adjacent floodplain. Given the flow entering the area, various system properties (channel size, roughness, slope) and algorithms representing an understanding of physics (laws of energy, mass, momentum), a hydraulic model outputs the water surface elevation, velocity and flow rate for specified calculation points. Hydraulic models do not calculate the quantity of water entering the channel network. Input flows at boundaries must be measured, calculated by a hydrological model or otherwise estimated or assumed.

Term	Applied definition
Conceptual model	A representation of how a person or group understands the flow of water through a catchment, typically in the form of diagrams, flow charts and text. This consists of how people decide to divide the catchment into different spatial and vertical units to be considered separately, and a description of the perceived processes, flows and connections within and between these units. **Note:** The term "conceptual model" also commonly refers to a numerical model (defined below) with algorithms that are considered more "conceptual" vs. "physical" in that their parameter values are not individual, physically measurable properties. It will generally not be used this way here unless specifically clarified.
Numerical model	Used here as short form for "numerical catchment hydrological model". A set of mathematical equations and logic statements used to quantitatively describe the processes and connections in a conceptual model of catchment. When applied to the required numerical inputs, it produces quantitative predictions of flows.
Algorithm	A step-by-step set of operations used to obtain an output from certain inputs. This can be an ordered set of equations and/or logic statements and can diverge into branches. Numerical models are examples of complex algorithms. They are generally combinations of many internal, individually described algorithms that predict the occurrence and output of different particular hydrologic processes (e.g. infiltration of water into soil, percolation of soil water downward to the ground water).
Model structure	The form of a numerical model: the specific way in which the land surface and subsurface is divided into different units and connected and the specific set of process algorithms that are applied within and between units.
Parameter	Numerical values that form part of model algorithms and describe properties of a system, such as the porosity of soil, the gradient of a hillslope or the LAI of vegetation. These properties are often assumed to be constant in the model, at least over a period of time or within a scenario. Some model structures allow some parameter values to change over time, such as a seasonal pattern of LAI values for a vegetation type. Despite potentially varying, parameters differ from "input variables" in that parameters are part of the definition of how an input and output variable relate, e.g. the LAI value is part of the equation that calculates how the rainfall input becomes the throughfall output, representing the process of canopy interception.
Input variables	Numerical value inputs to model algorithms that are considered to be an inherently changing feature or condition of the system, such as daily precipitation, evaporative demand, irrigation application or water withdrawals.
Validation	Evaluation of the model to determine whether or not it is a sufficient representation of the system, the catchment's hydrology, to be used for its desired purpose. This includes assessment of the inputs, structure and outputs compared to our understanding of the system. Statistical tests can be applied to compare model outputs to field measurements for quantitative assessments of accuracy. Criteria and thresholds of model acceptance need to be defined by users. When the term "validation" is used in conjunction with "calibration" (defined below), it refers to model performance testing that is done for a different time period or set of inputs than those that were used in the calibration exercise.
Calibration	Adjustment of model parameter values to improve the accuracy of model outputs against user-defined measures of accuracy (e.g. goodness-of-fit statistics of model outputs to comparable field measurements or patterns). Parameter value options used in calibration are typically constrained to value ranges considered realistic given the physical meaning of the parameter and knowledge about physical properties of the system.
Scenario	One of many alternative possible states of the system that is represented with a particular model structure, a set of parameter values and input variables.

Term	Applied definition
Modelling (software) tool	Computer software program designed to help users build and run numeric models. Different programs encode different sets of algorithms and require users to input parameter values and input variables. Different programmes allow for different levels of spatial discretisation of the catchment area and subsurface layering. Some include several different options for discretisation and options for the algorithms used for hydrologic processes. This means that even within a single modelling software program, different model structures can be built to represent the same catchment based on user decisions. For this reason, “modelling software” will be differentiated from a “model”. Also referred to as: “modelling software”, “modelling tool”, “modelling program”, “modelling platform”.
Model building	Deciding upon the model structure with spatial discretisation, process algorithms, parameter values and input variable data to use to represent a specific catchment for a specific time period and operationalising its implementation to produce outputs using existing modelling tools and associated software and code. This is differentiated from designing and testing a more generic modelling software tool that allows users to build models of a variety of catchments – see “modelling tool development”.
Modelling tool development	Creating a software program or set of code that can be used to build and run models of a variety of catchments given structural specifications, parameter values and input data that can be given by a user.

3.2 TERMINOLOGY ACROSS MODELLING TOOLS

Working across the documentation and interfaces of the different tools, it became clear that each modelling tool has its own “language”. It was often the case that different terms were used for the same concept across different tools (e.g. what is called “interflow” in WRSM-Pitman is called “lateral flow” in SWAT). Alternatively, there were cases where the same term, or a very similar one, was used for different concepts across tools (e.g. “ground water outflow” refers to subsurface flow of ground water between neighbouring subcatchments in SPATSIM, while it refers to flow from an aquifer into a channel in SWAT). This is not surprising and is not likely to pose a challenge to the user of a single tool. However, it required consideration and care in the structural review in this project and is noteworthy for users of multiple tools. To describe how the tools operate in comparison to one another, a common set of terms needs to be applied across them.

A set of terms, the way in which they are used in this project and the alternative words used for the concept in each modelling tool are given in Table 3.2. When different terms are used across tools and refer to a similar broader concept, but there are differences in the precise application in a tool, an effort was made to highlight this. This table is not a comprehensive comparison of all the tools’ vocabularies: it does not cover all parameter and variable names across all tools. Instead, it focuses on some main model component and process concepts.

As Table 3.2 demonstrates, there are many terminology differences between the tools. Some may cause confusion when comparing process algorithms, inputs and outputs across them. For some cases, it is just a simple difference in word choice, but when there is a mismatch in meaning, more attention is required. Some key differences worth highlighting are the following:

- **PE and PET:** Different tools use different inputs for considering atmospheric evaporative demand in calculating ET. Some use pan evaporation (PE), while others use potential evapotranspiration (PET) for a reference vegetation type. Recognising this is particularly important when comparing input data and parameter values across tools.

- **AET:** Some tools (SWAT, MIKE-SHE) include evaporation from canopy interception when referring to and outputting AET (or “total ET”), while others do not (Pitman tools, ACRU4). This needs to be recognised when looking at model output water balances across tools.

- **Baseflow vs aquifer outflow:** In this project’s documentation, water leaving a ground water aquifer and entering a river channel (or surface water body) will be referred to as “aquifer outflow to channel”. Several of the modelling tools refer to this as “baseflow” (ACRU, MIKE-SHE when using the linear reservoir ground water option). The term “baseflow” can refer to the portion of river flow that continues even during drier periods, without indicating the flow path taken to reach the river. Water contributing to baseflow has necessarily followed a much slower path from rainfall to channel compared to water contributing to peak flows following storms. However, it is possible that river flows classified as “baseflow” in a stream’s hydrograph will have contributions from “interflow”, which is not considered “ground water” under typical definitions. Because most of the tools endeavour to represent interflow processes separately from aquifer outflow, the word “baseflow” was not used for water that is specifically aquifer outflow to hopefully avoid confusion.

Table 3.2: Terminology used in this project and terms used for the same or similar concepts across the considered tools

SPATIAL UNITS

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Catchment (Cat)	All land area that drains to a specific point in the landscape (catchment outlet), often a point on a river or a water body. *Assumed to be a surface flow catchment: topographically delineated by the direction of potential surface flow. Boundaries are ridge lines or highest points.*	**Catchment,** Network* *WRSM models are networks of connected modules.* *The “network” refers to a model’s extent, which could include multiple catchments*	**Catchment**	**Catchment**	**Basin, watershed**	**Catchment,** Model domain* *Model domain: full extent of the area modelled, not forced to follow topographic (surface water) catchment boundaries*
Subcatchment (Subcat)	Smaller catchment (topographically defined) within a larger catchment. *When a catchment is delineated into subcats, there will be:* • ***headwater subcats****, with no other subcat upstream* • ***non-headwater subcats****, which do have other subcats upstream* *For non-head water subcats:* • *the* ***accumulated subcat*** *is all the land draining to the outlet point of the subcat, so includes all upstream subcats as well* • *the* ***incremental subcat*** *is only the additional area draining to the*	**Subcatchment,** Runoff module* *Runoff modules function as subcats, but do not include channels and special area types represented with separate modules.* *A collection of linked modules (e.g. runoff module + irrigation module + channel module) would together represent what*	**Subcatchment** *Runoff outputs for incremental subcat.* *Streamflow output for accumulated subcat*	**Subcatchment** *Runoff outputs for incremental subcat.* *Streamflow output for accumulated subcat*	**Subbasin, subwatershed** *Runoff outputs for incremental subcat.* *Streamflow output for accumulated subcat*	**Subcatchment** *Runoff outputs for incremental subcat.* *Streamflow output for accumulated subcat*

General term	Concept	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
	subcat's outlet point that is not included in any upstream subcats. Non-headwater, incremental subcats can have one or more inflow points from upstream subcats.	*would be a subcat in another tool. Outputs for channels linking subcats will represent the accumulated subcat*				
Hydrological response unit (HRU)	Area with relatively homogenous hydrological processes in comparison to the rest of the landscape. *Often a combination of land cover, soil type and topographic position. Area included is not necessarily contiguous.*	Module* *Runoff and special land area modules function similarly to HRUs, but the process algorithms used across the different module types are more diverse vs. across HRUs in other tools.*	(not used)	**HRU**	**HRU**	(not used) *MIKE allows landscape property parameters (e.g. vegetation properties, surface roughness properties, soil properties) to input for user-defined zones. These different zones do not need to line up with one another.*

RUNOFF AND STREAMFLOW

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Runoff	All water leaving a catchment as streamflow, or all water leaving an incremental subcat, HRU or other land unit to enter a downslope unit or the channel network. Runoff includes both surface and subsurface flow contributions.	**Runoff**	**Runoff**	**Runoff**	**Water yield**	*Tool and texts only refer to individual components (overland flow, interflow, baseflow) and streamflow*
Surface runoff (SRO)	Water flowing on the land surface. In modelling: water leaving a subcat or HRU as surface flow and reaching the modelled channel network. Includes surface flow created by both saturation excess and infiltration rate excess.	**Surface runoff**	**Surface runoff**	"Non-delayed" stormflow* *ACRU calculates total "stormflow" generated in a rain event (surface runoff + some interflow) in one step.* *Some of this is lagged in reaching the channel to represent interflow ("delayed stormflow")* *The portion that is **not** lagged can be considered surface runoff. There is no specific term used for this in the tool.*	**Surface runoff**	**Overland flow**

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
				NB: *“Quickflow” = total “stormflow”* *Despite the name it is not only the “non-delayed” portion*		
Streamflow (Q)	Water flowing in the channel network at a point, generally at a subcat outlet. Includes contributions of the incremental subcat, and all upstream subcats. If there are diversions, transfers, dams and/or if channel bed losses are handled separately, streamflow at a subcat outlet may not be equal to the runoff from the contributing landscape area.	**Streamflow, route flow** *Streamflow: output of a “route” leaving a runoff module or a channel module*	**Streamflow, total downstream flow**	**Streamflow, channel flow**	**Streamflow, channel flow**	**Streamflow, river discharge**
Channel transmission loss	River channel flow that infiltrates the channel bed material. It could become bank storage, part of the unsaturated zone and/or recharge ground water.	**Bedloss**	**Channel loss**	(not used) *ACRU does not explicitly model channel transmission loss*	**Channel transmission loss**	**Saturated zone (SZ)-river exchange, River discharge to baseflow reservoir** *With finite difference ground water modelling: dynamic two-way exchange between “SZ” and channel*

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
						With linear reservoir ground water modelling: transmission loss routed to “baseflow reservoir”

EVAPOTRANSPIRATION

General term	Concept	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Potential evapo-transpiration (PET) **and** **reference PET**	Maximum ET from a surface given a set of climate conditions and no water availability restrictions. This is determined by the atmospheric demand (energy for evaporation and capacity to hold additional moisture, i.e. solar radiation, temperature, humidity, wind) and by the properties of the surface (cover, stomatal conductivity of vegetation). **Reference PET** is PET for a standardised surface. It gives information about atmospheric demand and a basis to estimate PET and AET for other land covers. The frequently used FAO-56 method (Allen et al., 1998) applies the Penman-Monteith equation to estimate PET for a reference grass (i.e. input climate variables, assume standard grass properties with no water restriction)	**Potential evaporation, PE** *WRSM uses pan evaporation for atmospheric ET demand (not a veg reference PET). Symon's pan (S-pan) evaporation is used in general, but some modules use/can use A-pan* *"PE" is calculated for the specific veg being modelled using a pan factor:* *PE = pan evap * pan-factor for veg*	Pan evaporation, PEVAP, PET* *S-pan evaporation is generally used as the atmospheric demand input.* *The tool does not apply a pan factor. This could be done externally by the user* *"PET" and "pan evaporation" are used interchangeably in SPATSIM texts.* *These are considered different in other contexts: i.e. PET from a vegetated surface vs open water evaporation from a pan.*	Reference potential evaporation (E_r)* and **maximum evaporation (E_m), PET** *ACRU typically uses A-pan evaporation as its "reference potential evaporation (E_r)" input. Other options are provided.* *"Maximum evaporation (E_m), also referred to as PET in ACRU texts, is PET for the specific veg being modelled, estimated from the reference:* E_m = *A-pan evap * A-pan crop coefficient for veg type*	**PET** *SWAT can calculate PET or reference PET using different algorithm options.* *The full Penman-Montieth option calculates both PET and AET for a modelled veg type directly using LAI and stomatal conductance.* *Without full climate data, SWAT estimates grass reference PET and adjusts this to get PET for the modelled veg.*	**Reference evapotranspiration (ET_{ref}) and crop reference ET rate (ET_{rate}), PET** *MIKE-SHE uses FAO-56 grass reference PET as its "Reference evapotranspiration (ET_{ref})"* *"Crop reference ET rate (ET_{rate})", also referred to as PET in MIKE texts, is PET for the specific veg being modelled, estimated from the reference:* $ET_{rate} = ET_{ref}$ ** crop coefficient for veg type* $ET_{max} = ET_{rate}$ ** timestep length* ***Note**: There is some use of ET_o and ET_p in texts without clarification.*

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Crop coefficient (K_c)	Scaling factor to adjust a reference PET, or other measure of atmospheric demand, to get PET for the specific vegetation type being modelled: PET * K_c = ET from veg type if soil moisture were not limiting	Pan factor***** *Pan factor used to modify S-pan evaporation, not grass reference PET*	(not used)	**Crop coefficient (K_c)** *Crop coefficient used to modify A-pan evaporation, not grass reference PET*	(not used) *When using methods that calculate reference PET first, the crop coefficient is calculated by SWAT from the LAI*	**Crop coefficient (K_c)** *Crop coefficient used to modify grass reference PET*
Actual evapo-transpiration (AET)	Total ET from an area, including evaporation from canopy interception storage, evaporation from open water surfaces, evaporation from soil moisture transpiration by vegetation from soil moisture and from ground water ***Note:*** *Sources can differ in which of these components get included in “AET”* AET will be less than PET when water availability is limiting.	Catchment evaporation (E)* *“E” refers to soil moisture evaporation + transpiration* *Does not include canopy interception evaporation, evaporation from water bodies*	AET* *“AET” refers to canopy interception evaporation + soil moisture evaporation + transpiration from soil* *Does not include transpiration from ground water, evaporation from water bodies*	Total evaporation (E, AET)* *“E” and “AET” refer to soil moisture evaporation + transpiration* *Does not include canopy interception evaporation, evaporation from water bodies*	AET, ET* *“AET” and “ET” refer to soil moisture evaporation + transpiration* ***Note:*** *Canopy interception is not explicitly modelled in standard daily timestep application* *Does not include evaporation from water bodies*	**AET** *“AET” refers to canopy interception evaporation + soil moisture evaporation + transpiration + ponded surface water evaporation*

SOIL AND THE UNSATURATED ZONE

General term	Concept	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Unsaturated zone (UZ)	Soil, sediment, regolith and rock layers above the ground water water table. May become temporarily saturated from storm events, but generally does not remain saturated for months at a time. *May not all be strictly considered **"soil"** under typical soil definitions, i.e. material having both organic and mineral content.*	**Soil + percolation storage zone (or unsaturated storage)** *WRSM has two UZ components: "soil" (root zone) and "percolation storage zone" (below root zone).* *The "percolation storage zone" is also referred to as the "unsaturated storage" in the model interface.*	**Soil, moisture store, upper zone** *One UZ unit per subcat.* *Several terms for this unit are used in tool and texts.*	**Soil** *The ACRU UZ is the soil profile, which has two layers.* *ACRU3 and some research versions include an optional "intermediate zone" between the root zone soil and the aquifer.*	**Soil + vadose zone** *SWAT has two UZ components: "soil" (can be above and below roots) and "vadose zone".* *SWAT "soil" profile has separately parameterised layers and more complex handling vs the "vadose zone" below that just further lags recharge to aquifer.*	**Unsaturated zone, (+ interflow reservoir*)** *MIKE's UZ is a layered profile that can extend below the root zone.* *With finite difference ground water modelling: the UZ thickness is dynamic as the water table fluctuates.* *With linear reservoir ground water modelling: an "interflow reservoir" is included below the "UZ" profile.*
Root zone	Soil, sediment, fractured rock layers that contain roots, allowing direct withdrawal of stored water for transpiration. Deeper layers can feed ET *indirectly* via capillary rise into the root zone. In some cases, roots may reach the ground water, which makes the whole UZ profile part of the "root zone".	**Soil** *Soil unit functions as the root zone*	**Soil, moisture store, upper zone** *One UZ unit, functions as the root zone.* *Several terms for this unit are used in the tool and texts*	**Soil** *Two soil layers ("horizons") are included and both contain roots (can set the lower layer to contain very little of the roots)*	**Root zone** *Soil profile is input independently to the root depths and can include layers below the root zone.*	**Root zone,** UZ upper layer* *MIKE has options for representing the UZ.* *With simple, two-layer: the "upper layer" is the root zone + potential capillary fringe depth.* *With others: soil profile is independently defined and can include layers below root depths.*

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Saturation (soil) moisture (Sat SM)	Maximum water content of a soil layer or other porous media, determined by its porosity	Saturation moisture (ST)* *Pitman "ST" is maximum water storage at a monthly timestep. It is a threshold for surface flow generation, maximum interflow rates, and maximum recharge rates.* *Because of the monthly timestep, the value may not be directly equivalent to measured soil porosity Sat SM.*	Saturation moisture (ST)* *Pitman "ST" is maximum water storage at a monthly timestep. It is a threshold for surface flow generation, maximum interflow rates and maximum recharge rates.* *Because of the monthly timestep, the value may not be directly equivalent to measured soil porosity Sat SM.*	**Saturation, total porosity**	**Saturation (SAT)**	**Saturation**
Field capacity (FC)	Moisture content of porous media at which there is no vertical drainage due to gravity: all the pore water present is held by capillary forces stronger than gravity	Drainage limit* (SL) *Pitman "SL" is a monthly soil moisture storage threshold below which interflow and percolation stop. Because of the monthly timestep, the value may not be directly equivalent to measured soil FC.*	Drainage limit * (SL) *Pitman "SL" is a monthly soil moisture storage threshold below which interflow and percolation stop. Because of the monthly timestep, the value may not be directly equivalent to measured soil FC.*	**Drained upper limit (DUL)**	**Field capacity (FC)**	**Field capacity (FC)**

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Wilting point (WP)	Moisture content of porous media below which plants cannot withdraw water for ET because capillary forces are too strong	(not used) *The monthly soil moisture limit for ET withdrawal is a function of PE, ST and a shape parameter (R)*	(not used) *The monthly soil moisture limit for ET withdrawal is a function of PE, ST and a shape parameter (R)*	**Wilting point (WP)**	**Wilting point (WP)**	**Wilting point (WP)**
Infiltration	Water on the ground surface (from throughfall of rain or irrigation, from detained surface flow) entering into soil or sediment.	**Catchment absorption, infiltration**	**Catchment absorption, infiltration**	**Infiltration**	**Infiltration**	**Infiltration**
Interflow	Lateral flow in the porous material of the unsaturated zone, occurring above and separately from ground water flow in an aquifer. In models, it is water in the UZ leaving an HRU, subcat or unit to enter another unit or the model channel network. The "unsaturated zone" material may be temporarily saturated or near saturated, i.e. following a storm, when interflow is occurring.	**Interflow** *Flow from the soil moisture store to the channel that occurs when moisture exceeds SL.*	**Soil moisture runoff** *Flow from the soil moisture store to the channel that occurs when moisture exceeds SL.*	Delayed stormflow, Baseflow* *ACRU calculates total "stormflow" generated in a rain event (surface runoff + some interflow) in one step. Some of this is then lagged in reaching the channel to represent interflow ("delayed stormflow").* *Theory manual also suggests that some of the modelled "baseflow" may also represent interflow.*	**Lateral flow** *SWAT "lateral flow" from the soil profile can occur when moisture in a soil layer exceeds field capacity.* *There is no lateral flow from the SWAT "vadose zone".*	Upper layer saturated zone flow to river*, interflow* *With finite difference ground water modelling: MIKE does not calculate lateral subsurface flow unless saturation is reached in a layer. The "UZ" and "saturated zone" profiles overlap. Temporarily saturated layers are handled in the SZ when saturated. There can be lateral flow in an upper SZ layer that is perched (i.e. interflow).* *With linear reservoir ground water*

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics**				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
						modelling: an "interflow reservoir" is included below the "UZ profile" and above aquifer "baseflow reservoirs". Lateral flow to the channel from this "interflow reservoir" is called "interflow" in MIKE and does not require saturation of this reservoir to occur.
Percolation	Downward movement of water in the unsaturated zone. It can be movement between different layers or components of the UZ and so does not necessarily result in recharge of an aquifer.	Percolation,* Recharge* *In WRSM: "Recharge" refers to water leaving the soil moisture store and entering the "percolation zone storage" (also known as the "unsaturated storage")* *This water will eventually reach the aquifer,but is lagged.* *"Percolation" refers to water leaving the percolation storage and entering the aquifer.*	Recharge* *SPATSIM has one UZ unit and all water percolating out of this enters the aquifer below, so is called recharge.*	**Drainage**	**Percolation**	**Vertical flow,** Percolation* *In MIKE, "percolation" is only used in the context of the linear reservoir ground water option, for flow from the "interflow reservoir" downward into the "baseflow reservoir" (i.e. recharge).*

AQUIFERS AND GROUND WATER FLOWS

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Aquifer	Rock or sediment units that are saturated with water (water pressure ≥ atmospheric pressure) and remain saturated for relatively long time periods (i.e. months or more). This excludes soil, sediment, fractured rock that is only saturated for brief instances following storm events.	**Aquifer, ground water store** *One unit per subcat/runoff module*	**Aquifer, ground water store** *One unit per subcat*	**Baseflow store** *One unit per HRU* *ACRU3 and research versions have additional ground water routines that refer to a "ground water store"*	**Aquifer** *Two units (shallow and deep) per subcat*	**Saturated zone (SZ), baseflow reservoir** *Using finite difference option: "Saturated zone" (layered profile)* *Using linear reservoir option: "Baseflow reservoir" (units by subcat)*
Ground water (GW)	Water in an aquifer at or below the water table. This excludes water in soil, sediment, fractured rock that is only briefly saturated. This excludes interflow, which some sources may be included in GW.	**Ground water**	**Ground water**	**Ground water, baseflow storage**	**Ground water**	**Ground water, baseflow storage**
Recharge	Water entering an aquifer, thereby becoming ground water. The water can enter from unsaturated material above, from other distinct aquifer units, from river channels or water bodies if they are in direct contact, etc.	**Recharge (RE)** *In WRSM, "recharge" refers to water leaving the soil moisture store and entering the "percolation zone storage."* *This water will eventually reach the aquifer, but is lagged.*	**Recharge (RE)**	**Drainage to baseflow store, recharge**	**Recharge**	**UZ-SZ exchange, River-SZ exchange, Ponded OL-SZ exchange (negative), percolation, recharge** *Using finite difference option: various two-way exchanges with the SZ are considered separately and a negative flux is an inflow into the SZ*

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
						Using linear reservoir option: "percolation" and "recharge" are used interchangeably for flow from the interflow reservoir to the baseflow reservoir
Ground water flow	Flow of ground water from one location to another within an aquifer or between aquifers while remaining in the saturated subsurface.	**Ground water flow/outflow*** *In the theory text, "ground water outflow" is flow from one subcat aquifer to the aquifer of a neighbouring downslope subcat or out of the catchment following the regional gradient. However, the tool does not output this and the user manual text does not refer to it.*	**Lateral flow, Ground water outflow/drainage downstream** *"Lateral flow" refers to flow between two subunits within a subcat's aquifer: upper and lower drainage slope units* *"Ground water outflow" is flow from one subcat aquifer to the aquifer of a neighbouring subcat or out of the catchment following the regional gradient.*	Hillslope routing* *No GW flow between subcats in ACRU* *If a special "riparian zone" HRU is added to a subcat, baseflow output from upslope HRUs can be routed to the soil of the riparian HRU. This provides a subsurface flow connection within a subcat.*	Deep aquifer flow* *No GW flow between subcats (GW modelled at subcat scale)* *If a recession constant is specified for the deep aquifer unit, deep GW flows out of the modelled catchment.*	**Ground water flow, saturated zone flow, SZ boundary outflow*** *Using finite difference option: GW flow is modelled in a 3D grid (no subcat boundaries), and can flow out of the model domain depending on boundary settings.* *Using linear reservoir option: No GW flow between subcats or out of the model domain (can have "dead storage")*

General term	**Concept**	**EQUIVALENT terms are bold;** RELATED/SIMILAR terms are not bold and have an asterisk (*); *use notes are given in italics*				
		WRSM-Pitman	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
Aquifer outflow	Ground water that flows out of an aquifer to become surface water, generally entering a river channel or other surface waterbody.	**Ground water baseflow/outflow/ discharge** *Various terms used in the tool and texts.* *NB: user manual uses "GW outflow" for GW coming to the surface while theory manual uses it for GW flowing between subcats as GW.*	**Ground water runoff/ outflow/drainage, baseflow** *Various terms used in the tool and texts.*	Baseflow* *Theory text indicates that ACRU "baseflow" could include flow from interflow pathways, as well as aquifer outflow. It is flow coming via slower pathways, rather than necessarily all from GW aquifers.*	**Ground water flow, baseflow**	**SZ-river exchange, SZ-OL exchange (positive), baseflow** *Using finite difference option: various two-way exchanges with the SZ are considered separately and a positive flux is an outflow from the SZ.* *Using linear reservoir option: "Baseflow" refers to aquifer outflow from "baseflow reservoirs" to channel.*
Baseflow	River flow that continues between storm response flows, even during prolonged dry periods. This may include flow contributions from multiple pathways, the slower ones in the landscape. Aquifer outflows are often the dominant source, but baseflow can include interflow and bank storage drainage as well.	**Total baseflow** *WRSM texts differentiate "ground water baseflow" (aquifer outflow) and "total baseflow" (aquifer outflow + interflow)*	Baseflow* *Refers to aquifer outflow only*	**Baseflow** *Theory text indicates that ACRU "baseflow" could include flow from interflow pathways, as well as aquifer outflow. It is flow coming via slower pathways, rather than necessarily all from GW aquifers.*	Baseflow* *Refers to aquifer outflow only*	Baseflow* *Refers to aquifer outflow only (only used in context of linear reservoir option)*

CHAPTER 4: MODELLING TOOL STRUCTURAL REVIEW

4.1 INTRODUCTION

This chapter presents a review of process representation and functionality across the five selected modelling tools: WRSM-Pitman, SPATSIM-Pitman, ACRU4, SWAT2012 and MIKE-SHE. The review was intended to assist in understanding the following:

- The relative capabilities of each tool with respect to different model use cases (i.e. representing particular catchment types, spatial scales and types of change scenarios) and the approaches needed to build a relevant model using a given tool
- How and why model predictions made with different tools for the same catchment and input data may differ from one another
- How inputs and parameters used for a model built in one tool could be transferred (potentially with a particular transformation) to a model built with a different tool (if possible)

The intention was to review both “model structure”, in terms of the representation of hydrological processes, and the “modelling software tool structure”, in terms of the user interface, software requirements and capabilities. These aspects are intertwined in the design and use of the tool.

The tools’ structural options are described in growing levels of detail: an overview of broad capabilities, more specific descriptions of model spatial discretisation and connections between units, and the characterisation of the process representation algorithms applied for these units. These modelling tools estimate a large number of individual processes within a catchment. To make the review more readable, more detailed descriptions of representation by process are included in appendices A1 to A10. Summaries are presented in the main text. Key similarities and differences have been highlighted with implications for model application.

Some of the modelling tools also represent sediment movement processes, and the fate and transport of certain nutrients and other chemicals. These capabilities are mentioned, but the process representation is not reviewed here. This would be a valuable addition in further work.

4.2 INTENDED APPLICATIONS AND CAPABILITIES OVERVIEW

These software tools have different development histories and somewhat different intended uses. The structural options and design of the tool will reflect the intended applications, as well as the balance struck by the developers between potentially competing concerns, such as parsimony, detailed representation for representing specific changes, ease of use, uncertainty analysis, data needs, computing time, etc.

Table 4.1: Modelling tool curation, version and references considered

Characteristic	WRSM-Pitman	SPATSIM-Pitman	ACRU	SWAT	MIKE-SHE
Developed in South Africa	Yes	Yes	Yes	No	No
Free to access	Yes	Yes	Yes	Yes	No
Version reviewed	WRSM-Pitman version 2.9	SPATSIM GWv3 Global Options Threaded model	ACRU4	SWAT2012 and ArcSWAT2012	MIKE-SHE and MIKE Hydro River, version 2019–2020
Current curator/ developer	Bailey and Pitman Water Resources Ltd	Rhodes University Institute of Water Resources	University of KwaZulu-Natal Centre for Water Resources Research	Texas A&M University and US Department of Agriculture	Danish Hydrologic Institute
Reference documents	**Theory manual:** Bailey, 2015 **User manual:** Bailey and Pitman, 2016	**Theory papers:** Hughes, 2004; 2013; Kapangaziwiri, 2007 **User manual:** Hughes, 2019	**Theory manual:** Schulze, 1995 **Note:** ACRU3 theory **User manuals:** Clark et al., 2012; Schulze and Davis, 2018	**Theory manual:** Neitsch et al., 2011 **User manuals:** Arnold et al., 2012; Winchell et al., 2013	**Theory manuals:** DHI, 2019a; 2019b **User manuals:** DHI, 2019c; 2019d
Specific tool development focuses	Flexible network for managed systems with water transfers Irrigation, invasive alien plants and plantation forestry water use GW-SW interaction	Parsimony Uncertainty assessment GW-SW interaction	Detailed land cover type representation Crop and irrigation detail Invasive alien plants and plantation forestry water use Flexible network	Detailed land cover type representation Crop and irrigation detail Coupling to GIS tools	Flexible spatial discretisation Fine-scale processes GW-SW interaction Coupled hydraulic channel model and flooding processes
INTENDED APPLICATIONS					
Water balance estimation	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Design hydrology (flood peaks)	*No*	*No*	**Yes**	**Yes**	**Yes**
Supply planning (general)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Reservoir yield	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Irrigation planning	**Yes**	*(Limited: coarse scale)*	**Yes**	**Yes**	**Yes**
Ground water recharge	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Characteristic	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU**	**SWAT**	**MIKE-SHE**
GW-SW interaction and pump impact	**Yes**	**Yes**	*No*	**Yes**	**Yes**
Land cover change impact	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Climate change impact	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

An overview of the modelling tools in terms of curation, development and intended uses is given in Table 4.1. The modelling tools have progressively added capabilities to improve performance and allow for more types of application. An overview of some of the current capabilities of the tools is given in Table 4.2. This table focuses on capabilities that differ more between tools. For example, all the tools run using input climate time series and are all able to model impacts of changes in climate, although there will be differences in how they do this. More detailed coverage is given in sections 4.4 and 4.5, comparing tool discretisation, connections and process algorithms.

All the tools were intended for application across a range of spatial scales and for a wide array of modelling assessments. The intended uses generally overlap, but there are a few differences to note:

- **Flood peak analysis:** The Pitman-based tools use a monthly time scale and were not intended for flooding and design hydrology. Daily versions have been developed. However, they have had limited testing and use to date. The basic algorithms were developed for a monthly timestep.
- **Ground water-surface water (GW-SW) interaction:** MIKE-SHE, SWAT and the Pitman-based tools expressly set out to be able to simulate interactions in a way that allows a model to investigate the impacts of ground water withdrawals on hydrological processes. The tools have used different strategies to represent these exchanges, with MIKE-SHE, including the option of a 3D, gridded, physics-based ground water model. SWAT2012 is somewhat more limited in its two-way aquifer to channel connections, but configurations of SWAT have been linked to a more physical ground water model, MODFLOW, producing a modelling system much like MIKE-SHE. This linked modelling was not included in this review as this general type of modelling system is represented by MIKE-SHE, but exploration of this in further work would be useful.
- **Flooding and floodplain processes:** Another focus of MIKE-SHE has been integrating a full channel hydraulic model to more explicitly represent channel properties.

There is a significant diversity between model capability sets (Table 4.2). Some of the key points drawn from this comparison are the following:

- No one tool had all the capabilities listed. All the tools have differing sets of advantages over the others.
- Although both were based on the same predecessor model structure and shared many basic process algorithms (see Section 4.5), WRSM-Pitman and SPATSIM-Pitman have diverged in capabilities across several aspects. These differences are linked to WRSM's modular network structure compared to the SPATSIM version's focus on the subcatchment as the primary unit for process representation. For example, a WRSM model can include user-defined artificial water transfers between channel units in a model network, which SPATSIM does not include. SPATSIM's simpler structure greatly facilitates parameter sensitivity analyses, calibration and uncertainty analyses.
- Only MIKE-SHE has a fully coupled hydraulic model, allowing it to model channel-floodplain interactions in more detail and model flooding extent. The other tools can represent some aspects of overbank flooding and the fate of the flood water using their specific wetland modules or routines.

Table 4.2: Modelling tool capabilities overview

Capability	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE**
Climate (rain and PET)					
Spatially variable across model domain	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Spatially variable within subcatchment	*(limited)*	No	**Yes**	No	**Yes**
Inter-annual variability in PET	No	**Yes**	**Yes**	**Yes**	**Yes**
Land cover and change					
Processes explicitly linked to land cover	*(limited)*	*(limited)*	**Yes**	**Yes**	**Yes**
Multiple land cover types included	*(limited)*	*(limited)*	**Yes**	**Yes**	**Yes**
Cover has explicit location in subcatchment	*(limited)*	No	*(limited)*	*(limited)*	**Yes**
Cover can vary over model run timespan	**Yes**	No	*(limited)*	**Yes**	*(limited)*
Irrigation + dynamic demand and supply	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Potential direct ET from GW (deep root)	**Yes**	**Yes**	*(limited)*	*(limited)*	**Yes**
Peak flows and flooding					
Maximum daily or subdaily peak flow estimation	No	No	**Yes**	**Yes**	**Yes**
Explicit impacts of channel capacity on flow	*(limited)*	*(limited)*	*(limited)*	*(limited)*	**Yes**
Calculation of flooded area extent	*(limited)*	No	*(limited)*	*(limited)*	**Yes**
Flood water subject to infiltration, ET, etc.	*(limited)*	No	**Yes**	No	**Yes**
Reservoirs, dams and channel flow modification					
Reservoirs explicitly modelled	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Facility to represent many small dams	**Yes**	**Yes**	*(limited)*	*(limited)*	No
Abstractions and external inputs	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Internal transfers between model units	**Yes**	No	**Yes**	**Yes**	*(limited)*
GW representation and GW-SW interactions					
Dynamic, two-way, GW-SW exchange	**Yes**	**Yes**	No	*(limited)*	**Yes**
GW table elevation predicted	*(limited)*	*(limited)*	No	*(limited)*	**Yes**
GW pumping included	**Yes**	**Yes**	No	**Yes**	**Yes**
Wetlands and riparian zones					
Wetland processes included	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
On-channel wetlands	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Off-channel wetlands (fed by channel spill)	**Yes**	**Yes**	**Yes**	No	**Yes**
GW fed (receive GW from surroundings)	*(limited)*	*(limited)*	*(limited)*	*(limited)*	**Yes**

Capability	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE**
Other catchment and vegetation processes					
Sediment movement	No	No	**Yes**	**Yes**	**Yes**
Water quality	No	No	**Yes**	**Yes**	**Yes**
Crop yield	No	No	**Yes**	**Yes**	No
Uncertainty and parameter calibration					
Tools for uncertainty, parameter sensitivity and auto-calibration (batch runs)	No	**Yes**	No	No	**Yes**

4.2.1 Coupling models and modelling tools to enhance capabilities

The intercomparisons presented here cover tool options and capabilities focused on hydrological processes and without any coupling to other modelling software tools. However, it should be noted that catchment hydrological models can be combined with models developed for other processes and/or other scales or levels of detail to extend their capabilities, and model full systems of interest. For example, hydrological models can be coupled with the following:

- Channel and floodplain hydraulic models
- Finite-difference or finite-element mechanistic ground water models
- Sediment movement, channel evolution or landscape evolution geomorphological models
- Tidal coastal systems hydraulic models
- Nutrient, ion or pollutant models (cycling, movement, sorption, degradation, metabolism)
- Vegetation growth or specific crop yield models
- Climate models (land surface models)
- Urban drainage system models
- Water supply system management models
- Stakeholder decision making simulation models, economic models, agent-based models, land cover change prediction models, etc.

“Coupling” can be a simple one-way connection: the outputs of one model are simply used as inputs to the second. It can also be two-way and dynamic, including feedback between the two models, sometimes in an iterative calculation process. In this case, some outputs of one model are fed into the second model for a timestep, algorithms of the second are run for the timestep, some outputs of the second model are fed back into the first for the start of the next timestep, etc. Iterative calculations may be required for each timestep to resolve exchanges between the two systems.

Over time, some hydrological modelling software tools have incorporated algorithms developed in these other types of models to build a single system that simulates the set of processes and feedbacks. For example, MIKE-SHE has a coupled channel hydraulic model and finite-difference ground water model. SWAT2012 includes vegetation growth modelling (including crop yield). ACRU4 has a crop growth and yield model. MIKE-SHE and SWAT2012 have some sediment, nutrient and pollutant tracking options. Some sediment, salt and nutrient facilities have been designed for South African tools but not all are fully incorporated into the versions used here.

A common and important model coupling in the South African water sector is using modelled catchment hydrology as input to water supply system models, most often the WRYM and WRPM developed by the Department of Water and Sanitation (DWS). Using stochastic timeseries of flow inputs into a supply system set up in the model, with storages, transfers, demands, rules, etc., these tools determine yield reliability curves for the system, and components and responses to demand changes, curtailments and augmentation over a planning horizon.

These tools were specifically designed to work with WRSM-Pitman outputs: monthly timestep "naturalised" flows coupled with catchment "demand" series. "Naturalised" flows refer to streamflow predicted without invasive alien vegetation, commercial forestry, agriculture or withdrawals. The decrease in flow due to these alterations can be viewed as a "demand", theoretically changable with management interventions. WRSM is specifically designed to model "naturalised" and "current development" flows to supply system input points with one model set-up. Other tools could theoretically provide the inputs required by WRYM and WRPM. However, a model set-up and output processing method would need to be designed for this.

4.3 HANDLING STRUCTURAL OPTIONS IN TOOL REVIEW

All the tools have some flexibility in how a catchment model can be set up. This adds a layer of complexity when comparing them. An effort has been made to document and consider the main structural options in a tool in this review. In the case of MIKE-SHE and the Pitman-based modelling tools, some specific approaches were assumed as more typical and so were used in describing the tools in parts of the review. Descriptions and rationales for this are given below. It should also be noted that different versions of most of these tools have been made for research projects with modules or adaptations of particular use to the research question, some of which are mentioned in published literature. This review only covers standard versions of the tools being distributed by their curators.

4.3.1 MIKE-SHE structural options and coverage in review

The MIKE-SHE modelling tool includes a wider diversity of discretisation options and algorithms than the other tools being reviewed. It allows users to build models with very different levels of complexity. For example, it can be used to set up a "fully distributed" model, in which the landscape and subsurface are broken up into grid cells for process calculations, or a "semi-distributed" model, in which the catchment is represented as a group of larger areas or HRUs. For any MIKE-SHE model, a computational grid must be defined and many algorithms are solved by grid cell. However, parameters and climate inputs can be specified by polygons of areas considered to have relatively uniform properties, rather than for each grid cell individually. In addition, surface run-off and ground water flows can be represented with algorithms solved at a polygon-scale rather than by grid cell. For most processes, there are also representation algorithm options that are more conceptual, often needing fewer parameters, and those that are more physics-based. Certain representation options for one process or component may only be compatible with certain other choices. A tree of the major structural options and compatibilities is shown in Figure 4.1. Discretisation and algorithm options in MIKE-SHE are described in further detail in the sections below.

To facilitate comparisons of process representation across tools within this review, MIKE-SHE will be described for two model set-up approaches at opposite ends of the complexity spectrum:

- **MIKE-SHE simple – semi-distributed, more conceptual:** Parameters and inputs by polygon, simple overland flow routing, two-layer method for ET and soil moisture accounting, linear reservoirs for interflow and ground water representation.
- **MIKE-SHE complex – fully distributed, more physical:** Spatially distributed gridded inputs where relevant, finite difference diffuse wave calculation for overland flow, Kirstensen and Jensen ET algorithm, gravity flow or Richard's equation for water movement through soil layers, finite difference solution of Darcy's Law to calculate ground water flow in 3D.

It is important to note that these particular modelling strategies are not enforced by the MIKE-SHE tool and many combinations of these different component options are possible (Figure 4.1).

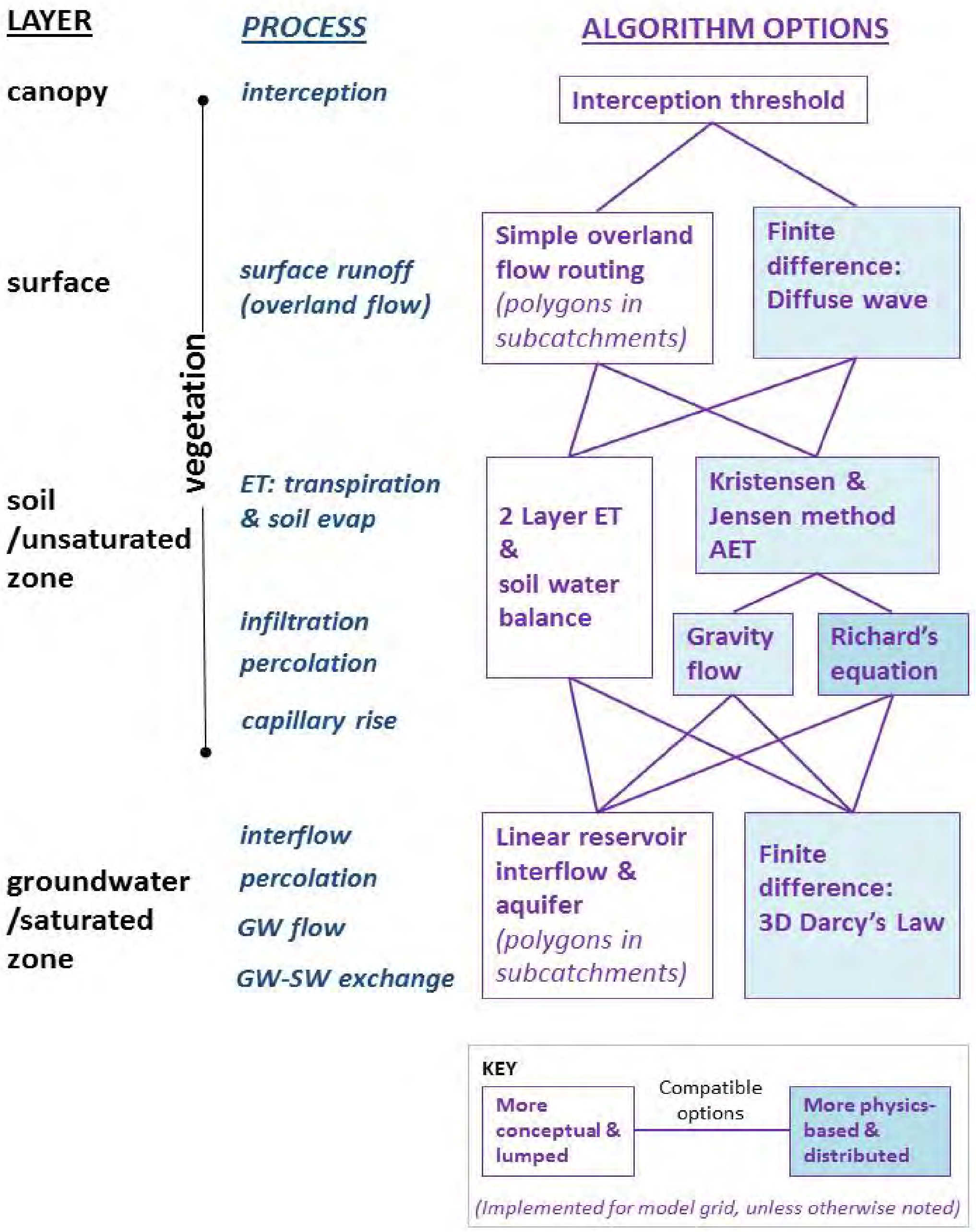


Figure 4.1: Schematic diagram of process representation algorithm options and their compatibilities in MIKE-SHE

4.3.2 SWAT structural options and coverage in review

One of the process representation options within the SWAT modelling tool that notably impacts other aspects of the model structure is the choice of which infiltration and runoff generation algorithm to use. The options included are the SCS-CN method and the Green-Ampt Mein-Larson method (Neitsch et al., 2011). The SCS-CN method is an empirical equation originally developed to predict runoff generation specifically, rather than being part of a comprehensive catchment water balance model. If the SCS-CN approach is used, canopy interception is not explicitly modelled, so its impact must be implicitly considered in the calculations of other processes. This changes how other processes in the model (infiltration, ET from soil) should be viewed conceptually. The Green-Ampt Mein-Larson infiltration option allows canopy interception to be calculated as a separate process, but this method can only be used if the model is run at a subdaily timestep for which the infiltration algorithm is considered appropriate.

This will increase the computation burden when doing long simulations. In addition, subdaily climate input data is not often available. To address the latter issue, SWAT includes algorithms to generate it from daily data, although this comes with an additional set of embedded assumptions. The SCS-CN approach has been used in SWAT since the tool originated and is the option more commonly applied at present. As a result, SWAT, as applied with the SCS-CN method for runoff generation, is the structure presented in the summary comparisons in the main review document. However, both options are covered in the detailed process tables in appendices A1 to A10.

4.3.3 ACRU structural options and coverage in review

The ACRU modelling system allows users to build models that are discretised at the scale of subcatchments or to further discretise subcatchments into HRUs. Some of the process representation options presented in the ACRU theory documentation (Schulze, 1995) are only relevant when using subcatchments as the unit of calculation, available in the ACRU3 version. Because ACRU4 is being more widely taught and distributed with a focus on HRU scale representation, this is the version and approach that will be considered in this review.

4.3.4 Pitman-based tool development and coverage of modules in review

The two tools included here that are based on the original Pitman model structure (Pitman, 1973), WRSM-Pitman (Bailey and Pitman, 2015) and SPATSIM-Pitman (Hughes, 2005), have diverged from one another in some aspects more than others. However, their development has not been totally independent. A major addition in both tools has been the separate representation of ground water, compared to the total subsurface storage considered in the original. Two different methods were developed: the Hughes method (Hughes, 2004) and the Sami method (Bailey and Pitman, 2016). The WRSM-Pitman tool includes the option to implement the original model algorithm, the Hughes ground water algorithm, or the Sami ground water algorithm, while the SPATSIM-Pitman tool includes the Hughes ground water algorithm. The SPATSIM-Pitman formulation of the Hughes method has evolved further since its incorporation into WRSM-Pitman, and has received more testing as applied in the SPATSIM-Pitman tool, which has other differences in structure and representation to WRSM-Pitman. The WRSM-Pitman tool was used for the Water Resources of South Africa 2012 Study (WR2012) (Bailey and Pitman, 2015), in which it was applied to all quaternary catchments in South Africa, calibrated where possible, using the Sami ground water option.

For these reasons, process representation using these two tools will be considered using the following:

- **WRSM-Pitman** with the **Sami ground water algorithms (monthly version)**
- **SPATSIM-Pitman** with the **Hughes ground water algorithms (monthly version)**

Daily timestep versions of both WRSM-Pitman and SPATSIM-Pitman have also been developed. However, these have very rarely been applied to date and there has been less testing and experience in calibrating them. As such, only the monthly versions have been considered in this review.

4.4 DISCRETISATION AND CONNECTIONS

This section focuses on discretisation, how a catchment area is broken up into separately represented units and connections, and how these units are linked to one another to represent catchment hydrological processes in a model. When units or layers are differentiated from one another, the inflows, storage versus outflow rules, and the connections between other units and layers need to be defined. Discretisation determines the level and scale of process representation, and hence what algorithms are appropriate. The discretisation of space and processes also interacts with the timesteps of calculations.

4.4.1 Tool approach descriptions

The modelling tools differ in their strategies for breaking up the surface and subsurface of a catchment into calculation units. A summary of the main options for discretisation in each modelling tool is given in Table 4.3. These basic approaches are illustrated with schematic diagrams in Figure 4.2. Table 4.3 goes on to summarise how each tool discretises the land surface and land cover types, soils, aquifers and river channels into model units, and how these can be linked.

Discretisation of space is linked to discretisation in time: longer timesteps are more appropriate for large modelling units because of the time needed for water to move across or through such a unit. The Pitman-based tools run with a monthly timestep, ACRU4 runs with a daily timestep, while SWAT and MIKE-SHE can run with user-selected daily to subdaily timesteps. The Pitman tools represent many hydrological processes at the scale of a subcatchment. However, AET can be calculated separately for two land covers per subcatchment. Processes for certain sub-area types or land covers (irrigated areas, wetlands and impervious areas) can also be calculated separately within each subcatchment. Multiple subcatchments can be represented in a connected network within a larger catchment.

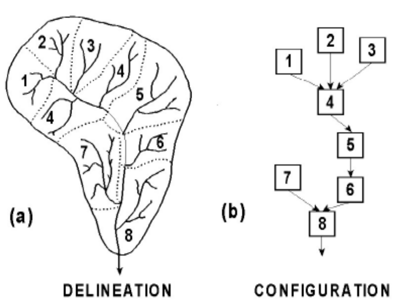
ACRU4 and SWAT2012 are semi-distributed, representing most processes at the scale of HRUs within subcatchments within a catchment. Surface and subsurface runoff from all HRUs in a subcatchment are allocated to its river reach. Subcatchments within a catchment are linked through a river network. SWAT requires some inputs, such as rainfall, to be specified. Some processes, such as ground water outflow, should be represented at the subcatchment scale rather than the HRU scale.

MIKE-SHE can be used to build a distributed, 3D, gridded SW-GW model. It can also be used to build a model in which surface and shallow subsurface processes are represented for grid cells, but surface flow is routed through zones, and ground water flow is represented with a number of conceptual aquifer reservoirs within subcatchments.

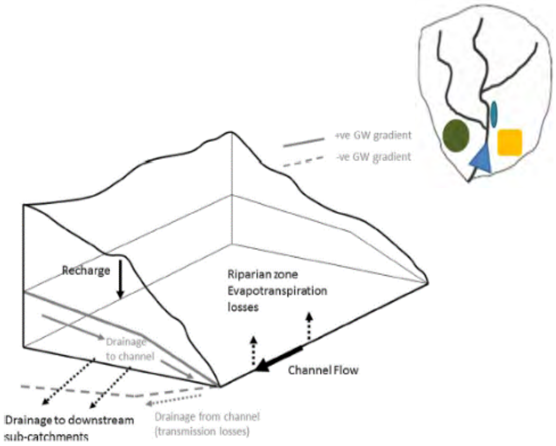
Table 4.3: Structure overview across modelling tools

Structure characteristic	**WRSM Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE Semi-distributed, more conceptual**	**MIKE-SHE Distributed, more physical**
Timestep	Monthly* *(Daily versions exist. Limited use to date)*		Daily	Daily, subdaily	Daily, subdaily* *(dynamic timesteps by process; outputs saved for selected step)*	
Spatial discretisation	Modules connected by routes *("runoff modules" + special area modules + channel modules create subcatchments)*	Subcatchments + limited internal sub-area types	HRUs within subcatchments		Gridded surface and soils + zones within subcatchments: overland flow, interflow, "baseflow reservoirs"	Gridded (3D), no subcatchments *(topography is explicit: flow is dictated by gradients)*
Spatial model units for:						
Climate input	Modules	Subcatchments	Subcatchments or HRUs* **laborious*	Subcatchments	Grid cells or zones	Grid cells or zones

Structure characteristic	**WRSM Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE Semi-distributed, more conceptual**	**MIKE-SHE Distributed, more physical**
Surface and shallow subsurface processes	“Runoff modules” + special area modules	Subcatchments (+ internal special sub-areas)	HRUs		Grid cells + overland flow zones + interflow reservoir zones	Grid cells
Ground water processes	“Runoff modules”	Subcatchments	HRUs	Subcatchments	Baseflow reservoir zones	Grid cells
Channel processes	Channel “modules”, flexible connections to other modules	One channel unit within a subcatchment	Channel units with flexible connections to HRUs and dams within a subcatchment	One channel unit within a subcatchment	Spatially and topographically explicit channel reaches between nodes, connected to bordering landscape units (surface and subsurface), flexible spatial layout	
Waterbodies (optionally added)	Reservoir “modules”, flexible connections to other modules	One reservoir at outlet of subcatchment channel (not for irrigation) + single/lumped dam internal to subcatchment (can irrigate)	Dam units with flexible connections to HRUs and channels within a subcatchment	One reservoir at outlet of subcatchment channel (can irrigate) + “pond” and “depression” units internal to subcatchment (not for irrigation)	Storage created with explicit bathymetry cross-sections in channel reach set-up (can irrigate) OR Simple storage unit attached to reach (not for irrigation)	

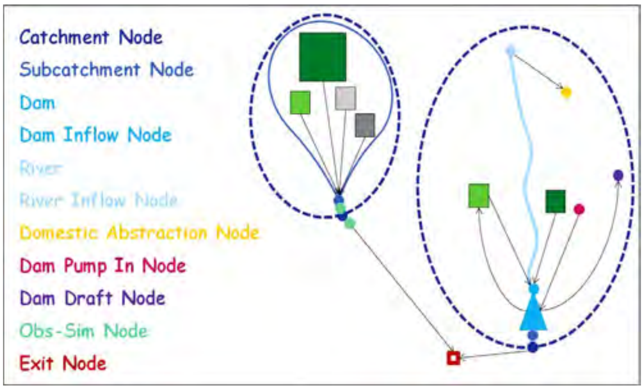


Subcatchment delineation (all tools, except MIKE distributed): Incremental subcatchments (left) linked in a network (right) within the catchment (Schulze, 1995)

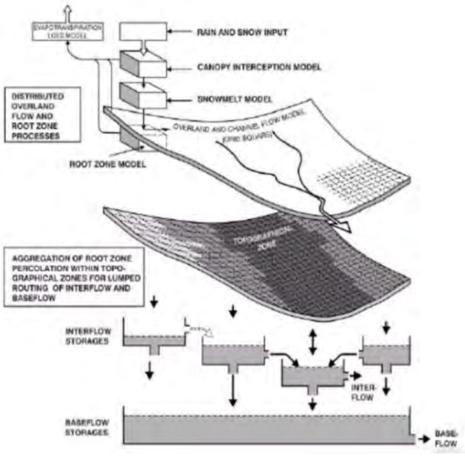


Subcatchment as the dominant model unit (SPATSIM-Pitman and WRSM-Pitman): Special subareas (right) and hillslope scale GW representation (left) (Hughes, 2004)

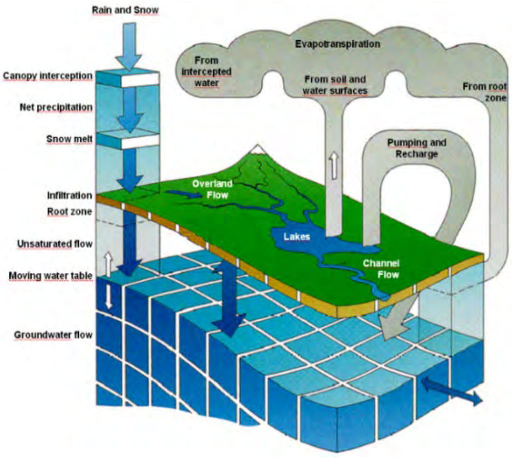
Network of land and waterbody modules (WRSM-Pitman): Runoff modules (pentagons), irrigation (squares) channels (circles), reservoirs (triangles) (Bailey and Pitman, 2015)



HRUs and waterbody units in subcatchments (ACRU4 and SWAT): HRUs (squares), channels, reservoirs linked within subcatchments (ovals) in ACRU (Clark et al., 2012)



Semi-distributed layered zones and linear reservoirs (MIKE-SHE): Parameterised by zone with linear reservoirs for interflow and aquifer representation (DHI, 2017)



Fully distributed, 3D model grid (MIKE-SHE): Calculation grid cells, surface and subsurface (DHI, 2017)

Figure 4.2: Schematic diagrams from modelling tool documentation illustrating discretisation and connection approaches

Table 4.4: Horizontal and vertical discretisation approach in each modelling tool for land cover, unsaturated zone, aquifers, river channels, reservoirs, wetlands and irrigated area

LAND COVER

COMPONENT	WRSM-Pitman (Sami GW)	SPATSIM-Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Spatial units for land cover type/property distribution	**Modules and sub-areas within (limited type and number)** Extents of cover types are either defined in set-up of a "runoff module" or special area modules (which are tied to, and act as subareas of, a "runoff module") Each runoff module can have different general cover specifications and linked special areas.	**Sub-areas within subcatchments (limited type and number)** Extents of cover types are defined as special sub-areas within a subcatchment Each subcatchment can have different general cover and sub-area specifications.	**HRUs** Each HRU has its own cover and vegetation parameters.	**HRUs** Each HRU has cover and vegetation parameters. HRUs are assigned cover types using an input cover type map. Properties are input by type.	**Cover type polygons applied to grid cells** Each grid cell is assigned a cover type using an input cover-type map. Surface flow parameters (roughness and detention storage) can be assigned for separately mapped zones. (It does not need to align with cover or soil-type boundaries)	**Cover type polygons applied to grid cells** Each grid cell is assigned a cover type using an input cover-type map. Surface flow parameters (roughness and detention storage) can be assigned for separately mapped zones. (It does not need to align with cover or soil-type boundaries)
Limitations to types and number of types	**Yes** Types represented by unit: **Runoff module (RM):** General vegetation Impervious Riparian zone **Special module, one per RM:** Afforestation Invasive alien vegetation **Special module, multiple per RM:** Irrigated crops Mines	**Yes** Types represented: General subcatchment vegetation Impervious area Higher ET vegetation (forest, tree plantation, alien vegetation) Irrigated crops **Only one type of each explicitly represented within a subcatchment.**	No No limit on number of HRUs (hence cover types) per subcatchment.	No No limit on number of HRUs or cover types per subcatchment.	No No limit on number of cover types.	No No limit on number of cover types.

SOILS AND UNSATURATED ZONE

COMPONENT	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Spatial units for distribution of soil types/ properties	**Runoff modules and irrigation modules** Each "runoff module" can have its own soil moisture store and "percolation storage" properties. Afforestation and alien vegetation modules use the soil of the runoff module they are linked to or part of. Irrigation modules have their own soil properties.	**Subcatchments** Each subcatchment can have its own soil moisture store properties.	**HRUs** Each HRU can have its own soil properties	**HRUs** Each HRU can have its own soil properties. HRUs are assigned soil types using an input soil-type map. Properties are input by soil type. Individual HRU soil properties can be modified.	**Soil type polygons applied to grid cells and "interflow reservoir" extent polygons** Each grid cell is assigned a soil type using an input soil-type map. Interflow reservoir "type" extents are input as a map (boundaries do not need to align with soil types or subcatchments)	**Soil type polygons applied to grid cells** Each grid cell is assigned a soil type using an input soil-type map.
Vertical layers	**Two layers** A runoff module has two "UZ" layers: Soil moisture storage Percolation lag storage	**One layer** A subcatchment has a single soil moisture storage unit.	**Two layers** An HRU has two soil layers: A horizon B horizon Both in root zone	**11 layers (maximum)** A soil type can have up to 10 layers (user input layers). Profile can extend below the root zone. Each HRU also has a vadose zone (lag storage) "layer" below the soil profile	**Two or three layers*** A soil type has vertically uniform parameters (no layers), but each model grid cell has two computational UZ layers: Upper layer (root zone) Lower layer (below roots) Interflow reservoir: lumped storage unit fed by all overlying grid cells	**Unlimited layers** A soil type can have an unlimited number of layers (user input layers). Profile can extend below the root zone.

COMPONENT	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Surface runoff routing, with regard to landscape units	**Parallel*** Parallel for runoff and irrigation modules Other special area modules modify runoff module flow	(n/a) Subcatchment scale	**Parallel** Parallel from HRUs in subcatchment	**Parallel** Parallel from HRUs in subcatchment	**Series or parallel** Across a series of mapped flow zones within a subcatchment OR each zone in parallel	**Series** Across grid cells based on elevation.
Interflow routing, with regard to landscape units	**Parallel*** Parallel for runoff modules and irrigation modules Other special area modules modify runoff module flow	(n/a) Subcatchment scale	**Parallel** Parallel from HRUs in subcatchment	**Parallel** Parallel from HRUs in subcatchment	**Series** Through a series of interflow reservoirs in a subcatchment	**Series** Through grid cells based on head.
Capillary rise from aquifer to UZ	**Yes*** Only in riparian zone, represented as ET deficit met by GW	**Yes*** Only in riparian zone, represented as ET deficit met by GW	No* Water in the baseflow store of an ACRU4 HRU cannot move back to the soil profile or be used for ET in that same HRU. The set-up option in which upland HRU baseflow is routed to riparian HRU soil has a similar impact to riparian zone GW access in subcatchment-scale models.	**Yes** Represented as ET deficit met by GW	**Yes*** Only in riparian zone, represented as ET deficit met by GW	**Yes**

AQUIFER (AND SATURATED ZONE

COMPONENT	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Spatial units for distribution of aquifer types or properties	**Runoff modules** Each runoff module can have its own aquifer properties.	**Subcatchments** Each subcatchment module can have its own aquifer properties. There is a spatial division into two slope sections, riparian and upslope, for process calculation, but these do not have separate property parameters.	**HRUs** Each HRU can have its own "baseflow storage" properties.	**Subcatchments/HRUs*** Aquifer storage and outflow is calculated per subcatchment, but some aquifer properties can be input per HRU (to model capillary rise, pumping)	**"Baseflow reservoir" extent polygons** "Baseflow reservoir"-type (aquifer-type) spatial extents are input as a map (boundaries do not need to align with other inputs)	**Layer and lense polygons applied to grid cells** Each grid cell has a layered profile of aquifer material types based on the layers and lenses it overlies. Property "layers" cover the entire model domain, can have spatially variable thickness (grid input). "Lenses" occur in certain areas (map input) also with variable thickness.
Vertical layers within aquifers	**One layer** A runoff module has one aquifer unit	**One layer** A subcatchment has one aquifer store. There are two linked horizontal subsections, but no vertical divisions.	**One layer** An HRU has one "baseflow" storage.	**Two layers*** A subcatchment has two aquifer units: a shallow aquifer (outflow to channel) and a deep aquifer (no outflow)	**Two layers*** A mapped "baseflow reservoir"-type can have two internal storage units with different parameters.	**Unlimited layers** No limit on the aquifer material layers and lenses that can be input. Calculation grid layers can be set differently to the aquifer property layers. In this case, thickness-averaged parameters are assigned.

COMPONENT	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
GW flow routing between spatial units	**Yes** GW flow between subcatchments	**Yes** GW flow between subcatchments	(Limited) No GW flow between subcatchments Upslope HRU baseflow can be routed to riparian HRU soil within a subcatchment No other HRU GW exchanges included	*No* No GW flow between subcatchments	*No* No GW flow between subcatchments No GW flow between “baseflow reservoirs” (aquifer types) within subcatchment	**Yes** GW flow between grid cells
GW flow routing vertical aquifer units or layers	(n/a – single unit)	(n/a – single unit)	(n/a – single unit)	*No* Shallow and deep aquifers each receive a portion of total recharge and do not interact (more like units than vertical layers)	*No* The two units in a mapped baseflow reservoir type each receive a portion of total recharge and do not interact (more like units than vertical layers)	**Yes** GW can flow between vertical layers based on head and conductivity
GW flow out of model domain (catchment)	**Yes**	**Yes**	No	Yes* Only deep aquifer can have GW flow the model. (Deep aquifer does not feed channel, can be pumped)	No* Recharge can be allocated to “dead storage”, which has a similar impact.	**Yes** GW outflow boundary condition must be set up.
GW abstraction included	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**
Limits on abstraction points	One per runoff module	Two per subcatchment: one per subcatchment aquifer section upslope and riparian	*(n/a)*	Two per subcatchment: one per subcatchment aquifer unit: one shallow and one deep	Flexible number	Flexible number

COMPONENT	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Abstraction routing options	Removed from model	Removed from model	*(n/a)*	Removed from model, applied as irrigation	Removed from model, applied as irrigation	Removed from model, applied as irrigation

RIVER CHANNEL NETWORK

COMPONENT	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Channel units by subcatchment (or catchment)	**Flexible** Channels represented with channel modules in a network. No limit to number of channel modules. Multiple connection configurations possible: maximum 10 input and 10 output routes per channel module.	**One per subcatchment** Subcatchment channel receives flow from the channels of upstream subcatchments and flows out to channel of downstream subcatchment.	**Flexible** Multiple channel units can be included in a network in a subcatchment. In non-headwater subcatchments, a channel is needed to receive flow from upstream subcatchments and route to the subcatchments outflow node. Each special riparian HRU and wetland HRU needs its own linked channel unit. No limit to the number of channel units included.	**One per subcatchment*** Each subcatchment has one “main channel” that receives flows from the main channels of any upstream subcatchments and flows out to the channel of the downstream subcatchment. Each subcatchment also has one conceptual “tributary” that routes HRU runoff to the main channel. This allows for additional delay and loss to aquifer if relevant.	**Flexible** Channels are represented as a spatially explicit network of reaches between calculation nodes (cross-sections) at specified intervals. Reaches with nodes mapped in subcatchment can exchange water with that subcatchment. No limits to numbers of river branches or of reach units that can be in a subcatchment.	**Flexible (no subcatchments)** Channels are represented as a spatially explicit network of reaches between calculation nodes (cross-sections) at specified intervals. Reaches exchange water with grid cells that border them. No limits to the numbers of river branches or of reach units in a model. There cannot be two reaches in one grid cell (node spacing compatible with model grid).

COMPONENT	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Surface flow from land units into channel	**Yes** Runoff, irrigation, mine modules to a linked channel module.	**Yes** Subcatchment to its channel.	**Yes** HRU to a linked channel in subcatchment.	**Yes** All HRUs in subcatchment to tributary then subcatchment's main channel.	**Yes** "Overland flow" zone in subcatchment to reaches in subcatchment. Series routing: only from most downslope zone.	**Yes** Grid cells bordering a reach to that reach (if surface flow is over bank height).
Flow from channel onto land surface (overbank flooding)	*(to wetland unit only)* A wetland can be included within a channel module.	*(to wetland unit only)* A wetland can be included at downstream end of subcatchment.	*(to special riparian or wetland HRUs only)* Special HRUs for riparian areas and wetlands can be included. Each needs a linked channel unit with an overflow threshold.	No A wetland can be included in a subcatchment, but is not on the "main channel", not fed by overflow.	**Yes** Channel flow over capacity is routed onto floodplain surface. This water can infiltrate into flooded grid cells.	**Yes** Channel reach to bordering grid cells
Interflow into channel	**Yes** Runoff, irrigation, mine modules to a linked channel module.	**Yes** Subcatchment to its channel.	**Yes** HRU to a linked channel in subcatchment.	**Yes** All HRUs in subcatchment to tributary then subcatchment's main channel.	**Yes** Most downslope"“interflow reservoir" in subcatchment to reaches in subcatchment.	**Yes*** MIKE handles perched temporarily saturated layers, "interflow" in its "saturated zone". The channel can receive water from such a layer from bordering cells.
Flow from channel (direct) into unsaturated zone (transmission loss)	No Channel transmission loss leaves the model	No Channel transmission loss only to aquifer	No No channel transmission loss	**Yes*** Main channel transmission loss is added to "bank storage" – accessible for ET and not part of subcatchment aquifers.	No	**Yes*** MIKE handles perched temporarily saturated layers, "interflow" in its "saturated zone". The channel can lose water into such a layer in bordering cells.

COMPONENT	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Ground water (GW) flow into channel	**Yes** Runoff module to a linked channel module.	**Yes** Subcatchment (downslope aquifer portion) to its channel.	**Yes** HRU to a linked channel in subcatchment.	**Yes** Subcatchment shallow aquifer to channel (not from the deep aquifer).	**Yes** All “baseflow reservoirs” in subcatchment to reaches in subcatchment.	**Yes** Saturated layers of grid cells bordering a reach to that reach.
Flow from channel into GW (transmission loss)	No Channel transmission loss leaves the model.	**Yes** Channel transmission loss to subcatchment aquifer (downslope portion).	No No channel transmission loss.	No* Main channel transmission loss does not enter subcatchment aquifer. Tributary can lose to subcatchment’s shallow aquifer.	**Yes** Reach in subcatchment to baseflow reservoir in subcatchment.	**Yes** Reach into saturated layers of grid cells bordering it.
River abstraction: water leaves model	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
River transfer: managed exchange between channels	**Yes**	No	No	**Yes**	Yes* (complex hydraulic set-up)	Yes* (complex hydraulic set-up)
External point source inputs	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Location options for: abstraction, transfer, external input	**Flexible (avoiding circular routing)**	**Subcatchment channel outlet (above reservoir)**	**Flexible**	**Subcatchment main channel outlet (above reservoir)**	**Flexible**	**Flexible**

RESERVOIRS, DAMS, LAKES

COMPONENT	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE (all approaches)
Water body unit types	**One type*: Reservoir module** Wetlands modelled as water body; different unit type (see below)	**Two types*: Reservoir and dam** Wetlands modelled as water body; different unit type (see below)	**One type: Dam**	**Three types*: Reservoir, pond, depression** Wetlands modelled as water body; different unit type (see below)	**Two approaches: Explicit bathymetry and wall, simple storage volume**
Units per subcatchment	**Flexible**	**One reservoir per subcatchment** **And one dam per subcatchment**	**Flexible**	**One reservoir per subcatchment and one pond per subcatchment and multiple depressions**	**Flexible**
Flows into water body units	Reservoir module can receive the following: • Rain • Flow/transfers from up to five other modules routed to it (land areas, channels and other reservoirs) – from runoff modules it can receive a set proportion of total runoff. • External source input routed to it A reservoir receiving a set proportion of runoff from a runoff module can be thought of as internal to the subcatchment that the runoff module represents.	A **reservoir** is on the subcatchment channel at the outlet, so receives: • Rain • Local subcatchment runoff • Channel flow from upstream A **dam** is internal to a subcatchment and receives: • A set proportion of total subcatchment runoff	A dam can receive the following: • Rain • Flow from channels and HRUs routed to it • External source input routed to it	A **reservoir** is on the subcatchment channel at the outlet, so can receive: • Rain • Local subcatchment runoff • Channel flow from upstream subcatchments • Transfers from channels and reservoirs in other subcatchments A **pond** is internal to a subcatchment and receives: • Rain • A set proportion of total subcatchment runoff	Handled in the channel hydraulic model (MIKE-Hydro). Waterbody bathymetry cross-sections and dimensions of a dam wall can be input in a channel reach. A reach can receive the following: • Rain • Runoff from bordering units (cells, zones) • Channel flow from upstream reach • Transfers from other reaches • External point source inputs

COMPONENT	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE (all approaches)
	If it receives all the runoff, it is at the subcatchment outlet.			A **depression/pothole** is ponded water on a specified HRU and receives: • Rain • A set proportion of runoff from other specified HRUs in the same subcatchment	Alternative: simple "storage" volume unit added to the end (or side) of a channel branch, which receives flow from the branch
Flows out of water body units	Water can leave a reservoir module as: • Evaporation • Overflow and controlled release to linked channel module downstream • Withdrawal to linked irrigation modules • Withdrawal transferred other reservoirs and channels • Withdrawal removed from model A reservoir can have a maximum of five outflow routes.	Water can leave a **reservoir** as: • Evaporation • Overflow and controlled release to downstream subcatchment channel • Withdrawal removed from model Water can leave a **dam** as: • Overflow to subcatchment channel • Withdrawal to subcatchment irrigation sub-area	Water can leave a dam as: • Evaporation • Overflow, controlled release and seepage to linked downstream channel or subcatchment outflow node • Withdrawal to linked irrigation HRU • Withdrawal removed from model	Water can leave a **reservoir** as: • Evaporation • Overflow and controlled release to downstream subcatchment channel • Seepage to subcatchment aquifer • Withdrawal to linked irrigation HRU • Withdrawal transferred to other reservoirs and channels • Withdrawal removed from model Water can leave a **pond** as: • Evaporation • Overflow and controlled release to downstream subcatchment channel	Water can leave a reach storage created with bathymetry and a wall structure as: • Evaporation • Overflow and controlled release to downstream reach • Seepage to bordering unit ground water • Withdrawal to linked irrigation area • Withdrawal transferred other reservoirs and channels • Withdrawal removed from model Water can leave a "storage" volume unit as: • Overflow to a downstream branch (no irrigation direct from storage unit)

COMPONENT	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE (all approaches)**
				• Seepage to subcatchment aquifer Water can leave a **depression** water body as: • Evaporation • Overflow and controlled releases to subcatchment main channel • Seepage to local HRU soil (local HRU also has vegetation ET and subsurface runoff generation)	

WETLANDS

COMPONENT	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Specific wetland unit	**Yes*** Within channel module	**Yes**	**Yes**	**Yes**	No* Wetland conditions can be recreated with topography, channel, aquifer, soil and cover set-up	No* Wetland conditions can be recreated with topography, channel, aquifer, soil and cover set-up
Location of wetland unit in subcatchment (catchment)	**On channel: flexible location in network**	**On subcatchment channel at subcatchment outlet**	**HRU + associated channel: flexible location in network**	**Internal to subcatchment: NOT on main channel**	**Flexible**	**Flexible**

COMPONENT	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Surface water into wetland	Channel flow over threshold (or all)	Channel flow over threshold (or all)	Channel flow over threshold (or all)	Proportion of subcatchment surface runoff	Surface runoff from upslope zone, channel overflow	Surface runoff from upslope grid cells, channel overflow
Wetland outflow to surface water	Outflow to channel module	Outflow to subcatchment channel outlet	Outflow routed in network (to channel, dam or subcatchment outlet node)	Outflow to subcatchment main channel	Outflow to downslope zones or to channel	Outflow to downslope cells and/or to channel
Ground water into wetland (direct)	No	No	No	**Yes*** Proportion of subcatchment subsurface runoff	**Yes*** Capillary rise only	Yes
Wetland seep to ground water	No	No	**Yes*** Wetland HRU has a "baseflow store"	**Yes**	**Yes**	**Yes**

4.4.2 Key similarities and differences, potential implications

Viewed at a very basic level, the five catchment modelling tools under review are similar in some notable ways:

- **Catchments divided into subcatchments:** All the tools *can* represent a larger catchment as an accumulative flow network of smaller subcatchments. In this way they are all "semi-distributed" to a certain extent, allowing spatial distribution of climate and catchment properties to be explicit in a model. MIKE-SHE also offers "fully distributed" (3D grid) representation as an option.
- **Same major vertical layers:** All the tools represent hydrological processes for the same broad set of vertical layers – vegetation canopy and land surface, soils or unsaturated zone, and aquifer materials – which are then linked to a channel network.
- **Multiple land cover types per subcatchment:** All the tools allow different land cover types to be explicitly represented across different subcatchments and within them. At a minimum (some tools allow more), within each subcatchment, all the tools can explicitly represent the following:
  - A dominant generalised vegetation type per subcatchment (i.e. local indigenous veld, non-irrigated grazing land)
  - A separate tree-dominated vegetation type per subcatchment (e.g. forest, commercial tree plantations, invasive alien tree stands)
  - An area of irrigated crops
  - Impervious cover (urban area, bare rock)
- **Reservoirs, dams and waterbodies:** All tools can include reservoirs, dams and waterbodies fed by the channel network.

However, despite their high-level similarities, there are numerous differences in how the tools allow users to discretise and represent various components of catchments, in terms of scales, unit types and connections as documented in Table 4.4. These differences have implications for what a model can represent explicitly and for how model-building decisions, such as discretisation into subcatchments and other model units, parameterisation, etc., influence process representation. Major differences in approach and their implications are summarised in Table 4.5 regarding differences in the following:

- Spatial units for climate input
- Spatial units for land cover property input and their connectivity
- Spatial units used to represent aquifers and their connectivity
- Channel units and their links to landscape units

Table 4.5: Key differences in model structure approaches across tools and implications for model use

CLIMATE: Spatial units for which climate inputs are specified			
Why it can be important and when	Determines **if and how spatial variation in climate over the catchment can be represented** in the model. *Likely more important for outcomes for catchments with the following:* • *Larger gradient magnitudes across the catchment area (e.g. larger catchment size, more mountainous terrain)* • *Generally drier areas in which the higher rainfall parts are frequently the only places where thresholds for runoff production are reached (i.e. if more averaged rainfall were applied for a larger area, then no runoff would be modelled)* ***Note:*** *Potential advantages of including more spatial climate variability in a model also depend on the level of data available about the spatial distribution of rainfall and PET.*		
Alternative approaches	**Subcatchment**	**HRU / module / waterbody**	**Individual grid cells** (i.e. "data cube" input) **or independent zones** (not tied to the boundaries of other inputs like land cover, subcatchments, etc.)
Tools using approach	• **SPATSIM-Pitman** • **WRSM-Pitman** (uniform within "runoff module" + associated treed modules) • **SWAT2012** • **ACRU4** (most user-friendly way to input)	• **ACRU4*** (possible, but very labour-intensive) • **WRSM-Pitman – limited*** (irrigated areas, reservoirs, channels + wetlands can have own climate input)	• **MIKE-SHE** (applies to both semi- and fully distributed options for other processes)
Potential implications of approach	**Areas with important differences in climate need to be delineated as separate subcatchments to include this. This may entail compromises between directly representing climate variability and directly representing flow pathways that are effectively broken by subcatchment boundaries.** In some tools, there is no GW flow between subcatchments. Areas feeding dams, wetlands, riparian areas and irrigation may need to be in the same subcatchment.	Can include spatial variability in climate *within* a subcatchment. Avoids potential compromises in connectivity that could be imposed by subcatchment boundaries (see left). HRU or module delineations may be altered to include climate gradients: i.e. breaking up a broad land cover type into multiple units that receive different climate inputs. In ACRU4 and WRSM, setting up HRUs and modules is a many-step, manual process.	Spatial variability in climate can be included without the need to compromise on representing hydrological connectivity and with relatively little added effort (see notes to left). Climate inputs and land cover, soil and other properties are each specified using independently delineated zones and then separately assigned to each grid cell by the modelling tool.

LAND COVER: Units used to represent different land cover types and their connectivity		
Why and when it can matter	• Influences the **number of different land cover types** that can be explicitly represented and what types of land cover changes can be modelled. *The importance of this will depend on the purpose of the modelling project and the diversity of cover types within the modelled area.* ***Note:*** *Potential advantages of being able to explicitly represent more different land cover types in a model will also depend on the property information available to reliably parameterise them as being different from one another.* • Influences if and how the **specific location of a land cover within a landscape is considered** when modelling its processes (e.g. upland vs riparian). ***Note:*** *Relevant when modelling at spatial scales that can capture position differences vs larger scales that must average over them.* *Likely more important in more water-limited areas and with diverse topography: position is a more significant determinant of water access.*	
Alternative approaches	**Each subcatchment has one "main" land cover type and additional types are represented as proportions of the subcatchment area.** Each additional cover type is represented with different type-specific algorithms (e.g. tree plantation, irrigated crops)	**Land cover properties are assigned to HRUs within subcatchments, or to individual grid cells.** Units (HRUs, grid cells) use the same basic process algorithms with respect to land cover – differences between covers come from property parameters.
Tools using approach	• **SPATSIM-Pitman** • **WRSM-Pitman**	• **ACRU4** • **SWAT2012** • **MIKE-SHE**
Potential implications of approach	**Fewer different cover types can be explicitly included vs other approaches.** Particularly limits the number of non-irrigated, non-afforested types (e.g. veld types, grazing land, levels of degradation). In theory, more types can be included using more (smaller) subcatchments. This becomes unwieldly to set up, limits aspects of connectivity (see above), and algorithms may not apply to very small subcatchments. SPATSIM allows fewer types overall, but has some flexibilities. It allows two types of non-irrigated cover per subcatchment: a portion is assigned a higher ET rate. This rate is flexible, so could be a second veld type, plantation, invasives or a lumped combination of these. WRSM has modules for tree plantations and invasive alien trees. Both can be added in one subcatchment, but their algorithms are specific to those covers. The riparian area within a "runoff module" can be given its own ET pan-factors, allowing it to be another cover type flexibly defined. This could cause "double counting" with the treed area modules that effectively act on the full runoff module. (See riparian areas page LINK for more.)	No tool-imposed limit on the number of different cover types that can be explicitly included in a model. Limitations will come from the information available to reliably parameterise types as different from one another, as well as from the practicality of setting up many types in the tool (see Interface section) Linkages allowed between units (HRUs, grid cells) determine if and how the location of a cover type within a subcatchment is explicitly considered. If each unit's runoff is routed directly to a channel in parallel to others, without interacting, relative position is not represented. **Position is explicit in MIKE-SHE: Flows are routed into or onto neighbouring units or zones.** **This is more limited in ACRU4 and SWAT2012, which have mostly parallel routing, but there are ways in which location (i.e. riparian vs upland) can be represented for certain HRUs, hence cover types.**

LAND COVER: Units used to represent different land cover types and their connectivity		
	A more detailed cover composition can be represented implicitly, with parameters for broader model types calculated from the local mix of more detailed types. With conceptual parameters, this may not be straightforward. **Most cover types do not have an explicit spatial location within a subcatchment**. The riparian zone of a WRSM runoff module is an exception. The SPATSIM riparian area does not have its own separate cover type.	In ACRU4, special riparian HRUs receive “baseflow” runoff from linked upslope HRUs. Special riparian and wetland HRUs are also linked channels and can receive overflow. In SWAT2012, the level of access to ground water for ET can be set by HRU. This can be set higher for some HRUs to differentiate riparian vs uplands. Aquifers are subcatchment scale, so uplands can recharge the store used by riparian. Special “depression” waterbodies can also be set up on specified HRUs, which receive routed runoff from linked upslope HRUs.

AQUIFERS: Units used to represent aquifers and their connectivity				
Why and when it can matter	• Determines if and how **spatial variability of aquifer material** (sediment deposits, geological formations, layers) within a subcatchment can be explicitly represented (if information on this is available). *This will be more important when there are large known differences at the subcatchment scale, so also depends on choice of subcatchment sizes.* • Determines the **scale of model output** for ground water storage and potentially water table depth. • Determines **where within a model catchment ground water can outflow to a channel**: If there is no subsurface GW flow between modelled units, then any recharge within a unit that is thought to contribute to outflow of the larger catchment will need to emerge as baseflow from that same unit in the model. In reality, there may be subsurface flow with the GW emerging further down. **Having the GW emerge further upstream can impact other modelled processes linked to channel flows at different locations** (overbank flow, transmission loss, waterbody storage, irrigation). • Influences the **vegetation access to ground water in different parts of the catchment**, which can impact modelled seasonal and total ET and the modelled impact of vegetation cover changes. (Linked to model representation of the location of a land cover type – see above). *Likely more important for model outcomes for the following:* • *Catchments where GW contributes more substantially to the overall hydrograph* • *Cases where disconnected units (e.g. subcatchments) are small in comparison to connectivity of aquifers important to the hydrograph (delineation accounting for other factors, i.e. climate and land cover)* • *Areas where GW is an important water source for vegetation (particularly GW recharged by a large surrounding area)* • *Modelling projects focused on low flows and/or flows at points within the catchment*			
Alternative approaches	**Subcatchment-scale aquifers** ***No GW flow between subcatchments***	**Subcatchment-scale aquifers** ***GW can flow between subcatchments***	**HRU-scale aquifer units** (or other units smaller than subcatchments) ***No GW flow between aquifer units***	**3D grid of connected volume units** ***All units can interact***

AQUIFERS: Units used to represent aquifers and their connectivity				
Tools using approach	• **SWAT2012** • **MIKE-SHE using semi-distributed, linear reservoir GW option*** (can have a subcatchment-scale unit)	• **SPATSIM-Pitman** • **WRSM-Pitman**	• **ACRU4*** (partial exception: riparian HRU) • **MIKE-SHE using semi-distributed, linear reservoir GW option*** (can have multiple units in a subcatchment)	• **MIKE-SHE using fully distributed, finite difference GW option**
Potential implications of approach	Subcatchment aquifer parameters reflect average or net storage and flow properties of material in subcatchment. **Subcatchment-scale GW model outputs**. **Within a subcatchment:** Model can allow vegetation in one area to access GW that was recharged in another location in the subcatchment. **Between subcatchments:** If it is important for vegetation in a downstream subcatchment to access GW recharged in an upstream subcatchment, work-arounds are needed. Water to feed this ET needs to leave the upstream subcatchment as channel flow and become accessible downstream, e.g. via channel bed loss. Alternatively, revise the subcatchment delineation. To model total catchment outflow, some GW may need to enter the channel network in upstream subcatchments that in reality emerge further down (in downstream model subcatchments).	Subcatchment aquifer parameters reflect average or net storage and flow properties of material in subcatchment. **Subcatchment-scale GW model outputs.** **Models can allow vegetation in one area to access GW that was recharged in another location in the same subcatchment or another subcatchment** (only applies to the specified “riparian zones” in SPATSIM-Pitman and WRSM-Pitman subcatchments or runoff-modules). Avoids potential subcatchment delineation and aquifer parameterisation compromises or water routing workarounds (see notes to left)	Aquifer parameters can differ across units within a subcatchment to **represent spatial distribution of different aquifer materials** (e.g. fractured rock in uplands, alluvium over rock in lowlands). **GW model outputs can be obtained for different areas within a subcatchment**. Separated model GW stores that do not interact implies separate aquifers outflowing to channel network independently. This may not be the case in reality. This would impact parameter choices (i.e. vs. field property data). **Within a subcatchment:** Vegetation can only access GW recharged in the same unit (ACRU4 HRU, MIKE baseflow reservoir extent): lowland units cannot access GW recharged in highlands. This could result in unrealistically low ET. ACRU4 and MIKE have optional routines to overcome this. ACRU4’s special riparian HRU soil receives “baseflow” from linked upland HRUs.	Aquifer parameters can differ across units within a subcatchment to **represent spatial distribution of different aquifer materials** (e.g. fractured rock in uplands, alluvium over rock in lowlands). **GW model outputs can be obtained for specific grid cells in the model as needed.** Because there can be flow between all aquifer units (determined by relative head and conductivity between neighbouring cells) and no subcatchment boundaries limiting subsurface connectivity, vegetation in lowlands would be able to access GW recharged elsewhere in the model when conditions allow. The approach can have **high computational demand,** so model runs are longer (runtimes depend on computing power).

AQUIFERS: Units used to represent aquifers and their connectivity				
	This could influence aquifer parameter choices (i.e. vs field data on properties). If having more water in the channel higher up has significant impacts on other processes (upstream dams, etc.), adaptations may need to be made to these and/or the subcatchment delineation revisited.		In MIKE, water from “baseflow reservoirs” can be routed to the soil of a riparian zone. *Implications of also not modelling GW flow* ***between subcatchments*** *are the same as those described to the left.*	

CHANNEL NETWORK: Channel units and links to landscape units			
Why and when it can matter	• Determines the **locations within the catchment where model predicted streamflow outputs will be available.** *This can be important if there are monitoring points or other points of interest where these outputs would assist, i.e. water supply withdrawal points, areas for flood assessment, aquatic habitat assessment.* • Influences **where reservoirs, waterbodies, wetlands that are fed by the channel network can be located** with respect to model subcatchments and what areas feed them. • Determines the potential for representing **spatial variability in channel properties***, where these are understood and thought to be important* • Flow from channel units to landscape unit surface and subsurface can **allow for water exchanges between delineated subcatchments** (see notes above about the need for this). • Channel **processes that are not explicitly included (e.g. transmission losses, overbank flooding) will need to be implicitly represented**, likely through parameterisation (to generate net aquifer outflow, net surface runoff). *This will be more important in catchments where channel transmission loss and/or overbank flooding are frequent and make a notable impact on the flows.*		
Alternative approaches	**One channel reach unit per subcatchment.** ***Two-way channel-landscape subsurface exchange. Limited or no overbank flooding.***	**Flexible number and arrangement of channel reach units manually connected to HRUs, modules or reservoirs in a network** ***One-way landscape subsurface to channel exchange. Limited or no overbank flooding.***	**Channel reach units spatially linked to landscape grid cells and have explicit elevation.** ***All units can interact, surface and subsurface.***
Tools using approach	• **SWAT2012** • **SPATSIM-Pitman** • **WRSM-Pitman*** (some channel exchange processes are calculated *within* “runoff modules”)	• **ACRU4** • **WRSM-Pitman*** (separate channel modules in network)	• **MIKE-SHE**

AQUIFERS: Units used to represent aquifers and their connectivity			
Potential implications of approach	**To get model output streamflow for a point, it needs to be the outlet of a subcatchment.** Reservoirs on the channel network will be at the outlets of subcatchments (not in WRSM), so also influence subcatchment delineation (see specific waterbody table below). Subcatchment delineation also has implications for subsurface flow connectivity and other aspects of representation (see above) – various compromises may be needed in the delineation. SPATSIM and SWAT2012 partially address the restriction in reservoir location by including other waterbody unit types that can be internal to subcatchments, fed by proportions of subcatchment runoff. The set-ups of these types have other restrictions (see waterbody table below). Subcatchment-scale channel and subcatchment-scale aquifer representation facilitates the calculation of exchange (GW to channel, channel to GW, "transmission loss") considering storage and properties of both. This is done in SPATSIM and in WRSM within a run-off module. In SWAT2012, channel transmission loss goes to a separate bank storage unit, not the subcatchment aquifer. SPATSIM and WRSM only include overbank flooding in wetland modules. SWAT2012 does not include overbank flooding onto land units (wetland module not on the channel). Channel transmission loss in SWAT2012 and SPATSIM and overbank flooding to wetland units provide *means by which downstream areas can access water that entered the channel network from upstream units.*	**Flexibility in where streamflow outputs can be obtained and where reservoirs or waterbodies and transfers can be located.** This can reduce some delineation-related compromises. In ACRU4, channel units are fed by linked HRUs. This impacts the delineation of HRUs (e.g. an area of a cover type in a subcatchment may be split into multiple HRUs to feed different points in the channel network, e.g. above or below a reservoir, etc.). The manual process of setting up HRUs in ACRU4 means that taking advantage of this flexibility comes with significant additional labour. In WRSM, portions of a runoff module's outflow can be routed to multiple channels and reservoirs. These are then effectively *inside* the subcatchment represented by the runoff-module. This reduces the number of runoff-modules that need to be set up. All outflow from a "runoff module" can be routed to one channel module. Multiple runoff modules can contribute to a channel module. This allows modules with different cover to contribute at different points. ACRU4 does not explicitly represent channel bed loss. WRSM calculates this within runoff modules. Additional "bedloss" can be specified for channel modules, but this is removed from the model, not added to an aquifer or available for ET. **Water entering the channel network from upstream landscape units cannot be accessed for ET in downstream landscape units *via channel transmission loss*.** ACRU4 and WRSM only include **overbank flooding in their wetland units or HRUs and ACRU4 riparian HRU. This is a *means by which downstream areas can access water that entered the channel network from upstream units.***	Model streamflow **outputs can be obtained for any point in the channel network.** Reservoirs and water bodies can be added at any location. Because these have explicit locations in the model grid, the approach of lumping many small farm dams into a single unit can be difficult to operationalise, depending on the drainage network, etc. **Using fully distributed options**: Explicit location and elevation in the model grid allows calculation of exchanges between channel reaches and their neighbouring cells based on the water levels in each and conductivity. The explicit depth of the channel impacts how much ground water enters it. Bank topography can limit surface flow entering the channel. Overbank flooding and channel transmission losses occur when levels allow. The approach comes with notable practical implications. It requires careful vetting of landscape topography data and the channel cross-section inputs to make sure these correspond so that flow exchanges are realistically modelled. The method has high computational demand, so model runs are longer (runtimes depend on computing power). **Using the more lumped surface and ground water options:** Surface and GW flows into the channel are not calculated using the explicit elevation of the channel. Channel transmission loss and overbank flooding can still be included using different algorithms. These provide *means by which downstream areas can access water that entered the channel network from upstream units.*

4.5 PROCESS REPRESENTATION ALGORITHMS

This section describes the mathematical methods used to estimate different flows within and between the model units (units and connection options described above in section 4.4). The algorithms and parameters are informed by the scale and timestep of the process representation, so it is expected that algorithms will differ more between tools when the discretisation levels differ (i.e. subcatchment-scale aquifer unit vs a grid-cell of aquifer material).

4.5.1 Tool approach descriptions

Table 4.6 gives basic characteristics of the process representation algorithms for different processes for each tool. More detailed narrative descriptions of the calculation methods are given in appendices A1 to A10. For each, the inputs for the function, hence the factors influencing the process, are given very generically, as well as more specifically, to highlight general similarities at a broader view where these exist. In addition, basic mention of the types of relationships between the relevant variables and the process rate are mentioned (i.e. linear, non-linear). Particular attention was paid to what thresholds determine when a process starts and/or cuts off. Thresholds are key to understanding a catchment's functions and something that can be studied in the field. These can provide links between representation approaches across tools.

4.5.2 Key similarities and differences, potential implications

Tabel 4.6 illustrates that tools generally explicitly calculate the same basic set of processes (similar "process discretisation" level) despite their differences in the spatial and vertical discretisation. It is also notable that, for most processes, the tools use the same inputs or input types at a coarse scale and have the same types of thresholds. For most process calculations, MIKE-SHE demands a greater number of input parameters. Although the exact input parameters may differ, the same types of properties can be used across tools. This could lead one to think the parameter values themselves might be comparable across tools. However, this would have to consider the scale of representation: e.g. "saturation" soil moisture for a subcatchment-scale soil unit for a month is a different thing conceptually to the saturation soil moisture one might measure in the field or find for a daily model looking at soil layers within a profile in an HRU.

The surface process representation methods appeared to be more similar in form to one another across tools, with more diversity in approach for the interflow and ground water processes. This is linked to how the tools discretise and represent the subsurface. In particular, interflow is estimated in very different ways. In ACRU4, it is a fixed, lagged fraction of stormflow runoff. In the Pitman tools, it is a non-linear function of the soil or unsaturated zone unit moisture. In SWAT2012 and distributed MIKE SHE, which explicitly represent many subsurface layers and redistribute water between them, interflow is only modelled when a perched water table develops and connects to the stream. In the more semi-distributed MIKE-SHE, soil moisture has to first percolate to an interflow storage and then it can become interflow. When processes are represented very differently, it is less likely that two different models would estimate similar rates for that process on shorter time scales (longer-term averages might be comparable) for the same process in the same catchment.

Table 4.6: Process algorithm characteristics for the representation of processes in each modelling tool (linked to timestep and spatial discretisation)

Process and algorithm description	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
CANOPY INTERCEPTION ET (CI) VS. THROUGHFALL						
Function of	**Rain, cover properties** Rainfall, maximum interception	**Rain, cover properties** Rainfall, maximum interception	**Rain, PET, cover properties, canopy storage (state)** Rainfall, canopy storage (state) maximum interception (or LAI), PET	*Not explicit – part of "initial abstraction" calculation, see infiltration and surface runoff below*	**Rain, PET, cover properties, canopy storage (state)** Rainfall, canopy storage (state) LAI, interception coefficient, PET	**Rain, PET, cover properties, canopy storage (state)** Rainfall, canopy storage (state) LAI, interception coefficient, PET
Function type	Exponential and threshold	Exponential and threshold	Threshold		Threshold	Threshold
Thresholds?	**Yes (interception capacity – calculated)**	**Yes (interception capacity – calculated)**	**Yes (interception capacity – input)**		**Yes (interception capacity – input)**	**Yes (interception capacity – input)**
INFILTRATION INTO SOIL MOISTURE STORE (SM), WHEN SURFACE IS NOT IMPERVIOUS						
Function of	**Rain, soil properties, unit state** Rainfall, rainfall distribution factor, SM (state), Sat SM, subcatchment infiltration rate distribution	**Rain, soil properties, unit state** Rainfall, rainfall distribution factor, SM (state), Sat SM, subcatchment infiltration rate distribution	**Throughfall, soil properties, unit state** Throughfall, macropore by-pass, SM (state), Sat SM, infiltration SM depth	**Throughfall, soil properties, unit state** Throughfall, macropore by-pass, SM (state), Sat SM, curve number	**Throughfall, soil properties, unit state** Throughfall, macropore by-pass, SM (state), Sat SM, Sat hydraulic conductivity (K_{sat}),	**Throughfall, soil properties, unit state** Throughfall, macropore by-pass, SM (state), Sat SM, Sat hydraulic conductivity (K_{sat}), SM retention curve
Function type	Non-linear and threshold	Non-linear and threshold	Power and threshold	Power and threshold	Linear (rate) and threshold	Non-linear and threshold
Thresholds?	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**

Process and algorithm description	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
SURFACE WATER GENERATION ON LANDSCAPE UNITS						
Function of	**Rain, infiltration into SM** Rainfall, infiltration into SM* *(Sat excess added to interflow)*	**Rain, infiltration into SM** Rainfall, infiltration into SM* *(Sat excess added to interflow)*	**Throughfall, infiltration into SM, surface property** Rainfall, infiltration into SM, lag coefficient (separate surface flow and interflow)	**Throughfall, infiltration into SM** Rainfall, infiltration into SM	**Throughfall, infiltration into SM** Rainfall, infiltration into SM	**Throughfall, infiltration into SM** Rainfall, infiltration into SM PET
Function type	Threshold	Threshold	Threshold + fraction	Threshold	Threshold	Threshold
Thresholds?	**Yes (maximum infiltration rate)**	**Yes (maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (Sat SM, maximum infiltration rate)**
SURFACE RUNOFF TO CHANNEL NETWORK						
Function of	**Surface water present (state)** ****Note:** Month timestep – not lag surface flow*	**Surface water present (state)** ****Note**: Month timestep – not lag surface flow*	**Surface water present (state)** ****Note:** "Surface water" available is a function of:rainfall vs. infiltration, lag coefficient (separates surface flow and interflow) – surface flow = portion not lagged (reach channel same day generated)*	**Surface water present (state), surface path properties** Surface water present (state), path length, path slope, path roughness (Manning's n)	**Surface water present (state), surface path properties** Surface water present (state), detention storage, path length, path slope, path roughness (Manning's n)	**Surface water present (state), surface path properties** Surface water present (state), detention storage, path length (topographic grid), path slope (topographic grid), path roughness (Manning's n)

Process and algorithm description	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Function type	(no transformation)	(no transformation)	(no transformation)	non-linear	non-linear and threshold	non-linear and threshold
Thresholds?	No	No	No	No	**Yes (detention storage)**	**Yes (detention storage)**
EVAPOTRANSPIRATION FROM UNSATURATED ZONE SOIL MOISTURE (SM)						
Function of	**ET demand, SM (state), vegetation properties, UZ properties** Pan evaporation, SM (state), crop coefficient (vs pan), ET coefficient (determine WP SM and rate vs. SM and PET), Sat SM	**ET demand, SM (state), vegetation properties, UZ properties** Pan evaporation, SM (state), ET coefficient (determine WP SM and rate vs. SM and PET), Sat SM	**ET demand, SM (state), vegetation properties, soil properties** Pan evaporation, SM (state), crop coefficient (vs pan), soil/root depth, root distribution, FC SM, WP SM	**ET demand, SM (state), vegetation properties, soil properties** PET – CI, SM (state), LAI, root depth, root distribution, demand redistribution, FC SM, WP SM	**ET demand, SM (state), vegetation properties, soil properties** PET – CI – surface ponding evaporation, SM (state), crop coefficient, soil/root depth, root distribution, FC SM, WP SM	**ET demand, SM (state), vegetation properties, soil properties** PET – CI – surface ponding evaporation, SM (state), crop coefficient, shape parameters, AET vs root depth, root distribution, SM retention curve
Function type	Linear and threshold	Linear and threshold	Non-linear and threshold	Non-linear and threshold	Non-linear and threshold	Non-linear ane threshold
Thresholds?	**Yes (ET demand, WP SM)**	**Yes (ET demand, WP SM)**	**Yes (ET demand, WP SM)**	**Yes (ET demand, WP SM)**	**Yes (ET demand, WP SM)**	**Yes (ET demand, WP SM)**
EVAPOTRANSPIRATION FROM GROUND WATER *(also represented with CAPILLARY RISE)*						
Function of	**ET demand, riparian area, vegetation properties, aquifer storage (state), aquifer properties**	**ET demand, riparian area, vegetation properties, aquifer storage (state), aquifer properties**	*Indirect and special case only:*	**ET demand, vegetation properties, soil properties, aquifer storage (state), aquifer properties**	**ET demand, vegetation properties, soil properties, aquifer storage (state), aquifer properties**	**ET demand, vegetation properties, soil properties, aquifer storage (state), aquifer properties**

Process and algorithm description	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
	Pan evaporation, riparian area, crop coefficient (vs pan), aquifer storage (state), aquifer water level limit for ET	PET – AET, riparian area, aquifer storage (state), aquifer water level limit for ET	*Riparian zone HRU soil unit can receive aquifer outflow from upslope HRUs, wetland HRU ET from shallow water table in the soil* *AET from SM in these units calculated as above.*	PET, capillary rise, rate coefficient, aquifer storage (state), aquifer water level limit for capillary rise + *inputs for SM ET above*	PET*K_c – ET from SM, aquifer storage (state), aquifer water level limit for capillary rise + *inputs for SM ET above*	PET*K_c – ET from SM, water table depth (state), material conductivity + *inputs for SM ET above*
Function type	Non-linear	Non-linear		Non-linear	Non-linear	Non-linear
Thresholds?	**Yes (ET demand, aquifer level limit for ET)**	**Yes (ET demand, aquifer level limit for ET)**		**Yes (ET demand, aquifer level limit for capillary rise)**	**Yes (ET demand, aquifer level limit for capillary rise)**	**Yes (ET demand, aquifer level limit for capillary rise)**
INTERFLOW PRODUCTION AND ROUTING TO CHANNEL						
Function of	**SM (state), UZ properties, aquifer storage (state), aquifer properties** SM (state), Sat SM, FC SM, interflow rate, power coefficient, maximum interflow rate, lag coefficient, percolation zone + aquifer storage (state) vs. capacity	**SM (state), UZ properties** SM (state), Sat SM, FC SM, interflow rate, power coefficient, maximum interflow rate, lag coefficient	**Throughfall, infiltration into SM, surface property** Rainfall, infiltration into SM (see above), lag coefficient (separates surface flow and interflow)	**SM (state), soil properties, slope** SM (state), FC SM, Sat SM, drainage slope, Sat hydraulic conductivity (K_{sat}), depth to impermeable – facilitate layer SM > FC	**SM/UZ storage (state), UZ properties, aquifer storage (state), aquifer properties** *Input to interflow zone (IZ):* Throughfall *Macropore by-pass, SM (state), FC SM, Sat hydraulic conductivity (K_{sat}), *Lateral flow from interflow zone (IZ):* IZ storage (state), IZ storage limit for outflow lateral rate constant vs. vertical rate constant, aquifer	*Not a separately modelled process:* *3D modelling of GW flow through aquifer material layers may result in a perched saturation layer, which has lateral flow to the channel (see GW flow description below)*

Process and algorithm description	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
					storage (state), aquifer storage capacity	
Function type	Non-linear	Non-linear	Threshold + fraction	Non-linear	Two-step: Non-linear and linear reservoir	
Thresholds?	**Tes (FC SM, percolation zone + aquifer maximum storage)**	**Yes (FC SM)**	**Yes (Sat SM, maximum infiltration rate)**	**Yes (perched layer, Sat SM)**	**Yes (FC SM, interflow storage limit for outflow, aquifer maximum storage)**	
AQUIFER RECHARGE						
Function of	**SM (state), UZ properties, aquifer storage (state), aquifer properties** *Input to vadose zone (VZ):* SM (state), Sat SM, FC SM, percolation power coefficient, maximum percolation rate *Recharge from VZ:* Recharge lag coefficient, VZ + aquifer storage (state) vs. capacity	**SM (state), UZ properties** SM (state), Sat SM, FC SM, recharge power coefficient, maximum recharge rate	**SM (state), soil properties** SM (state), Sat SM, FC SM, K_{sat},	**SM & vadose zone storage (state), UZ properties** *Input to vadose zone (VZ):* SM (state), FC SM, K_{sat}, *Recharge from vadose:* VZ storage (state), VZ FC, VZ K_{sat},	**Interflow zone storage (state) interflow zone properties** Interflow zone (IZ) storage (state), vertical rate constant vs. lateral rate constant and IZ storage limit for outflow	**SM (state), UZ properties, aquifer storage (state), aquifer properties** Throughfall *Macropore by-pass, SM (state), SM retention curve, K_{sat}, aquifer water table depth, aquifer material conductivity
Function type	Non-linear	Non-linear	Non-linear	Two-step: Non-linear	Linear reservoir	Non-linear
Thresholds?	**Yes**	**Yes (FC SM)**	**Yes (FC SM)**	**Yes**	**Yes**	**Yes**

Process and algorithm description	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
	(FC SM, vadose zone + aquifer maximum storage)			**(FC SM, FC vadose zone)**	**(Aquifer maximum storage)**	**(Sat SM, maximum infiltration rate)**
GROUND WATER FLOW (LATERAL FLOW WITHIN SATURATED ZONE)						
Function of	**Aquifer storage (state), aquifer properties** Aquifer storage: GW level (state) (Aquifer specific yield) Aquifer transmissivity River channel level (GW flow limit) Regional GW slope	**Aquifer storage (state), aquifer properties** Aquifer storage: GW level (state) (Aquifer specific yield) Aquifer transmissivity River channel level (GW flow limit) Regional GW slope	GW flow between HRU aquifers not modelled (Riparian zone HRU soil layer can receive aquifer outflow from upslope linked HRUs)	GW flow between subcatchment aquifers not modelled	GW flow between aquifer units not modelled	**Aquifer storage (state), aquifer properties** *3D grid solutions of Darcy's law* Aquifer storage: water table depth gradients (Aquifer specific yield) Aquifer conductivity
Function type	Non-linear	Non-linear				Non-linear
Thresholds?	**Yes (GW level limit for flow)**	**Yes (GW level limit for flow)**				N/A
AQUIFER EXCHANGE WITH CHANNEL: AQUIFER OUTFLOW OR CHANNEL TRANSMISSION LOSS						
Function of	**Aquifer storage (state), aquifer properties, channel flow (state) channel properties**	**Aquifer storage (state), aquifer properties, channel flow (state) channel properties**	**Aquifer storage (state), aquifer properties**	**Aquifer storage (state), aquifer properties, channel flow (state) channel properties**	**Aquifer storage (state), aquifer properties, channel flow (state) channel properties**	**Aquifer storage (state), aquifer properties, channel flow (state) channel properties**
	Aquifer storage: GW level (state) (Aquifer specific yield)	Aquifer storage: GW level and GW slopes vs channel (state)	***Only aquifer outflow modelled, not***	Aquifer storage (state)	Aquifer storage (state)	*3D grid solutions of Darcy's law*

Process and algorithm description	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
	River channel level Subcatchment runoff / area (estimated local channel store) Maximum exchange flow rate Flow power parameter	(Aquifer specific yield + GW wedge shape) River channel level Subcatchment drainage density (to determine drainage slope wedge dimensions) Length of channel Aquifer material conductivity	***channel transmission loss*** Aquifer storage Aquifer outlow lag parameter	Aquifer storage limit for outflow Aquifer specific yield Aquifer recession constant Channel flow (state) Channel shape – wetted perimeter Channel bed conductivity – loss rate	Aquifer storage limit for outflow Aquifer specific yield Aquifer recession constant Channel losing vs gaining specification Channel flow (state) Channel shape – wetted perimeter Channel bed conductivity – loss rate (can apply to flooded land surface)	Aquifer storage: water table depth gradients (Aquifer specific yield) Aquifer material conductivity *Hydraulic modelling of channel water height* Channel flow (state) Channel shape – wetted perimeter Channel roughness Channel bed conductivity (can apply to flooded land surface)
Function type	Non-linear	Non-linear	Rate	Non-linear	Linear reservoir	Non-linear
Thresholds?	**Yes – to switch flow direction** **(River channel level vs. aquifer GW level)**	**Yes – to switch flow direction** **(River channel level vs. aquifer GW level)**	No	**Yes – to switch flow direction** **(Aquifer storage limit for outflow)**	**Yes** **(Aquifer GW level limit for outflow)**	**Yes – to switch flow direction** **(River channel level vs. aquifer GW level)**

4.5.3 WRSM representation of alien invasive vegetation and commercial forestry plantations

While tools had various differences in their process algorithms, for the most part, their approaches to modelling a given process were similar on a basic conceptual level. An important exception is the method used in WRSM to represent alien invasive vegetation and commercial forestry plantations, which differs notably from the approaches in the other modelling tools. Given that this a very common use of catchment hydrological models, it is important to note this difference in approach and explore the impacts on prediction.

Other tools model water use by non-indigenous treed cover types in the same way that any other vegetation is modelled. There is not a specific, different algorithm for them, and the approach is relatively physical/mechanistic. Using ACRU, SWAT or MIKE-SHE, these vegetation types would be represented by assigning appropriate vegetation property parameter values to the areas in which they are present. Parameters would be LAI or maximum canopy interception, stomatal conductance or ET coefficients, water stress ET response parameters, and root depth and distribution parameters.

Somewhat similarly, in SPATSIM-Pitman, an ET multiplier parameter can be input for a sub-area of different cover in a subcatchment. This was included in the tool for alien tree cover, but can be used for any cover type considered distinct from other vegetation in a subcatchment. For example, it could be used for areas of indigenous forest when the rest of the cover is open. The parameter scales up canopy interception and ET from soil and ground water for a specified portion of the subcatchment, in as much as water is available. It is analogous to inputting the ratio of the interception and crop coefficients of the treed area compared to that of the rest of the vegetation.

In contrast, WRSM applies what is essentially an empirical approach: estimating a runoff reduction directly based on catchment-scale field studies, rather than modelling the individual processes to arrive at this reduction amount. Several paired-catchment (afforested or invaded vs. cleared or natural) studies and before and after planting or clearing studies have been done in South Africa (Scott et al., 2000). Data from these observational studies have been used to derive run-off reduction curves that relate the area of a certain kind of treed cover (i.e. plantation of a given species at a certain age, invasive vegetation of a given stature) to the runoff reduction that would be expected. Several of these relationships have been incorporated into WRSM (Bailey, 2015). The WRSM user only inputs the type of cover, the “condensed” area, and a ranking of the growing conditions (i.e. wet, deep soil vs dry, shallow soil). If the treed cover or invasion is sparse, “condensed” area refers to the area it would cover if it were a closed canopy stand. Subcatchment runoff is first modelled as if there was no afforestation or invasive alien plant (IAP) cover (“naturalised” runoff). WRSM then uses the appropriate curves to find an expected reduction in mean annual runoff and low flow runoff for the subcatchment.

These empirical runoff reduction relationships apply to total runoff and not specifically to surface flow, interflow and aquifer outflow. To deal with this, WRSM internally recalculates parameter values for interception, soil storage, interflow rates and percolation rates for the treed sub-area such that the MAR for the subcatchment will be as close as possible to the MAR expected based on the reduction curves and the naturalised MAR. While most of these appear as soil property parameters, they implicitly represent the root network and efficiency of the vegetation drawing water out. The model then runs with these back-calculated sub-area parameters for the treed portion, adding that to what was modelled for the rest of the subcatchment area, to produce monthly timeseries of subcatchment total runoff, as well as surface flow, interflow, aquifer outflow, soil storage and aquifer storage. In effect, the calculation method is not so different to the other tools in the sense that the process algorithms are the same with parameter values altered to represent the treed area. However, the approach to arriving at those parameter values is very different. In WRSM, a target amount of runoff reduction is selected before the model is run based on literature (curves from observational studies). The parameters for the treed area are then back-calculated using a solver algorithm within the tool to try to reproduce this amount. The model user does not select or input process parameters based on physical properties of the vegetation.

Over time several different runoff reduction curves have been derived and built into WRSM. The older methods have been kept in the current software version for continuity and comparison. For afforestation, the older method ("Van der Zel method") was not species-specific, while recent methods consider plantation species ("Smoothed Gush/Pitman") or both species and rotation length ("CSIR method"). The more recent methods relate inputs of species (pine, eucalypt or wattle) and plantation rotation to biomass and then relate biomass to runoff reduction. For IAP cover, input proportions of large trees, small trees and shrubs are used to estimate biomass, and the biomass is related to the runoff reduction, using curves developed by the CSIR (Bailey, 2015; Bailey and Pitman, 2015).

4.6 VARIABILITY OF CATCHMENT PROPERTIES AND PARAMETERS OVER TIME

It can be important to explicitly include changes in catchment properties over time in modelling. For example, this would be the case if there is substantial change, such a major increase in the area of commercial forestry in a grassland region or the addition of a large storage dam within a time period that is being modelled to be compared to an observed timeseries for calibration. If these changes are not included in the model, i.e. the relevant properties stay static in the model run, and the changes had large impacts on observed streamflow, the model outputs cannot be expected to match the observational data equally well across the whole timeseries. There can also be large seasonal changes in vegetation properties, such as with crop harvesting, which could also have notable hydrological impacts depending on the relative size and nature of the area (i.e. slope, rain intensity, etc.). If these are not included in the model, longer-term average predictions may achieve acceptable accuracy, while seasonal ones do not.

The modelling tools reviewed differ in their options for explicitly considering variability in catchment characteristics and parameter values over time within a model run as described in Table 4.7. Of this set of tools, WRSM-Pitman makes it the easiest to incorporate temporal changes in commercial forestry cover, IAP cover, irrigated agriculture and reservoirs over a model timeseries. There are ways to set up landcover transitions during a run in SWAT2012 and MIKE-SHE, but these are somewhat more difficult and reservoirs cannot be changed. On the other hand, WRSM does not include seasonal or temporal variation in other process parameters, with the exception of irrigated agriculture, while the other tools include this.

In cases where it is important to explicitly include major temporal changes, but the modelling tool does not have this capability, the time period to be modelled can be broken up and different model set-ups used for different subperiods. While feasible, this can be complicated and unwieldy to implement, particularly when attempting to calibrate parameters. In this case, all the various set-ups would need to get the parameter adjustments being tested. Stringing runs of different model set-ups together for a continued time period can also entail using the conditions at the end of the previous sub-period to "hotstart" the model run for the next sub-period (i.e. provide starting values for the soil, aquifer, dam and wetland water storages). MIKE-SHE includes a facility that automates hotstarting, but for the others, this would be a manual process.

Table 4.7: Overview of the temporal variability capabilities for properties and parameters across modelling tools

Capability	WRSM-Pitman	SPATSIM-Pitman	ACRU4	SWAT2012	MIKE-SHE
Land cover change *during a model run*	**Yes**	*No*	*No*	**Yes**	**Yes***
	Areas of commercial forestry, IAP, irrigated agriculture can vary by water year			Can input specific dates on which specified HRUs switch between one cover type and another	Properties for vegetation types can be input as a timeseries – this could represent a change in cover. ("Cover type"

Capability	WRSM-Pitman	SPATSIM-Pitman	ACRU4	SWAT2012	MIKE-SHE
	(can be 0 in some years)			type. ("Cover type" map input would need to consider this.)	map input would need to consider this.)
Reservoir presence/ capacity change *during a model run*	**Yes** Reservoir volume and area can vary by water year (can be 0 in some)	*No*	*No*	*No*	*No*
Vegetation property parameters can vary during run	*(only irrigated agriculture, month of year)*	**Yes, two seasons**	**Yes, month of year**	**Yes, daily model**	**Yes, timeseries input**
Soil property parameters can vary during run	*No*	*No*	*No*	*No*	*No*
'Hotstart' facility: Assist to start a run with initial water storage conditions from end of another run	*No*	*No*	*No*	*No*	**Yes**

4.7 MODELLING TOOL USER INTERFACE AND MODEL SET-UP PROCESS

As found during the case study modelling exercises, the user interfaces of modelling software tools can notably influence the overall approach of the modeller and the resulting structure of the model. Highly cumbersome model set-up processes reduce what can be achieved in a given time and can more easily result in user-error in the set-up. They also incentivise simplification of the model structure. This can have some benefits: prompting more careful consideration of the level of detail necessary to the goal of the modelling exercise and so reducing the potential for over-parameterisation. However, it could also lead to simplification of details that may assist in overall model performance, such as limiting the number of areas with differentiated climate inputs. The ease with which parameter values can be adjusted and batches of runs done will facilitate sensitivities analyses, uncertainty analyses and calibration. The ease with which water balance outputs can be obtained can facilitate more sense-checking of the process representation.

4.7.1 Efficiency of model set-up process

The process of setting up models was found to differ significantly across the tools (Table 4.8). ACRU4 and WRSM-Pitman have the most manual and laborious set-up processes of the set: every modelled unit (HRU, module, etc.) and connection is individually set up by the user, moving through a series of menu windows for each one. This provides control and flexibility in design, but is time consuming, and can be quite error-prone in complex set-ups. Neither tool provides a visual mapping of the connections, which are presented as lists. WRSM has an in-built connectivity checking function that will flag errors such as missing connections. In ACRU4, connection ("relationship") lists are not sortable, but stay in the order that the user added connections, which makes error checking difficult.

ACRU4 will not run and will show error messages if certain types of connections are missing, such as an HRU missing a climate assignment (each HRU needs a reference climate to be individually assigned, even when using subcatchment-scale climate input). However, other connection mistakes, such as not connecting a river inflow node to a river unit or not connecting an HRU to a river inflow node, will not trigger any error messages. Changing parameter values in ACRU4 needs to be done for each individual HRU separately, even if HRUs share a land cover type. WRSM allows value sets of the basic "runoff module" parameters to be batch-specified for sets of modules. However, this does not apply to the ground water parameters.

An implication of these set-up approaches is that modelling land cover scenarios can be intensive and time-consuming, particularly in ACRU4. In WRSM, there is a facility to do a "naturalised" run, which automatically disregards modules attached to a runoff module, such as afforestation or IAP modules. Depending on the nature and spatial layout of the land cover change, many manual parameter value alterations, deletions of connections or modelled units, or establishment of new ones, may be required to represent the alternative scenario.

In contrast, SWAT2012 and MIKE-SHE use spatially explicit map inputs of topography, land cover and soil types, and for MIKE-SHE, aquifer types, to drive an automated set-up of modelled units and parameter assignments. The modelling unit connections derived by the tool can be checked in tables. However, there are limited options to change them. Parameters are entered by land cover type and soil type, and are automatically assigned to all units of that type. These are largely entered through series of menu inputs. Automated derivation of the structure from map inputs increases efficiency and reduces opportunity for certain kinds of user errors, but it can limit possibilities for some structural decisions and simplifications that may be helpful, like lumping many small farm dams or lumping several parallel tributaries into a conceptual subcatchment. Changing a land cover scenario is a relatively simple process of changing the map input.

SPATSIM uses an input map of subcatchments, which helps with the visualisation of the set-up and the outputs. However, the flow connections between the subcatchments need to be manually specified. The parameters are input in a series of externally prepared tables as text files with columns for each subcatchment. This makes parameter adjustments, either for calibration or representing alternative scenarios, relatively easy as all the parameter values are visible and editable in one place and there is no need to click through series of drop-down menus to enter them. The table can simply be adjusted and relinked into the model.

ACRU4 and SWAT2012 both have built-in vegetation and soil type parameter databases that users can opt to use. This can significantly speed up model set-up, although it can lead to the use of inappropriate parameter values if database values are used without local evaluation. The SWAT databases were developed primarily in the USA, while the ACRU Compoveg and Autosoils databases were developed for South African vegetation types. MIKE-SHE does not include an in-built parameter database. However, its input file structure allows users to build their own databases that can be used across models. Users can also add entries to the SWAT2012 database, which can be used in different models, although the mechanism of adding this to new models is less obvious. The ACRU4 databases are not easily editable for general users.

4.7.2 Transparency of set-up process

MIKE-SHE, ACRU4 and the Pitman tools force users to engage with all set-up steps and parameter entry, which may be time consuming, but ensures the user knows what the model is basing calculations on. MIKE-SHE and ACRU4 both have visible data entry structure trees that highlight what the user has or has not input satisfactorily in the set-up. Similarly, being forced to manually work out the model unit connectivity structure for building models in WRSM, SPATSIM and ACRU4 ensures that the user is very aware of what routing of flows is being represented and what is not.

These connections are made automatically in MIKE-SHE and SWAT2012 based on topography. Although they are generally visually displayed, the user could potentially fail to check that they have been established as intended.

ArcSWAT2012 automatically models plant growth and senescence, sediment movement, and nutrient cycling and mobility, in addition to the hydrological processes. There is no option to exclude the calculation of these additional calculations if only the hydrology is being considered. This means that SWAT models use many more parameters than other tools. To facilitate model set-up, the software comes with the vegetation and soils parameter databases mentioned previously. For other values (i.e. ground water parameters or channel properties), it automatically has default parameter values pre-entered. Altering parameter values in ArcSWAT requires moving through a layered set of drop-down menus. Users can easily set up and run a model without being aware of many, or even most, of the parameter values it is using. The user is not forced to go through these in the set-up and a concerted effort is needed to find and understand many of them.

4.7.3 Batch runs and adjustments for testing, uncertainty assessment, calibration

MIKE-SHE, ArcSWAT2012 and SPATSIM have batch-run facilities and autocalibration routines available, while ACRU4 and WRSM do not. For SWAT, this is an independently produced software: SWAT-CUP (Abbaspour, 2015). For all three tools, the user can select which parameters to vary across a set of runs, the value ranges over which to test them (and value probability distributions if desired) and the objective functions with which to calculate and evaluate the performance of each parameter set. There are also facilities to run a batch of user-specified parameter sets to test specific values or combinations of interest, rather than having the tool generate sets across the ranges provided. For MIKE-SHE AutoCal and SWAT-CUP, the process of setting up the tool with its links to the base model is relatively intensive and has a fairly big learning curve at the outset, whereas the SPATSIM tool is more simply and easily integrated.

ACRU4 and WRSM do not include any batch run facilities to assist with testing different parameter adjustments. Each adjustment or combination of adjustments needs to be made manually, the model needs to be run, and the outputs exported and processed separately each time, with the careful recording of versions by the user. This is very time-consuming and limits the exploration of the parameter value space deemed physically feasible for a catchment.

4.7.4 Run times

Run times for models built with a given tool can vary considerably with the size and complexity of the set-up, the number of timesteps in the run and the computer being used. This makes is difficult to generalise. However, due to their relative simplicity, WRSM, SPATSIM and ACRU4 models in these exercises generally ran in a matter of a few minutes for a 30-year run, while the ArcSWAT2012 and MIKE-SHE models could range from 15 minutes to several hours to complete this run.

The run times have importance particularly for parameter adjustment testing, limiting how much can be done in the time available for a project. However, the tools with long run times, as well as SPATSIM, have made the parameter adjustment process quick and include batch run facilities. Once the batch is set up, time-consuming testing runs will run in sequence without manual intervention needed from the modeller, freeing their time for other work. Although WRSM and ACRU4 run quickly, the process of making parameter adjustments in the model set-up to be tested takes a long time and a lot of manual effort, as described above, and there are no in-built facilities to set a batch of model set-ups to run in sequence in these tools.

Table 4.8: Modelling tool interface characteristics and features

Interface characteristic	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHE**
Graphical user interface (vs. code prompt)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Catchment map display	No	**Yes**	No	**Yes**	**Yes**
Set-up efficiency					
Manual creation of model units and connections	**Yes**	**Yes**	**Yes**	No	No
Automated creation of model units and connections from map inputs	No	No	No	**Yes**	**Yes**
Input and change model unit parameters in batches by type (e.g. cover type, soil type)	*(limited)*	**Yes**	No	**Yes**	**Yes**
In-built parameter database (optional use)	No	No	**Yes**	**Yes**	No
Build own parameter database for use across multiple models	No	*(limited)*	No	**Yes**	**Yes**
Set-up transparency					
Interface prompts user to interact with every component and parameter entry window	**Yes**	**Yes**	**Yes**	No	**Yes**
Default parameter values pre-entered	*(limited)*	No	*(limited)*	**Yes**	*(limited)*
Tool checks connection errors	*(limited)*	**Yes**	*(limited)*	**Yes**	**Yes**
Batch run and calibration tools					
In-built facility for batch runs, uncertainty, parameter sensitivity and auto-calibration	No	**Yes**	No	No	No
Associated tool for batch runs, uncertainty, parameter sensitivity and auto-calibration	No	**(n/a)**	No	**Yes**	**Yes**
Run times					
Rough estimate of time needed for a 30-year run of a 300 km^2 catchment *(Note: dependent on model complexity and computing power)*	seconds to minutes	seconds to minutes	seconds to minutes	minutes	minutes to hours
Accessing model output					
Associated output viewer for streamflow	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Associated output viewer for water balance components	*(limited)*	**Yes**	No	*(limited)*	**Yes**
All water balance components calculated by the model can be exported	No	No	**Yes**	**Yes**	**Yes**
Batch export of water balance components for model units	No	**Yes**	**Yes**	**Yes**	**Yes**
Automated extraction of water balance components for different scales	No	No	No	*(limited)*	**Yes**

4.7.5 Obtaining modelled water balance component outputs

The tools also differed in how easy it was to export certain water balance outputs for different scales. It can be an intensive process to check whether or not a model is predicting the water balance in agreement with one's conceptual model of the catchment's processes. The implication of this may be that it is not common practice to do so. For ACRU4, WRSM-Pitman and SPATSIM-Pitman, most modelled outputs need to be exported for each model unit, i.e. HRU or subcatchment, and externally processed to get catchment-scale estimates for various fluxes. SWAT2012 and MIKE-SHE make water balance export at different scales somewhat simpler, although some outside processing was generally still required.

Obtaining the available water balance outputs was found to be most challenging for WRSM-Pitman and ACRU4, with WRSM-Pitman being the most laborious per module. In WRSM, total "route flows" between every module can simply be batch-exported. However, all the other outputs (e.g. surface runoff, interflow, etc.) need to be individually exported for each module. This is done by clicking through a set of menus for each module and each output. The process must be repeated each time the model is rerun. The software includes some internal timeseries plotting facilities for individual runoff modules, but not for all outputs or for the catchment as a whole. As with WSRM, getting catchment-scale outputs beyond streamflow for an ACRU4 model requires exporting the outputs for each HRU and processing them outside the model. Although each output to be saved needs to be individually selected for every HRU, a set of output specifications created by the user can be saved so that the same export process will be automated in subsequent runs of the model. A notable challenge is that ACRU4's naming conventions for the output variables are not user-friendly if many outputs are being saved. Outputs are clearly labelled in terms of the state or flux variable name. However, they are numbered by the order in which they were selected in the output specification set-up process. The output data is not labelled for the HRU or subcatchment that the output is for. A correspondence table of output variable names and model units cannot be exported from the tool interface. For the purpose of this project, the ACRU4 developers created a custom tool to export the needed table that matches the variable name in the output file with the modelled unit, e.g. the HRU each output is for (Thornton-Dibb, personal communication, 2020).

As shown in Table 4.9, not all of the tools have output values for the same fluxes or flow paths, either because processes were represented implicitly by the tool or processes were explicitly calculated, but the results were not output. Outputs are also produced at different spatial scales in different tools, requiring additional interpretation for catchment-scale values. Outputs can also have somewhat different conceptual meanings across tools, despite referring to the same process in general, given differences in scales and algorithms. A goal in the case study modelling exercise in this project was to compare predicted water balances across the models built across different tools and the changes in the water balances predicted under change scenarios. The sections below present challenges in obtaining comparable, catchment-scale outputs for a set of water balance components, and how these were handled in this project.

Table 4.9: Model water balance outputs by tool and calculation approaches applied for fluxes not output directly

Flux or storage	**Tool output and/or calculation approach**					
	WRSM	**SPATSIM**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**	**MIKE-SHEc**
AET total	***not output by tool*** ***calculate:*** *long term ave AET = precip.* *– runoff* *– Δ soil storage* *- ΔGW storage* *(cannot becalculated monthly due to lags)* by runoff module	***not output by tool*** ***calculate:*** *ET output (includes canopy interception) + AET from GW (external calculation)* by subcatchment	***not output by tool*** ***calculate:*** *canopy evap. + AET from soil* by HRU	***not output by tool*** ***calculate:*** *AET from soil + AET from GW* by HRU	**Timeseries output** * by grid cell, polygon, catchement	**Timeseries output** * (includes evaporation from surface ponding) by grid cell, polygon, catchment
Canopy interception evaporation	***not output by tool*** [#]	**Timeseries output** by subcatchment	**Timeseries output** by HRU	*(N/A)*	**Timeseries output** * by grid cell, polygon, catchment	**Timeseries output** * by grid cell, polygon, catchment
AET from soil	***not output by tool*** [#]	**Timeseries output** by subcatchment (includes canopy interception)	**Timeseries output** by HRU	**Timeseries output** by HRU, subcatchment and catchment	**Timeseries output** * by grid cell, polygon, catchment	**Timeseries output** * by grid cell, polygon, catchment
AET from GW	***not output by tool*** [#]	***not output by tool*** ***calculate:*** *algorithm* by subcatchment	*(n/a)*	**Timeseries output** *(“Revap”)* by HRU	**Timeseries output** by subcatchment aquifer and catchment	**Timeseries output** * by grid cell, polygon, catchment, by aquifer layer or all

Flux or storage	**Tool output and/or calculation approach**					
	WRSM	**SPATSIM**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**	**MIKE-SHEc**
Runoff (RO) total	**Timeseries output** by runoff module and route (any scale)	**Timeseries output** by subcatchment	**Timeseries output** by HRU, subcatchment and catchment	**Timeseries output** by HRU, subcatchment and catchment	**Timeseries output** by river cross-section	**Timeseries output** by river cross-section
Surface runoff	***not output by tool*** ** ***calculate:*** *RO total – interflow – aquifer RO* by runoff module	**Timeseries output** by subcatchment	***not output by tool*** ***calculate:*** *“Quickflow” – “DelayedStormflow”* by HRU	**Timeseries output** by HRU, subcatchment and catchment	**Timeseries output** * by grid cell, polygon, catchment	**Timeseries output** * by grid cell, polygon, catchment
Interflow	**Timeseries output** by runoff module	**Timeseries output** *(“soil moisture runoff”)* by subcatchment	**Timeseries output percentage** *(“DelayedStormflow”)* by HRU	**Timeseries output** *(“Lateral Q”)* by HRU, subcatchment and catchment	**Timeseries output** by subcatchment interflow reservoir	**Timeseries output** * *(saturated zone upper layer)* By grid cell, polygon, catchment
Aquifer to channel	**Timeseries output** by runoff module	**Timeseries output** by subcatchment	**Timeseries output** *(“Baseflow”)* by HRU and subcatchment	**Timeseries output** by HRU, subcatchment and catchment	**Timeseries output** by subcatchment, aquifer and catchment	**Timeseries output** * By grid cell, polygon, catchment, aquifer layer or all
Aquifer GW flow in/out	***not output by tool***	**Timeseries output** by subcatchment	*(N/A)*	*(N/A)*	*(N/A)*	**Timeseries output** * by grid cell, polygon, catchment

Flux or storage	**Tool output and/or calculation approach**					
	WRSM	**SPATSIM**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**	**MIKE-SHEc**
Soil profile storage	**Timeseries output** by runoff module	**Timeseries output** by subcatchment	**Timeseries output** by soil layer in HRU	**Timeseries output** by HRU, subcatchment and catchment	**Timeseries output *** by grid cell, polygon, catchment	**Timeseries output *** by grid cell, polygon, catchment
Aquifer storage	**Timeseries output** by runoff module	***not output by tool*** [#]	**Timeseries output** by HRU	**Timeseries output** by HRU and subcatchment	**Timeseries output** by subcatchment, aquifer and catchment	**Timeseries output *** by grid cell, polygon, catchment, aquifer layer or all
Percolation out of soil storage	**Timeseries output** *(“total recharge”)* by runoff module	**Timeseries output** *(same as recharge)* by subcatchment	**Timeseries output** *(same as recharge)* by HRU	**Timeseries output** by HRU, subcatchment and catchment	**Timeseries output *** by grid cell, polygon, catchment	**Timeseries output *** by grid cell, polygon, catchment
Aquifer recharge	**Timeseries output** *(“aquifer recharge”)* by runoff module	**Timeseries output** by subcatchment	**Timeseries output** *(“SaturatedFlow” B horizon* *+ ‘UnsaturatedFlow’ B horizon, if option to include is selected)* by HRU	**Timeseries output** by HRU and subcatchment	**Timeseries output** by subcatchment, aquifer and catchment	**Timeseries output *** by grid cell, polygon, catchment, aquifer layer or all

AET: Actual ET; GW: Ground water; MIKE-SHEs: Simpler, more lumped; MIKE-SHEc: Complex, distributed

(N/A): Not applicable – denotes that the model does not explicitly calculate this

[#] *could calculate externally using model’s algorithms, not overly complex, but not done given time constraints*

[**] *WRSM has an output called”‘total surface runoff”, but this includes infiltration excess runoff (i.e. surface) and interflow out of soil moisture store, whereas the “interflow” output includes interflow from the soil moisture store and from potential recharge in excess of aquifer capacity.*

[%] ACRU documentation suggested “delayed” stormflow runoff represents interflow; however, the calculation method differs significantly from other tools (i.e. this water never enters the soil profile in the model) and so cannot be expected to have the same values or represent all the same water as the other tools.

* MIKE-SHE outputs for most variables are “data-cubes”, timeseries of gridded surfaces. MIKE’s extraction tools can be set up to pull out spatial average timeseries for polygons (i.e. full catchment, subcatchments, consolidated areas of a vegetation type. The water balance extraction tool graphical user interface allows extraction for one polygon per set-up; however, coding for customised procedures is possible)

Implicit representation of processes

In some cases, a process of interest was represented implicitly in a calculation potentially representing multiple processes, rather than explicitly and individually:

- **SWAT2012, canopy interception:** When ArcSWAT2012 is run at a daily timestep, canopy interception is not explicitly calculated. In a rain event, surface runoff generation is calculated using the SCS-CN approach, and water that does not become surface runoff is added to the top soil layer. The SCS-CN method estimates "initial abstractions" during a rain event, which conceptually include canopy interception. However, SWAT routes all this water into the soil. In other tools, the potential ET (PET) is discounted by the amount of canopy interception evaporation to then calculate AET from soil. In SWAT, the full PET demand is used, so the ET output could be interpreted as ET from both the surface and the soil. However, with no clear way of getting a value for canopy interception from this output, this component was left out of the SWAT water balances for the case studies.

- **ACRU4, surface runoff vs interflow vs aquifer outflow:** For each HRU, ACRU4 calculates "quickflow", of which a portion is lagged in reaching the stream ("delayed stormflow"), and "baseflow" runoff. These terms refer to relative flow speed for a subset of runoff, without specifying the path or mechanism. This contrasts with terms like "overland" or "surface" flow, "interflow" and "aquifer" or "ground water" outflow. ACRU documentation suggests that the "delayed stormflow" represents interflow, but also suggests that the "baseflow" calculated could represent outflow from both an intermediate (vadose) zone and/or aquifers (Schulze, 1995), which could be interpreted as including interflow as well.

  To compare water balances in this exercise, the following assumptions were made:

  - **Rain-day quickflow** is the most equivalent output to **surface runoff** (not actually output directly, but easily calculated from outputs: "quickflow" – "delayed stormflow")
  - **"Delayed stormflow"** is the most equivalent output to **interflow**
  - **"Baseflow"** is the most equivalent output to **aquifer outflow**

  It is understood that these ACRU outputs were not necessarily intended to be interpreted strictly in this way. ACRU's "speed-based" runoff outputs could be interpreted as implicit representations of multiple contributing flow paths in different cases. The "baseflow" output could include interflow and aquifer outflow. Rain-day quickflow could include both surface and faster shallow subsurface flow.

  It should also be noted that the way "delayed-stormflow" is calculated differs notably from the way other tools estimate interflow. In ACRU, a total "stormflow" amount is calculated from a rainfall event using antecedent soil moisture for a critical soil depth. This amount is then portioned into rain-day and "delayed stormflow". The generation of interflow may be governed by different moisture thresholds to the generation of surface flow. This is discussed further in section 3.2.2.

- **ACRU4, ET drawn from ground water:** Like other tools, ACRU4 includes a mechanism by which specified riparian areas are essentially given access to ground water to meet ET demands. In ACRU4, "baseflow" output (see above) from upland HRUs can be routed to the lower soil layer of special riparian HRUs. This could potentially represent different flow paths that increase riparian zone water access: interflow from uplands increasing riparian soil moisture and/or ground water recharge occurring in uplands contributing to a shallow water table in the riparian zone that is accessible to the vegetation. ACRU4 calculates AET for an HRU drawing only from its soil profile, not its "baseflow storage". The riparian HRU soil profile will contain water that was once in the upland "baseflow store", but this water is not separately tracked once it reaches the soil profile, so there is no model output of the proportion of riparian ET fed by this water in particular. This could be calculated from a detailed water balance for each riparian HRU, but this was beyond the scope possible in this project.

Tool calculates the flux, but does not save/output

In some cases, a process is explicitly calculated by a modelling tool, but the tool does not save or output the results of the calculations, only more distal fluxes:

- **WRSM, ET (all component fluxes):** WRSM explicitly calculates canopy interception evaporation, ET withdrawals from soil moisture, ET withdrawals from ground water, evaporation from reservoir surfaces and evaporation from wetland surfaces. None of the results of these calculations are saved or output by the software. Some components were calculated from the tool output for this exercise:
  - Evaporation from wetlands and reservoirs was back-calculated using the output timeseries of flow in, flow out and storage volume, as well as rainfall and the storage-surface area relationship used in the input.
  - Total AET from “runoff modules” (subcatchments) was back-calculated using input rainfall and output timeseries of runoff and soil and ground water storage. Because interflow and aquifer outflow amounts generated in a month, hence leaving storage, can be lagged in becoming streamflow, hence showing up in the runoff output, this calculation was done for years or longer time periods, not for individual months.
  - Components of total AET from the runoff modules (canopy interception, ET from soil and ground water) could be calculated by applying the model’s algorithms outside the model, but this was deemed beyond the scope of this project.
  - AET from irrigated area modules was calculated as the difference between inflow and return flow route outputs for the module.

- **SPATSIM, ET from ground water:** SPATSIM calculates ET drawn from the ground water store for the riparian zone of the subcatchment, but does not output this. The model’s algorithm for the process (Hughes, 2004) was re-applied outside of the software, a function of the riparian zone area, the evaporative demand minus rainfall (both input) and the ground water storage (hence gradient).

- **SPATSIM, evaporation from farm dams:** SPATSIM calculates evaporation from small farm dams, modelled as a single reservoir fed by a portion of the subcatchment, but does not output this. It was calculated from the tool outputs as the difference between the total runoff produced by the subcatchment, calculated as the sum of the “surface runoff”, “soil moisture runoff” (interflow) and “ground water runoff” outputs, and the “total downstream flow” output (minus any upstream channel inflow if applicable).

4.7.6 Calculation of catchment-scale water balances, considering connectivity of modelled units and multi-part flow pathways

When catchment-scale outputs were not produced by a tool, outputs can generally be exported by HRUs, modules or subcatchments and, where appropriate, summed for the catchment, with area-weighted averaging for values expressed as a depth. This is appropriate for processes like canopy interception, ET withdrawal from soil moisture or ground water recharge, for which there is no proximal interaction with other modelled units. However, for runoff components (i.e. surface flow, interflow, aquifer outflow) the connectivity between model units needs to be considered when interpreting model unit output to obtain a catchment-scale output, with implications for the meaning of this output:

- WRSM and SPATSIM calculate and output surface runoff, interflow and aquifer outflow reaching the channel network at the subcatchment scale. This allowed the simple accumulation of runoff component output to the catchment scale. Once in the channel network, flow could be lost to evaporation from dams, for example, before reaching the catchment outlet. The ratio of the runoff sources from the pre-loss subcatchment output was simply applied to the final amount of streamflow output at the catchment outlet.

- ACRU4 calculates and outputs “quickflow” (same-day and “delayed stormflow”) and “baseflow” at the HRU scale (see descriptions above). HRU outflows are routed in parallel (no interaction across HRUs) to channels, reservoirs or subcatchment nodes, unless the subcatchment includes special riparian HRUs. The baseflow outflow of other HRUs can be routed to the soil of a riparian HRU. A riparian HRU also has an associated river channel with a flow capacity threshold. Channel flow over the threshold is added to the surface of the riparian HRU to infiltrate or run off.

  - **With no riparian HRUs:** HRU-scale runoff outputs can simply be accumulated for the catchment. The tool outputs accumulated quickflow and baseflow by subcatchment.
  - **With riparian HRUs, hence routing from upland to riparian and/or channel overflow:** Simply accumulating runoff outputs from all HRUs results in double-counting. Runoff leaving riparian HRUs can include water also counted in baseflow output from upland HRUs and/or runoff from upstream HRUs. Avoiding double-counting requires a decision about which part of the two-part flow-path to focus on: runoff leaving the riparian or the non-riparian HRUs. Water routed to a riparian HRU will feed additional ET and/or baseflow in the HRU. However, with sufficient inflow versus drainage and ET, the soil will saturate and generate surface flow in the model. This may be the real process occurring in a catchment. To apply simplified flow path categories in a catchment-scale water balance, a user could decide to classify this as surface runoff, because this is how it enters the channel in the model, or aquifer outflow, if it is thought that the baseflow flux from the upland dominated the length of the flow path in the landscape.

  Another complication arises because ACRU4 routes upslope input to the soil of the riparian HRU. This is done to allow this to feed ET because the tool only calculates ET from soil moisture and does not calculate capillary rise from ground water. In some cases, this is representing what is actually ground water flow and capillary rise that is less likely to saturate the riparian soil and generate surface runoff than the model’s soil routing represents.

  In this study, the approach to catchment-scale accumulation favoured the distribution of the runoff component modelled for the upland (non-riparian) HRUs: Total runoff and its source composition were calculated for all non-riparian HRUs. This was compared to the catchment outlet streamflow, and the residual was assumed to be additional runoff generated from the riparian HRUs. This amount was divided into contributing runoff sources using the source ratio of the gross runoff leaving the riparian HRUs. In some cases, there was a net loss of runoff across the riparian HRUs due to high ET. In this instance the source distribution of upland areas was applied to net streamflow output.

- ArcSWAT2012 routes HRU outflows in parallel to the channel network. (It should be noted that SWAT+ offers landscape routing to riparian zones similar to ACRU4, but this software version was not used here.) This means it is appropriate to simply accumulate HRU output to the catchment scale. For some fluxes, the software already does this internally and outputs a catchment-scale water balance, but this did not include all the flows of interest, such as ET drawn from ground water or capillary rise, so the HRU scale outputs were needed. Evaporative water losses along the channel network can be calculated after the HRU input. The runoff source ratio from the accumulated HRU flows was applied to the catchment outlet runoff.

- MIKE-SHEs (simpler algorithm options, more semi-distributed) can automatically output modelled surface flow and lumped subsurface flow reaching the channel network at the catchment. Subdivision between interflow and aquifer outflow required working with the software’s subcatchment-scale output and accounting for interflow routing. In a MIKE-SHEs set-up, interflow is modelled with a user-input catena series of “interflow reservoirs”, in which the lowest reservoir within a subcatchment discharges to the stream. Aquifer outflow to the stream is modelled using one or more “baseflow reservoirs”, which discharge in parallel to the stream within a subcatchment. The tool outputs storage and different inflows and outflows for each modelled “reservoir” in a subcatchment. The output “lateral outflow” from the lowest interflow reservoir in each subcatchment was extracted to get catchment-scale interflow contribution. All baseflow reservoir lateral outputs were accumulated to get catchment-scale aquifer outflow. It was confirmed that the sum of these two components equalled the total subsurface flow output produced by the tool.

- MIKE-SHEc (complex algorithm options, more fully distributed) can automatically output the amount of surface flow reaching the channel network and the amount of subsurface flow from different user-defined layers in the "saturated zone" reaching the channel network at the catchment scale. Output from an upper layer in the model's saturated zone may be interpreted as interflow, depending on the layer set-up used and whether it develops saturation perched above that in the lower aquifer layers.

The scale of process representation differs across tools and influences their calculation of different flow pathways. Water can follow complex flow pathways through a landscape, which include a mixture of the simplified components or paths listed in the water balances. For example, rainfall may become surface runoff where it hits the ground, but surface flow may be detained and infiltrate elsewhere, with some reaching the stream as subsurface flow. Alternatively, rainfall may infiltrate and percolate where it lands and become subsurface flow that could saturate an area lower down. Some of this water may emerge as a seep and enter the stream network that is being modelled as surface flow. If the scale of representation of the modelling tool is coarser than the path length over which these different processes are occurring, they will not be explicitly modelled. Even if they are explicitly modelled, tools may vary in how the flow is described in the output produced.

Some tools used here explicitly represent "multi-part" runoff pathways at the subcatchment or catchment scale and others do not, which is relevant to the interpretation of the software tool's automatic outputs:

WRSM and SPATSIM calculate processes at the subcatchment scale, so there is no explicit representation of potential multi-part flow paths. Algorithms calculating the amounts of flow for each simplified pathway (surface flow, interflow, aquifer outflow) are assumed to represent flows for which that pathway or mechanism at least dominates the journey at the subcatchment scale.

- ACRU4, when including riparian HRUs and associated routing, can explicitly include some multi-part flow pathways, as described above. However, the modelling tool itself does not provide output at a catchment scale that categorises contributing paths. The extraction, calculation and interpretation of flow paths is up to the user if it is needed. The approach and assumptions applied in this exercise were described in the preceding section on considering routing.

- ArcSWAT2012 calculates and outputs surface and shallow subsurface processes at the HRU scale, but does not route flows from one HRU to another. A transmission loss along the flow path can be imposed on HRU surface and interflow, so that some is lost to shallow aquifer recharge before reaching the stream. Aquifer outflow is calculated at the subcatchment scale. In this way, some types of multi-part flow pathways can be partially represented if this loss function is parameterised to do so. HRU output includes both the surface runoff and interflow generated by the HRU and the portion calculated to reach the stream, as well as an aquifer outflow associated with the HRU.

- MIKE-SHE, using either set-up option being considered in this study, explicitly models multi-part flow pathways at different scales: at the scale of user-defined overland flow zones and spatially explicit subsurface "reservoirs" in the simpler algorithm approach, or the grid cell-scale input in the complex algorithm approach. Overland flow moving between units can infiltrate along its path, interflow can percolate to an aquifer along its path, water tables can rise and saturate soils creating surface flow, etc. The catchment-scale water balance outputs provided by MIKE-SHE give the pathways by which water entered the stream channel, regardless of whether this route dominated the path length through the landscape or not. Seep water surfacing meters from the channel will be classified as surface flow in the catchment water balance output, even though it may have flowed through most of the landscape in the subsurface. Water that flowed on the surface or as interflow through most of the landscape, recharging a riparian zone aquifer shortly before entering a channel, would be classified as aquifer outflow.

These output and interpretation differences limit how much the catchment-scale water balances across tools can be expected to be similar when looking at more specific fluxes, even if they may actually be representing similar processes when viewed at a coarser scale. The division of runoff into simplified contributing components is artificial, but can be useful, given that this is understood. The ACRU modelling tool required the most user interpretation and external calculation of runoff generation and flow pathway composition. In the other tools, runoff component outputs either represented the dominance of a path type along the full path length through the landscape (WRSM, SPATSIM, potentially SWAT) or the specific pathway by which the water entered the stream at the end (MIKE-SHE, potentially SWAT). In this study, the processing of the HRU output from ACRU was more similar to the former approach.

CHAPTER 5: COMPARATIVE CASE STUDY MODELLING

5.1 INTRODUCTION

The focus tools were used to build models of four case study catchments selected to cover a variety of climate, geomorphological and land cover settings. These were the Mistley catchment in the Upper Mvoti River in KwaZulu-Natal, the Upper Berg River catchment in the Western Cape, the Upper Kromme River catchment in the Eastern Cape and the Middle Letaba catchment in Limpopo (Table 5.1). For each, one or more alternative scenarios were applied to assess how differently they predicted the responses to the change. These were land cover scenarios for the Mistley, Berg and Kromme catchments, and a change in irrigation water sources in the Letaba catchment. Model outputs were compared in terms of fit to observed streamflow, magnitude and pattern of change predicted when a scenario was applied, and the modelled catchment water balances under baseline and scenario conditions.

The goals of this exercise were as follows:

- Gain a better comparative understanding of the practical implications of the structural and interface differences across the different tools in common use cases
- Compare the modelled water balances across the different tools for each case study to see to what degree they differed
- Assess if there were any evident patterns in model predictions when using a certain tool across different case studies, e.g. consistently predicting higher baseflow than other tools, consistently predicting more ET than other tools, etc.
- Draw lessons from the experience relevant for other users of these tools applying them to similar use cases

These specific catchments were chosen in part because they had been modelled in other projects for which the input data and scenario descriptions could be made available to the project team (Cornelius et al., 2019; Haasbroek et al., 2015; Rebelo and Holden, 2020; Scott-Shaw, 2020). This reduced the time needed to obtain, vet and process input data, allowing more time to focus on model structures and outputs. The pre-existing models were used as starting references for structure and parameter decisions made in the other tools when relevant.

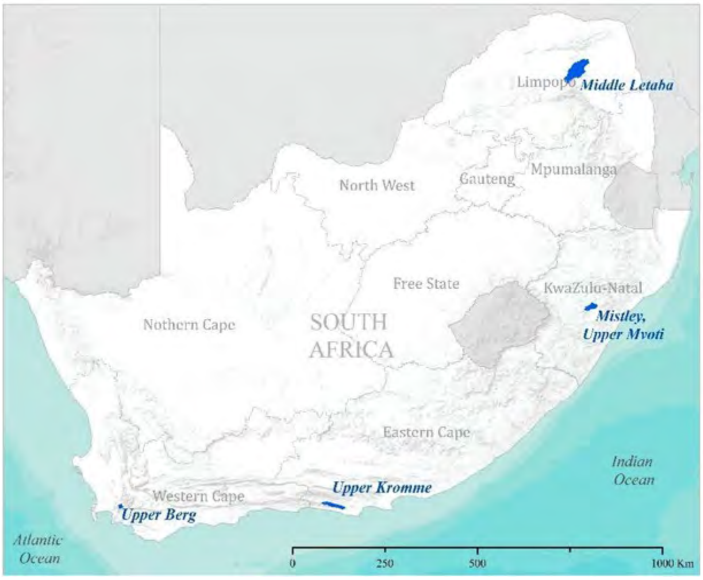


Figure 5.1: Locations of the four case study catchments

Table 5.1: Case study catchments, use case demonstration scenario types and highlighted process representation issues encountered in model building

Case study catchment	**Climate type**	**Geology, geomorphology, natural vegetation**	**Scenario types**	**Highlighted model representation issues**
Mistley, Upper Mvoti (U40A), KwaZulu-Natal	Summer rain, sub-tropical	Shale and dolerite, rolling hills, grassland	Commercial forestry extent and riparian or wetland buffers	Riparian zone processes
Upper Berg (G10A), Western Cape	Winter rain, sub-humid / semi-arid, Mediterranean	Table Mountain Group quartzite, steep mountain, fynbos	Invasive alien tree extent and location	Interflow in steep, rocky mountains
Upper Kromme (K90A,B), Eastern Cape	Bimodal rain, semi-arid	Table Mountain Group quartzite – steep mountain + floodplain alluvium, fynbos	Invasive alien tree extent, wetland extent	Spatial rainfall distribution and flow connectivity both interact with subcatchment delineation; valley bottom wetland representation
Middle Letaba (B82A-D), Limpopo	Summer rain, semi-arid, temperate	Gneiss and granite, relatively flat, woodland	Irrigation amount and irrigation from ground water	Irrigation from ground water and from multiple sources; numerous small farm dams; channel transmission loss

The sections below cover the following:

- The overarching methodologies applied to all the case studies
- Overviews of the modelling process, focusing on highlighted representation issues that became salient in the model building (Table 5.1)
- Model outputs and key findings for each case study
- Discussion of results across case studies

Model performance and scenario outputs are described here, while more detailed accounts of the model set-ups are given in appendices C1 to C4. The appendices describe the structure of each model, the parameter values used and the rationale behind key model-building decisions.

5.2 OVERARCHING METHODS

The intention of the model-building exercise for each case study was to come up with models that represent typical applications of the modelling tool for a given type of catchment and application (i.e. type of change scenario to be assessed with the model). An effort was made to represent a shared conceptualisation of the case study catchment, informed by the same climate and catchment property datasets. Generalised methods for doing this, which were consistent across cases studies, are described below. For the MIKE-SHE modelling tool, which includes many spatial discretisation and algorithm options, two simplified strategies were identified in the model structural review (see section 4.3.1): more complex and discretised, referred to in the tables as “MIKE-SHEc”, and simpler and more lumped, referred to as “MIKE-SHEs”. At least one option was applied in each case study.

It is acknowledged that the data used as inputs and to inform and evaluate the model structures and parameterisation had shortcomings, and may not be the most accurate data currently available given ongoing research, improvements in remote sensing products, etc. However, the focus of the exercise was the intercomparison of the models built with different software tools when aiming to represent the same catchment as described by the same data. There was little assessment of the accuracy of the underlying data, which was obtained from modelling exercises that had been conducted outside this project. Instead, it was accepted that the datasets obtained for the case studies at a minimum provide reasonable descriptions of general types of catchments and climate conditions, and also represent the types of datasets to which modellers would typically have access. With all the models referring to a common dataset, the focus was on assessing the differences in structures and outputs across them.

5.2.1 Group modelling process

For each case study, an initial introductory session was held with the project team in which the catchment setting, available data, conceptual understanding of processes, pre-existing reference model set-ups and the potential alternative scenarios to be modelled were presented and discussed. Each case study was selected because a relatively detailed modelling exercise had already been conducted for the site, which entailed gathering relevant input data and processes information. This session was followed by preliminary discussions about potential model structures in other tools and further inputs and parameters required. Two to three team members would meet separately to work on building and testing a model set-up in a selected tool over the following month. A team check-in meeting regarding structural approaches across tools was held within the first week once the team had a chance to review the case study in more detail. Meetings were conducted online and recorded.

Both conceptual and technical challenges slowed the process of completing calibrations and assessments of internal water balance elements across the tools. It was deemed important to explore all the case studies to some extent because they cover different landscape types and applications. As such, the team would progress to the next case study exercise before full completion of the previous one to ensure that, at a minimum, model structure ideas were considered and discussed for all four cases.

5.2.2 Consistency conceptual model and key inputs across tools

Climate inputs

A concerted effort was made to ensure that the climate inputs, rainfall and atmospheric evaporative demand applied in all the tools was the same, at least at the scale of the full catchment area. Different tools require climate inputs at different spatial scales or employed different module unit delineations, so it was not always possible for all internal model unit inputs to be the same. However, an underlying spatial surface or distribution, and catchment-scale spatial average, was determined based on the reference model inputs and used to derive equivalent inputs for each tool. Each case study exercise started with a pre-existing model set-up (Table 5.1), which included choices about how to go from available climate datasets to the required model inputs, and how spatial gradients would be included. These original inputs from the starting reference model were accepted and not interrogated in this exercise. In some cases, the reference model inputs were spatially lumped further for use in a specific tool, but no additional data was sought to increase the spatial resolution from the reference.

Table 5.2: Climate input from the pre-existing model set-up for each case study catchment and steps applied to prepare input for other modelling tools that represent equivalent climate conditions

Case study catchment	Pre-existing reference model set-up	Climate inputs	Spatial distribution of inputs	Process to prepare inputs for other tools
Mistley, Upper Mvoti	ArcSWAT2012 (Scott-Shaw, 2020)	Daily rainfall, temperature, wind speed, humidity, solar radiation	Data for station point locations; Data from the nearest station applied to each subcatchment (73 subcatchments)	Apply Penman-Monteith equation to produce reference vegetation PET series for each station and convert to A-pan and S-pan. Use SWAT subcatchment polygons assigned to each station as a “climate zone”, which can be input into MIKE-SHE. Overlay maps of the subcatchments used in other tools onto these zones to calculate area-weighted average climate series for each.
Upper Berg	MIKE-SHE complex options (Rebelo and Holden, 2020)	Daily rainfall and reference vegetation PET	Station rain data interpolated using an elevation lapse rate within a thiessen polygon PET applied at catchment scale	Convert PET to A-pan and S-pan. Overlay subcatchments used in other tools onto rainfall surface to extract spatially averaged timeseries for each polygon.
Upper Kromme	MIKE-SHE simpler options (Cornelius et al., 2019)	Daily rainfall and reference vegetation PET	Data input for topographic climate zones	Convert reference PET to A-pan and S-pan. Overlay subcatchments used in other tools onto the climate zones to calculate area-weighted average climate series for each.
Middle Letaba	WRSM-Pitman (Haasbroek et al., 2015)	Monthly rainfall and average monthly S-pan evaporation	Data input for quaternary catchments	Convert S-pan to A-pan and reference PET. Use quaternaries as climate zones for input into MIKE-SHE. Overlay subcatchments used in other tools onto the quaternaries to calculate area-weighted average climate series for each.

In the case of the reference WRSM model used as the starting point for the Middle Letaba case study, the input data was at a monthly timestep, while the other tools required daily inputs. For this case study, daily station data was obtained from the South African Weather Service (SAWS) and DWS. This was re-scaled to ensure a match to the monthly quaternary catchment timeseries used in the WRSM model.

The different tools use different evaporative demand inputs:

- Pitman tools use S-pan evaporation,
- ACRU4 generally uses A-pan evaporation (it can use and specify other inputs, but the crop coefficients in the in-built database assume A-pan; using others would require manual input),
- MIKE-SHE requires Penman-Monteith reference vegetation PET

- SWAT2012 requires climate parameters to calculate PET using Penman-Monteith, Priestly Taylor or Hargreaves and Samani methods, depending on the data available. SWAT can also be run using externally calculated reference vegetation PET input. In this latter case, only a single input timeseries is accepted and is then applied at the catchment scale.

Conversions between these data types were done using factors suggested in Schulze (1995), applying climate zone-specific monthly ratios between A-pan and S-pan evaporation derived by Louw (1966) and a 1.2 conversion from standard short vegetation reference PET to A-pan ET.

Subcatchments, hydrologic response units other model units

The subdelineation of the case study catchment area into subcatchments and other model spatial units was guided by each tool's input interface, typical or suggested scales of application, and the implications of unit divisions for process representation, which differed across tools. It was deemed inappropriate to force the use of exactly the same set of spatial units across tools in every case as it would misrepresent the typical use of the tool. Tool interfaces and input processes lend them to different model unit delineations. For example, both SWAT2012 and ACRU4 model many processes at the scale of HRUs, intended as units of relatively homogenous land cover, soil type, topography and climate. However, the ArcSWAT2012 interface facilitates the inclusion of many unique HRUs, while the process of setting up HRUs in ACRU4 incentivises simplification into fewer HRUs whenever reasonable. The interface of ArcSWAT2012 automatically generates HRUs by overlaying input soil and land cover maps and a digital elevation model (DEM), assigning parameters through databases linked to cover and soil type codes and internal topographic analyses of the DEM. There is relatively little penalty to including more unique cover and soil types. In ACRU4, each individual HRU in a model is manually added, and manually assigned parameters and spatial connectivity. This is a much more time-consuming set-up process. Whenever a parameter associated with a land cover or soil type needs to be adjusted, this needs to be done manually for each HRU of that type. Therefore, given the same land cover and soil datasets, a SWAT2012 user and an ACRU4 user would likely come up with very different numbers of HRUs to include. Similarly, modules in WRSM are added and parameterised manually and individually, while SPATSIM allows users to input and parameterise subcatchments using maps and uploaded tables of parameter values, which makes the process easier and reduces the penalty of including a greater number of subcatchments.

Land cover

The same land cover-type map that was used for the reference model of the case study catchment was used as the starting point for structures in the other tools. For WRSM and SPATSIM, the cover was simplified into the primary natural vegetation (grassland, fynbos, savanna, thicket, etc.) and, where present, IAP areas, forestry plantations, irrigated areas, impervious cover and wetlands. For ACRU4, the number of separately considered cover classes was also generally reduced, lumping any relatively similar classes that take up small areas to reduce the number of HRUs (see model unit section above).

Parameter values for each land cover type in the reference model were used to determine parameter starting values in the other tools whenever relevant. For example, all tools except SWAT2012 include a canopy interception parameter; MIKE-SHE, ACRU4, in some set-ups SWAT, and WRSM use ET coefficients or pan coefficients; and MIKE-SHE, ACRU4 and SWAT2012 include vegetation root depth. This required various unit conversions and timestep considerations.

Subsurface material properties: soil, sediment, rock

The same soil type and geology maps used in the reference model were used to inform model structures in the other tools. Tools differ significantly in their approaches to modelling lateral and vertical subsurface flows, with different required or allowed layering options and storage reservoir types. For example, MIKE-SHE explicitly models a layered unsaturated zone profile that extends from the ground surface to the (dynamic) water table, while SWAT2012 and WRSM consider a soil profile that is separate from an underlying vadose zone that, in turn, overlies an aquifer.

ACRU4 only includes soils in the root zone, while all subsurface flows occurring below the root zone are represented with a single ground water outflow parameter. Nevertheless, an effort was made to maintain the conceptual spatial and depth distribution of higher and lower water storage, retention and conductivities across the case study landscape in all tools.

5.2.3 Model assessment against observed streamflow and adjustment to improve calibration

Modelled catchment outlet streamflow was compared to observed data at a daily timestep for the daily models and at a monthly timestep across all the tools. Statistics of goodness of fit were applied to evaluate performance for both timesteps: percentage error in long-term mean flow, the Nash-Sutcliffe efficiency (NSE) of flow and log-transformed flow (which increases the weight of low flows), root mean square error (RMSE) and correlation (R^2). In addition, assessments of hydrographs and flow duration curves were used to diagnose model shortcomings.

Limited attempts at improving model fit to the observed streamflow through parameter adjustments were attempted, with value ranges consistent with parameter meanings, guidance documentation and the conceptualisation of processes for the particular catchment. MIKE-SHE, SWAT and SPATSIM have associated automated uncertainty analysis and calibration tools. For SWAT, this is an independent software package, SWAT-CUP (Abbaspour, 2015). These tools were employed in at least one case study for each tool to gain an understanding of their use. In all cases, the user selects which parameters are to be adjusted and the value ranges, or probability distributions, over which to test. The tools generate an input number of parameter sets by sampling values across the input ranges or distributions, run the model using each set, and calculate the performance statistics for each. These statistics can be used to further constrain value ranges in subsequent rounds of testing, either manually by the user or using optimisation search algorithms. In general, when parameter adjustments produced improvements in one aspect of model fit, but resulted in large losses in performance on others, for example improving peak flows and likely NSE at the expense of lower flows and likely NSE of logged flow, or improving the accuracy of the long-term average at the expense of the temporal pattern of flows (represented by R^2), the changes were not accepted.

Adjustment trials focused on parameters that were considered more conceptual, having less direct value derivation from measurable physical properties; for example, the runoff-generation curve numbers used in SWAT2012, which applies the empirical SCS-CN method of calculating runoff versus infiltration during rainfall events. When values were adjusted, proportional adjustments were applied to values for all cover types to maintain the relative differences across cover types. It is acknowledged that there is also uncertainty in the vegetation, soil and geological property data used to obtain more “physical” parameters in the models. There is often also a scale mismatch between the field measurements of physical properties of vegetation, soil and geological layers, and the scale and way in which these are used in catchment-scale model algorithms. As such, adjustment of model parameter values that are seemingly more “physically based” away from a priori values may actually be realistic within constrained ranges. However, this was avoided in this exercise in an effort to maintain consistency across what was being physically represented by the models built using different tools.

Models were considered to have reached an “acceptable” level of performance when the modelled mean flow was within 15% of the observed flow, the daily modelled flow timeseries NSE was 0.5 or greater, the monthly flow timeseries NSE was 0.6 or greater, and the R^2 was 0.5 or greater for monthly and daily flows when available. In this exercise, targets needed to reflect the uncertainties in the data and limited time available for adjustment trials. The process of adjustment and testing required significantly different amounts of time and labour across the tools (see Section 4.2). This prohibited the establishment of a common calibration effort target across the tools, other than a limit on the amount of time spent by the modelling team. In an ideal applied use case, the acceptable amount of uncertainty should be defined in light of the types of decisions being made based on the model predictions. The additional time and effort can be allocated to assessing and improving underlying data and/or model process representation when needed. This was beyond the scope of this study and efforts here instead served to identify differences in calibration approaches across tools.

It is important to note, in light of the points above, the performance measures of the case study models built for this exercise cannot be seen as conclusive comparative indicators of each modelling tool's potential capability or relative capability compared to the other tools. The performance statistics are a function not only of the capabilities of the modelling tool to represent local processes, but also the input and performance evaluation data being used and many decisions made by the modellers, including the calibration approach.

What this study instead aims to compare is the modelling experience and representation decisions that need to be made in each tool for different kinds of catchments, and explore the potential range of predictions that could reasonably arise across different modelling efforts for the same area, even when given the same underlying data and information. When reporting outcomes from a model built for a case study using a particular tool, for brevity and readability, it may be referred to by the modelling tool name, i.e. “the SWAT2012 model”, in this report. This should be interpreted as “the model of case study X built using the ArcSWAT2012 tool during this exercise”, rather than broadly referring to the SWAT2012 modelling tool and all models that could be built with it.

5.2.4 Model water balance assessment

The initial intention in this exercise had been to assess the modelled water balances during the model testing and calibration process to determine if the baseline models were representing processes in roughly the same way and conforming to the conceptual model of the catchment. However, it was found that obtaining and processing water balance outputs at the catchment scale for many tools was far more challenging and time-consuming than anticipated as some of the tools are not designed to facilitate this process (see structural review, section 4.7.5 and 4.7.6). As such, this became a parallel workstream and the water balance assessments were mostly completed post-hoc, once modelling was completed. This was a finding in and of itself as it suggests that this level of assessment is not typical, and calibrating the models without checking the water balance may represent the more “normal use” of these tools.

For all models and all scenarios run, a set of basic water balance outputs was exported or obtained in as much as possible: total AET, canopy interception, ET drawn from soil, ET drawn from ground water, evaporation from waterbodies when relevant, net runoff, surface flow, interflow, aquifer outflow to channel and subsurface storage change. As described in the structural review in section 4.7.5 and 4.7.6, not all tools export the same water balance components or fluxes, and not all shared outputs have perfectly comparable meanings. The approaches for obtaining various water balance components are described in the structural review sections 4.7.5 and 4.7.6. Average annual water balances were compared across models of the same catchment built in different tools, aware of potential conceptual mismatches. The predicted changes in average annual water balance components under the different scenarios were also compared across tools to determine if the modelled changes in streamflow were predicted for the same reasons.

5.3 CASE STUDY OVERVIEW: MISTLEY CATCHMENT, UPPER MVOTI RIVER (U40A), KWAZULU-NATAL – FORESTRY AND RIPARIAN ZONES

5.3.1 Catchment description and modelling goals

Table 5.3: Mistley catchment and modelling overview

Catchment property	Description	Implication
Scale	$316.6\ km^2$ One quaternary (U40A) catchment of the Mistley weir (U4H002)	
Climate	MAP 860 mm Summer rainfall	
	Spatial rainfall gradient: estimated MAP ranges from 1058 mm in the western highlands to 781 mm downstream.	A quaternary scale model could lose important processes: sub-areas have quite different water access, influencing process
Runoff ratio	~8 % (medium, low)	
Topography	Rolling topography, upland scarps grade to near flat with a large unchanneled wetland	Surface flow likely to be relatively low, high proportion infiltrating
	Mean slope: 14%	
Soils and geology	Deep, well-developed soils, predominantly overlying shale, some dolerite and sandstone	Lateral interflow through soils is likely more significant than bedrock aquifer contributions
	Drainage line and riparian soils remain wet across dry periods: support indigenous wetlands (when not disturbed)	Vegetation in riparian zones will have more subsurface water access and a higher AET
Vegetation	Dominated by commercial forestry (63% of area): eucalyptus, some wattle and pine; 17% grassland/range; 10% pasture Pre-alteration, would have been grassland, wetland, scarp forest	
Modelling		
Previous modelling	SWAT model set-up, calibrated (Scott-Shaw, 2020)	Input database and conceptual model reference point
Modelling goals or scenarios	Estimate the hydrological impacts of removing tree plantations from all areas mapped as potential (pre-disturbance) wetland and within a 20 m buffer of these; a $37\ km^2$ (18%) decrease in plantation cover, replaced with herbaceous wetland with grassland buffers.	Differences in potential ET rates between eucalyptus and wetlands and grasslands need representation in models. Greater subsurface water access for vegetation in low-lying areas vs uplands needs representation in models.
Climate data	UKZN, NCEP-CFSR, SAWS/Lynch 2003 rain gauge and weather station daily rain and ET demand: 1979-01-01 to 2017-09-08 *(1987 and 1988 large event data potentially problematic)*	**Model runs:** 1983-10-01 to 2016-10-01 **Calibration and scenario comparison (excluding warm-up):** 1988-10-01 to 2016-09-30 (28 years)
Streamflow data	DWS weir (U4H002), daily streamflow: 1985-01-01 to 2018-09-30	

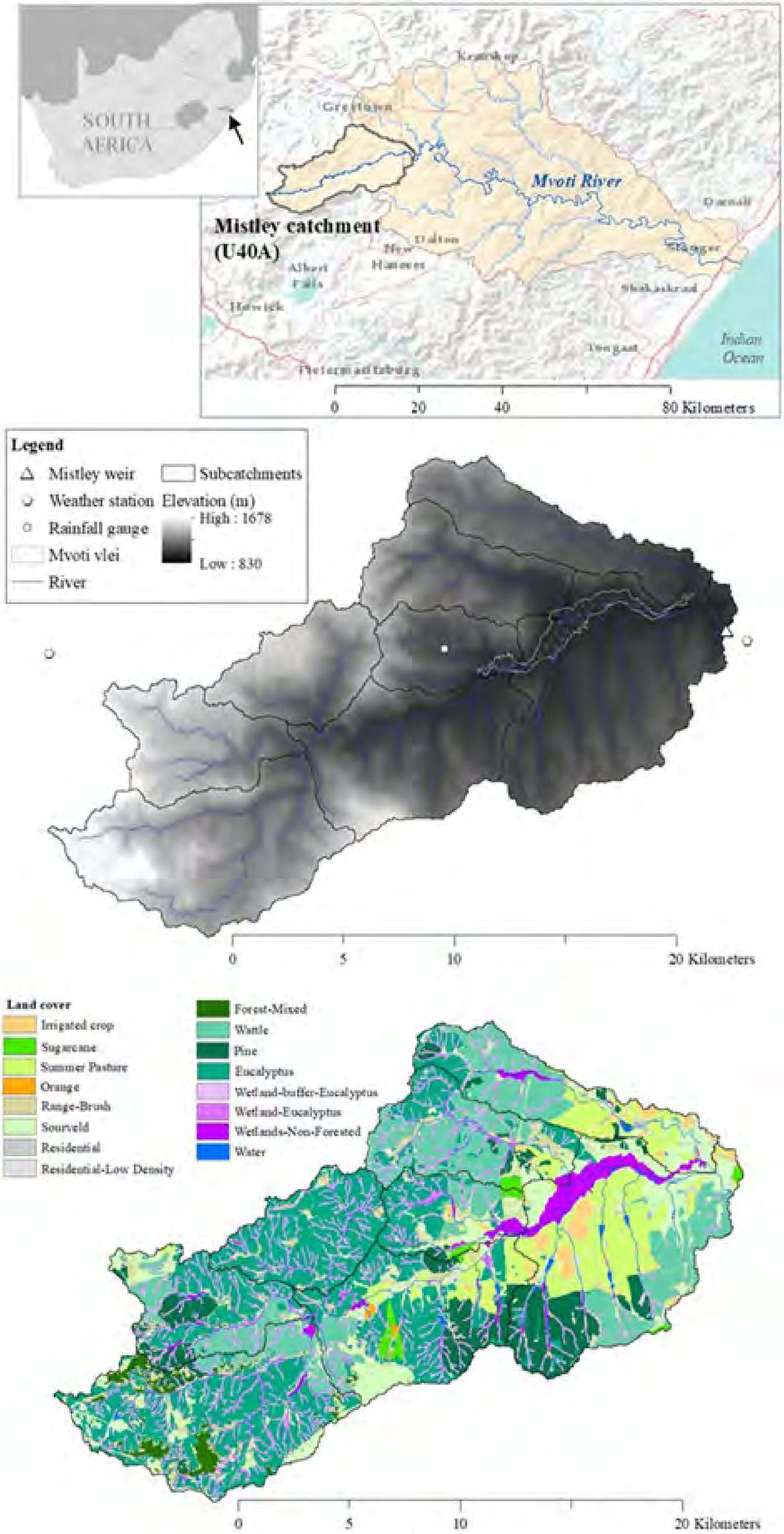


Figure 5.2: Regional location, topography and gauging stations, and land cover of the Mistley catchment on the Upper Mvoti River, KwaZulu-Natal

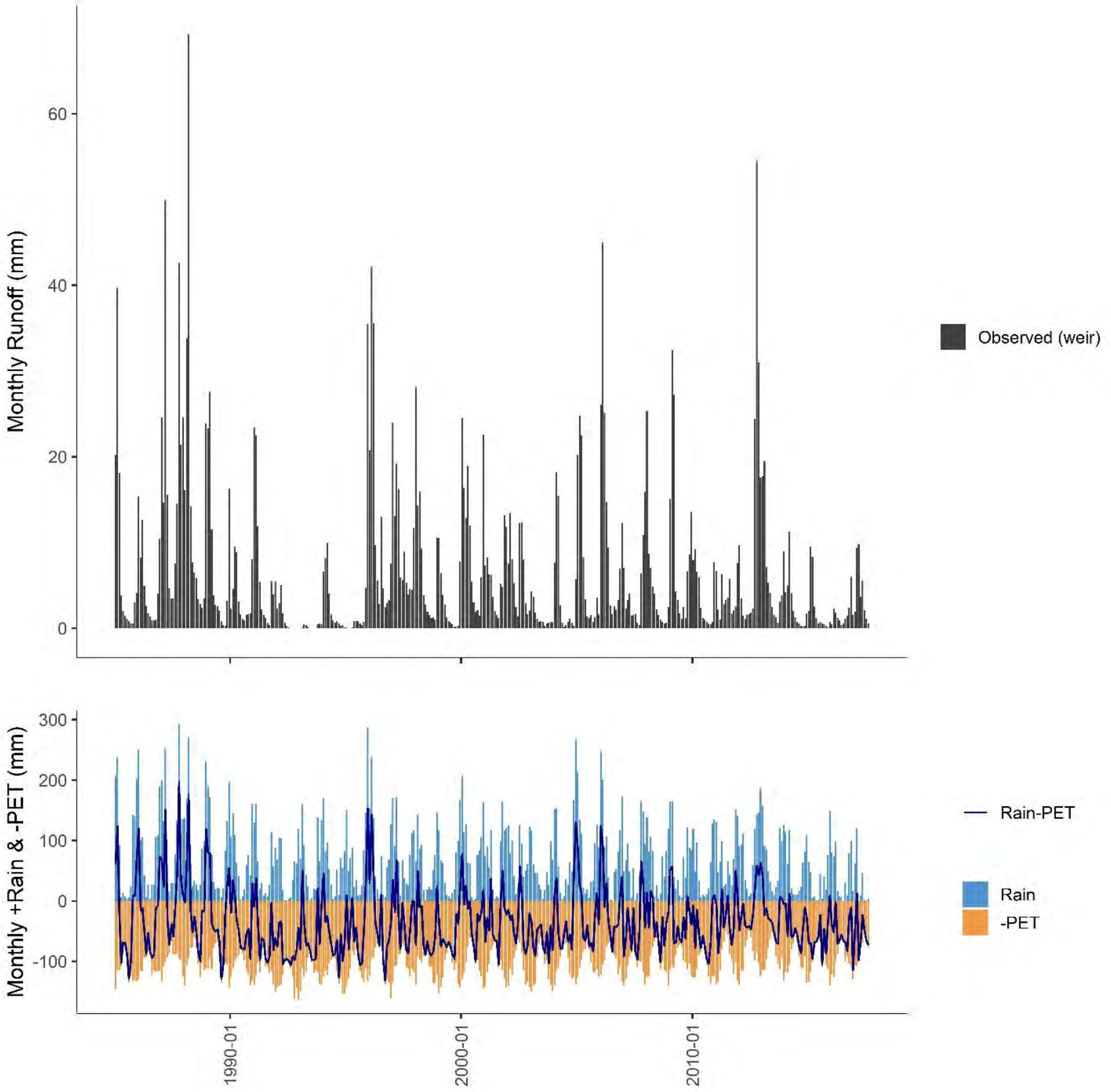


Figure 5.3: Monthly runoff for the Mistley catchment based on streamflow data from Weir U4H002 for January 1985 to August 2017, compared to the balance of estimated catchment-scale rainfall and evaporative demand, shown as rainfall – PET

5.3.2 Highlighted representation issue – riparian zone processes and land cover

All the tools included ways to specify riparian areas in a catchment and give them greater water availability for ET than uplands. However, the mechanisms assumed to drive this and the algorithms used differed. With the tools, riparian areas access ground water to meet ET demands not met by soil storage, but the conditions and limits of this varied. MIKE-SHE also routes surface flow across landscape units, which can increase water availability in riparian areas. For all tools except SPATSIM, particular land cover in the riparian zone could be specified. These differences had implications for modelling the impacts of clearing riparian plantations specifically, making it likely that predictions would differ.

WRSM-Pitman (Sami ground water)

WRSM allows the specification of a proportion of each “runoff module” (subcatchment) in which vegetation can access ground water for ET when ground water storage is over the threshold for outflow. Plantation areas can be represented with an afforestation submodule linked to the runoff module. The interaction between these modules meant that an appropriate approach for specifically including, and removing, afforestation in a riparian zone was not obvious. The afforestation submodule reduces the modelled runoff from the associated subcatchment as a whole, both upland and riparian. The reduction is a function of area afforested, species, age and growing conditions, based on empirically derived relationships. An alternative IAP submodule acts similarly, but allows for the explicit input of the proportion of the treed area that is riparian. Flow reductions increase with the proportion of riparian area based on empirical relationships. For this case study, it was decided to use the afforestation submodule to represent the non-riparian plantations and the IAP submodule, specifying mature trees and riparian proportion, to allow for the specification of riparian plantation.

SPATSIM-Pitman (Hughes ground water)

SPATSIM allows the specification of a proportion of each subcatchment in which the vegetation can access ground water. ET withdrawal is reduced with decreasing ground water storage down to a threshold for flow. Subcatchments can also have an input proportion, which is forested, and so given a higher potential ET rate than the remaining area. However, the fraction afforested applies equally to both the riparian and upland area in the model, similar to WRSM. Riparian afforestation was therefore accounted for with the input value for the ET demand increase for the afforested area. When afforestation included riparian areas, a larger ET demand increase was applied than when the afforestation was confined to uplands.

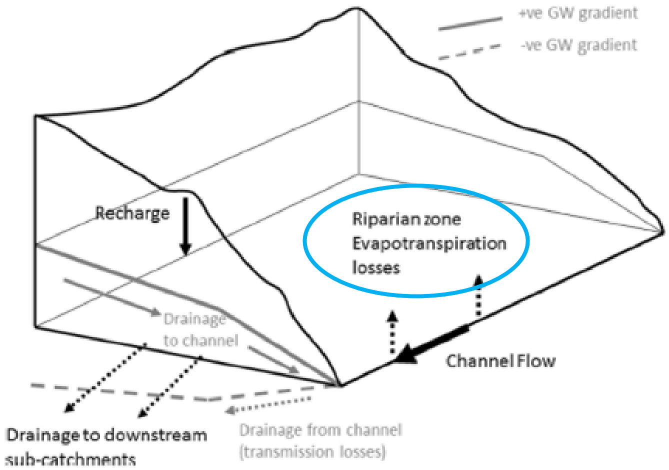


Figure 5.4: Conceptualisation of ground water flow at the subcatchment scale in SPATSIM-Pitman, highlighting riparian zone water access (Hughes, 2004)

ACRU4

ACRU4 includes a specific riparian zone HRU that can receive the “baseflow” outflows from linked upland HRUs within the same subcatchment. This water is added to the lower soil horizon of the riparian HRU and is available to its vegetation unless it percolates. This was used to represent the plantation area in the riparian zone separately from upland plantations. The vegetation cover in these riparian units was simply changed to represent the buffer clearing scenario.

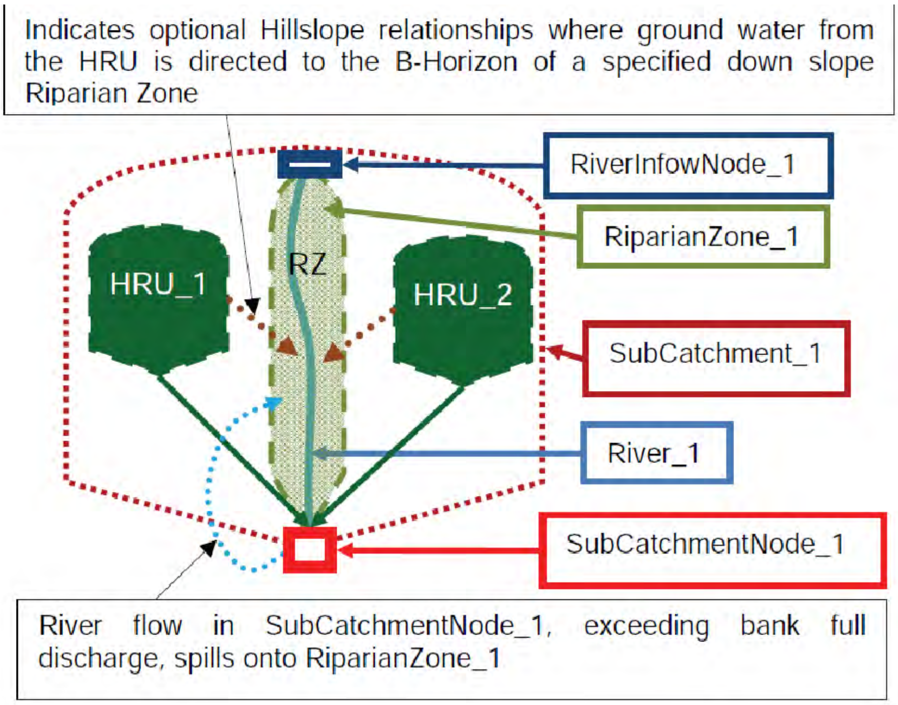


Figure 5.5: Conceptual linkage diagram of riparian zone representation in ACRU4 (Figure 3.3 in the ACRU4 User Manual)

ArcSWAT2012

ArcSWAT2012 models soil processes at the HRU scale with no surface or subsurface flow routing between HRUs. Surface flow and interflow are routed directly to the channel network and so cannot contribute to water availability in riparian areas. However, capillary rise from ground water to meet HRU ET demand can be modelled. The maximum relative contribution of capillary rise to ET is specified for each HRU. This allows riparian areas to be parameterised to have more access to ground water than others in the landscape. The ground water store is modelled at the subcatchment scale, and so recharge in an upland area can become available to a riparian HRU in the model. SWAT limits capillary rise to a maximum of 20% of the ET demand.

MIKE-SHEs (simpler algorithm options)

MIKE-SHEs allows user-delineated riparian areas to access a specified proportion of aquifer outflows to meet ET demand. Unlike SWAT, this is not limited to a proportion of the ET demand, but is limited by the predicted outflow of the aquifer (a function of aquifer storage). Ground water that is predicted to be stored in a time-step, rather than becoming potential outflow to the channel, is not available for this process. Aquifer units are modelled at the subcatchment scale, so recharge from other parts of the subcatchment could benefit riparian ET. In addition, unlike other tools, landscape routing of surface flows is modelled. This includes potential infiltration along the flow path, so it can serve to wet riparian zone soils and recharge aquifers in large events.

MIKE-SHEc (complex algorithm options)

MIKE-SHEc models surface and subsurface flows across a 3D grid so that low-lying riparian areas will have more soil moisture and/or shallower ground water in the model if this is driven by the input topography and specified surface and subsurface parameters. If additional soil moisture and/or a shallower ground water table is not predicted in the model in these areas when it exists in reality, this suggests incorrect inputs for one or more aspect of the model.

5.3.3 Modelling outcomes

Models of the Mistley catchment were built for both a current cover, “full forestry” (FF) scenario and a riparian and “wetland buffer” (WB) clearing and restoration scenario using all five modelling tools. Structures and parameterisations across the tools were guided by the structure and property parameters used in the pre-existing SWAT model of the catchment (Appendix C1). Calibration adjustments were made comparing modelled streamflow to weir-measured flow data (DWS weir, U4H002) for the 1989 to 2016 water years. Weir data was available from 1985 onwards, but comparison of the rainfall and flow datasets for large events in 1987 and early 1988 suggested that either one of the rainfall station records was in error and/or the weir capacity was exceeded in these events. It was beyond the project scope to resolve this, so the period was left out of the analysis. Models were run with a five-year warm-up period. Adjustments made to improve performance are described in Appendix C1. In several cases, calibration attempts produced performance trade-offs rather than net improvements. Calibration of the MIKE-SHE model using the tool’s complex and more distributed representation options was not completed in the time available, so this model is not presented.

Model predictions vs observations

Flow duration curves and hydrographs for the calibration period are shown in figure 5.6 to 5.9, with statistics given in Table 5.4. Performance varied across the models, with none fulfilling all acceptability criteria (section 5.2.3). All models underpredicted the mean flow, but were within 2–17% of the observed mean, not far from the target 15%. However, NSE and R^2 values were low, particularly NSE for daily predictions (-0.09–0.22). The models built with SWAT2012 and SPATSIM came close to the desired 0.6 NSE for monthly predicted flows with values of 0.59 and 0.56, respectively. The models built with SWAT2012, ACRU4 and WRSM had very different NSE values for untransformed flow compared to log-transformed flow, showing greater accuracy predicting higher versus lower flows (SWAT2012, WRSM) or the opposite (ACRU4). If being used in a decision-making context, further exploration of both the input data and model structures would be warranted.

Table 5.4: Statistics for observed and modelled streamflow at Mistley Weir, U4H002, Upper Mvoti River

Statistic	**Observed**	**WRSM**	**SPATSIM**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**
Monthly streamflow yield (mm^3/mon), October 1988 to September 2016						
Mean	1.84	1.62	1.54	1.55	1.80	1.58
difference vs observed		*-0.22*	*-0.30*	*-0.29*	*-0.04*	*-0.26*
percentage difference		*-12%*	*-17%*	*-16%*	*-2%*	*-14%*
Standard deviation	2.54	2.17	2.09	2.77	2.12	2.72
Coefficient of variance	1.38	1.33	1.36	1.79	1.18	1.72
Minimum	0.00	0.00	0.02	0.03	0.00	0.01
5th percentile	0.04	0.00	0.06	0.08	0.04	0.05
25th percentile	0.26	0.51	0.36	0.19	0.38	0.16
50th percentile	0.8	1.0	0.9	0.6	1.0	0.5
75th percentile	2.4	1.8	1.9	1.6	2.4	1.6
95th percentile	7.6	5.6	5.2	6.4	5.6	6.5
Maximum	17.3	16.6	16.0	19.2	13.0	17.7
RMSE		2.22	1.69	2.30	1.63	2.03
MAE		1.24	0.85	1.25	0.94	1.08
NSE		0.23	0.56	0.18	0.59	0.36
NSE log		-0.20	0.37	0.39	-0.02	0.41
R^2		0.32	0.58	0.40	0.59	0.50
Daily streamflow (cm), 1988-10-01 to 2016-09-30						
Mean	0.70			0.59	0.68	0.60
difference vs observed				*-0.11*	*-0.02*	*-0.10*
percentage difference				*-16%*	*-2%*	*-14%*
Standard deviation	1.28			1.28	1.02	1.22
Coefficient of variance	1.83			2.17	1.48	2.04
Minimum	0.00			0.01	0.00	0.00
5th percentile	0.01			0.03	0.00	0.01
25th percentile	0.10			0.07	0.10	0.06
50th percentile	0.25			0.18	0.35	0.17
75th percentile	0.76			0.55	0.87	0.53
95th percentile	2.82			2.38	2.45	2.82
Maximum	19.12			23.94	26.80	16.69
RMSE				1.33	1.13	1.23
MAE				0.53	0.48	0.51
NSE				-0.09	0.22	0.08
NSE log				0.37	-0.46	0.32
R^2				0.21	0.29	0.27

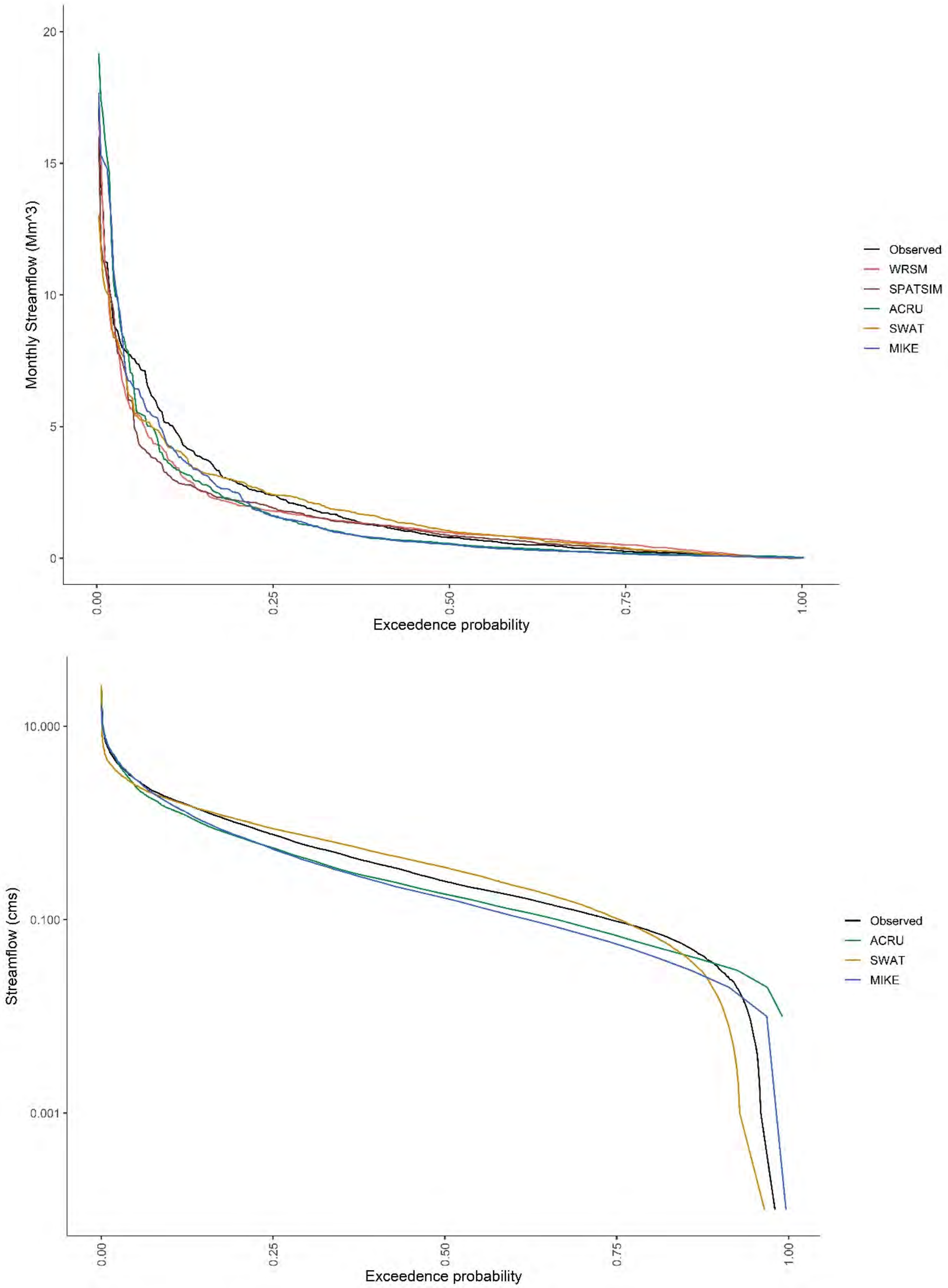


Figure 5.6: Observed and modelled monthly and daily flow duration curves at Mistley Weir, U4H002, Upper Mvoti River (Note: Daily streamflow displayed on a log axis, 0 cm, values shown as 0.00001 cm)

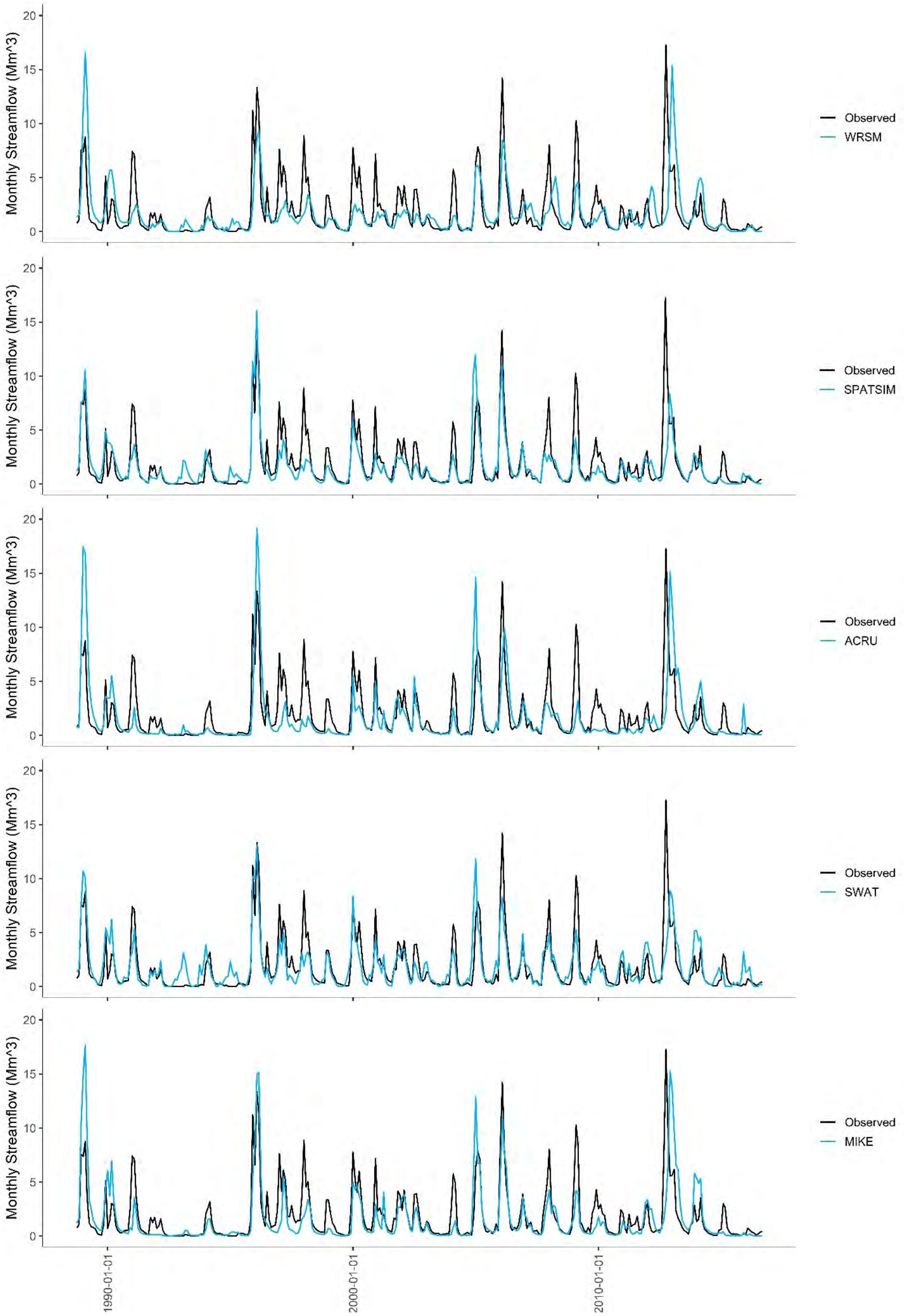


Figure 5.7: Observed and modelled monthly hydrographs at Mistley Weir, U4H002, Upper Mvoti River, October 1988 to September 2016, for models built in each of the five modelling tools

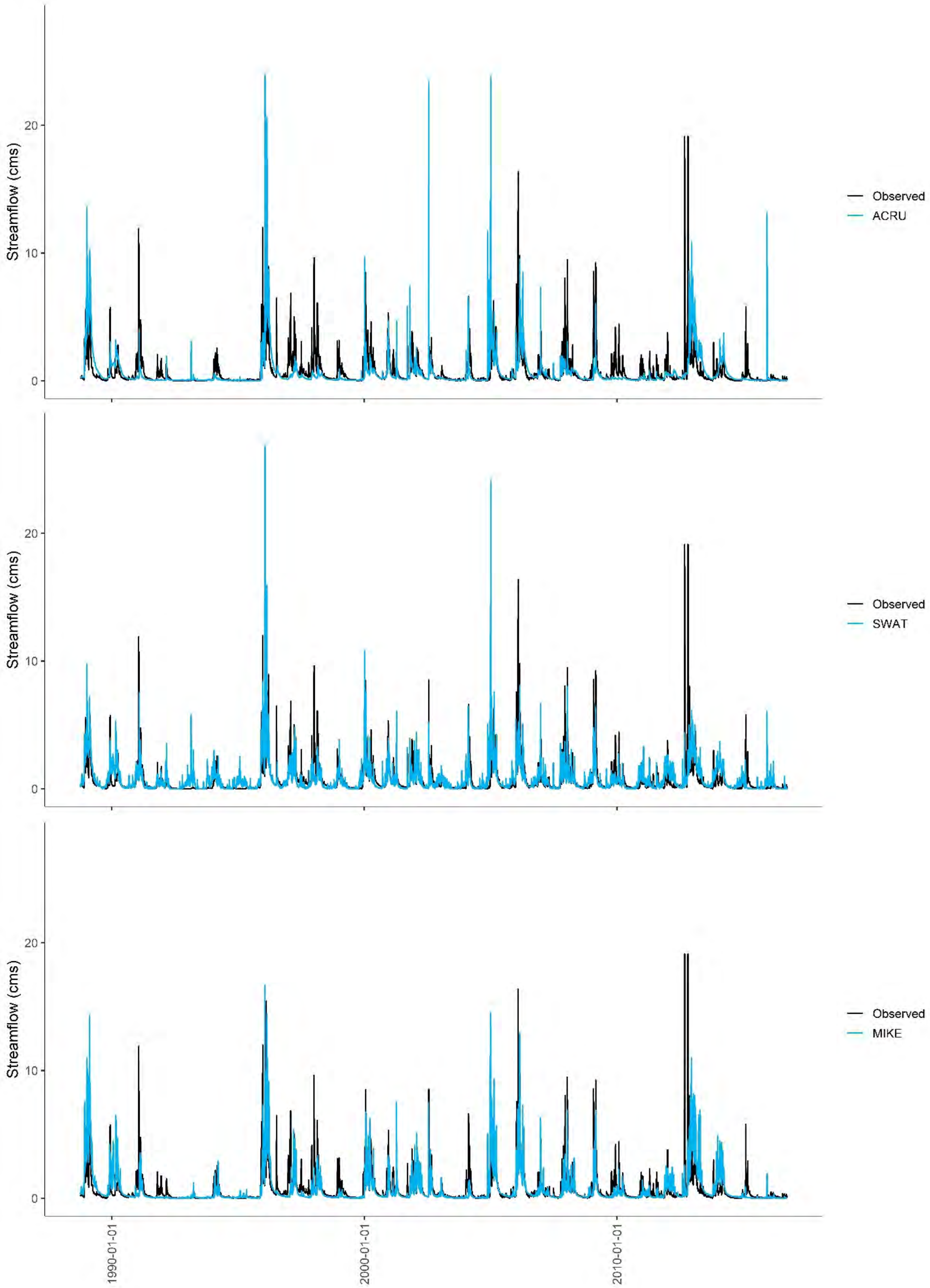


Figure 5.8: Observed and modelled daily hydrographs at Mistley Weir, U4H002, Upper Mvoti River, 1988-10-01 to 2016-09-30, for three daily timestep models

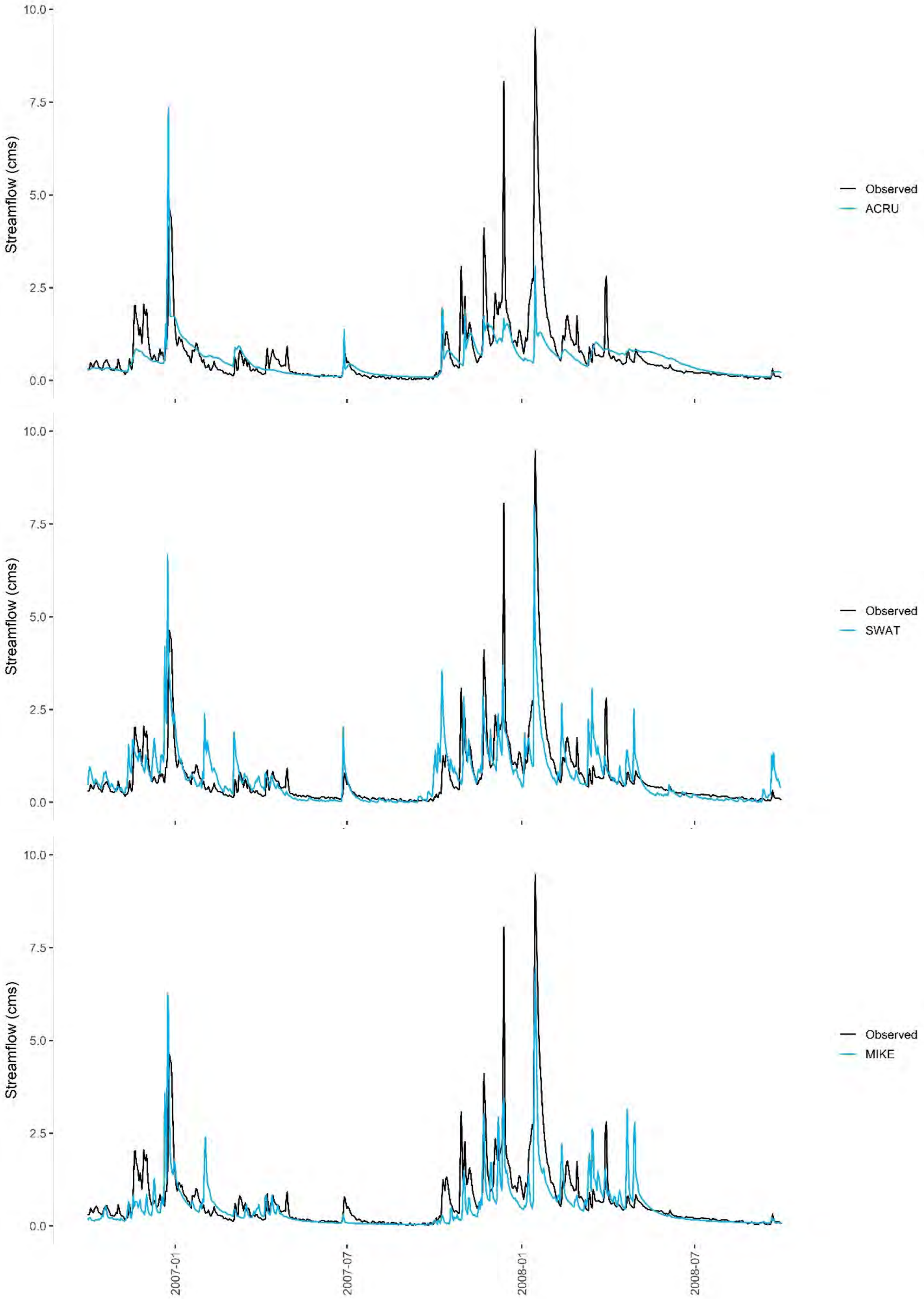


Figure 5.9: Observed and modelled daily hydrographs at Mistley Weir, U4H002, Upper Mvoti River, 2007–2008 two-year demonstration period, for three daily timestep models

The hydrographs and NSE values showed that the models differed in their patterns of inaccuracy, indicating differences in process representation. The observed hydrograph (Figure 5.3) shows the sensitivity of summer peak flows both to the balance of atmospheric ET demand in drier times, strongly decreasing proportional flow responses, and to building antecedent moisture over wetter periods, increasing proportional flow responses. The SWAT2012 model overestimated flow responses to rain events in drier times, while the MIKE-SHEs and ACRU4 models did this less. However, the MIKE-SHEs model more often underpredicted daily peaks in wet times. The ACRU4 model overpredicted peak responses to very large individual events and underpredicted peaks from rain events after prolonged wetness. Daily flow inaccuracies compensated for one another when aggregated monthly, improving month prediction. Of the monthly models, the SPATSIM model overpredicted small monthly peaks in dry periods more than the WRSM model, but had a better prediction of wet period peaks. WRSM underestimated most wet period peaks, with a few overestimates for high rainfall months, giving a reasonable mean.

Model fit statistics and flow distributions for the calibration period highlighted differences in prediction patterns and showed that each model had some representation advantages over others:

- The SWAT2012 model produced the most accurate mean flow for the period, 2% less than observed. Its flow timeseries also had the highest NSE and R^2 values of the set, both monthly (NSE 0.59, R^2 0.59) and daily (NSE 0.22, R^2 0.29). However, the NSE for log-transformed flows was negative: -0.02 monthly and -0.46 daily, showing poor performance for lower flows. The model overpredicted mid- and upper-mid range daily flow (median to 75th percentile), balanced by underpredicting both higher peaks (95th to 98th percentile) and low flows (10th percentile and below). It predicted a dry river for 7% of the period versus 4% observed. The monthly pattern of over- and underprediction was similar.
- The MIKE-SHEs model underpredicted the mean flow by 14%. It had a low daily flow NSE of 0.08, but better performance for log flow (NSE 0.32) and a similar R^2 to SWAT (0.27). While underpredicting the maximum, modelled 90th to 98th percentile flows were closer to the observed flows (within 10%) than the other daily models. Below this, mid-range flows were generally underpredicted, while the lowest flows (5th percentile and below) were overpredicted, modelling a dry river for 1% of the period versus 4% observed. The monthly pattern was similar. It had the most balanced NSE for untransformed versus log-transformed monthly flow, 0.36 and 0.41, and the highest monthly log flow NSE of the set.
- The ACRU4 model showed a more similar distribution of under- and overprediction to the MIKE than the SWAT2012 model: underprediction of mid-range, but overprediction of both the maximum and the lowest daily flows (5th percentile and below), never predicting a dry river. The result was a 16% underprediction of the mean and low daily NSE (-0.09) and R^2 (0.21) values. This pattern was preserved in monthly aggregation, and monthly flow NSE (0.18) was low. However, the daily log flow NSE (0.37) was the highest achieved, and the monthly log flow NSE (0.39) was the second highest of the set, showing that patterns in lower flow periods were better captured.
- The SPATSIM model generally overpredicted lower and underpredicted higher flows, resulting in a model mean 17% lower than observed. However, it had the closest median flow to the observed (within 8%) and second-highest monthly NSE (0.56) and R^2 (0.58), indicating a replication of the pattern. The monthly log flow NSE (0.37) was not as far below the untransformed flow NSE as the other models.
- The WRSM model had the second-most accurate predicted mean flow for the calibration period, 12% lower than the observed flow. However, it had the second-lowest monthly NSE (0.23) and lowest monthly log flow NSE (-0.2) in the set. It overestimated the median to the 10th percentile monthly flow, but underpredicted higher and lower flows than this, predicting more dry river conditions than observed.

Water balance comparison for current cover scenario models

The five models of the Mistley catchment predicted similar runoff ratios, 7–8%, for the period assessed. However, the modelled streamflow source composition differed substantially. Modelled annual average water balances for 1988–2016 under the full forestry cover scenario are presented in Table 5.9. Not all listed fluxes are output by all tools, and some classification of outputs into these categories is not equivalent (section 4.7.5). However, these are the outputs a user would have if interested in these fluxes.

- Interflow was the dominant runoff source in the SWAT, SPATSIM and WRSM models. It dominated strongly in the SWAT2012 model, accounting for 82% of runoff compared to 55% in WRSM, and 44% in SPATSIM. Interflow was also a sizeable contributor (31–32%) in the MIKE-SHEs and ACRU4 models.
- Aquifer outflow was the dominant average contributor in the MIKE-SHEs and ACRU4 models, accounting for 68% and 55% of runoff, respectively. Ground water was also a sizeable contributor in the WRSM (31%) and SPATSIM (19%) models, contributing much less in the SWAT2012 model (8%).
- Surface runoff was the smallest contributor in the MIKE-SHEs, ACRU4 and WRSM models, and was in the middle for SPATSIM and SWAT2012. Contributions ranged from 0.4% in the MIKE-SHEs model to 36% in SPATSIM. It had a similar, small contribution, 10–14%, in the SWAT2012, ACRU and WRSM models.

The differences in flow path contributions appear to correspond to the models' differing output hydrographs (despite reasonably similar predictions of mean flow). No two had very similar runoff source distributions. However, the SWAT and SPATSIM models shared the same rank order of sources: interflow > surface runoff > aquifer outflow. While the flux outputs are not equivalent across tools, they broadly represent flow paths of different speeds. The SWAT2012 and SPATSIM models had the highest NSE (0.59 and 0.56) and R^2 (0.59 and 0.58) values for monthly flow prediction, but both overpredicted flow peak responses in drier periods. The MIKE-SHEs and ACRU4 models shared a source ranking, aquifer outflow > interflow > surface runoff, and had the highest NSE values for log-transformed flows (0.32 and 0.37 daily, 0.41 and 0.39 monthly), reflecting better representation of the lower flows.

Models predicting the highest runoff were not always those predicting the lowest ET in the set, primarily due to differences in modelled soil and ground water storage change. The assessment period was preceded by notably wet years, 1986–1987, and ended with notably dry years, 2015–2016 (Figure 5.3). This resulted in a modelled net decrease in soil and ground water storage over the period, feeding ET and streamflow. Averaged over the period, this equated to 4 to 16 mm per year, 1–2% of the period's rainfall. The WRSM and SWAT2012 models predicted the largest drop in stored water, supporting higher AET and runoff.

Modelled mean annual total AET was very similar across the SPATSIM, ACRU4, SWAT2012 and MIKE-SHE models (765–766 mm) and slightly higher in WRSM (774 mm). Relative contributions of different fluxes to total AET differed across models, but to a much lesser degree than for runoff sources:

- Canopy interception accounted for 21–29% of total AET in models that output this. The ACRU4 model predicted the least, 164 mm (21%) versus 216–221 mm (28–29%) in SPATSIM and MIKE-SHE.
- Of the models with this output, the contribution of ground water to AET in the SPATSIM and MIKE-SHEs models was similar (10–11 mm, 1% of AET), while it was much greater in SWAT2012 (88 mm, 12%).
- Evaporation from farm dams contributed less than 1% (0.2–0.8%) to the total AET across all models. Modelled evaporation was much less in the SPATSIM, ACRU4 and MIKE-SHEs models than in WRSM and SWAT, which predicted twice and three times that of the others, respectively.
- Representation of the Mvoti vlei wetland differed substantially across the models (Appendix C1), but modelled AET was similar, 2% of total AET, for all but the SWAT2012 model, which predicted half as much.

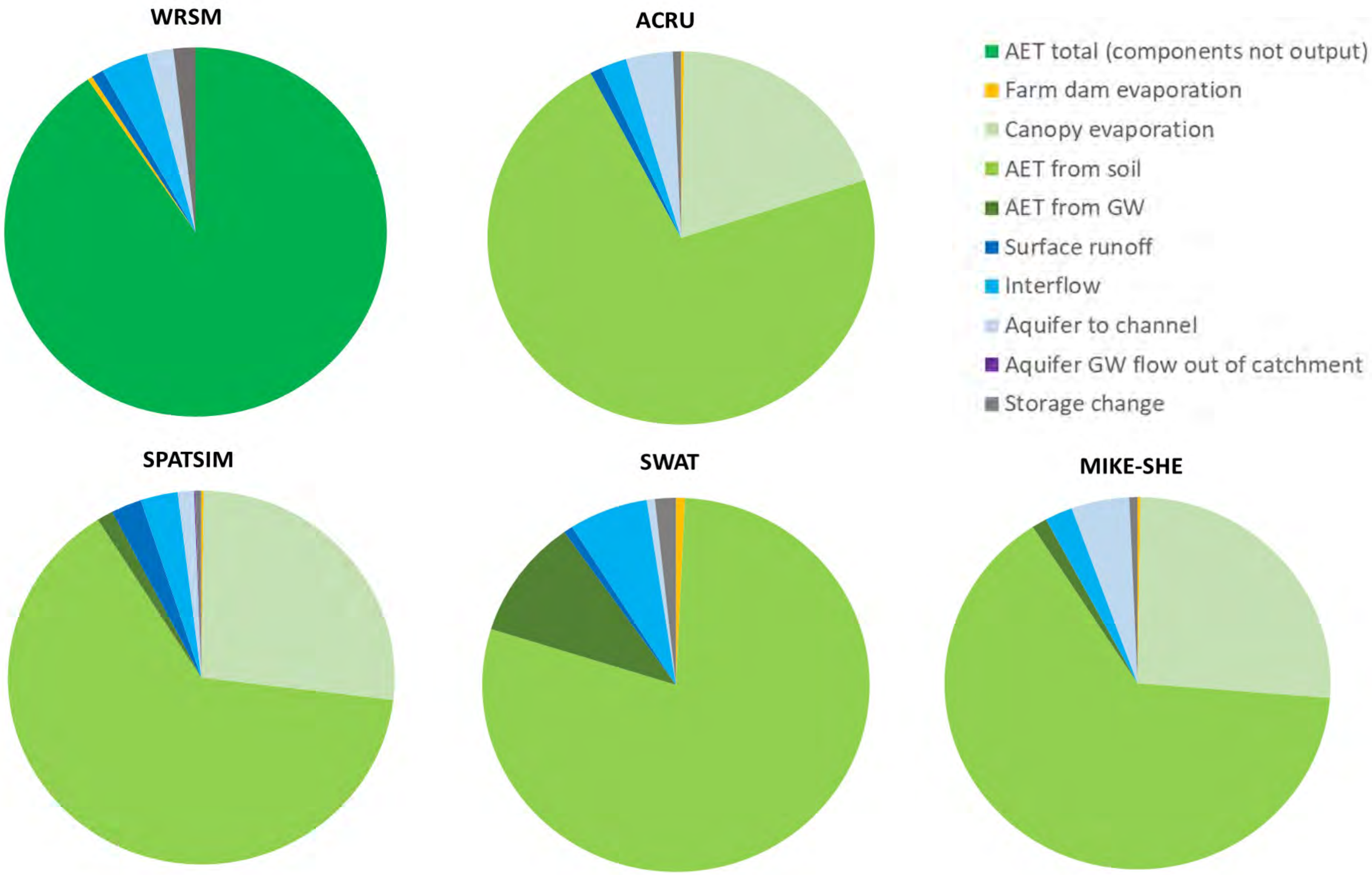


Figure 5.10: Modelled mean annual water balances for the Mistley catchment for 1988-10-01 to 2016-09-30, predicted using five different modelling tools shown as proportions of catchment mean annual precipitation (Note: Not all fluxes are modelled or output by all tools)

Table 5.5: Modelled mean annual water balances for the Mistley catchment for 1986-10-01 to 2016-09-30, predicted using five different modelling tools

(All fluxes given in mm over full catchment area)

Mean annual flux	WRSM			SPATSIM			ACRU4			SWAT2012			MIKE-SHEs		
	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*
Precipitation	819			819			819			819			819		
AET total	**774**	***94%***		**765**	***93%***		**766**	***94%***		**766**	***93%***		**765**	***93%***	
Farm dam evaporation	4	*0.4%*	*0.5%*	2	*0.2%*	*0.2%*	2	*0.3%*	*0.3%*	6	*1%*	*1%*	2	*0.2%*	*0.3%*
Canopy evaporation				221	*27%*	*29%*	164	*20%*	*21%*				216	*26%*	*28%*
AET from soil*				530	*65%*	*69%*	601	*73%*	*78%*	671*	*82%*	*88%*	537	*65%*	*70%*
AET from GW*				11	*1%*	*1%*				88	*11%*	*12%*	10	*1%*	*1%*
(Mvoti vlei AET, subset)*	*(16)*	*(2%)*	*(2%)*				*(17)*	*(2%)*	*(2%)*	*(7)*	*(1%)*	*(1%)*	*(13)*	*(2%)*	*(2%)*
Runoff total	**62**	***8%***		**58**	***7%***		**59**	***7%***		**68**	***8%***		**60**	***7%***	
Surface runoff[#]	9	*1%*	*14%*	21	*3%*	*36%*	8	*1%*	*14%*	7	*1%*	*10%*	0.2	*0.03%*	*0.4%*
Interflow[#]	34	*4%*	*55%*	26	*3%*	*44%*	18	*2%*	*31%*	56	*7%*	*82%*	19	*2%*	*32%*
Aquifer to channel[#]	19	*2%*	*31%*	11	*1%*	*19%*	33	*4%*	*55%*	6	*1%*	*8%*	40	*5%*	*68%*
Aquifer GW flow out of catchment	0	*0%*		1	*0.1%*		0	*0%*		0	*0%*		0	*0%*	
Net storage change (soil and GW)	-16	*-2%*		-4	*-1%*		-6	*-1%*		-15	*-2%*		-6	*-1%*	

AET = Actual evapotranspiration; GW = Ground water; Canopy evaporation = Canopy interception evaporation
MIKE-SHEs = MIKE-SHE using simpler, more lumped algorithm options
Note: Missing water balance components indicate that the tool does not save outputs of these components separately, although it may explicitly calculate the flux.

**Modelling tools differ in what is considered ET from soil vs GW and the outputs that can be exported. "AET from soil" includes water on the soil surface, and in the SWAT model, canopy interception is implicitly included in the value presented as "AET from soil" here.*
(*Mvoti vlei wetland AET includes components of the total values presented for canopy interception, AET from soil/surface and AET from GW – tools differ in wetland representation).*

[#] *The interpretation of runoff source subdivisions differs somewhat across tools.*

Model predictions of change across scenarios

Comparing modelled streamflow for the restored wetland and buffer scenario (WB), in which 37 km^2 (18% of the catchment) is cleared of commercial forestry plantation, to that for the FF scenario, all five models predicted an increase in flow, but magnitudes and patterns of change varied widely (Table 5.6 and figures 5.11 and 5.12). Predicted increases in the 1988–2016 mean flow ranged from 4% using the SWAT2012 model up to 40% using the ACRU4 model:

- The SWAT2012 model stood out in predicting a much smaller change, a 0.85 mm^3 or 4% increase, compared to 22–40% with the other models. The model predicted similar, small proportional changes (3–5%) across the daily hydrograph, with slightly larger increases for higher flow months.
- The SPATSIM and WRSM models predicted similar 4.36–4.45 mm^3 or 22–24% increases, despite having very different approaches to modelling water use by forestry. Their patterns of predicted change differed, with SPATSIM predicting a larger proportional increase for low flows, hence relatively similar magnitude increases across high and low flows, while WRSM predicted more similar proportional increases across high and lows flows, hence greater magnitude increases for high flows.
- The MIKE-SHEs model predicted a 6.5 mm^3 or 34% increase in average flow, with relatively similar proportional increases across high and lows flows, meaning greater magnitude increases for the high flows, a similar pattern to the WRSM model.
- The ACRU4 model predicted the largest increase in average flow, 7.4 mm^3 or 34% increase in average flow. As with the SPATSIM model, it predicted larger proportional flow increases for lower flows, but to a lesser degree than the SPATSIM model, so that predicted magnitudes of increase were higher for higher flows.

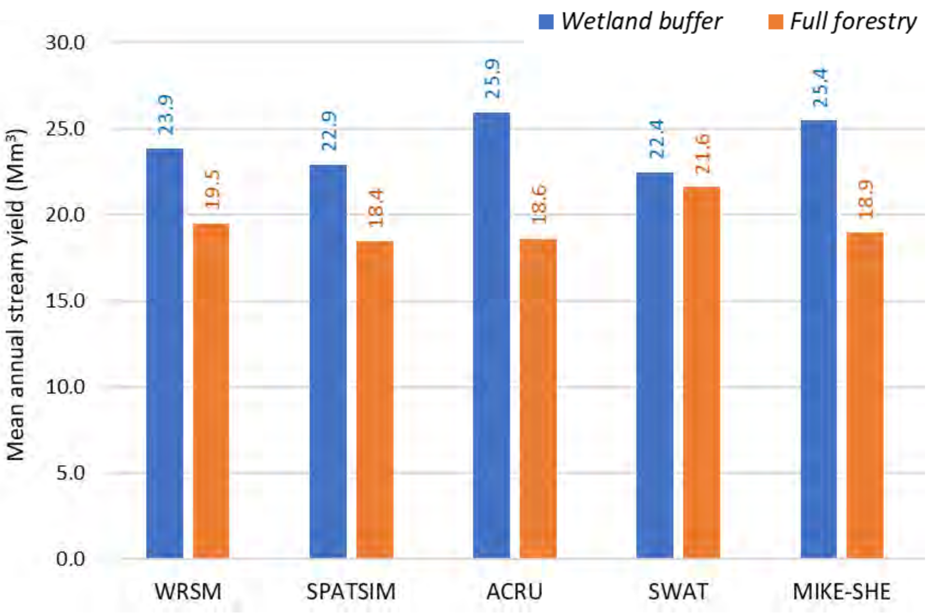


Figure 5.11: Modelled mean annual streamflow yield for the Mistley catchment for 1988–2016 under the full forestry and wetland and buffer restoration scenarios, as predicted by five different models

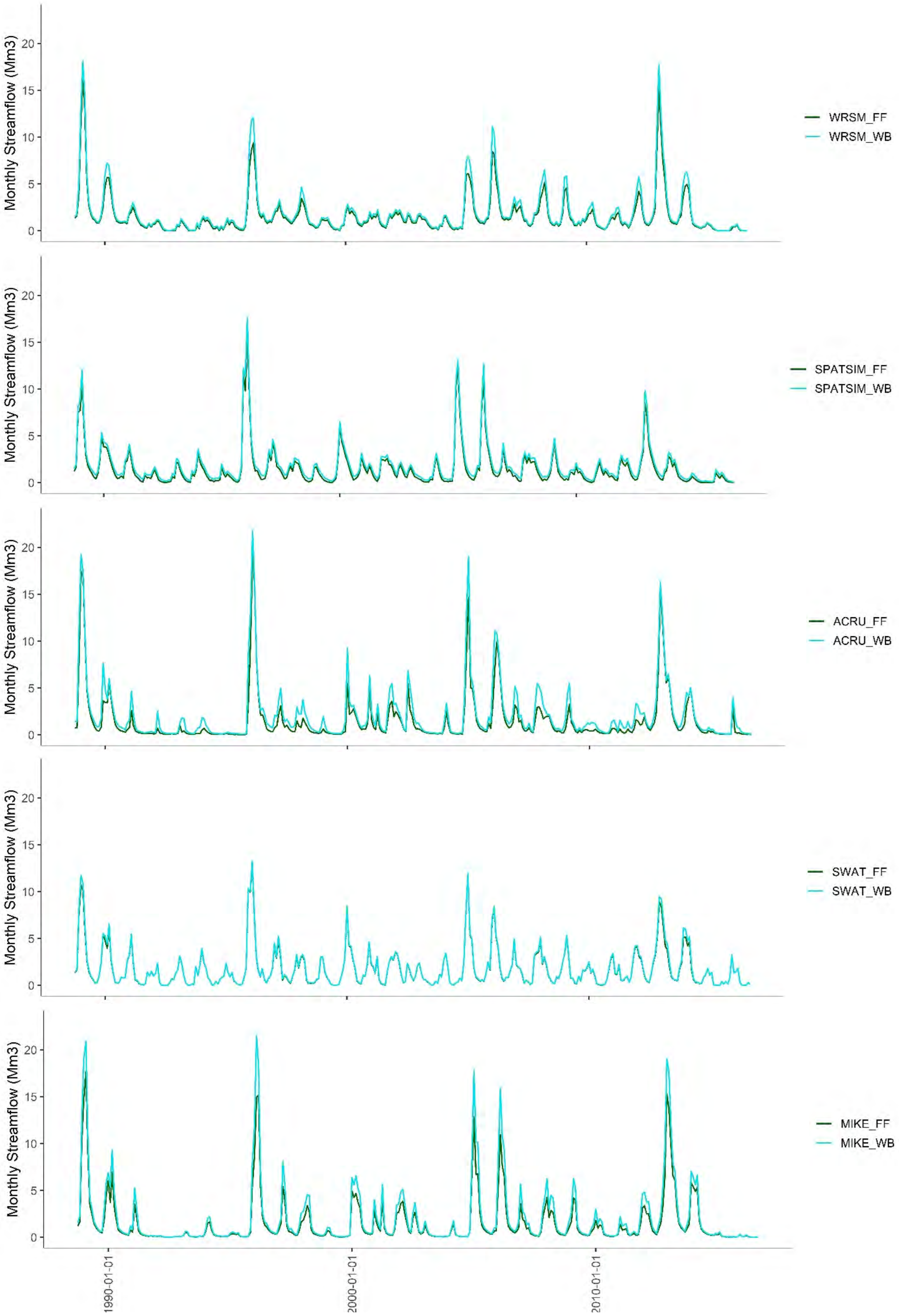


Figure 5.12: Modelled monthly hydrographs for Mistley weir, Upper Mvoti River, October 1988 to September 2016 for models built in each of the five modelling tools for two land cover scenarios: full forestry, and wetland and buffer restoration

Table 5.6: Model predicted changes in streamflow for the Mistley catchment with clearing timber plantations from riparian wetlands and buffer zones compared to the full forestry scenario using five different modelling tools

Statistic	**Absolute and relative CHANGE in modelled streamflow, October 1988 to September 2016, wetland and buffer restored – full forestry scenario**									
	WRSM		**SPATSIM**		**ACRU4**		**SWAT2012**		**MIKE-SHEc**	
Annual stream yield (mm^3)										
Change in:										
Mean	4.36	22%	4.45	24%	7.37	40%	0.85	4%	6.52	34%
Standard deviation	2.89	19%	1.34	10%	2.64	13%	0.77	6%	5.44	28%
Minimum	0.64	38%	2.45	107%	0.88	104%	0.09	1%	0.09	9%
Maximum	8.97	15%	8.22	14%	14.36	21%	0.94	2%	17.99	26%
Monthly streamflow (mm^3)										
Change in:										
Mean	0.36	22%	0.37	24%	0.61	40%	0.07	4%	0.54	34%
Standard deviation	0.44	20%	0.17	8%	0.43	15%	0.09	4%	0.84	31%
Minimum	0.00		0.06	287%	0.05	200%	0.00		0.00	39%
5th percentile	0.06		0.16	261%	0.05	67%	0.01	15%	0.01	19%
50th percentile	0.18	18%	0.38	44%	0.50	90%	0.04	4%	0.12	23%
95th percentile	1.44	26%	0.48	9%	2.45	38%	0.64	11%	2.71	42%
Maximum	1.52	9%	1.62	10%	2.56	13%	0.19	1%	3.85	22%
Daily streamflow (cm)										
Change in:										
Mean					0.23	40%	0.03	4%	0.21	34%
Standard deviation					0.18	14%	0.03	3%	0.43	35%
Minimum					0.02	200%	0.00		0.00	
5th percentile					0.02	67%	0.00		0.01	100%
50th percentile					0.19	106%	0.01	3%	0.04	24%
95th percentile					0.75	32%	0.12	5%	1.04	37%
Maximum					3.95	16%	0.14	1%	5.30	32%

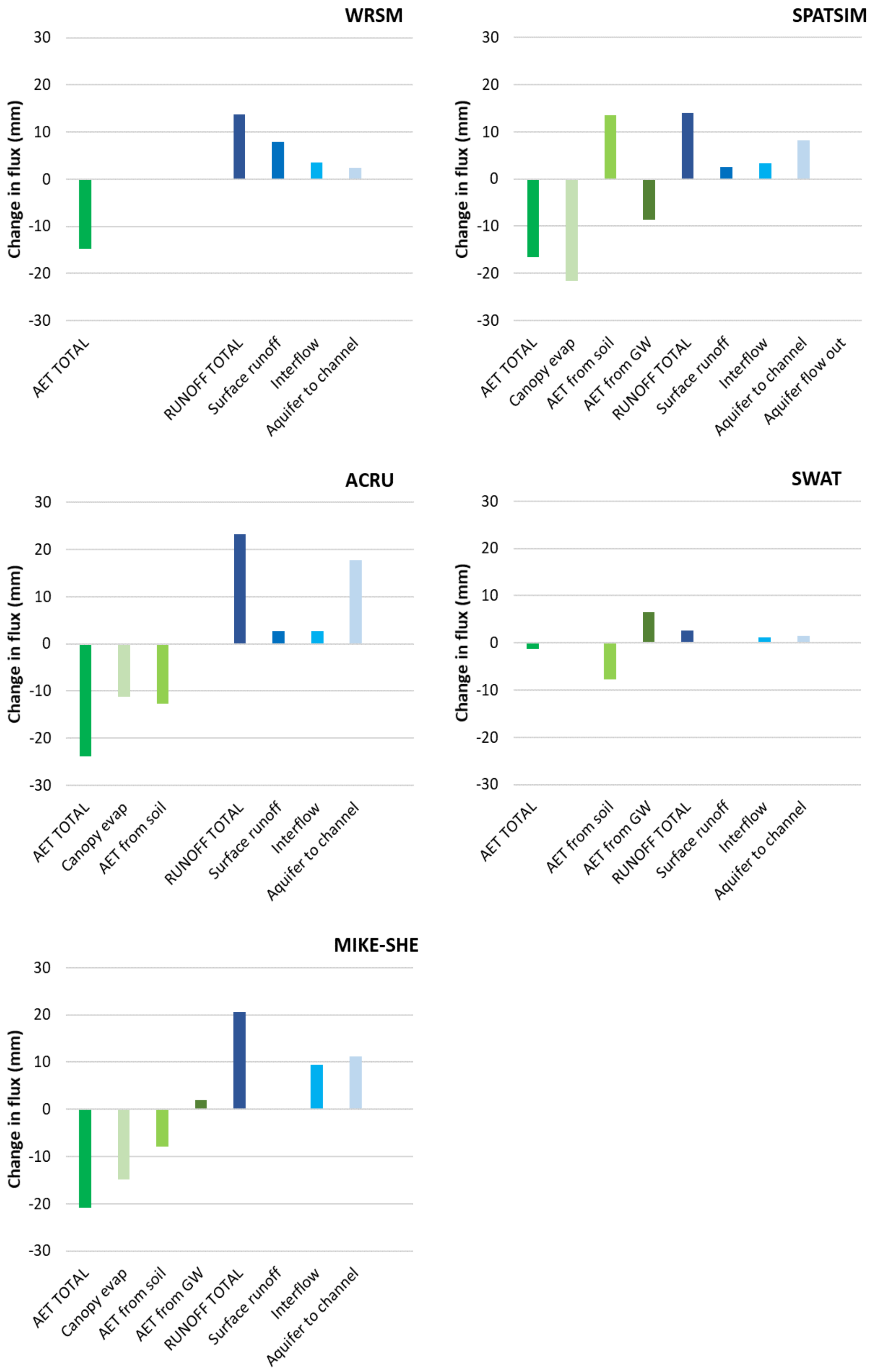


Figure 5.13: Predicted change in mean annual water balance fluxes for the Mistley catchment with clearance of forestry plantations from riparian wetlands and buffer zones, estimated using five different modelling tools (Note: not all fluxes are modelled or output by all tools)

Table 5.7: Predicted change in mean annual water balance fluxes for the Mistley catchment with clearance and restoration of plantations in riparian wetlands and buffer zones, estimated using five different modelling tools

Flux	**Absolute and relative CHANGE in modelled mean annual water balance components, October 1988 to September 2016, wetland and buffer restored – full forestry scenario** *(All fluxes given in mm over full catchment area)*														
	WRSM			**SPATSIM**			**ACRU4**			**SWAT2012**			**MIKE-SHEs**		
	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*
AET total	**-15**	***-2%***		**-17**	***-2%***		**-24**	***-3%***		**-1**	***-0.2%***		**-21**	***-3%***	
Farm dam evaporation	0.01	*0.3%*	*-0.08%*	0.05	3%	*-0.3%*	0.0	*0.0%*	*0.0%*	0.0	*0.0%*	*0.0%*	0.03	*1.5%*	*-0.14%*
Canopy evaporation				-22	*-10%*	*130%*	-11	*-7%*	*47%*				-15	*-7%*	*71%*
AET from soil*				13	*3%*	*-81%*	-13	*-2%*	*53%*	-8	*-1.1%*	*595%*	-8	*-1%*	*38%*
AET from GW*				-9	*-76%*	*52%*				6	*7%*	*-495%*	2	*18%*	*-9%*
(Mvoti vlei AET, subset)*	*(0.06)*	*(0.4%)*	*(-0.41%)*				*(9)*	*(56%)*	*(-40%)*	*(0.03)*	*(0.4%)*	*(-2%)*	*(0.08)*	*(0.6%)*	*(-0.4%)*
Runoff total	**14**	***22%***		**14**	***24%***		**23**	***40%***		**3**	***4%***		**21**	***34%***	
Surface runoff$^{\#}$	8	*90%*	*58%*	3	*12%*	*18%*	3	*33%*	*12%*	0.06	*0.9%*	*2%*	0.01	*6%*	*0.1%*
Interflow$^{\#}$	3	*10%*	*25%*	3	*13%*	*23%*	3	*15.4%*	*12%*	1	*1.9%*	*41%*	9	*49%*	*45%*
Aquifer to channel$^{\#}$	2	*12%*	*17%*	8	*73%*	*59%*	18	*55%*	*76%*	2	*27%*	*57%*	11	*28%*	*55%*
Aquifer GW flow out of catchment				0.1	*0.7%*										
Storage change	-0.9	*-6%*		-3	*-61%*		-0.6	*-10%*		1.4	*9%*		-0.3	*-4%*	

AET = Actual ET; GW =Ground water; Canopy evaporation = Canopy interception evaporation;, MIKE-SHEs = MIKE-SHE using simpler, more lumped algorithm options

Note: Missing water balance components indicate that the tool does not save outputs of these components separately, although it may explicitly calculate the flux.

**Modelling tools differ in what is considered ET from soil vs GW and the outputs that can be exported. "AET from soil" includes water on the soil surface, and in the SWAT model, canopy interception is implicitly included in the value presented as "AET from soil" here.*

(Mvoti vlei wetland AET includes components of the total values presented for canopy interception, AET from soil/surface, AET from GW – tools differ in wetland representation.)

$^{\#}$ *The interpretation of runoff source subdivisions differs somewhat across tools.*

Models predicted increased streamflow with wetland restoration because of the parameterisation of the vegetation types. Wetlands were given lower potential ET rates and rooting than the eucalyptus that were removed, so modelled catchment average AET decreased. However, although an effort was made to use equivalent parameterisation across the models where possible (Appendix C1), differences in structure and process representation resulted in differing predicted magnitudes of net AET change and balances of changes in contributing processes (Figure 5.13 and Table 5.7).

- Canopy interception had a similar relative decrease across the SPATSIM, ACRU4 and MIKE-SHEs models: 7–10% decrease in mean. However, this accounted for notably different proportions of the overall decrease in total AET, due to the modelled responses of other fluxes.
  - In the SPATSIM and MIKE-SHEs models, the interception decrease was the dominant contributor to the decrease in total AET. In the MIKE-SHEs model, it accounted for 71%. In the SPATSIM model, decreased interception was coupled with increased ET from soil, and the change in interception represented 130% of the net AET decrease predicted.
  - In the ACRU4 model, interception did not dominate, accounting for 43% of the AET change.
- Predicted change in vegetation transpiration from soil and ground water storages and soil evaporation varied across models. Average annual ET drawn from model soil and ground water storages was predicted to decrease by 0.2% (1.3 mm) in the SWAT model; 1% (6 mm) in the MIKE-SHEs model; and 2% (13 mm) in the ACRU model. By contrast, the SPATSIM model predicted a net increase in transpiration and soil moisture evaporation by 1% (5 mm).
  - Both the SWAT2012 and MIKE-SHEs models, predicted an increase in average ET drawn from model ground water stores, reducing the net decrease in total AET. This was more significant in the SWAT2012 model, in which it all but counteracted the decrease in ET from the surface and soil (canopy interception not explicit), resulting in minimal net change in total AET. The increase in ET from ground water was due to greater ground water availability, rather than any increase in root depth or ET demand. The wetland's lower interception and ET rate increased ground water recharge during wet periods. The added ground water in the wetland scenario supported ET in drier times, increasing annual average ET and partially compensating for the lower ET rate of the wetland. In the full forestry scenario, lower ground water water availability in dry periods curtailed ET in these models.
  - In the SPATSIM model, the opposite pattern was predicted with wetland restoration: an increase in ET from the soil store with a decrease in ET drawn from ground water. This reflects differences in storage and movement between the soil and ground water compared to the SWAT2012 and MIKE-SHE models. Decreased canopy interception increased soil moisture storage, which supported transpiration into drier periods as ground water did in the other models. Increased water access over time compensated for the decreased ET rate without the eucalyptus to the degree that there was a net increase in average transpiration from soil, and in total. Greater soil water storage meant there was less need to draw on ground water stores to meet ET demand than with full forestry. In the full forestry scenario, ET from ground water compensated for lower soil moisture, but this was restricted to the riparian zone and limited by the amount of ground water available, which was lower in this scenario.
  - The WRSM and ACRU4 models represent ET drawn from ground water. However, the tools do not output the amount of this directly (see section 4.7.5).

The net change in catchment-scale AET was not only due to changes at the location of land cover change. As seen in Table 5.7, ET for the downstream Mvoti vlei wetland, and in some cases evaporation from small farm dams, was predicted to increase given greater water availability without the plantations.

5.4 CASE STUDY OVERVIEW: UPPER BERG RIVER CATCHMENT (PORTION OF G10A) WESTERN CAPE – STEEP ROCKY CATCHMENT, INVASIVE ALIEN VEGETATION

5.4.1 Catchment description and modelling goals

Table 5.8: Upper Berg River catchment and modelling overview

Catchment property	Description	Implication
Scale	73.25 km^2	
	Less than one quaternary (G10A), catchment of the Berg River Dam	
Climate	MAP 2 550 mm (wet)	
	Winter rainfall	
	Spatial rainfall gradient: Estimated MAP ranges from 3 100 mm in the southwestern peaks to 2 300 mm downstream.	Despite the relatively small catchment area, different sublocations have different water access, influencing processes.
Runoff ratio	63% (high)	
Topography	Steep, rocky	Surface runoff likely to be significant.
	mean slope: 65%	
Soils and geology	Mostly thin sandy soils over fractured rock layers of Table Mountain Group (TMG) quartzite, grading to slightly deeper and more loamy soils in the toe slopes. TMG rock is more fractured, and has more open fractures near the surface.	Interflow through more highly fractured shallow rock layers and/or tallus. Deep, regional fractured rock aquifer's contribution is thought to be small. Potential deep ground water flow out of the catchment.
Vegetation	Dominated by fynbos vegetation.	
	8% of the catchment area covered with invasive pines, all located in uplands.	
Modelling		
Previous modelling	MIKE-SHE, complex options version calibrated, for SEBEI project (http://www.acdi.uct.ac.za/socio-economic-benefits-ecological-infrastructure-sebei#Outputs)	Input database and conceptual model reference point
Modelling goals / scenarios	Estimate the hydrological impact of clearing the pines (replacing with fynbos).	Higher potential ET rates of pines vs fynbos needs representation in models.
	Estimate the difference in impact of the pines if they were located in riparian areas rather than the uplands.	Greater subsurface water access for vegetation in low-lying areas vs uplands needs representation in models.
Climate data	SAWS, Agricultural Research Council (ARC), SAEON rain gauge and weather station daily rain and ET demand: 2004-01-01 to 2018-12-31 (15 years)	**Model runs:** 2004-01-01 to 2018-12-31 **Output comparison (excluding warm-up):** 2006-10-01 to 2018-09-30 (12 years)
Streamflow data	DWS Weir (G1H076), daily streamflow: 2008-03-15 to 2018-08-15 (10.4 years)	**Calibration**: 2008-03-15 to 2018-08-15 (daily); 2008-04 to 2018-07 (monthly)

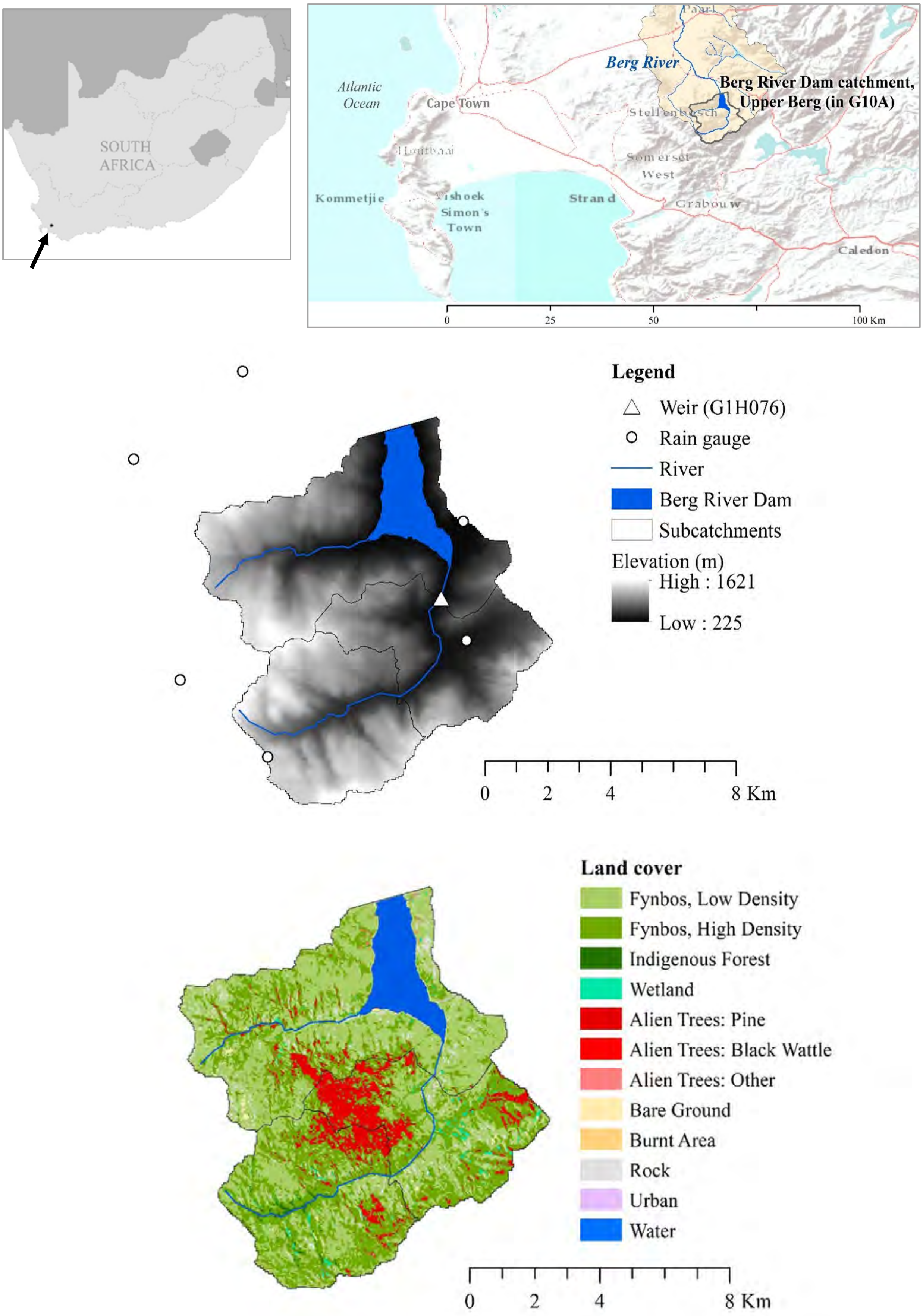


Figure 5.14: Location of the Upper Berg River case study catchment (top), subcatchments and monitoring points (middle), and land cover distribution mapped for the baseline/current cover scenario (bottom)

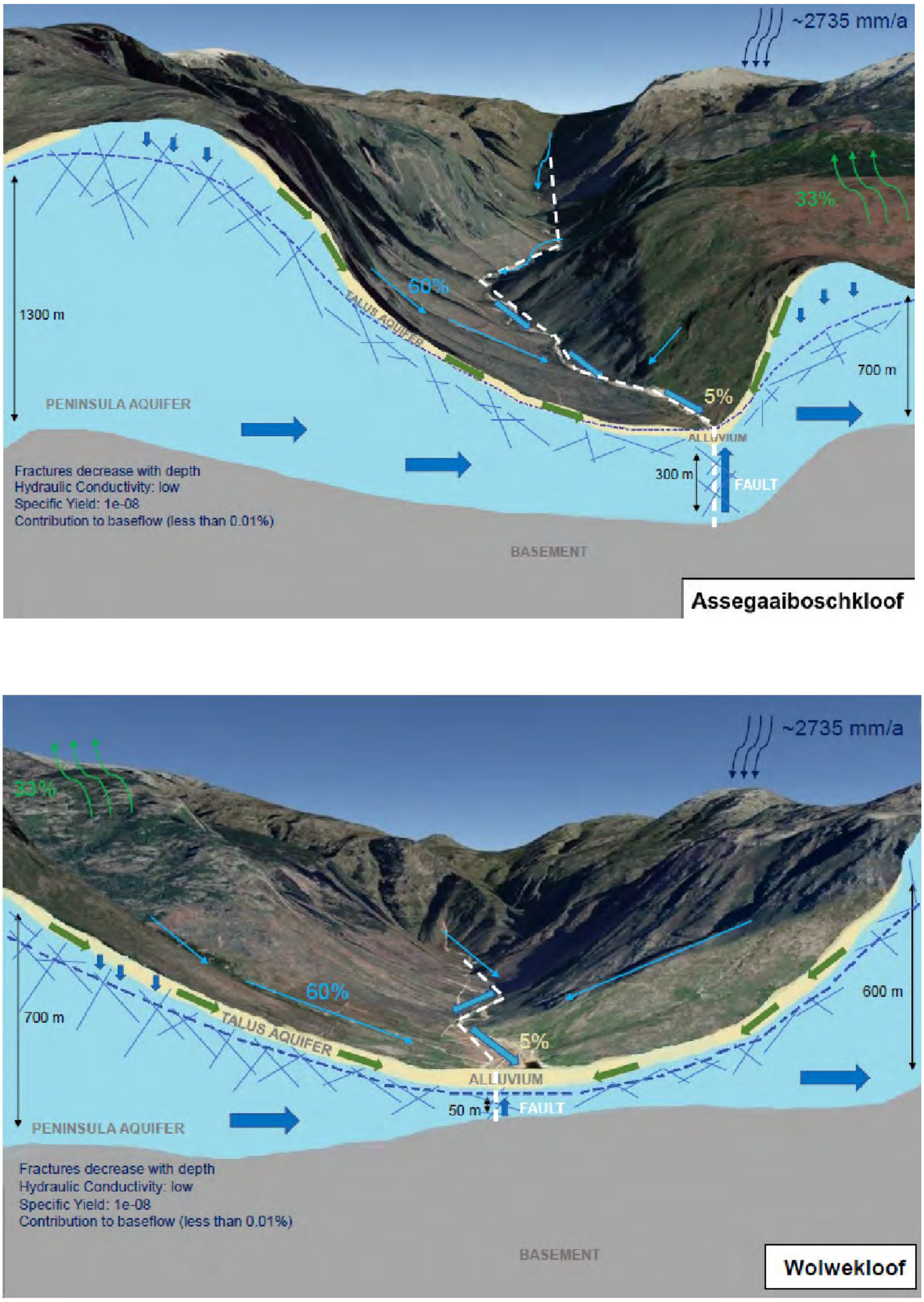


Figure 5.15: Conceptual models of surface and subsurface flows shown in cross-sections for the two main tributaries in the Upper Berg, as developed in the MIKE-SHE modelling process (Rebelo and Holden, in preparation)

5.4.2 Highlighted representation issue – interflow, steep slopes, rocky and thin/transmissive soils, fractured rock

Recreating the flashy hydrograph (high peaks, steep recessions), as well as the low, but maintained baseflow in dry seasons, that is observed in the Upper Berg proved challenging. The exercise highlighted how the modelling tools vary in generating and handling subsurface flows in general, and interflow in particular. Interflow has been found to be a significant streamflow contributor in mountainous catchments across the Table Mountain Group geological region, occurring as preferential flows through a tallus layer, connected fracture networks in highly fractured surface rock, and/or at rock-soil interfaces given the relatively transmissive sandy soils (Midgley and Scott, 1994; Roets et al., 2008; Xu et al., 2003; 2009). Following rain events sufficiently large to generate interflow, water on this path is slower to reach the stream than surface runoff, but much faster than outflow from deeper ground water aquifers and much faster than flow through thicker- and/or finer-textured soils would be.

Decisions about what subsurface material layers to explicitly include and parameterise as part of the modelled “soil” and/or “unsaturated” components of the different tools did not prove to be straightforward given the role of highly fractured rock in “shallower” processes. Alternative subsurface structures in each tool were discussed, but testing all of them was beyond the scope and time available. With the exception of the model built with SPATSIM, for which layers are mostly lumped, all the Upper Berg models included some degree of explicit representation of a highly fractured rock layer below the sandy soils and above the regional bedrock aquifer. In the model built with ACRU4, a portion of flow thought to be interflow was generated as saturation excess overland flow as a workaround to compensate for the tool not including lateral flow directly from the soil profile.

Modelling approaches considered and applied for the unsaturated zone and interflow generation in the Upper Berg case study are described in the tool below, with more details of the models given in Appendix B.

SPATSIM-Pitman (Hughes ground water)

SPATSIM explicitly represents interflow from a subcatchment-scale “soil moisture store” unit. Lateral interflow and vertical percolation rates from this store are parameterised separately to control the balance between them, both declining with declining moisture. The rate equations are conceptual, but the store is parameterised with a maximum water storage capacity as a depth. This value should relate to the profile depth and porosity of the zone contributing to the interflow. Maximum flow rate and curve shape parameters should relate to conductivity and water retention. For the Upper Berg, Pitman’s “soil moisture store” was assumed to represent both the soil and fractured rock layers. Its storage capacity in the calibrated model, 450 mm, was higher than the values suggested for areas with thin soils (100–200 mm) in model documentation, but consistent with values suggested for areas with deeper regolith and temperate to subhumid climates (Hughes, 2019). The maximum interflow rate was set relatively high (47 mm per month), consistent with the steep catchment. The maximum percolation rate was also set relatively high (33 mm per month), but less than the interflow and with a steeper rate of decline with decreasing moisture (power coefficient of 3, vs 2 used for the interflow). The lumped representation of storage and outflow from soil and fractured rock as a single storage unit would likely introduce inaccuracies at a daily timestep, when further partitioning of quicker and slower flow paths is needed to recreate the observed hydrograph. It is less problematic for achieving adequate monthly predictions.

WRSM-Pitman (Sami ground water)

WRSM uses the same soil moisture store and primary interflow generation algorithm as SPATSIM. Calibrated SPATSIM parameter values were used as a starting point for the WRSM model’s soil moisture store, which also represented both soil and fractured rock. However, the Sami ground water module in WRSM includes the representation of an additional vadose zone storage (“percolation store”) between the soil and the aquifer, and a second interflow generation mechanism. The additional store lags percolating water in recharging the aquifer.

If the modelled aquifer reaches its input storage capacity in a timestep (a month), any excess "potential recharge" calculated to leave the vadose store that month is added to the interflow output. As a result, performance improved with a decrease in the maximum interflow rate from the soil moisture store compared to SPATSIM (40 vs 47 mm per month) because additional interflow was generated via this second mechanism in very wet periods.

ACRU4

ACRU4's subsurface flow algorithms did not allow for straightforward representation of interflow as conceptualised for the Upper Berg. Unlike other tools used, ACRU4 does not model lateral flow directly from HRU soil moisture stores. In ACRU4, total "stormflow" runoff calculated for a rain event is partitioned into same-day and delayed flows by lagging portions reaching the river. Documentation suggests that the "delayed stormflow" represents interflow (Schulze, 1995). Water predicted to infiltrate soil and percolate vertically from the bottom soil layer of the model joins the HRU's "baseflow store", which can outflow to the river directly or be routed laterally to the soil of a special riparian HRU.

As described in section 4.7.5, ACRU4 does not explicitly calculate surface runoff, interflow or aquifer outflow. The tool's same-day "stormflow", "delayed stormflow" and "baseflow" fluxes are the closest equivalents, respectively, but could implicitly represent elements of multiple mechanistic pathways. A limitation of ACRU4's "delayed stormflow", representing interflow, at least in certain settings, is that the model uses the same thresholds and parameters to generate both surface runoff ("quick stormflow") and interflow ("delayed stormflow"). Total stormflow generated by an HRU in a rain event is calculated using modelled antecedent soil moisture in a specified "response depth" and a land cover-specific coefficient of initial abstraction. In steep, rocky catchments, and with high intensity events, surface runoff could be generated with relatively little rain, justifying the use of a low soil-response depth. However, it is possible that surface flow can occur with less rain than needed to start interflow in this setting. Conversely, interflow could be generated from consecutive smaller rainfall events that may not produce surface flow. This poses a challenge to finding a storm response soil depth, coefficient of initial abstraction and stormflow lagging coefficient that can reproduce observed peaks and recessions across different types of weather events and seasons.

Outflow from the ACRU4 "baseflow store" is calculated using the volume of water in the store and an outflow rate parameter. In catchments with deeper soils, lower slopes and/or weathered material that has a lower conductivity, i.e. compared to TMG rock fracture networks, it may be reasonable for some lateral subsurface flow occurring above a deeper aquifer to be included in the "baseflow store" outflow in the model because there is less contrast between the outflow rates for the different paths. In the Upper Berg, however, the deep aquifer outflow appears much slower, maintaining a low, but relatively consistent dry season baseflow, compared to the relatively fast drainage presumed for interflow. In models trialled, the "baseflow store" was used to represent outflow from the deeper bedrock aquifer. An alternative approach, which would need more research and was not attempted here, could be to delineate HRUs assumed to primarily feed either interflow or deeper ground water recharge, based on topographic position, for example. In this case, ACRU4's "baseflow store" could be parameterised to represent the dominant subsurface pathway for each HRU type: fast-draining interflow or slow-draining aquifer.

After trying multiple soil profile parameterisations for the Upper Berg in ACRU4, a workaround for representing interflow was attempted, which also notably improved model performance in reproducing the observed hydrograph. In this approach, interflow was approximated with saturation excess overland flow, achieved by setting very low percolation-rate parameters for soil layers. Using this approach, large rainfall events and multiple successive events generate soil saturation in the model due to slow drainage, preventing further infiltration and resulting in overland flow. This allowed "stormflow", or quicker than aquifer outflow runoff generation to be governed by multiple thresholds: soil moisture in a shallow "response depth", representing surface flow generation on steep rocky slopes, and in the full soil, representing interflow triggered under wetter conditions.

If not purposefully using this workaround, the area's sandy soils would be reason to apply relatively high percolation rates, following model documentation (Schulze, 1995). However, the sandy soil layer is relatively thin and there are likely to be large changes in porosity and conductivity with depth that inhibit downward flow, further supporting the low percolation rates applied. An extensive parameter testing exercise in ACRU4 for a similar, steep TMG region catchment, the Groot Winterhoek, also found that setting a lower than recommended percolation rate coefficient for the lower soil layer allowed for a greatly improved fit to the observed hydrograph (Holden, in prep).

The soil profile modelled in ACRU4 is intended to represent the root zone with a suggested maximum depth of 2 m. With thin soils over highly fractured rock in the Upper Berg, the depth of material to include as "soil" in the model was not clear from the available data and had to be informed by modelling trials. It was found that, if only the sandy soil layer was included in the model soil profile, using measured depths (around 30 cm) and properties, there was not enough soil water storage to support AET, and modelled streamflow was therefore much too high. Deepening the profile, with the second layer parameterised to represent fractured rock, allowed for increased moisture storage and AET, improving model performance. Fynbos species can extend their roots into fractured rock (Manders and Smith, 1992).

ACRU4 has no explicit representation of vadose zone material below the root zone soil profile and above an aquifer. The "baseflow store" outflow rate coefficient therefore accounts for both the delay of water in reaching the aquifer after percolating from the root zone, which could be considerable given a deep water table, and the rate of outflow from the aquifer to the stream. The ACRU4 soil profile has two layers, each with a user-input proportion of roots, potentially allowing for a profile with minimal water withdrawal from the lower layer if needed. In this way, the lower soil layer could be used to approximate some of the recharge delay.

ArcSWAT2012

ArcSWAT2012 calculates interflow directly, separately to surface flow generation and aquifer ground water flow, as a lateral flow from the modelled soil profile of each HRU. In ArcSWAT2012, the model soil profile can extend below the root depth of the HRU's vegetation, which is defined separately, but the maximum total soil profile depth is capped at 3.5 m. The profile can be given up to ten separately parameterised layers. Interflow is calculated by layer based on the amount of drainable soil moisture above field capacity, the HRU slope and slope length, and the soil's saturated hydraulic conductivity. Percolation between layers is calculated before interflow in a timestep and is also a function of drainable moisture and conductivity. Water percolating from the lowest soil layer recharges ground water with an input time lag to represent passage through additional vadose zone material when relevant. Either one or two aquifer stores (shallow and deep) can be included with different rates of outflow.

For the Upper Berg, interflow from the fractured rock layer was modelled by including it in the "soil" profile. The real thickness of this layer may be greater than permitted by the tool, so in the model, it was assumed to extend down to the 3.5 m depth allowed. As in ACRU4, a thinner upper sandy soil layer (depth ranging from 5 cm on cliffs to 35 cm in lowlands) was assigned properties based on field sampling. The fractured rock layer below was parameterised based on literature and findings from MIKE-SHE trials, with lower porosity and conductivity than the soil, but higher porosity and conductivity than the bedrock aquifer. The approach produced reasonable recession characteristics after adjustments of a priori saturated hydrologic conductivity values, assumed to be relatively less certain than other inputs. The same conductivity value governs both lateral interflow and vertical percolation from a layer, which may not be realistic. This posed some limitations on improving fit, which could potentially have been addressed by altering layer thicknesses and/or HRU "slope lengths" that influence percolation and interflow rates, respectively. This was not attempted given limited time and constraints on the information available to assess the realism of altering these properties in the model.

As an alternative approach, it would have been possible to make use of the two different aquifer units in ArcSWAT2012 to represent flow through the fractured rock layer, rather than including it in the "soil" profile.

The shallow aquifer could have been parameterised with fast outflow to represent interflow, while the other was given very slow outflow to represent the deep bedrock aquifer. This approach was not attempted, however, because it was thought to introduce other process representation inaccuracies that may prove problematic. The lag of percolation recharging the two aquifer units is the same in the model. This does not conform to the conceptual model of the process in which there is little lag in reaching the shallow fractured rock layer for interflow, and a much larger lag in reaching the deep aquifer. In addition, ArcSWAT2012 allows relatively limited ET withdrawals from the shallow aquifer unit (maximum 20% of demand) in the model, which may overly restrict overall ET. This was not properly explored.

MIKE-SHEs (simpler algorithm options)

MIKE-SHEs, like ACRU4, does not model the lateral flow of water in the soil profile. However, unlike ACRU, it includes an "interflow reservoir" between the soil profile and the aquifer "baseflow reservoirs". In this interflow reservoir, rates of lateral outflow and vertical percolation to recharge aquifers are separately parameterised, allowing control over the balance between them, somewhat similar to the Pitman tools. The rate constants for these reservoirs are difficult to derive directly from the physical properties of the subsurface layers, but can be estimated from observed hydrograph analyses and calibration trials. This structure suggests that the "soil" profile in the model does not include the layer in which the interflow is predicted. However, the interflow unit in the model cannot feed ET. Calibration of this model set-up has not yet been completed, but based on the ACRU4 trials, it is anticipated that the model soil profile will need to include some material below the thin sandy soil to achieve sufficient ET.

MIKE-SHEc (more complex algorithm options)

MIKE-SHEc requires separate inputs of material layers in what is considered the typically unsaturated zone and the typically saturated zone. The model profiles for these two zones must overlap: the bottom unsaturated zone layer must extend into the top saturated zone layer to allow the water table to rise and fall over this boundary and to simulate capillary rise from an unconfined aquifer. No lateral flow is calculated in unsaturated layers, only vertical redistribution. However, perched water tables can develop in different layers in the model when there are distinct differences in layer conductivity. When this occurs in the saturated zone profile, it can lead to lateral flow to the channel from layers above a deeper aquifer, i.e. interflow. Saturated zone layers can be given different horizontal and vertical conductivities. Highly fractured surface rock layers would have greater horizontal than vertical conductivity overall, promoting lateral flow.

For the Upper Berg River catchment, a tallus or more highly fractured upper rock layer was explicitly included as the bottom layer of the unsaturated zone and the upper layer of the saturated zone. Because of the change in conductivity between this and the saturated zone layer, representing the deep bedrock aquifer below, the tallus layer frequently developed saturation and was a significant contributor to outflow in wet periods in the model, conforming to the conceptual model of TMG interflow.

5.4.3 Modelling outcomes

Models were built for the catchment of the Berg River Dam using all five modelling tools for the current land cover scenario (upland pines), a complete IAP clearing scenario (no pines) and a riparian pines scenario. Calibration was done by comparing model streamflow output for the 41.05 km^2 catchment area of DWS Weir G1H076 to weir flow data for March 2008 to August 2018. Calibration of the MIKE-SHE model using the tool's simpler, more lumped representation options was not completed in the time available, so the outputs of this model are not presented here. To explore the potential impacts of the land cover scenarios on flows entering the Berg River Dam, parameters from the calibration exercise for the weir subcatchment were extended to the full 73.25 km^2 area feeding the dam (see Figure 5.1). These models were run using the available 2004–2018 climate data. Their outputs were compared for the 2007–2018 water years to allow for a three-year model warm-up period.

Model predictions vs observations

Flow duration curves and hydrographs for the calibration period are shown in figures 5.15 to 5.18, with statistics given in Table 5.9. In terms of monthly streamflow prediction, all the models achieved acceptable fits to the observed flow with regard to NSE. For this period and assumed land cover, all models predicted mean monthly flow within 3–18% (0.2–1.0 mm^3) of the observed flow, with NSE values of 0.87–0.94 for their monthly flow timeseries (Table 5.9). NSE values for log-transformed monthly flows were generally close to the values for untransformed flows, suggesting that model fits were not highly biased towards higher flow months. Daily streamflow predictions from the daily time-step models were less accurate than those from the monthly models: higher RMSE and mean absolute error (MAE) relative to the mean and lower NSE values. Daily flow NSE values (0.48 to 0.57) were close to, or exceeded, the 0.5 target. For all three models, the NSE of log-transformed daily flows (0.76–0.78) was greater than for untransformed flows, showing that daily peaks were not captured as well as lower flows.

The models differed in the nature of their shortcomings:

- The MIKE-SHEc model had the lowest error in predicted mean flow (-4%) and second-highest NSE for monthly (0.92) and daily flows (0.55). However, it overpredicted lower (5–25th percentile) and underpredicted higher (95th percentile) monthly and daily flows more than others.
- The ACRU4 model overpredicted the mean flow by 18%, but predicted daily flow with the best fit to the overall pattern of the observed flow, having the highest daily flow NSE (0.57) and R^2 (0.63). This model had a better fit to lower daily flows, with more over-prediction of medium to high daily flows. Aggregated monthly, the model overpredicted monthly totals relatively evenly across high and low flow months, so that the modelled series matched the observed monthly pattern well (R^2 of 0.94).
- The SWAT2012 model overpredicted mid-range daily flows, resulting in a 7% over-prediction of the mean and a lower daily NSE (0.48) than the other daily models, but it had the best fit to the 5th and 95th percentile daily flows and better prediction of the mean flow than the ACRU model. Assessed at a monthly scale, it had the highest NSE (0.94) and correlation (R^2 of 0.94) of monthly flows in the set, but the lowest NSE for logged monthly flows (0.88) because of the overprediction of flow in low-flow months.
- The SPATSIM model overpredicted the mean by 7%, similar to the SWAT model. However, it underpredicted flow in low-flow months more than the other tools. It showed the best prediction of flows for the higher flow months, the 75th–95th percentiles, in the set.
- The WRSM model had the second-highest overprediction of the monthly mean (by 12%) and the lowest monthly NSE (0.87). However, it had the closest fit to the observed flow for the low to median flow months, 5th–50th percentiles, in the set.

Table 5.9: Statistics for observed and modelled streamflow at Weir G1H076, Upper Berg River

Statistic	Observed	WRSM	SPATSIM	ACRU4	SWAT2012	MIKE-SHEc
Monthly streamflow yield (mm^3 per month), April 2008 to August 2018						
Mean	5.94	6.67	6.38	6.98	6.38	5.71
difference vs observed		*0.74*	*0.44*	*1.04*	*0.44*	*-0.23*
% difference		*12%*	*7%*	*18%*	*7%*	*-4%*
Standard deviation	7.15	7.87	7.19	8.17	7.03	6.30
Coefficient of variance	1.20	1.18	1.13	1.17	1.10	1.10
Minimum	0.19	0.14	0.10	0.15	0.31	0.46
5th percentile	0.24	0.21	0.17	0.38	0.45	0.60
25th percentile	0.52	0.54	0.44	0.68	1.02	0.97
50th percentile	2.50	3.06	3.43	3.79	4.13	3.16
75th percentile	9.35	10.30	9.89	11.10	10.15	8.62
95th percentile	20.64	22.44	20.25	20.81	18.69	16.70
Maximum	31.34	36.81	33.19	38.28	33.37	31.42

Statistic	Observed	WRSM	SPATSIM	ACRU4	SWAT2012	MIKE-SHEc
RMSE		2.53	2.30	2.37	1.76	2.02
MAE		1.55	1.46	1.57	1.18	1.21
NSE		0.87	0.90	0.89	0.94	0.92
NSE log		0.90	0.90	0.90	0.88	0.89
R^2		0.91	0.90	0.94	0.94	0.93
Daily streamflow (cm), 2008-03-15 to 2018-08-15						
Mean	2.24			2.64	2.41	2.16
difference vs observed				*0.40*	*0.17*	*-0.08*
% difference				*18%*	*7%*	*-4%*
Standard deviation	5.45			5.57	4.97	4.57
Coefficient of variance	2.43			2.11	2.06	2.11
Minimum	0.04			0.05	0.02	0.13
5th percentile	0.09			0.10	0.09	0.19
25th percentile	0.16			0.17	0.24	0.29
50th percentile	0.54			0.80	0.79	0.65
75th percentile	1.81			1.95	2.41	1.56
95th percentile	9.98			13.39	10.11	9.81
Maximum	67.35			83.44	91.10	62.11
RMSE				3.59	3.93	3.67
MAE				1.28	1.30	1.31
NSE				0.57	0.48	0.55
NSE log				0.78	0.77	0.76
R^2				0.63	0.52	0.56

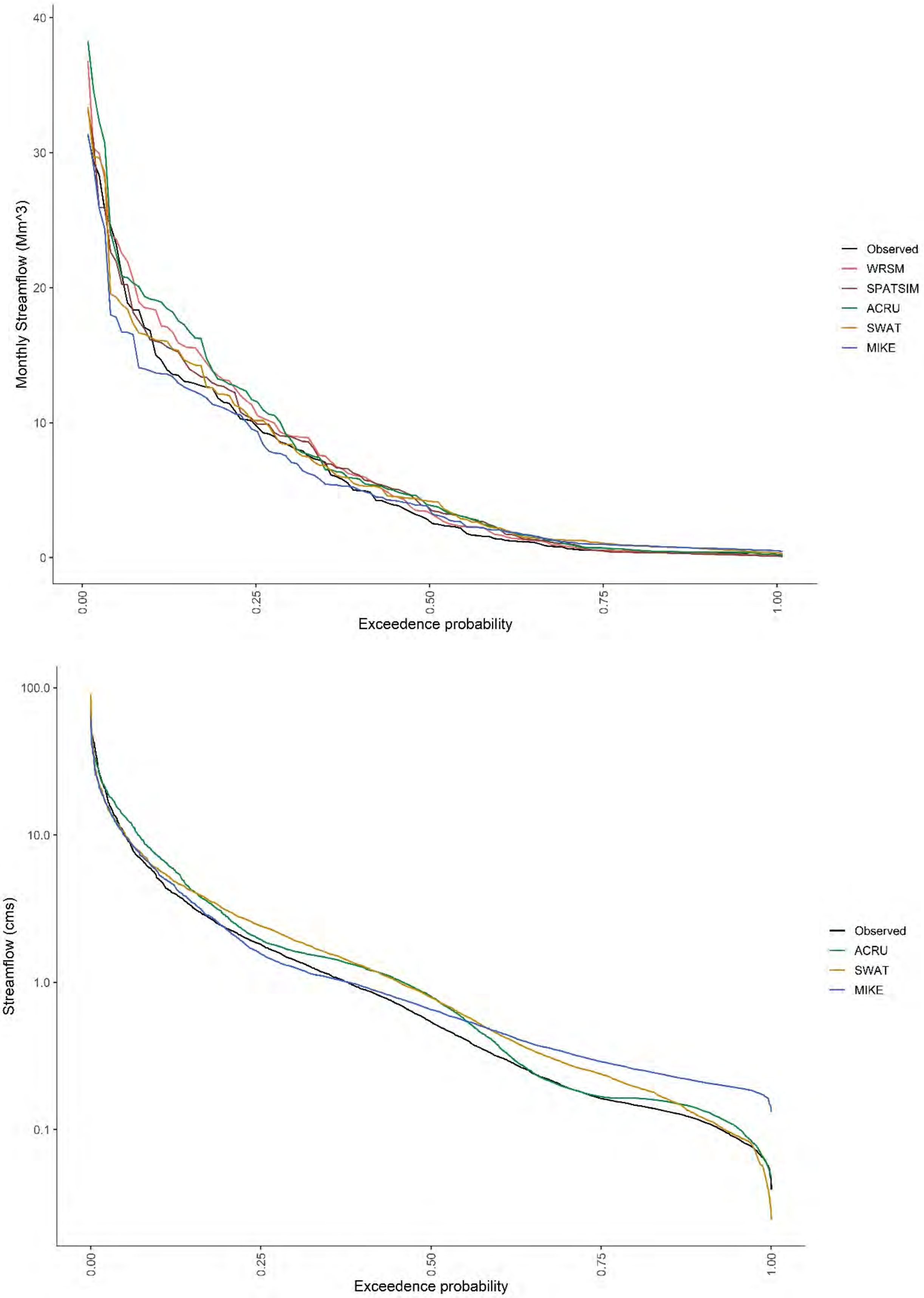


Figure 5.16: Observed and modelled monthly and daily flow duration curves at Weir G1H076, Upper Berg River (Note: Daily streamflow displayed on a log axis)

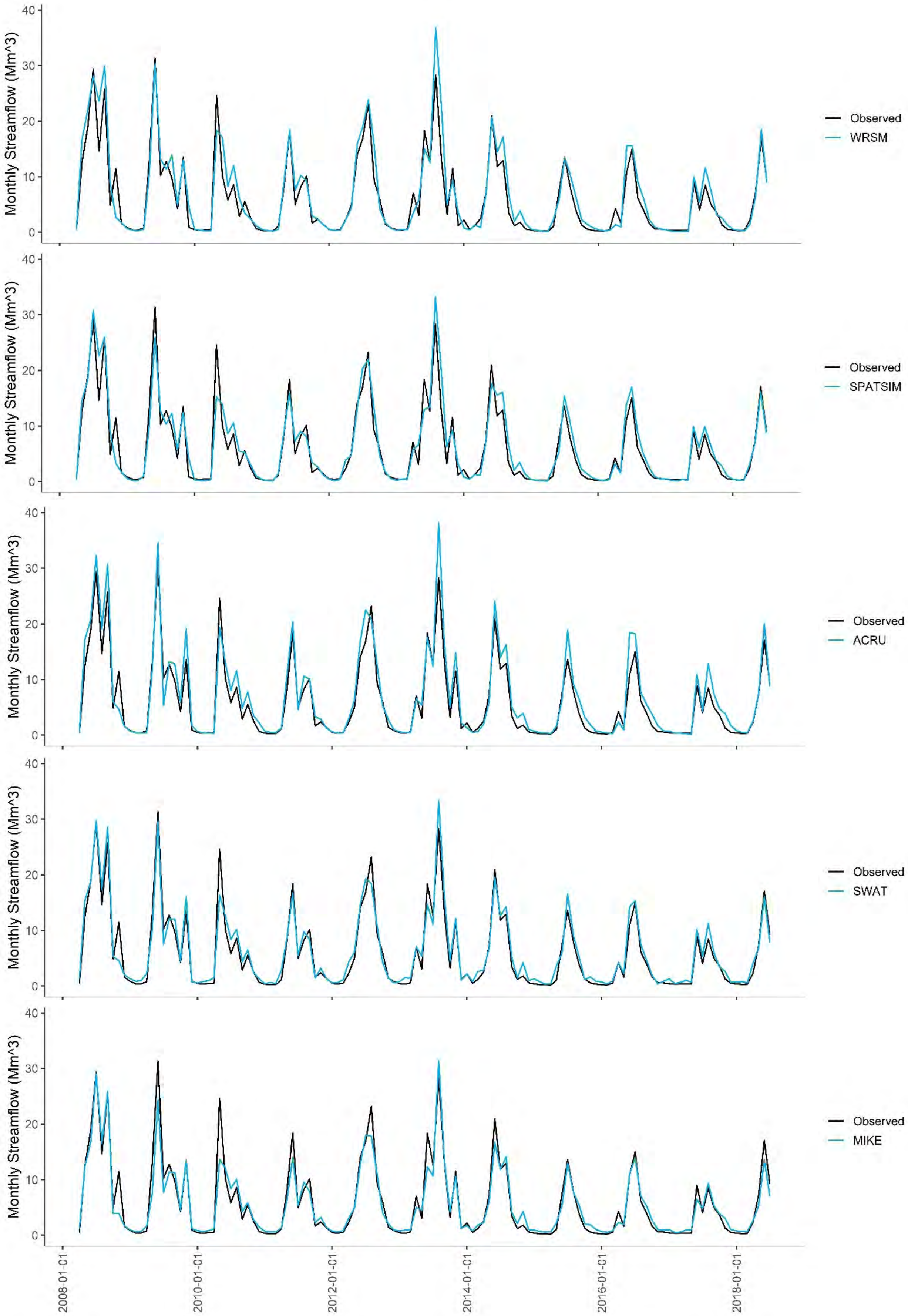


Figure 5.17: Observed and modelled monthly hydrographs at Weir G1H076, *Upper Berg River, April 2008 to July 2018 full calibration period, for models built in each of the five modelling tools*

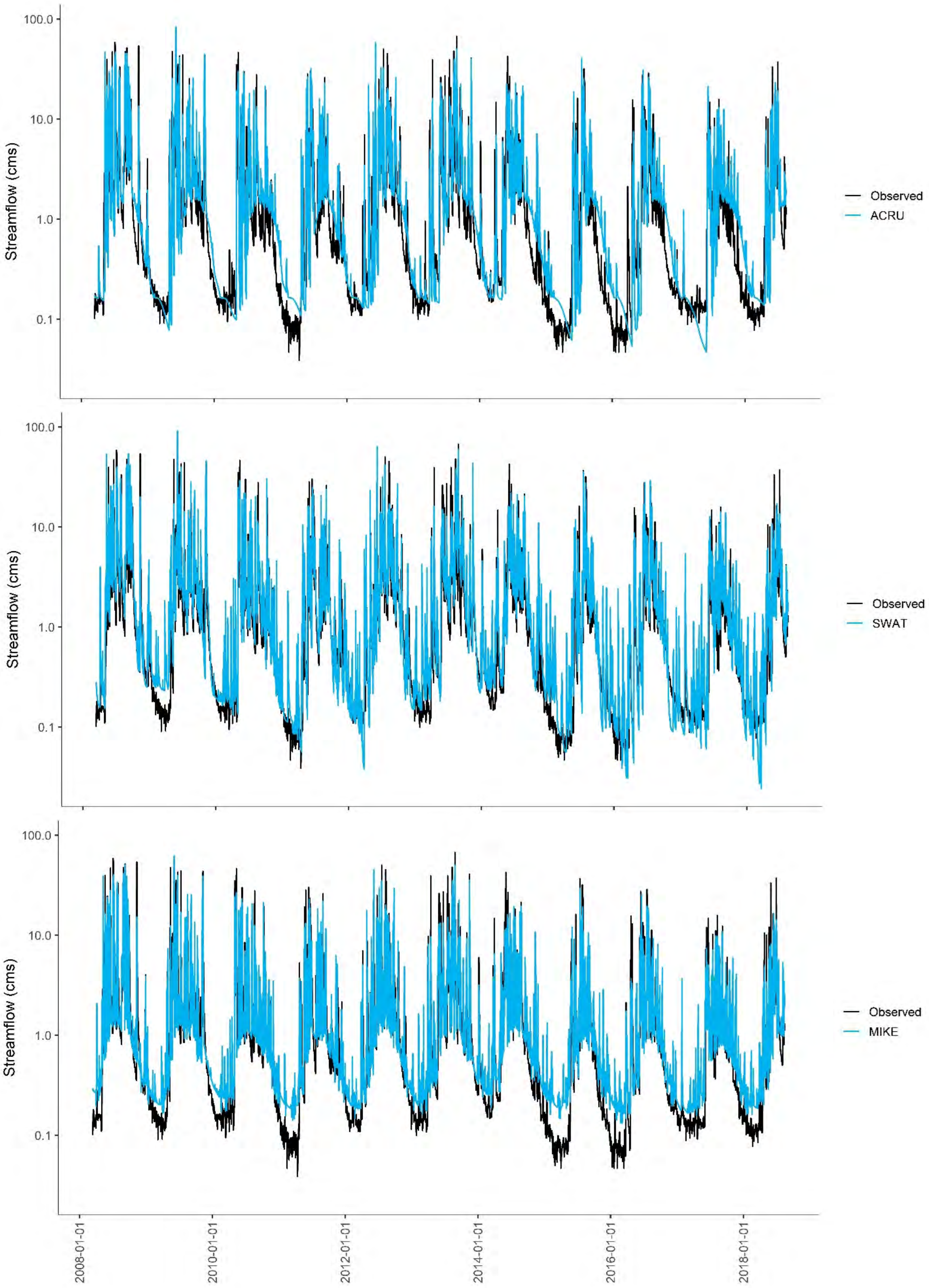


Figure 5.18: Observed and modelled daily hydrographs at Weir G1H076, Upper Berg River, 2008-03-15 to 2018-08-15 full calibration period, for three daily timestep models (Note: Log-scale streamflow axis)

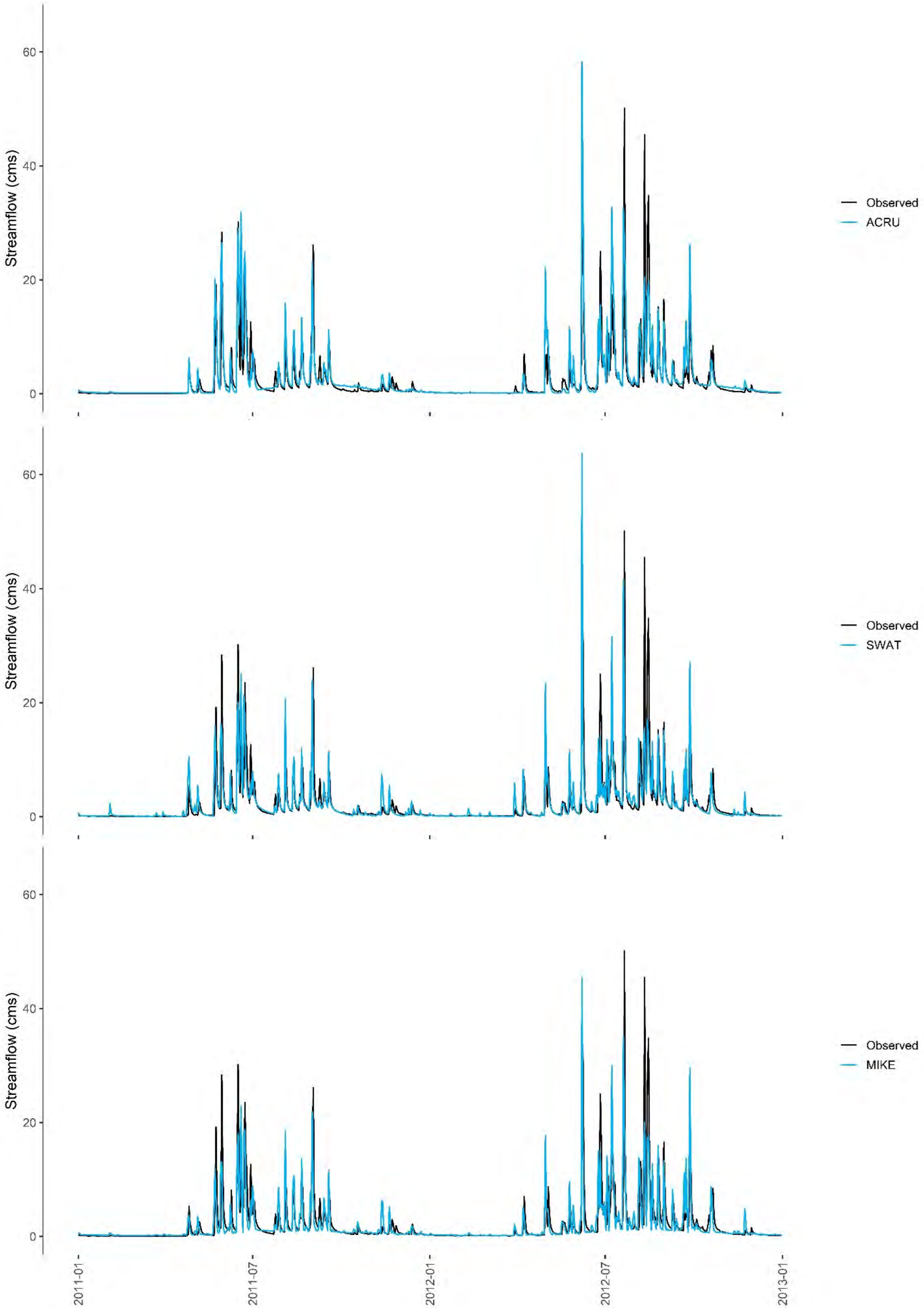


Figure 5.19: Observed and modelled daily hydrographs at Weir G1H076, Upper Berg River, 2011–2012 two-year demonstration period, for three daily timestep models

Water balance comparison for current cover scenario models

The models of the Upper Berg catchment built using the various tools predicted different relative contributions of surface flow, interflow and aquifer outflow to total runoff, as well as different contributions of canopy interception and capillary rise or ground water to total AET. Average annual model water balances for 2007–2018 for the 73.25 km^2 catchment feeding the Berg River Dam, assuming the current cover scenario with pine infestation in the uplands, are presented in Table 5.10.

The models predicted MAR values ranging from 1 674 mm (WRSM) to 1 934 mm (ACRU4), equating to catchment runoff ratios of 64% to 74% (Table 5.10). When modelling the weir subcatchment for the period with observed flow data, the model built in MIKE-SHE predicted the least streamflow, followed by the SPATSIM, SWAT and WRSM models, with the ACRU4 model predicting the most. The larger dam catchment area has a greater proportion of fynbos versus pine, lower spatial average rainfall and more lower slope area. This resulted in changes in the order of the models ranked by predicted MAR: the ACRU4 model still predicted the most, followed by the MIKE-SHE model. SPATSIM predicted more than SWAT2012 and WRSM. This shows that the models have different relative sensitivities to land and soil parameters, and to rainfall.

Differences in runoff predicted by the models were largely accounted for by differences in modelled AET. A smaller amount was also due to ground water predicted to leave the catchment in the subsurface in the MIKE-SHE and SPATSIM models. The model built in WRSM predicted the greatest mean annual AET (934 mm) and least runoff, while the ACRU4 model predicted the least AET (670 mm) and most runoff. ACRU4 does not include ground water flow from the model domain. No exiting ground water was included in the Upper Berg SWAT2012 model, although this could have been represented, in effect, by allocating a proportion of modelled recharge to an inactive aquifer. This would require a priori knowledge of amounts actually leaving the catchment. Of the AET modelled using tools that output its components, the SPATSIM model predicted the most canopy interception, both in quantity (189 mm) and proportion of total AET (23%). The ACRU4 model predicted a small amount (141 mm), but a similar proportion of the total AET (21%), while the MIKE-SHE model predicted less (92 mm) and a lower proportion (12%).

Because of differing subsurface representation across the models (i.e. what material layers were included in the “soil profile” vs below it, as well as the different ET outputs produced by the different tools, the proportions of ET “fed by groundwater” obtained from the tool outputs are not directly comparable. In the MIKE-SHE model, the highly fractured rock layer was included in both the unsaturated and saturated zone profiles. Only ET drawn from a saturated portion of this layer was output as “ET from ground water”, i.e. when and where enough water was predicted to be in the layer for saturation to develop up to the root zone in the model. In the other tools, much of this layer was included in model “soil profile” and ET drawn from it would not be output as “ET from ground water”, even if or when it was at or near saturation. ET from ground water calculated in WRSM, SPATSIM and SWAT represents water drawn from deeper rock aquifer layers, only close enough to the surface to be accessed by vegetation in lowland areas. As expected, given the differing definitions, MIKE-SHE’s “ET from groundwater” output is higher in amount (85 mm) and proportion (13% of AET) compared to that of the other models. The SWAT model predicted roughly twice as much ET from ground water compared to SPATSIM: 51 mm and 6% of total AET vs 24 mm and 3% of total AET.

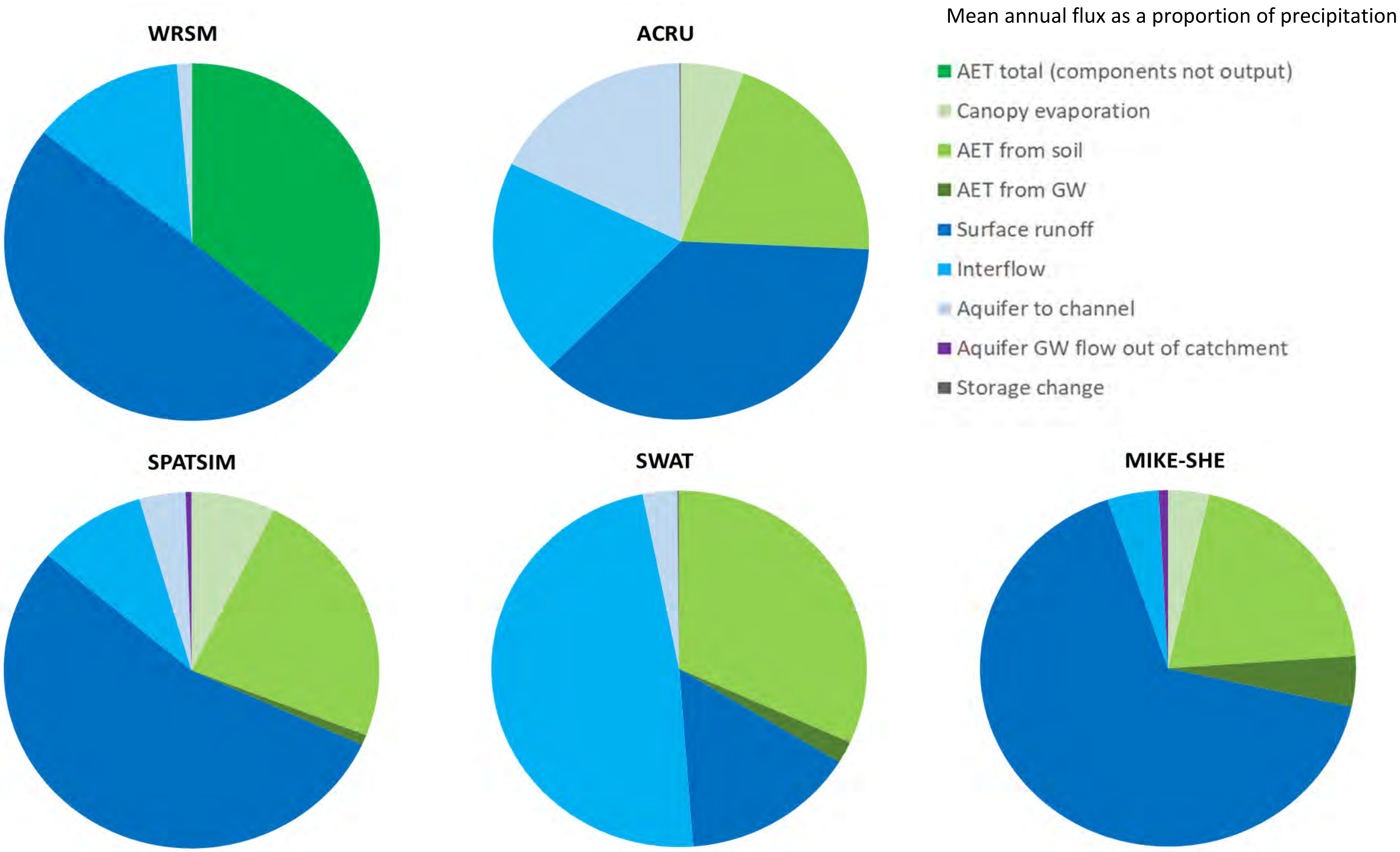


Figure 5.20: Modelled mean annual water balances for the Upper Berg catchment for 2006-10-01 to 2018-09-30, predicted using five different modelling tools shown as proportions of catchment mean annual precipitation (Note: Not all fluxes are modelled or output by all tools)

Table 5.10: Modelled mean annual water balances for the Upper Berg catchment for 2006-10-01 to 2018-09-30, predicted using five different modelling tools

(All fluxes given in mm over full catchment area)

	WRSM			**SPATSIM**			**ACRU4**			**SWAT2012**			**MIKE-SHEc**		
Mean annual flux	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*
Precipitation	2 608			2 608			2 608			2 608			2 608		
AET total	**934**	***36%***		**833**	***32%***		**670**	***26%***		**880**	***34%***		**742**	***28%***	
Canopy evaporation				189	*7%*	*23%*	141	*5%*	*21%*				92	*4%*	*12%*
AET from soil*				*620*	*24%*	*74%*	529	*20%*	*79%*	*829**	*32%*	*94%*	*531*	*20%*	*71%*
AET from GW*				*24*	*1%*	*3%*				*51*	*2%*	*6%*	*119*	*5%*	*16%*
Runoff total	**1 674**	***64%***		**1 762**	***68%***		**1 934**	***74%***		**1 723**	***66%***		**1 845**	***71%***	
Surface runoff[#]	1 296	*50%*	*77%*	1 418	*54%*	*80%*	957	*37%*	*49%*	393	*15%*	*23%*	1 730	*66%*	*94%*
Interflow[#]	344	*13%*	*21%*	245	*9%*	*14%*	515	*20%*	*27%*	1 253	*48%*	*73%*	115	*4%*	*6%*
Aquifer to channel[#]	33	*1%*	*2%*	104	*4%*	*6%*	461	*18%*	*24%*	77	*3%*	*4%*	0.18	*0.01%*	*0.01%*
Aquifer GW flow out of catchment	0	*0%*		13	*1%*		0	*0%*		0	*0%*		21	*1%*	

AET = Actual evapotranspiration; GW = Ground water; Canopy evaporation = Canopy interception evaporation

MIKE-SHEc = MIKE-SHE using complex, more distributed algorithm options

Note: Missing water balance components indicate that the tool does not save outputs of these components separately, although it may explicitly calculate the flux.

**Modelling tools differ in what is considered ET from soil vs ground water and the outputs that can be exported. "AET from soil" includes water on the soil surface, and in the SWAT model, canopy interception is implicitly included in the value presented as "AET from soil" here.*

[#] *The interpretation of runoff source subdivisions differs somewhat across tools*

In the Upper Berg ACRU4 model, a workaround for additional interflow representation was applied that used saturation excess overland flow generation as a proxy. This would increase both "quick" and "delayed stormflow" output, while only the "delayed stormflow" was interpreted as interflow for the water balance.

The amounts and proportions of runoff predicted to reach the outflow channel as surface runoff, interflow or aquifer outflow showed much greater variability across the models than the total runoff predicted. Modelled MAR values spanned a range of 263 mm, 15% of the average value for the group (1 788 mm). In contrast, the value range was 112% of the average for modelled surface runoff, 217% for interflow and 341% for aquifer outflow. However, when amounts classified as surface flow and as interflow are summed for each model, to collectively represent relatively fast surface and shallow-subsurface flows, the value range drops to 23% of the mean value across the models. This suggests less of a stark conceptual difference between the models if viewed at a broader scale.

As described (section 4.7.5), division of runoff into such simplified path or source categories will necessarily differ across models with differing scales of representation, process representation approaches, tool outputs and, in this case study in particular, differences in soil and aquifer layer definitions. In the MIKE-SHE model, outflow from the highly fractured upper rock layer within the "saturated zone" module could be output separately from deeper aquifer layer outflows. This was classified here as "interflow", equivalent to lateral flow from the "soil" profile in other tools, which included this layer. In ACRU4, supplementing "delayed stormflow", an additional interflow representation workaround was applied, generating saturation excess overland flow as a proxy. Flows specifically attributable to this would be complex to extract from model output. Additional saturation excess flow would add to both "quick" and "delayed" stormflow in the model, simply assigned as surface flow and interflow in the presented water balance, potentially under-representing intended interflow.

Tables 4.4 and 4.6 demonstrated how different modelling attempts could easily reach different conclusions about more detailed flow path descriptions. Surface flow was predicted to be the primary runoff source in all the Upper Berg models except the model built in SWAT2012. The SWAT2012 model predicted that the majority of catchment runoff (73%) came from interflow, having the lowest predicted surface runoff (393 mm, 23% of total runoff) of the models. Even though surface flow was the dominant runoff source predicted in the other models, the predicted proportion of runoff from surface flow ranged from 49% in ACRU4 to 91% in MIKE-SHE. A higher proportion of runoff classified as surface flow is expected for MIKE-SHEc, given its scale of flow path representation and output. Predicted mean annual aquifer outflow to the channel ranged from 0.18 mm and 0.01% of total runoff in MIKE-SHE to 461 mm and 24% of total runoff in ACRU4 (given the interpretation of the ACRU4 outputs described above). However, despite having the lowest modelled deep aquifer contribution of the models, the MIKE-SHE model actually had the highest predicted low flows of the group, likely due to slower modelled flow for some of the water coming through the highly fractured rock layer, interpreted as "interflow" in the presented water balance (Table 5.10).

Model predictions of change across land cover scenarios: clearing upland pines

When used to estimate the impact of clearing and restoring the 6.89 km^2 of invasive trees in the uplands (9% of the catchment), all models predicted an increase in average streamflow, but magnitudes varied. Predicted increases in annual average yield ranged from 0.1 to 8.7 mm^3, 0.1–7% (Figure 5.21 and Table 5.11):

- Models built in SPATSIM, ACRU4, and MIKE-SHE predicted similar small proportional increases in average flow, 0.8–1.3% (1.1 to 1.7 mm^3 increase in average annual yield). These three models also predicted similar general patterns of change across the hydrograph: greater proportional increases (2–5%) for low and medium flows compared to peaks (0.1–0.5%), but greater magnitudes of increase for high flows. This was consistent for daily and monthly flows in the daily models, and for predicted annual yields of drier versus wetter years across all three models.
- The WRSM model predicted the largest increase in mean flow, 7% (8.7 mm^3 increase in average annual yield), with a different pattern of response to other models. It predicted greater relative flow increases (5–7%) for medium and high flow months than for lower flow months (0–2%), with small declines predicted for the driest months. As with other models, annual yields for drier years were predicted to have greater relative increases, though lower absolute increases, than for wetter years.
- The SWAT2012 model predicted a negligible change in mean, 0.1% (0.07 mm^3) with IAP clearing. It predicted increases in daily 5th–30th percentile flows in similar ranges to ACRU4 and MIKE-SHE, however, little to no change in the median to high daily flows, with some upper daily flow percentiles having very small predicted decreases (-0.1%). As such, the median monthly flow was predicted to decline, as were annual yields in the driest years.

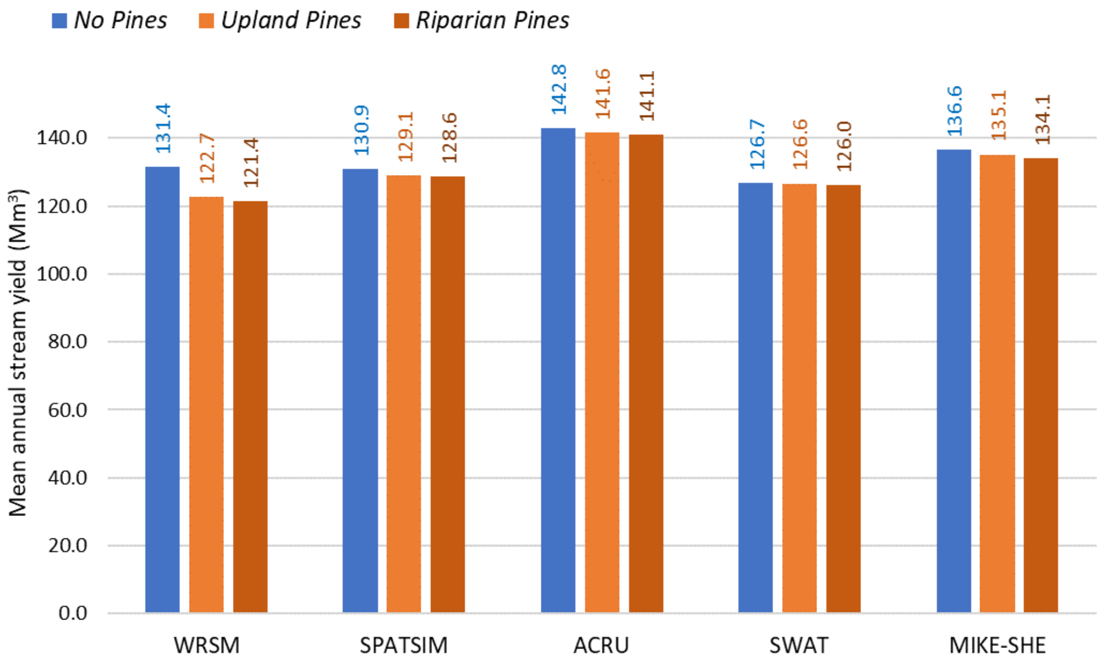
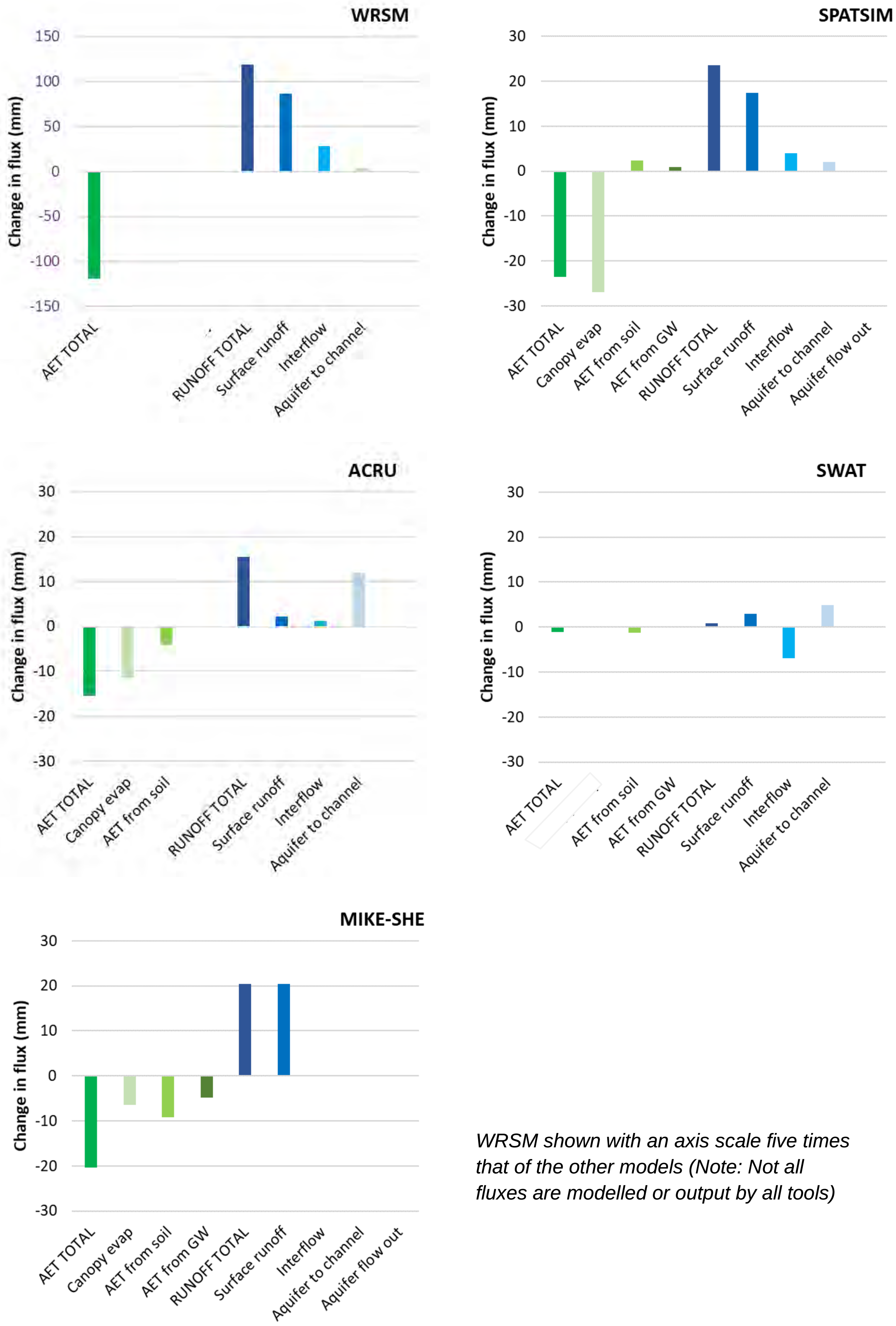


Figure 5.21: Modelled mean annual streamflow yield for the Upper Berg catchment, 2007–2018, under three cover land cover scenarios (no pines, upland pines – current cover, riparian pines), predicted by five different models

Table 5.11: Model predicted changes in streamflow for the Upper Berg catchment with complete IAP clearance compared to the current cover scenario (upland pines) using five different modelling tools

Statistic	**Absolute and relative CHANGE in modelled streamflow, October 2006 to September 2018, IAP cleared (no pines) – current cover (upland pines) scenario**									
	WRSM		**SPATSIM**		**ACRU4**		**SWAT2012**		**MIKE-SHEc**	
Annual stream yield (mm^3)										
Change in:										
Mean	8.67	*7.1%*	1.72	*1.3%*	1.13	*0.8%*	0.07	0.1%	1.50	*1.1%*
Standard deviation	2.56	*5.9%*	0.16	*0.4%*	0.18	*0.4%*	0.21	0.5%	0.24	*0.5%*
Minimum	4.81	*8%*	1.29	*2.0%*	0.75	*1.0%*	-0.29	-0.4%	1.07	*1.6%*
Maximum	12.95	*6%*	1.91	*0.9%*	1.46	*0.6%*	0.33	0.2%	1.95	*0.9%*
Monthly streamflow (mm^3)										
Change in:										
Mean	0.72	*7%*	0.14	*1.3%*	0.09	*0.8%*	0.01	0.1%	-0.01	*-0.1%*
Standard deviation	0.92	*8%*	0.07	*0.6%*	0.03	*0.2%*	0.02	0.2%	-0.09	*-0.8%*
Minimum	0.00	*0%*	0.01	*8%*	0.01	*3%*	0.01	3%	0.02	*4%*
5th percentile	-0.05	*-9%*	0.01	*3%*	0.01	*1%*	0.03	4%	0.10	*13%*
50th percentile	0.27	*5%*	0.14	*3%*	0.17	*3%*	-0.11	-2%	-0.10	*-2%*
95th percentile	2.45	*7%*	0.16	*0.4%*	0.17	*0.5%*	0.02	0.05%	0.06	*0.2%*
Maximum	3.94	*6%*	0.16	*0.3%*	0.13	*0.2%*	0.06	0.1%	-0.64	*-1.1%*
Daily streamflow (cm)										
Change in:										
Mean					0.035	*0.8%*	0.002	0.1%	0.047	*1.1%*
Standard deviation					0.012	*0.1%*	0.019	0.2%	0.048	*0.5%*
Minimum					0.002	*3%*	-0.009	-25%	0.037	*20%*
5th percentile					0.005	*3%*	0.009	7%	0.014	*5%*
50th percentile					0.075	*5%*	0.000	0%	0.032	*3%*
95th percentile					0.075	*0.3%*	-0.014	-0.1%	0.103	*0.5%*
Maximum					0.010	*0.01%*	0.173	0.1%	0.332	*0.2%*



WRSM shown with an axis scale five times that of the other models (Note: Not all fluxes are modelled or output by all tools)

Figure 5.22: Predicted change in mean annual water balance fluxes for the Upper Berg catchment with clearance of current IAP cover, estimated using five different modelling tools

Table 5.12: Predicted change in mean annual water balance fluxes for the Upper Berg catchment with clearance and restoration of current IAP cover, estimated using five different modelling tools

Flux	**Absolute and relative CHANGE in mean annual modelled water balance components, October 2006 to September 2018, IAP cleared (no pines) – current cover (upland pines) scenario** *(All fluxes given in mm over full catchment area)*														
	WRSM			**SPATSIM**			**ACRU4**			**SWAT2012**			**MIKE-SHEc**		
	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*
AET total	**-119**	***-13%***		**-24**	***-3%***		**-15**	***-2%***		**-1**	***-0.1%***		**-20**	***-3%***	
Canopy evaporation				-27	*-14%*	*114%*	-11	*-8%*	*74%*				-6	*-7%*	*31%*
AET from soil*				2	*0.4%*	*-10%*	-4	*-0.8%*	*26%*	-1.3	*-0.2%*	*123%*	-9	*-2%*	*45%*
AET from GW*				1	*4%*	*-4%*				0.3	*0.5%*	*-23%*	-5	*-4%*	*23%*
Runoff total	**119**	***7%***		**23**	***1%***		**15**	***0.8%***		**1**	***0.1%***		**20**	***1%***	
Surface runoff$^{\#}$	87	*7%*	*73%*	17	*1%*	*74%*	2	*0.2%*	*15%*	3	*0.8%*	*326%*	20	*1%*	*99.7%*
Interflow$^{\#}$	28	*8%*	*24%*	4	*2%*	*17%*	1	*0.2%*	*8%*	-7	*-0.5%*	*-757%*	0.1	*0.04%*	*0.3%*
Aquifer to channel$^{\#}$	4	*12%*	*3%*	2	*2%*	*9%*	12	*3%*	*77%*	5	*6.3%*	*531%*	0.002	*1%*	*0.01%*
Aquifer GW flow out of catchment				0.1	*0.7%*								0.01	*0.1%*	

AET = Actual evapotranspiration; GW = Ground water; Canopy evaporation = Canopy interception evaporation

MIKE-SHEc = MIKE-SHE using complex, more distributed algorithm options

Note: Missing water balance components indicate that the tool does not save outputs of these components separately, although it may explicitly calculate the flux.

**Modelling tools differ in what is considered ET from soil vs ground water and the outputs that can be exported. "AET from soil" includes water on the soil surface, and in the SWAT model, canopy interception is implicitly included in the value presented as "AET from soil" here.*

$^{\#}$ *The interpretation of runoff source subdivisions differs somewhat across tools*

Models predicted a streamflow increase with IAP clearing because pine-dominated areas were parameterised to have greater potential ET rates than fynbos. An effort was made to use equivalent parameterisations across the models, where possible and appropriate. Nevertheless, differences in structure not only resulted in differing predicted magnitudes of net AET change, but also differing balances of predicted changes in the contributing processes (Table 5.12 and Figure 5.22).

- In the SPATSIM and ACRU4 models, the change in predicted canopy interception dominated the response. In the ACRU4 model, the decrease in canopy interception evaporation predicted when pines were converted to fynbos. This accounted for 74% of the change in AET. In the SPATSIM model, the predicted decrease in canopy interception was so large that ET from soil and ground water were predicted to increase slightly, presumably due to increased water availability. As such the modelled decrease in canopy interception was greater than the predicted net decrease in total AET.
- In the MIKE-SHE model, the predicted decrease in canopy interception only accounted for 31% of the predicted AET change and the decreases in modelled ET from soil and ground water accounted for more (45% and 23%).
- The SWAT2012 model, in this case, predicted a much smaller decrease in AET compared to the other tools. The decrease was due to ET from the soil layer. SWAT2012 does not separately calculate canopy interception. ET from ground water was predicted to increase slightly, presumably because of increased water availability. A crop coefficient method was used. SWAT2012 limits K_c values to a maximum of 1, reducing the difference between pines and fynbos.

The decreased canopy interception and transpiration demand from replacing the pines with fynbos had differing impacts on the flow paths producing streamflow in the different models (Table 5.12 and Figure 5.22).

- In the WRSM, SPATSIM and MIKE-SHE models, the predicted increase in surface runoff dominated the flow response, accounting for 73–74% of the modelled streamflow increase in WRSM and SPATSIM, and 99.7% in MIKE-SHE. With decreased canopy interception, greater amounts of throughfall in rain events could exceed the soil infiltration rate in the model more often, and with decreased ET withdrawal, soil may also have been predicted to reach saturation more often. Interflow and aquifer outflow were also predicted to increase in these models, although in MIKE-SHE, the changes were almost negligible.
- The ACRU4 and SWAT2012 models also predicted increases in surface runoff, but the predicted increase in aquifer outflow to the channel accounted for most of the increase in modelled streamflow. Surface runoff was a less dominant contributor to streamflow in these two models compared to the others, with more of the rainfall predicted to infiltrate. With the decreased ET predicted when pines were converted to fynbos, more of this infiltrated water could percolate to ground water in the model, increasing predicted aquifer outflow.
- In the SWAT2012 model, interflow was actually predicted to decrease when the pines were replaced with fynbos, counteracting most of the increase in surface flow and aquifer outflow, so that the predicted change in net runoff was minimal. Interflow was the dominant flow path feeding streamflow in this model. The interflow decrease was an unexpected outcome given the decrease in ET. It is likely a result of changed temporal and depth patterns of inundation in the soil and the resulting balance of vertical percolation versus lateral interflow. In addition, lower ET could have meant saturation developing more often in the surface soil layer in the model during rainy periods, potentially resulting in less further infiltration into the profile overall, depending on the timing of the rain events and rate of percolation through the profile.

The predicted change in catchment-scale AET reflects the modelled difference in AET for fynbos versus pines at the location of the cover change, but may also include AET changes elsewhere in the landscape to the degree that hydrological connectivity is represented and predicted to be impactful. Simply allocating the modelled catchment-scale AET change to the 6.89 km^2 area of pines replaced with fynbos indicates a difference in AET between pines and fynbos of 1 263 mm in WRSM, 251 mm in SPATSIM, 217 mm in MIKE-SHE, 164 mm in ACRU4, and 12 mm in SWAT2012.

Because all the models included some level of landscape connectivity, these values are likely to underestimate the AET change modelled by differing amounts for localised pine versus fynbos.

Full exploration of the spatial distribution of modelled AET changes was not completed due to the complications of operationalising this. However, initial analyses suggest that this would be worthwhile in future studies. The extraction of modelled AET by vegetation type for the SWAT2012 and ACRU4 models were completed, but analyses at this scale are complicated by spatial differences in rainfall and soil properties included in the model. A change in overall spatial distribution of fynbos in the landscape (e.g. a greater percentage of the total fynbos cover occurring in a different subcatchment or on a different soil type) can result in a change in the catchment-scale average fynbos AET, regardless of any other interactions. Outputs for cover types that did not change area or location across modelled scenarios are more simply interpreted. In the SWAT model, the fynbos wetland area did not change size or location, but was predicted to have a 10 mm increase in AET in the pine removal scenario. This could only be due to increased ground water access because surface flow and interflow are not routed between HRUs in SWAT2012, while aquifer water storage is modelled at the subcatchment scale. This indicates that the predicted difference in AET between pine and fynbos at the locations of change in the SWAT2012 model was likely bigger than the 12 mm calculated using the catchment-scale AET output. The same applies to the SPATSIM model because AET from ground water, only occurring in the riparian zone in the model, was predicted to be greater in the pine-clearing scenario. The ACRU4 model included routing ground water from the uplands to riparian HRU soils. An almost negligible change, 0.5 mm, was predicted for riparian vegetation between scenarios, indicating that the upland cover change made little difference to water supply vs demand in the modelled riparian zone.

Model predictions of change across land cover scenarios: riparian vs upland IAP invasion

Comparing output for the current cover scenario versus a scenario with invasive pines located in riparian areas, all five models predicted a small decrease in average streamflow (0.4–1% decrease, Table 5.13). This was linked to increased ET from soil and ground water (Figure 5.23), without the canopy interception changes predicted with a net cover type conversion. Magnitudes and patterns of predicted streamflow changes varied, as did the predicted process changes leading to the net runoff outcome.

- The WRSM model predicted the largest average decrease in the group, a 1% or 1.3 mm^3 decrease in average annual yield, with greater decreases predicted for medium and high month flows than for drier months. Almost all the predicted change (over 95%) was due to decreased surface runoff, the dominant flow generation mechanism in the model. Increased ET reduced soil moisture to such an extent that rain produced surface runoff less often. There was also a small predicted decline in interflow, counteracted by a small increase in aquifer outflow.
- The MIKE-SHE model predicted the second-highest average decrease, a 0.8% or 1 mm^3 decrease in average annual yield, with greater proportional and absolute decreases for lower flow days than for higher flow days and a small increase predicted for the very highest daily flows. This produced a similar pattern monthly: greater decreases in lower flow months and negligible change for the wettest months. Reductions in both surface flow and interflow were predicted, the latter linked to increased ET from "ground water" in the water balance output, as this included the highly fractured rock layer. The model's gridded landscape routing of subsurface flows captured the impact of the pines located lower in the topography, where water would collect and be more accessible in their root zones.
- The SPATSIM, ACRU4 and SWAT2012 models predicted similar decreases in average flow, 0.4–0.5%, 0.5–0.6 mm^3 decrease in average annual yield, but had different patterns of change over the hydrograph and the impacted fluxes in the water balance.
    - The SPATSIM model predicted flow declines across high and low flow months, with greater proportional declines in drier months, although the magnitudes of the declines were smaller than predicted for wetter months. The modelled decrease in surface flow contributed the most (45%) to the overall decrease in streamflow, but interflow and aquifer outflow were also predicted to decrease, accounting for 34% and 21% of the net change.

- The ACRU4 model, similar to MIKE-SHE, predicted larger decreases for lower flow days, with a very small increase in flow for medium to high flow days, translating to a similar pattern at a monthly scale. A predicted decrease in surface flow was counteracted by an increase in aquifer outflow in the interpreted water balance. As described, the classification of flows into these simplified paths in an ACRU4 model with riparian zone routing is unavoidably artificial. Moving pines from the uplands to riparian areas resulted in more modelled aquifer recharge in the uplands and increased aquifer outflow from the upland HRU to riparian HRUs. However, this water was available to the riparian vegetation in the model, where the pines used it at a higher rate, explaining the decreases predicted for low-flow days. During very wet periods, the increased riparian pine ET did not compensate for the increase in water coming from the uplands in the model, producing small flow increases.
- The SWAT2012 model, in contrast, predicted greater flow decreases for higher flow days, small increases for medium-flow days, and no change in flow for the driest days. Because most months had at least one peak-forming event, this still generally resulted in decreasing monthly totals, except for extremely dry months (2nd percentile). The predicted streamflow decrease was due to a modelled decrease in interflow, the dominant source of runoff in this model, which was partially counteracted by an increase in modelled surface flow. The increase in surface flow was predicted as lower ET in rainier parts of the catchment led to wetter antecedent soil conditions modelled with certain rainfall event patterns, generating some increases in flow predicted on medium-flow days.

Despite the differing patterns, all models predicted a decrease in total annual yield for all years modelled, with larger proportional changes in drier years. In SPATSIM and WRSM, the absolute decrease in annual flows were predicted to be larger for wetter years than drier ones, while the other models predicted larger changes for dry years.

Table 5.13: Modelled predicted changes in streamflow for the Upper Berg catchment, if invasive pines were located in the riparian zone compared to the uplands, using five different modelling tools

Statistic	**Absolute and relative CHANGE in modelled streamflow, October 2006 to September 2018, riparian pines – current cover (upland pines) scenario**									
	WRSM		**SPATSIM**		**ACRU4**		**SWAT2012**		**MIKE-SHEc**	
Annual stream yield (mm^3)										
Change in:										
Mean	-1.28	*-1.0%*	-0.49	*-0.4%*	-0.59	*-0.4%*	-0.59	*-0.5%*	-1.04	*-0.8%*
Standard deviation	-0.40	*-0.9%*	-0.06	*-0.1%*	0.31	*0.7%*	0.02	*0.04%*	0.10	*0.2%*
Minimum	-0.76	*-1%*	-0.35	*-1%*	-1.13	*-1.5%*	-0.71	*-1.1%*	-1.19	*-2%*
Maximum	-2.05	*-1%*	-0.64	*-0.3%*	-0.05	*-0.02%*	-0.75	*-0.4%*	-0.85	*-0.4%*
Monthly streamflow (mm^3)										
Change in:										
Mean	-0.11	*-1%*	-0.04	*-0.4%*	-0.05	*-0.4%*	-0.05	*-0.5%*	-0.09	*-0.8%*
Standard deviation	-0.06	*-0.5%*	-0.02	*-0.2%*	0.02	*0.2%*	-0.03	*-0.3%*	0.08	*0.6%*
Minimum	0.000	0.00%	-0.01	-4%	-0.17	-66%	0.002	0.4%	-0.13	-20%
5th percentile	0.000	0.00%	-0.01	-3%	-0.14	-23%	-0.08	-11%	-0.16	-17%
50th percentile	-0.09	-2%	-0.04	-1%	0.02	0.2%	-0.05	-1%	-0.15	-3%
95th percentile	-0.38	-1%	-0.08	-0.2%	0.12	0.3%	-0.11	-0.3%	0.003	0.01%
Maximum	-0.16	-0.3%	-0.07	-0.1%	0.07	0.1%	-0.12	-0.2%	-0.004	-0.005%
Daily streamflow (cms)										
Change in:										
Mean					-0.019	*-0.4%*	-0.018	*-0.4%*	-0.034	*-0.8%*
Standard deviation					0.007	*0.1%*	-0.132	*-1.5%*	0.036	*0.4%*
Minimum					-0.054	-68%	-0.009	-25%	-0.037	-20%
5th percentile					-0.068	-38%	0.000	0.00%	-0.051	-18%
50th percentile					0.017	1.2%	0.009	0.7%	-0.040	-3%
95th percentile					0.015	0.1%	-0.235	-1.4%	-0.006	-0.03%
Maximum					-0.111	-0.1%	-0.472	-0.3%	0.343	0.2%

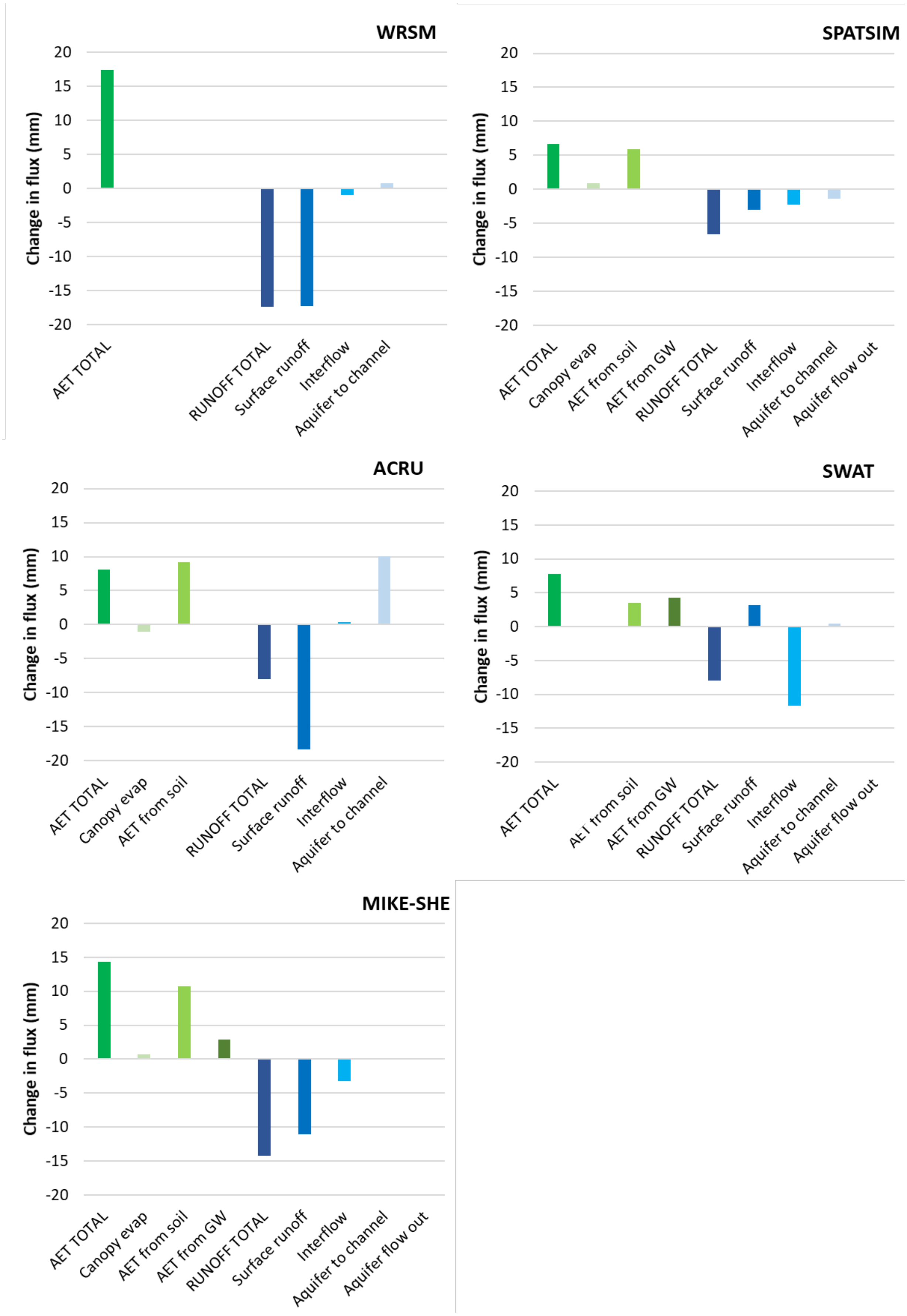


Figure 5.23: Predicted change in mean annual water balance fluxes for the Upper Berg catchment if the invasive pines were located in the riparian zone rather than the uplands, estimated using five different modelling tools (Note: Not all fluxes are modelled or output by all tools)

5.5 CASE STUDY OVERVIEW: UPPER KROMME RIVER CATCHMENT (K90A, B) EASTERN CAPE − MOUNTAIN RANGE RAINFALL GRADIENTS, MOUNTAIN VALLEY CONNECTIVITY, VALLEY BOTTOM WETLANDS, INVASIVE ALIEN VEGETATION

5.5.1 Catchment description and modelling goals

Table 5.14: Upper Kromme River catchment and modelling overview

Catchment property	Description	Implication
Scale	360 km^2 Two quaternaries (K90A, B), catchment of the Kromrivier River Dam	
Climate	MAP 650 mm Bimodal seasonal rainfall (average), high variability in pattern and quantity Spatial rainfall gradient: MAP decreases from mountain to valley, southern mountains to inland mountains (686 to 585 mm), East to west (590 to 704 mm)	Quaternary catchments span north and south mountains and valley between. This scale could lose important process thresholds; ideally, model with specific climate inputs for zones: mountain ranges, elevations, east-west
Runoff ratio	18–20 % (medium, regionally high)	
Topography	Two parallel mountain ranges with narrow valley floor between (5% of area), trellis drainage, more flow from southern mountains Mean slope: 26%	Expect relatively fast stormflow out of the mountains to be buffered by the central floodplain – connectivity of modelled spatial units needs to be considered
Soils and geology	Mountains have thin sandy soils over fractured rock layers of TMG quartzites, grading to deeper, more loamy. TMG rock is more fractured (and has more open fractures) near surface. Valley floor has 8 m+ alluvium and wetland peat overlying shale. Flow (surface and subsurface) from the mountains supports valley alluvial aquifer and wetlands	Expect significant interflow through more highly fractured shallow rock layers and/or tallus in the mountains Alluvial aquifer storage is separate to mountain bedrock aquifer, but fed by it, and supports baseflow and valley ET – connectivity of modelled units needs to be considered.
Vegetation	Dominated by fynbos vegetation; valley palmiet wetland basins, pasture and orchards; 8% wattle invasion (riparian)	
Modelling		
Previous modelling	MIKE-SHE, simple options version calibrated, for WRC K5-2927 project (Cornelius et al., 2019)	Input database and conceptual model reference point
Modelling goals/ scenarios	Estimate the hydrological impact of clearing all IAPs (restore indigenous vegetation). Estimate the hydrological impact of uncontrolled IAPs (spread to 67% of area).	Potential ET rates of wattle vs fynbos, woodland, palmiet needs representation Additional subsurface water access for vegetation in low-lying areas vs uplands
Climate data	SAWS, ARC, SAEON rain gauge and weather station daily rain and ET demand: 1950-01-01 to 2018-12-31 (69 years)	**Model runs:** 1957-01-01 to 2018-12-31 **Output comparison (excluding warm-up):** 1959-10-01 to 2018-09-30 (59 years)
Streamflow data	DWS estimated inflow to Kromrivier Dam: 1957-01-01 to 2017-09-10 (60.7 years)	**Calibration**: 1959-10-01 to 2017-08-31 (daily); 1959-10 to 2018-08 (monthly)

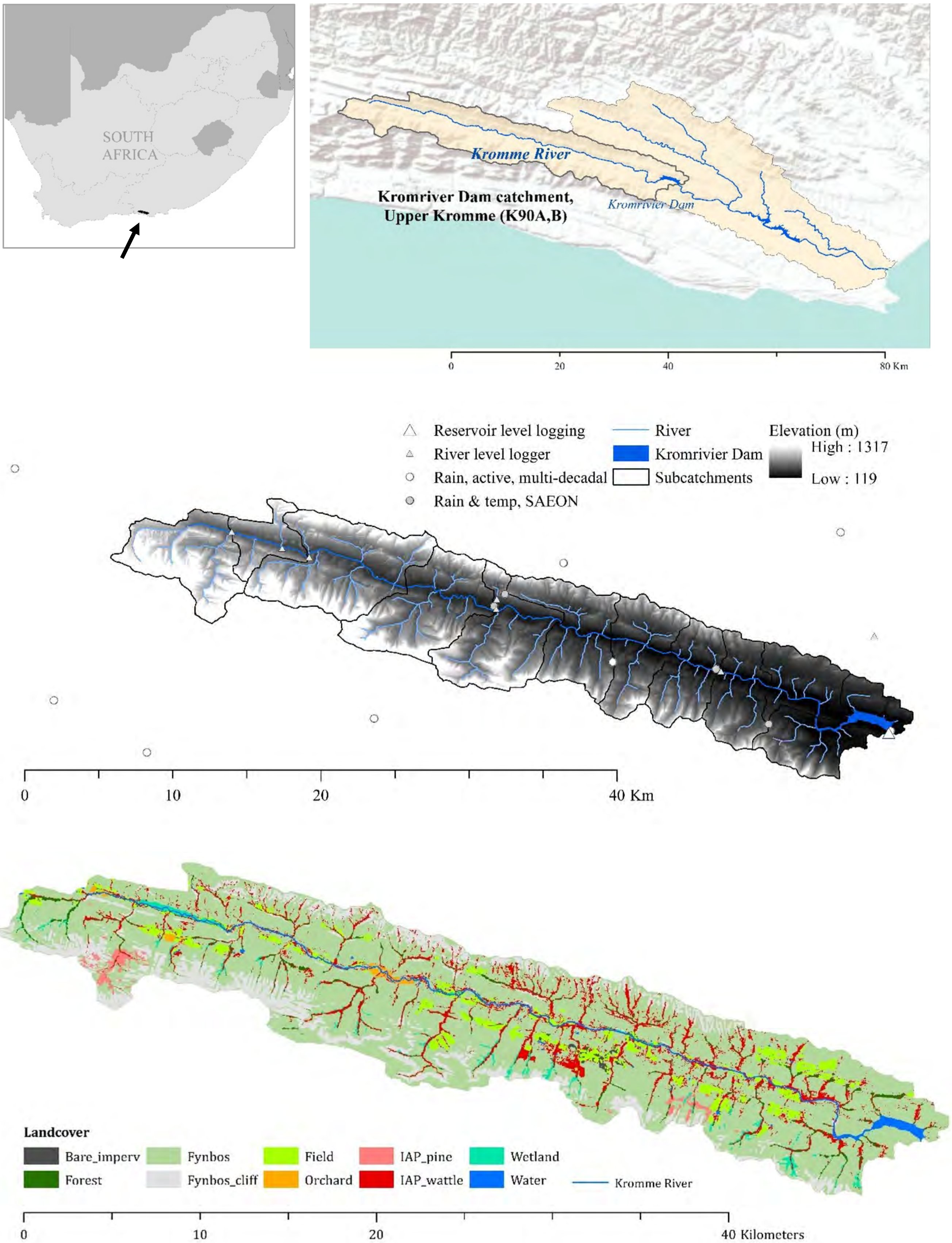


Figure 5.24: Location of the Upper Kromme case study catchment (top), subcatchments and monitoring points (middle), and land cover distribution mapped for the baseline/current cover scenario (bottom)

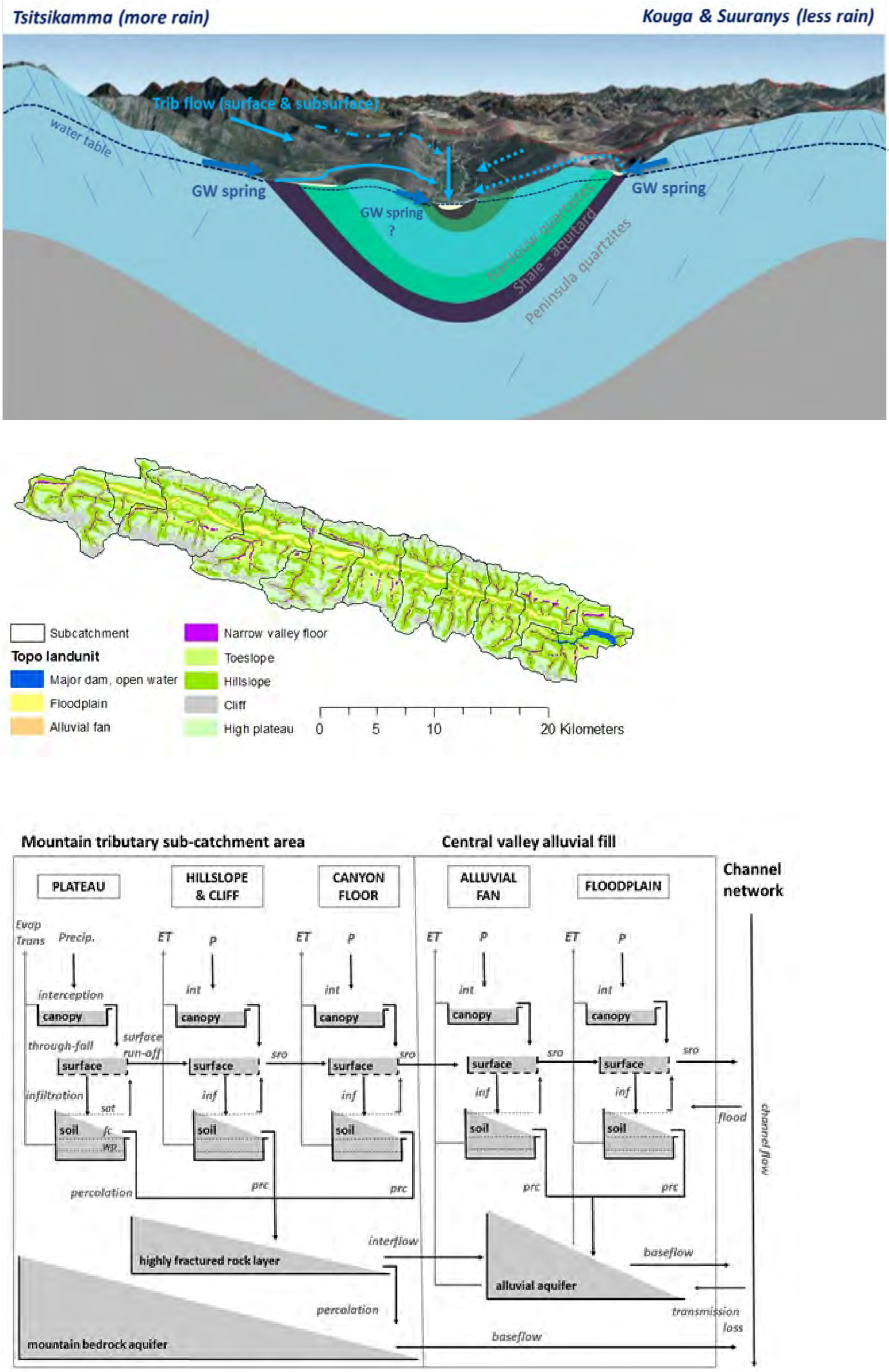


Figure 5.25: Conceptual models of the Upper Kromme catchment, geology and surface-subsurface flow paths (top), topographic land units (middle) and model structure built in MIKE-SHE (simpler options) (bottom) (Cornelius et al., 2019)

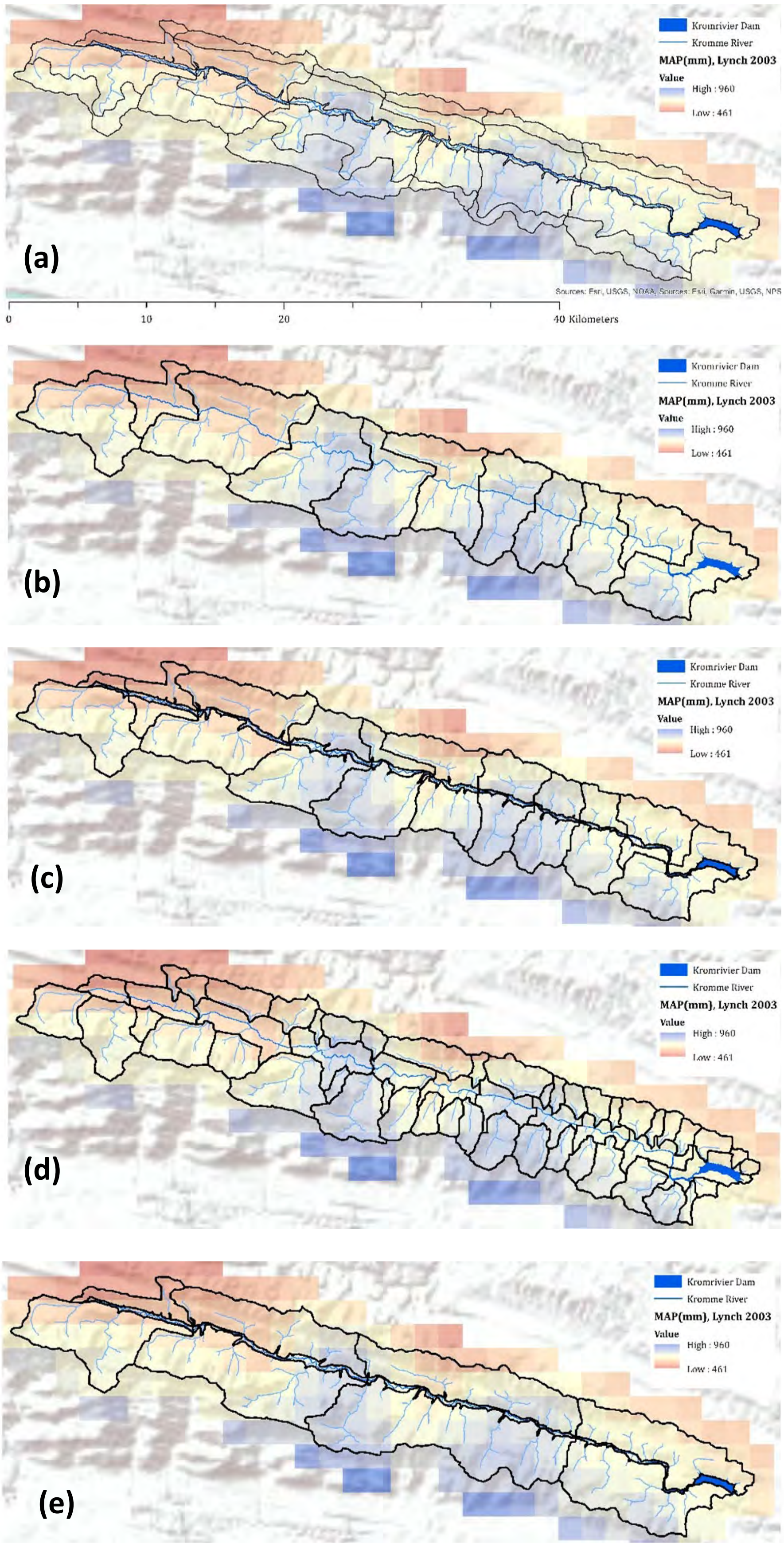
5.5.2 Highlighted representation issue – subcatchment delineation trade-offs between spatial rainfall gradients and surface-subsurface flow connectivity representation

For several of the tools used, trade-offs had to be made in trying to both explicitly include spatial rainfall gradients and represent the landscape surface and subsurface flow connectivity, understood to be an important part of the Kromme River catchment's hydrology (Cornelius et al., 2019; Tanner et al., 2019). Trade-offs were the result of the ways climate inputs were assigned, ways that subcatchments could be specified, and flow pathways allowed between modelled units in the different tools.

Spatial averaging over large rainfall gradients for model inputs can be problematic if this frequently results in no areas in the modelled landscape reaching wetness thresholds of runoff generation, when in reality the wettest parts of the area get sufficient rain to produce flows that actually reach the outlet of interest. Because semi-arid landscapes less frequently reach thresholds of runoff production, higher levels of spatial discretisation of rainfall inputs have been found to be more important in improving model accuracy than for wetter catchments (Clark et al., 2008; Maneta et al., 2008). As such, an effort was made to explicitly consider observed north-south and east-west rainfall gradients when modelling the Kromme River catchment.

In some of the tools, an effort to include the climate gradient impacted on the approach to delineating subcatchments. In SWAT2012 and both Pitman model tools, climate inputs are specified at the level of a subcatchment. In ACRU4, individual HRU's can be assigned separate climate inputs. However, the timeseries preparation and manual series linkage entry process needed for specifying HRU climate inputs that were different to the subcatchment climate was found to be highly arduous and time-consuming compared to applying the subcatchment reference climate. Even if a group of HRUs, such as all the HRUs in the southern mountains, were assigned the same climate inputs in ACRU4, if this climate dataset were different to the subcatchment reference climate, the full process of data linkage for each climate parameter would need to be followed for each individual HRU. This level of effort was considered outside of "typical use" given the number of HRUs used. Different to other tools, in MIKE-SHE, at any complexity level, climate inputs can be specified for user-defined zones, which are independent of any subcatchment delineations. Data cubes of climate surfaces can also be used.

Separating the mountains on the north and south into different subcatchments to apply different climate inputs in SWAT2012, ACRU4 and the Pitman tools led to other representation challenges. The north and south tributary catchments both feed into the same body of alluvial fill and the same trunk stream in the central valley of the catchment. One option would have been to assign the southern half of the central floodplain to the southern subcatchments and the northern half to the northern subcatchments. This would maintain some of the connectivity options available within subcatchments, but could also lead to a wetter southern half of the alluvial aquifer, potentially resulting in outflows it would not actually have if that water had been distributed across the full valley area. In ArcSWAT2012, such a delineation would not even be possible to input in any case as the tool delineates drainage lines and subcatchments within its interface based on the input DEM. Instead, south and north mountain tributary subcatchments were delineated to the entry of the central valley and a separate central valley subcatchment was included.



Climate zones used for rainfall inputs into MIKE-SHE (a),

11 subcatchments used in MIKE-SHE simple set-up (b),

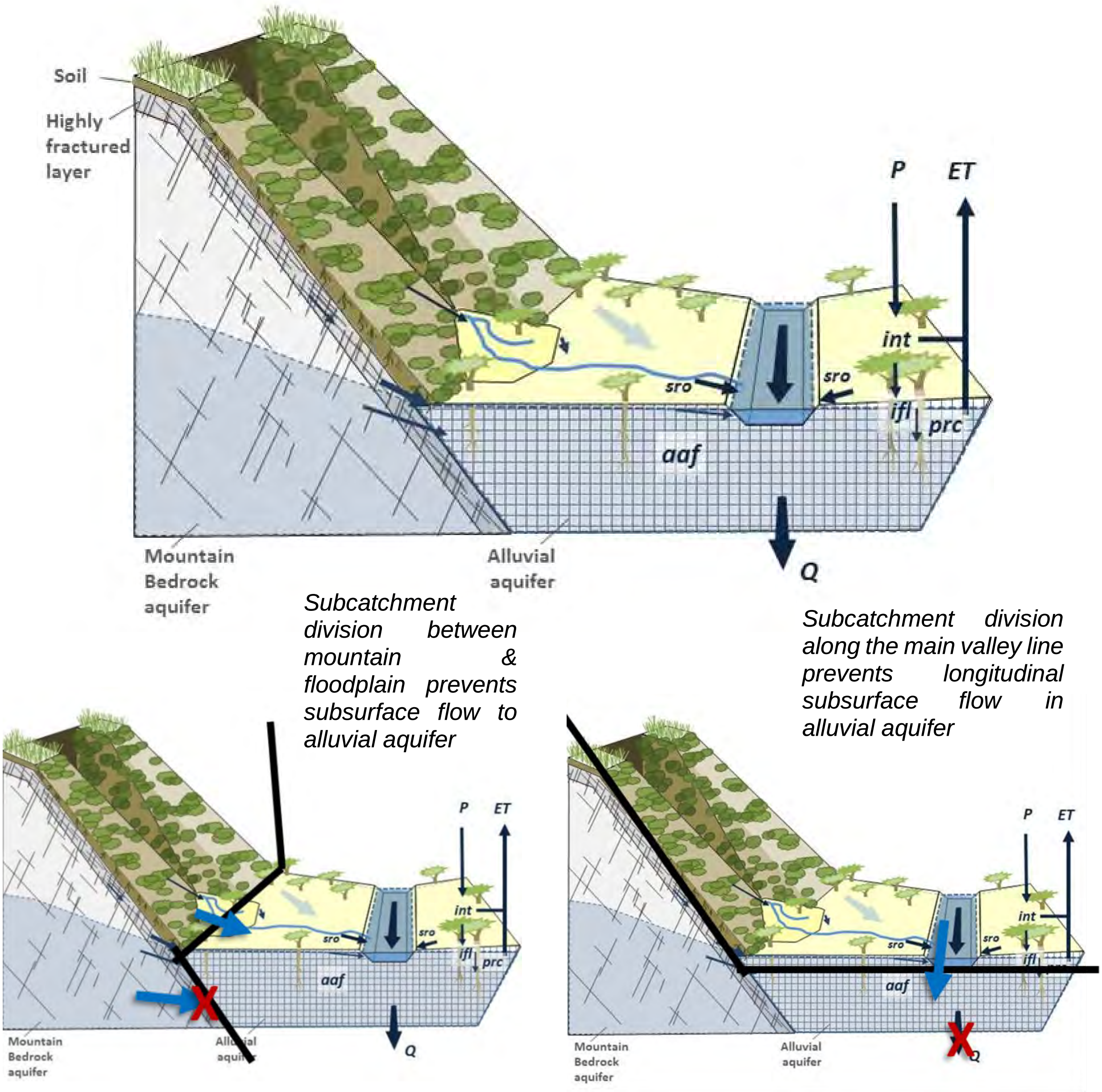
33 subcatchments used in SPATSIM to approximate the climate and subcatchment separation in MIKE-SHE (c),

55 subcatchments used in SWAT2012 because separating north and south required delineating individual tributary subcatchments (d),

12 subcatchments used in ACRU4 & WRSM to capture gradients while reducing manual input complexity (e)

Figure 5.26: Climate zones and subcatchments across tools used to model the Upper Kromme River catchment (approximate MAP distribution from Lynch, 2003)

Separating areas into different subcatchments limits the modelled flow connections between these areas in the different tools. WRSM and SPATSIM-Pitman can include ground water flow between subcatchments if sufficient gradients are predicted. In SWAT2012, ACRU4 and MIKE-SHEs (simple options), there is no subsurface flow between subcatchments in the model. In SWAT2012 and ACRU4, where the mountains and the central valley were separate subcatchments, this meant that the subsurface flows from the mountain tributary subcatchments that are known to reach the alluvial aquifer (Cornelius et al., 2019; Tanner et al., 2019) would need to be represented as additional surface flow, leaving the mountain subcatchments in the channel network. Once in the channel network, the different tools offer different ways that this water could get into the alluvial aquifer. This is an important process for predicting sufficient AET for the wetland and IAP invaded areas of the central floodplain. This was attempted using channel transmission losses in SWAT2012 and riparian zone river threshold overflow in ACRU4, although neither approach was likely to sufficiently capture the alluvial aquifer recharge from the mountains.



Subcatchment division between mountain & floodplain prevents subsurface flow to alluvial aquifer

Subcatchment division along the main valley line prevents longitudinal subsurface flow in alluvial aquifer

Figure 5.27: Conceptual diagram of mountain-floodplain connectivity and down-valley longitudinal ground water flow in the Kromme River catchment, illustrating how model subcatchment boundaries could interfere with process representation

The subcatchment delineations used and inherent trade-offs by tool are described below. The selections were driven by maintaining the climate gradient representation. However, given the major connectivity compromises this was found to come with, it would be a useful further exercise to test the relative performance and water balance of model structures with more lumped subcatchments that spanned both mountain ranges and floodplains. These would have more spatially averaged climate inputs, but more conceptually representative surface and subsurface flow pathways.

WRSM-Pitman (Sami ground water)

WRSM was set up with 12 subcatchments, derived from four subdelineation points, selected moving east to west along the main trunk stream and subdividing these subcatchments further into three to capture the north and south mountains and the central valley receiving area. The three north-south divisions were made using topographic zonation rather than contributing areas to a point on a stream. The north and south mountain tributary subcatchments in the model were therefore lumped representations of multiple neighbouring, parallel tributary catchments. The four east-west divisions were a reduction from the 11 east-west subcatchments used in the original MIKE-SHE model set-up. This was done because of the relatively intensive manual process of setting up modules in WRSM. Points were selected at the outlets of the main wetland basins and monitoring points.

High ground water gradient parameters were used for the mountain tributary subcatchments, compared to the central valley. However, the degree to which this actually produced ground water flow from the mountain subcatchments to the central valley subcatchments still needs to be evaluated. Flow leaving the mountain tributary subcatchments as channel flow cannot be made available to the central valley subcatchment. Unlike in SPATSIM-Pitman, channel transmission losses in WRSM are removed from the model completely.

SPATSIM-Pitman (Hughes ground water)

SPATSIM was set up with 33 subcatchments, derived from the 11 subcatchments delineated east to west that were used in the starting MIKE-SHE (simple options) set-up, each then subdivided into three to capture the north and south mountains and the central valley receiving area. This was facilitated by the relative ease of setting up many subcatchments in SPATSIM as it uses a parameter table-importing system. Each north and south mountain subcatchment in the model was a lumped representation of several neighbouring, parallel tributary catchments.

The degree to which the model ground water gradients actually produced ground water flow from the mountain subcatchments to the central valley subcatchments still needs to be evaluated.

Central valley areas were given access to some of the water leaving the mountain tributary catchments as channel flow by parameterising for high channel transmission losses in the central valley subcatchment. Channel loss water is added to the subcatchment ground water, available to meet ET demand deficits of vegetation in the specified riparian portion of the subcatchment.

ACRU4

ACRU4 was set up with the same 12 subcatchments as WRSM. Again, this reduction versus the starting MIKE-SHE structure was done because of the relatively intensive manual process of setting up HRUs in ACRU. This delineation meant that subsurface flows from mountain HRUs could not be directly routed to central valley floodplain HRUs. If the mountain areas and central valley were in the same subcatchment, subsurface flow from mountain HRUs to the central valley soils would have been possible using the special riparian zone HRUs for the central valley areas. However, in the set-up that was used, with separate mountain and central valley subcatchments, riparian zone HRUs were used within the mountain tributary subcatchments to represented water access of wattle and forest occurring along the mountain tributary streams.

In reality, much of the subsurface flow from uplands in the tributary subcatchments would concentrate along the tributary drainage lines first, and then flow along the surface and subsurface to the central floodplain. Subsurface flows from an upland HRU can only be directed to one riparian zone HRU. If mountain and central valley HRUs were included in one subcatchment for the purpose representing their subsurface connectivity, in order to achieve both mountain tributary riparian zone water access and central valley riparian zone water access in ACRU4, the upland areas in the mountains would have to be subdivided further into HRUs that feed subsurface flow to the tributary riparian zones and others that feed subsurface flows to the central valley riparian zones. It would not have been obvious how this subdivision should be done.

ACRU4 does not represent channel bed losses. A workaround was employed to give the central valley HRUs access to some of the water leaving the mountain tributary subcatchments as channel flow. Central valley HRUs were set up as riparian zone HRUs, which meant that they could receive overflow water from their associated river channel unit. A river channel flow threshold is input, and flows in excess of this are distributed onto the riparian zone HRU surface where they can infiltrate. This approach was considered to be suitably realistic for the portions of the central valley that have intact, unchanneled palmiet wetlands. In these areas, a channel overflow threshold of 0 was applied, so that all incoming channel flow was distributed across the wetland HRU surface, as would occur in reality.

This strategy was recognised as less than ideal when applied to the channelised parts of the central valley, which are the majority currently. It would be a suitable representation if a dominant source of floodplain alluvial aquifer recharge was overbank flooding. It is not a realistic representation of alluvial aquifer recharge from more consistent subsurface flow inputs, which is the standing conceptual model for the Kromme River catchment (Cornelius et al., 2019; Tanner et al., 2019). In this case, the recharge process would be occurring at lower rates all the time, rather than in episodic peak events. It would be better represented as a proportional loss from all channel flows, as done to represent channel bed loss in other tools. Looking at a longer-term average water balance, the approach could potentially succeed in allocating appropriate amounts of the mountain area outflows to the central valley alluvium. However, representation as a peak threshold process likely hindered calibration of daily peak flows. Given that, in reality, this is not a channel flow threshold process. There was no obvious physically rationalised way to select the overflow threshold. Allocating all the channel flow to the floodplain surface (0 flow threshold) resulted in too great a loss and was not considered realistic. The 50th percentile flow at the catchment outlet, scaled by the contributing catchment areas to the different river outlets in the model, was used as a first attempt and was progressively scaled back to the 75th percentile, reducing the average contribution to the central valley HRUs.

ArcSWAT2012

ArcSWAT2012 was set up with 55 subcatchments. This included the 11 subcatchment division points along the trunk stream in the main subcatchment, but also separated 44 individual mountain tributary stream subcatchments. This was done because ArcSWAT2012 delineates channels and subcatchments within the model interface based on the DEM input by the user. The user can select the flow accumulation limit for the channel definition and pick the outlet points along the channels to define subcatchments. To separate the northern and southern mountain areas, as was done in the other tools for separate climate inputs, subcatchment outlets needed to be located on the tributary streams where they meet the central valley. Lumping several parallel tributaries was not an option. However including many subcatchments and HRUs in an ArcSWAT model set-up requires relatively little additional input compared to using fewer subcatchments and HRUs. Parameters are input by soil type and land cover type applicable across the catchment, and climate inputs are added using a table of references to the required timeseries files for all subcatchments in the model.

This delineation meant that no ground water flow was simulated from the mountain areas to the central valley alluvium in the model. To give the central valley area access to some of the water leaving the mountain tributary areas as channel flow, channel transmission loss was included, similar to the approach in SPATSIM.

In SWAT2012, the channel transmission loss is added to a conceptual bank storage reservoir separate from the shallow aquifer of the subcatchment. The bank storage can be drawn upon to meet ET demands, although limited to 20% of the demand, similar to that governed by the same limitation as aquifer capillary rise. The bank storage also has a lagged outflow back into the channel. This representation may be adequate for the channelised portions of the central valley, but does not represent the water access of the unchanneled valley bottom wetlands. More of the ET demand is likely being met by water sourced from mountain areas (rather than the storage of direct rainfall).

MIKE-SHEs (using simpler options)

MIKE-SHEs was set up for the Upper Kromme River using 11 subcatchments delineated for points of interest and geomorphology change along the main river channel of the central valley. Each subcatchment therefore spanned the mountain areas on both the north and south side, and the central valley floor area. MIKE-SHE allows climate inputs to be specified by zones that are independently defined and do not need to correspond to subcatchments. Rainfall, interception, infiltration, ET and percolation are calculated at the grid cell scale for both the simple and complex sets of options in MIKE-SHE. In this set-up, within each subcatchment, surface overland flow, interflow and aquifer flow were routed through successive units from mountain uplands to tributary drainage lines and into the central valley. This allowed the desired rainfall distribution and flow connectivity within subcatchments.

Ground water flow between subcatchments is not considered in the model. While this is not a concern for mountain-to-valley connectivity in this set-up, it prevents modelling any subsurface flow along the length of the central valley in the alluvial aquifer. This may be a minor process relative to the flow inputs from the surrounding mountains, but unchanneled wetlands lower down in the catchment are also fed and recharged by incoming main channel flows. This was considered by including channel transmission losses along wetland reaches. Water lost from the channel is added to the underlying aquifer storage reservoir, which can feed the ET demands of the overlying vegetation.

MIKE-SHEc (using more complex, distributed options)

MIKE-SHEc does not use input subcatchments. Surface and subsurface saturated flows are routed based on gridded topography, head gradients and conductivity or roughness. Zonal climate inputs were the same as those used in the simpler set-up. This set-up meant that aquifer flow into the mountain tributaries and into the central valley floodplain would be simulated if given appropriate parameterisation of the subsurface layers. This is challenging to achieve, given limited information regarding actual local rock layer depths and properties.

5.5.3 Modelling outcomes

Models of the Upper Kromme River catchment were completed for both the baseline, current cover scenario and a relatively extreme IAP coverage expansion scenario (IAPx) using four of the five tools: SPATSIM-Pitman, ACRU4, SWAT2012 and MIKE-SHE. A baseline WRSM model was designed, but calibration and scenario modelling was not completed in the time available. The IAPx scenario assumes that all IAP clearing efforts cease, and wattles and pines expand to all non-farmed, non-developed, non-cliff areas, 67% of the catchment. Model structures and parameterisations were guided by the pre-existing MIKE-SHE model of the catchment (Appendix C3). Calibration adjustments were made by comparing modelled streamflow to estimated streamflow into the Kromme River Dam, as provided by DWS for 1960 to 2017-09-10 (start of data gap). This is based on recorded dam levels, outflows and evaporation rates, level volume-surface area relationships from bathymetry, and a level-spill rating curve from wall dimensions. These are used to calculate a dam water balance with stream inflow as the residual. Because of uncertainties and potential errors in all the contributing measures, this estimated inflow series is likely less accurate than a weir record, particularly at a daily timestep. As such, calibration focused on monthly performance. Models were run with a three-year warm-up period. Adjustments made to improve performance are described in Appendix C3.

Model predictions vs observations

Flow duration curves (FDCs) and hydrographs for the calibration period are shown in figures 5.28 to 5.30, with statistics given in Table 5.15. Models built in SWAT2012 and MIKE-SHE slightly underpredicted mean flow by 2–3%, while those built in ACRU4 and SPATSIM overpredicted it by 14–17%, just over the 15% target. Models built in SWAT2012, ACRU4 and MIKE-SHE achieved targets for monthly NSE and R^2, with an NSE of 0.65–0.86 and an R^2 0.72–0.87. The MIKE-SHEs model had the best performance statistics for untransformed data (monthly NSE of 0.86, R^2 of 0.87). Despite 14% overprediction of the mean, the ACRU4 model's fit statistics were very close to MIKE-SHE (monthly NSE of 0.85, R^2 of 0.85). The NSE of the log-transformed flows was higher than for the MIKE-SHEs model (0.66 vs 0.48), showing better prediction of lower flows. SWAT2012 captured the average better than ACRU4, but had poorer fit statistics. The model built in SPATSIM had a monthly NSE of 0.55, close to the 0.6 target, and an acceptable R^2 of 0.70, but the NSE of log transformed data was poor, 0.06. For the daily timestep models, daily performance statistics were much lower than monthly performance statistics: an NSE of 0.22–0.32 for untransformed data and 0.08–0.24 for log-transformed data. Although these values are below the 0.5 daily NSE target, the "observational" data was derived from the dam water balance, rather than direct streamflow gauging, making values more uncertain.

Table 5.15: Statistics for observed and modelled streamflow entering the Kromme River Dam

Statistic	**Observed**	**SPATSIM**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**
Monthly streamflow yield (mm^3 per month), January 1960 to August 2017					
Mean	3.91	4.57	4.44	3.83	3.80
difference vs observed		*0.67*	*0.54*	*-0.07*	*-0.10*
percentage difference		*17%*	*14%*	*-2%*	*-3%*
Standard deviation	8.94	4.14	7.94	5.25	7.48
Coefficient of variance	2.29	0.90	1.79	1.37	1.97
Minimum	0.01	1.22	0.03	0.04	0.01
5th percentile	0.15	1.55	0.16	0.44	0.05
25th percentile	0.53	2.19	0.62	1.17	0.25
50th percentile	1.2	3.1	1.8	2.2	1.2
75th percentile	3.1	5.3	4.9	4.2	4.0
95th percentile	16.3	12.7	17.8	12.1	16.3
Maximum	95.1	33.8	75.1	49.4	70.3
RMSE		5.98	3.46	5.26	3.30
MAE		3.03	1.82	2.22	1.54
NSE		0.55	0.85	0.65	0.86
NSE log		0.06	0.66	0.49	0.48
R^2		0.70	0.85	0.72	0.87

Statistic	**Observed**	**SPATSIM**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**
Daily streamflow (cm), 1960-01-01 to 2017-09-10					
Mean	1.49		1.69	1.46	1.45
difference vs observed			*0.20*	*-0.03*	*-0.04*
percentage difference			*14%*	*-2%*	*-3%*
Standard deviation	8.39		7.45	4.03	6.90
Coefficient of variance	5.64		4.41	2.76	4.77
Minimum	0.00		0.01	0.00	0.00
5th percentile	0.00		0.04	0.07	0.01
25th percentile	0.10		0.18	0.33	0.03
50th percentile	0.38		0.52	0.73	0.16
75th percentile	1.02		1.26	1.48	0.92
95th percentile	4.85		4.66	4.28	5.13
Maximum	576.95		350.72	223.50	331.68
RMSE			7.12	7.39	6.94
MAE			1.26	1.16	1.22
NSE			0.28	0.22	0.32
NSE log			0.24	0.08	0.21
R^2			0.36	0.22	0.36

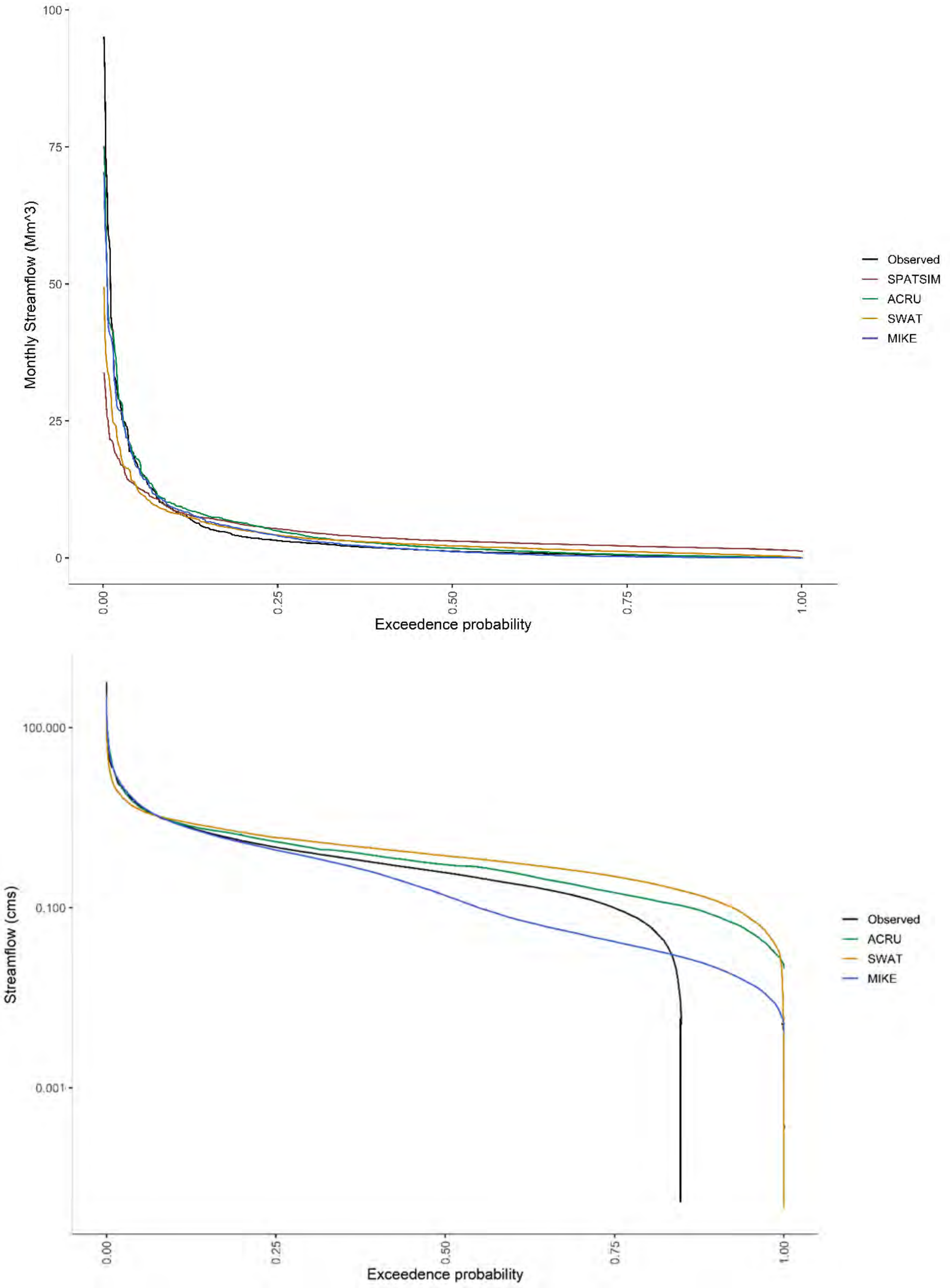


Figure 5.28: Observed and modelled monthly and daily flow duration curves for inflow into the Kromme River Dam (Note: daily streamflow displayed on a log axis, 0 cm values shown as 0.00001 cm)

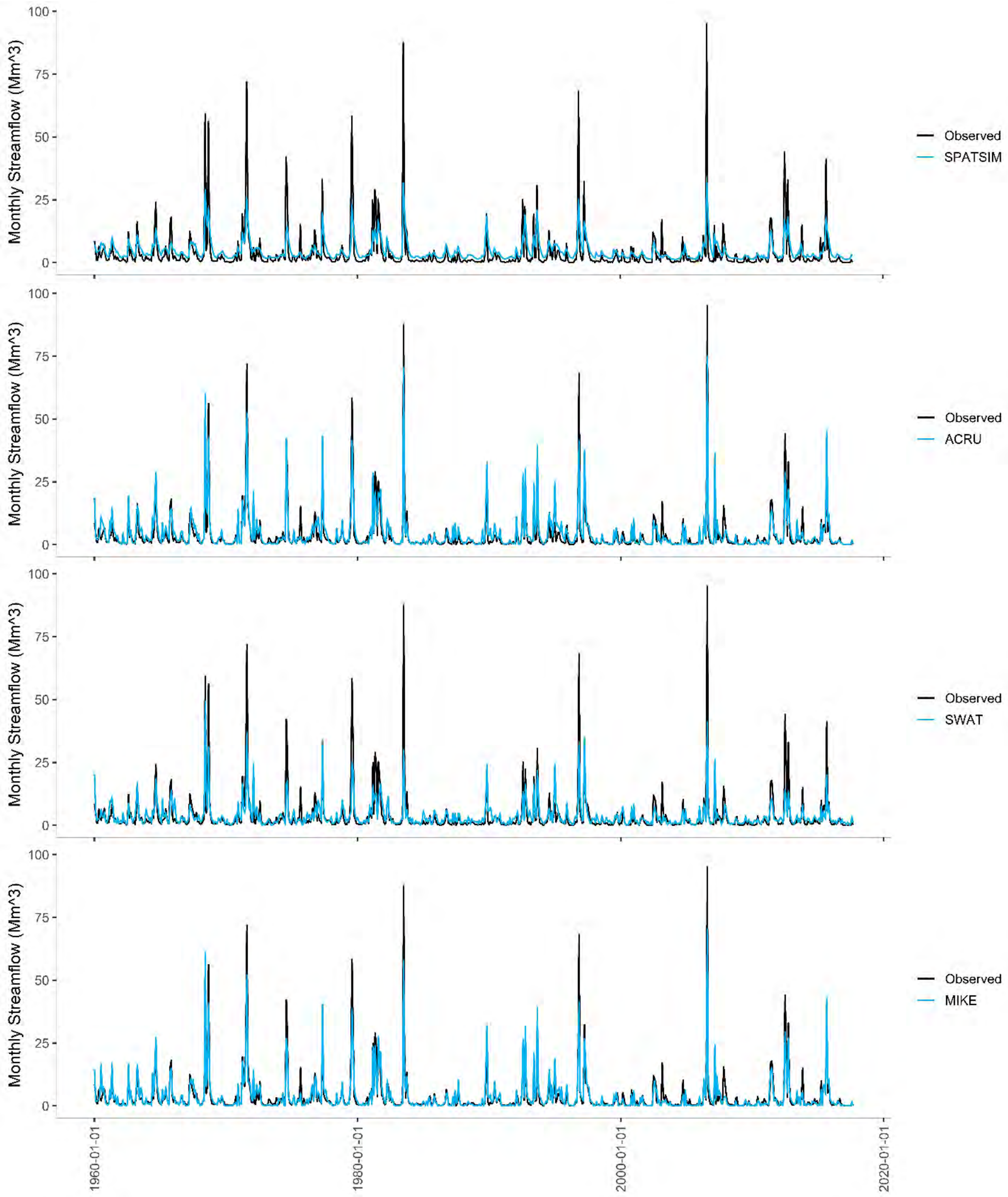


Figure 5.29: Observed and modelled monthly hydrographs for inflow into the Kromme River Dam, 1960 to 2018, for models built in four modelling tools

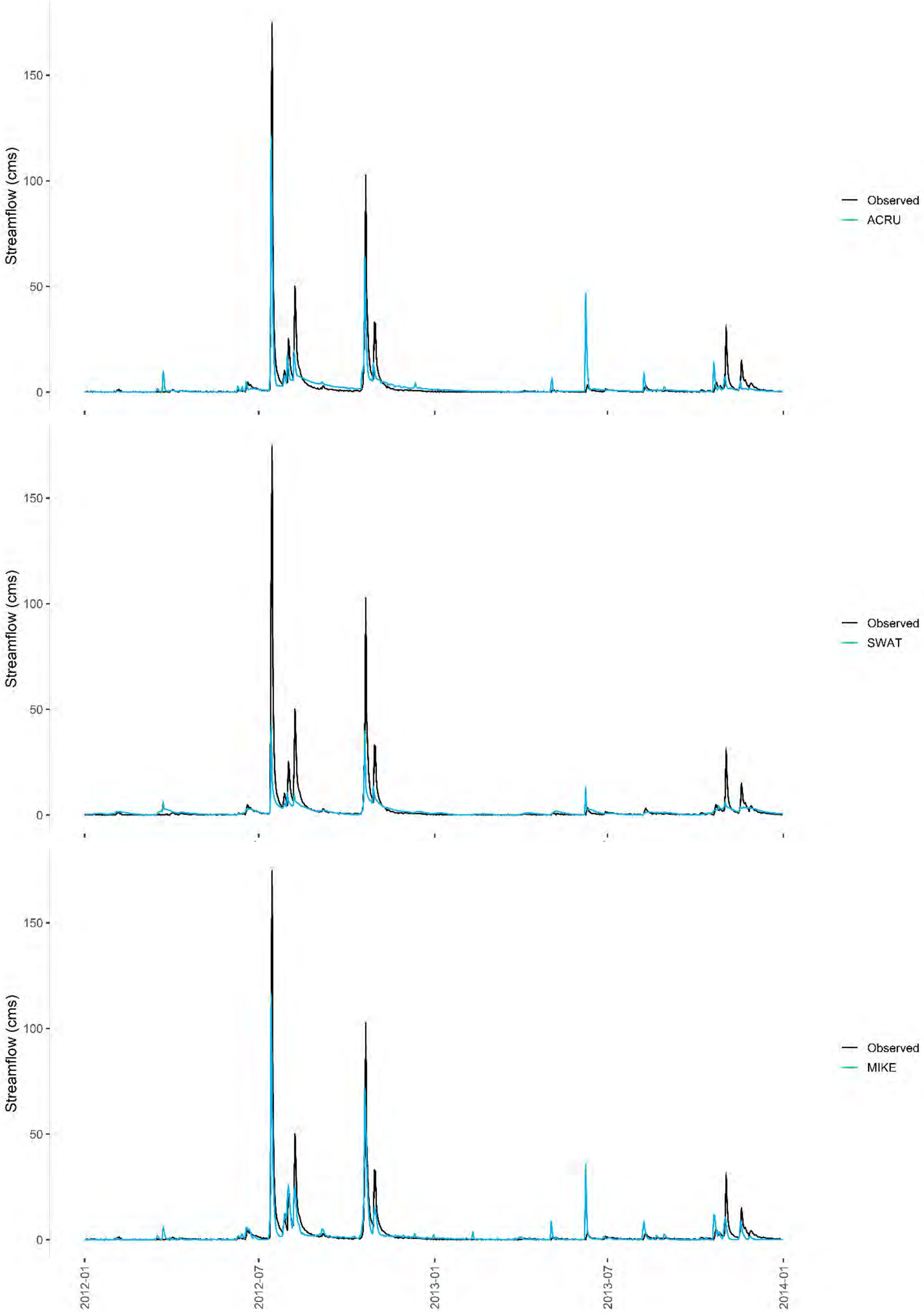


Figure 5.30: Observed and modelled daily hydrographs for inflow into the Kromme River Dam, 2012–2013 two-year demonstration period, for three daily timestep models

Some model performance shortcomings may be attributed to the data used for input and assessment. Hydrographs show the relatively “flashy” streamflow in the Kromme River: sharp peaks and steep recessions. None of the models captured the highest peaks very well, even at a monthly timestep, with all underpredicting these. This may be due to inaccurate rainfall inputs given the lack of actual measurements in the high mountains where it rains the most. Much poorer daily fit statistics compared to monthly fit statistics were partially because models often predicted peak flows a day before the peak in the dam inflow dataset. This could be a flow lag problem in the models or an issue of various measurement timings in the dam water balance inflow dataset. Looking at low flows, the estimated streamflow from the dam water balance calculation suggested that there was essentially no flow into the Kromme River Dam on about 10% of the days. However, this may be an artifact of the dam water balance calculation: estimated daily inflow to the dam calculated this way fluctuated up and down during low-flow periods more than would be expected for a stream in a baseflow condition.

Beyond these issues they had in common, the hydrographs and FDCs illustrate how the models differed in their patterns of inaccuracy, indicating differences in process representation. Although they underpredict for the very highest peaks, models built in MIKE-SHE and ACRU4 showed reasonable fits for the higher flows, e.g. around the 95th percentile and 5% exceedance range. In comparison, SWAT2012 and SPATSIM models notably underpredicted higher flows, suggesting that too little surface and/or fast subsurface flow was generated or too little made it to the outlet. Most of the models overpredicted medium and low flows, except for the MIKE-SHEs model, which generally underpredicted these, showing steeper recession than the observed flow, but not predicting complete drying out, such that the very lowest modelled daily flows were higher than the dam water balance values. Of the set, the ACRU4 model most closely replicated the lower flows. These differences reflect different degrees of storage and drainage from soil and ground water stores and amounts drawn for ET.

Water balance comparison for current cover scenario models

Models of the Upper Kromme River catchment predicted similar runoff ratios, 20–24% for the period assessed. However, the modelled streamflow source compositions differed substantially. Modelled annual average water balances for 1960 to 2018 under the current cover scenario are presented in Table 5.16. Not all listed fluxes are output by all tools, and some classification of outputs into these categories is not equivalent (section 4.7.5). However, these are the outputs a user would get.

- Interflow was the dominant path in the SWAT2012 and MIKE-SHEs models, accounting for 58% and 65% of the flow reaching the dam, respectively. Interflow was the smallest contributor in the ACRU4 and SPATSIM models. It still made a sizeable contribution (31%) in the ACRU4 model, which predicted a near even split across sources, but was small (10%) in the SPATSIM model.
- Surface runoff was the dominant runoff source in the SPATSIM model, contributing 53% of the total runoff. It should be noted that, in SPATSIM, this is before runoff passes through wetland units. Surface flow was the second contributor (33%) in the ACRU4 model and the lowest in the SWAT2012 (17%) and MIKE-SHEs (8%) models.
- Aquifer outflow was the dominant average contributor (36%) in the ACRU4 model, although the model predicted relatively similar contributions across sources. The SPATSIM model predicted a very similar 37% contribution, while SWAT2012 and MIKE-SHEs predicted the least at 24% and 27%, respectively.

The MIKE-SHEs and SWAT2012 models had the most similar distribution of flow path contributions (interflow > aquifer > surface flow) across the set of models and the closest prediction of the mean annual flow in the calibration period, so it was interesting that their predicted temporal distribution of flow and patterns was quite different. The SWAT2012 model underpredicted higher flows and overpredicted middle and low flows, indicating that the interflow release, and potentially the aquifer outflow, was slower than the MIKE-SHEs model. The model built in ACRU4 predicted a very different distribution of runoff pathways to the one built in MIKE-SHEs, with more surface and aquifer outflows, but had similar overall fit statistics and a better prediction of lower flows.

Despite appearing to predict much more surface runoff than the other models, SPATSIM underpredicted high monthly flows and overpredicted medium and low flows more than the other models, the opposite of what might be expected. This is at least in part because the “runoff sources” were categorised using subcatchment outputs before outflows passed through the wetland storage unit in the model, which would delay even runoff from reaching it as “surface flow” if there was storage space available. In other tools, the wetlands were land units, which contributed to the calculation of surface flow, interflow and ground water outflow outputs the tools produce.

The MIKE-SHEs and SWAT2012 models predicted similar average annual AET for the calibration period, 514–515 mm, higher than the other two models. The ACRU4 model predicted the lowest average annual AET (485 mm) of the set and yet did not predict the most runoff. The SPATSIM model predicted both more average annual AET (504 mm) and more runoff than ACRU4, associated with a net loss of water stored in the landscape. This was supported, in part, by storage in the model’s wetland units. The ACRU4 model predicted a net increase in storage. This was not explored fully, but the initial wetness of the riparian HRUs may have been too low. These receive water from uplands in the model and may have built up storage that was then maintained. The other two models predicted more negligible average storage changes, both with a small net loss.

The relative contributions of different fluxes to total AET differed across models:

- Canopy interception evaporation accounted for 11–20% of total annual average AET in models that output this. The ACRU4 model predicted the least, 55 mm, versus 71 mm in MIKE-SHEs and 103 mm in SPATSIM.
- Of the models with this output, the average annual contribution of ground water to AET in SPATSIM was the greatest (38 mm, 7% of average total AET) and the least in SWAT2012 (14 mm, 3%), with MIKE-SHEs in the middle (23 mm, 4%).
- Evaporation from farm dams contributed less than 1% (0.3–0.4%) to the total AET across all models without large variability in the average annual amounts (1.5–2.1 mm, catchment scale)
- Representation of the palmiet wetlands differed substantially across the models (Appendix C3) and resulted in different predicted AET. In both the ACRU4 and MIKE-SHEs models, these were riparian land units with greater vegetation water access. These had similar AET predictions (3 mm, catchment scale, 0.6–0.7% of total AET). In SPATSIM, these were more similar to an open water body, and the predicted average annual AET was much higher (16 mm, 3%). In SWAT2012, there was a land cover unit and also a rough, wide channel reach with bank storage, and the predicted AET contribution was closer to SPATSIM (10 mm, 2%).

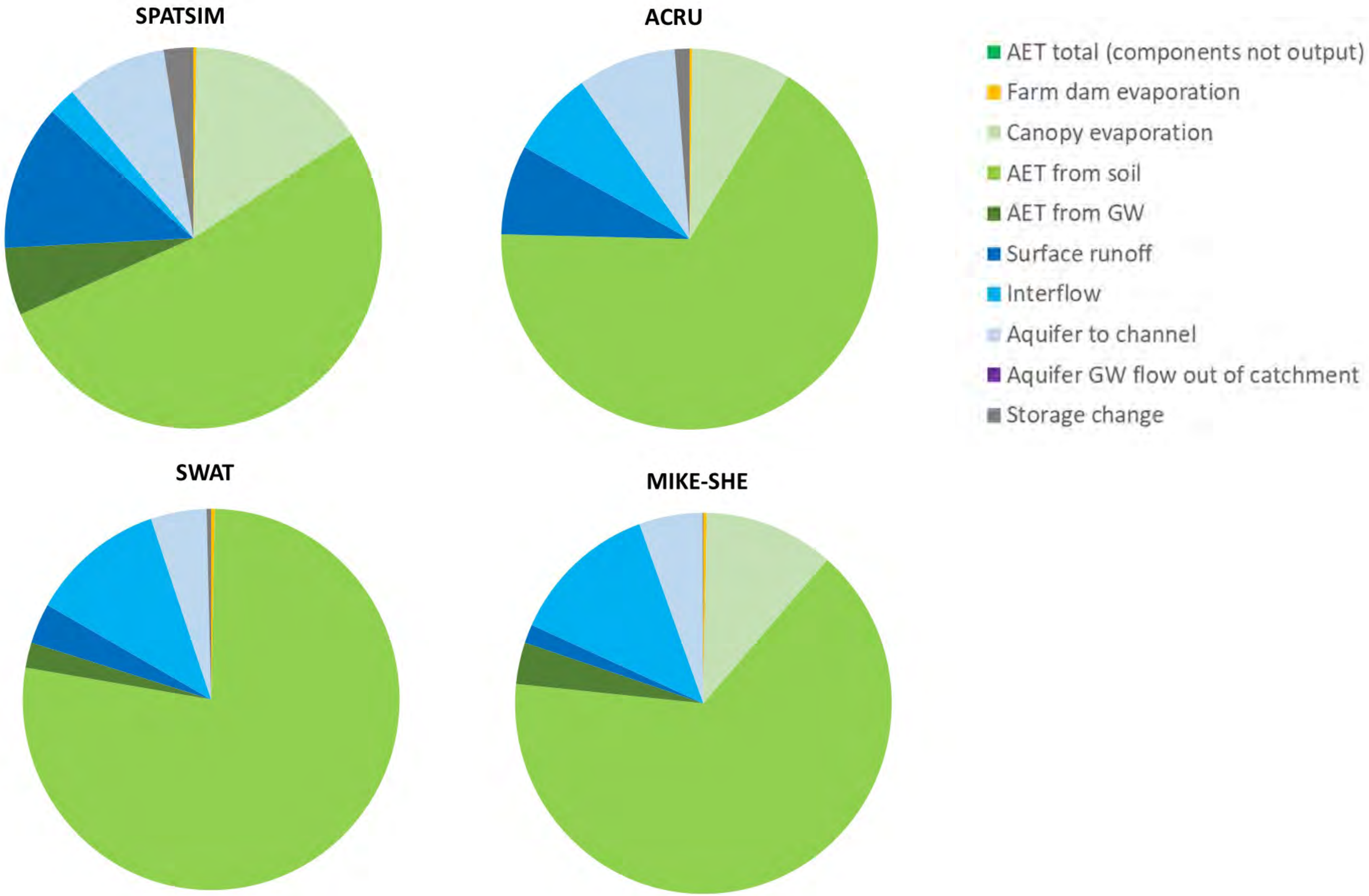


Figure 5.31: Modelled mean annual water balances for the Upper Kromme River catchment for 1960-01-01 to 2018-12-31, predicted using four different modelling tools shown as proportions of catchment mean annual precipitation (Note: Not all fluxes are modelled or output by all tools)

Table 5.16: Modelled mean annual water balances for the Upper Kromme River catchment for 1960 to 2018, predicted using four different modelling tools

(All fluxes given in mm over full catchment area)

Mean annual flux	**SPATSIM**			**ACRU4**			**SWAT2012**			**MIKE-SHEs**		
	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*	mm	*Percentage of precipitation*	*Percentage of AET or runoff*
Precipitation	640			640			640			640		
AET total	**504**	***79%***		**482**	***75%***		**515**	***80%***		**514**	***80%***	
Farm dam evaporation	1.7	*0.3%*	*0.3%*	1.5	*0.2%*	*0.3%*	2.1	*0.3%*	*0.4%*	1.8	*0.3%*	*0.4%*
Canopy evaporation	103	*16%*	*20%*	55	*9%*	*11%*				71	*11%*	*14%*
AET from soil*	346	*54%*	*69%*	426	*67%*	*88%*	499	*78%*	*97%*	418	*65%*	*81%*
AET from GW*	38	*6%*	*7%*				14	*2%*	*3%*	23	*4%*	*4%*
Palmiet wetland AET (subset)*	16	*3%*	*3%*	(3.4)	*(0.5%)*	*(0.7%)*	(10)	*(2%)*	*(2%)*	(3.1)	*(0.5%)*	*(0.7%)*
Runoff total	**153**	***24%***		**149**	***23%***		**128**	***20%***		**127**	***20%***	
Surface runoff[#]	81	*13%*	*53%*	49	*8%*	*33%*	22	*3%*	*17%*	10	*2%*	*8%*
Interflow[#]	15	*2%*	*10%*	47	*7%*	*31%*	75	*12%*	*58%*	82	*13%*	*65%*
Aquifer to channel[#]	56	*9%*	*37%*	54	*8%*	*36%*	31	*5%*	*24%*	35	*5%*	*27%*
Aquifer GW flow out of catchment	0.01	*0.002%*		0	*0%*		0	*0%*		0	*0%*	
Net storage change (soil, GW, wetland*)	-17	*-3%*		8.1	*1%*		-2.5	*-0.4%*		-0.5	*-0.1%*	

AET = Actual evapotranspiration; GW = Ground water; Canopy evaporation = Canopy interception evaporation

MIKE-SHEs = MIKE-SHE using simpler, more lumped algorithm options

Note: Missing water balance components indicate that the tool does not save outputs of these components separately, although it may explicitly calculate the flux.

**Modelling tools differ in what is considered ET from soil vs GW and the outputs that can be exported. "AET from soil" includes water on the soil surface, and in the SWAT model, canopy interception is implicitly included in the value presented as "AET from soil" here.*

Palmiet wetland AET: In SPATSIM, wetlands were modelled water body units. These contributed separately to total AET (and storage). For the others, the wetland AET is a subset of the other AET values presented, including components of the total values presented for canopy interception, AET from soil/surface, AET from GW. Subset values are shown in brackets.

[#] *The interpretation of runoff source subdivisions differs somewhat across tools*

Model predictions of change across scenarios

Comparing modelled streamflow for the IAP expansion scenario, in which 241 km^2 (67% of the catchment) is covered with wattle (183 km^2) and pine (58 km^2), to that predicted for the current cover scenario (9% or 31 km^2 IAP cover with 27 km^2 wattle and 3 km^2 pine), all four models predicted a significant decrease in average annual streamflow, with declines ranging from 21 to 59%. The IAP expansion scenario assumed that the palmiet wetlands had been overrun by wattle, drying out and losing their wetland functions. Magnitudes and patterns of predicted change varied notably across the models, with no two models having similar patterns (Table 5.17 and figures 5.32 and 5.33).

- The SWAT2012 model predicted the smallest decrease in average annual yield: 10 mm^3 or 21%. It predicted larger absolute and proportional declines for higher flows and less decline in low flows. Some of the lowest flows were predicted to have no change or a very small increase, potentially linked to the way wetlands were modelled, which were removed in the IAPx scenario.
- The MIKE-SHEs model predicted a somewhat bigger decline in average yield, 15 mm^3 or 32%, with a different pattern of change: largest magnitude decreases for the highest flows, but larger proportional decreases for the median to 75th percentile daily flows compared to both lower and higher flows (similar pattern for monthly flows).
- The ACRU4 model predicted a larger 24 mm^3 or 45% decrease in average flow with a different pattern: larger magnitude decreases for the highest flows and larger proportional decreases for the 10th percentile up to median flows. This produced more proportional change in lower monthly flows (10th to 25th percentiles).
- The SPATSIM model predicted the largest decrease in average annual yield: 32 mm^3 or 59%. The largest magnitude decreases were predicted for high monthly flows (i.e. 75th to 95th percentiles), though not the peaks, and the largest proportional decreases for the lowest flows. Predicted decreases for the low monthly flows were much larger than other models, such that the river was predicted to have no flow almost 5% of the time.

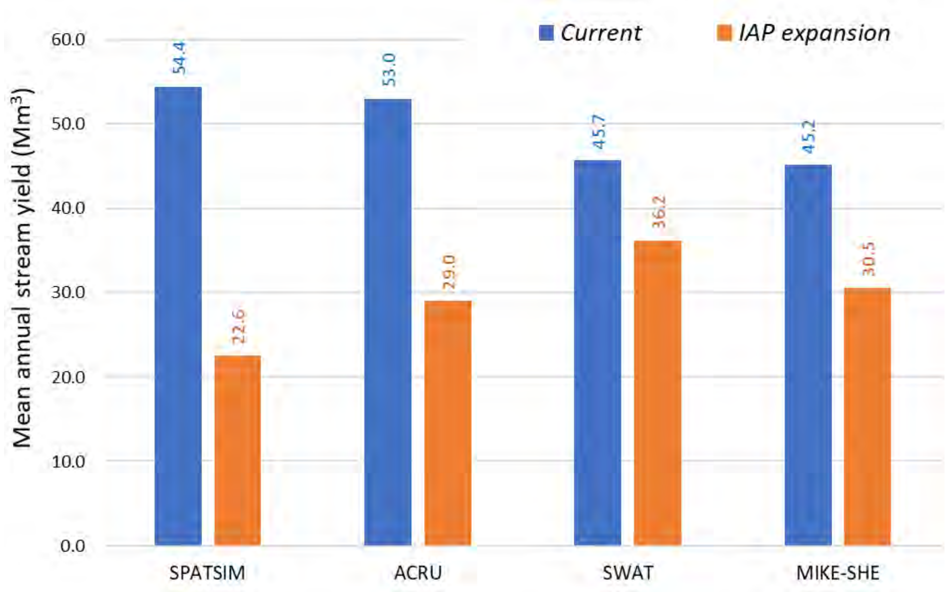


Figure 5.32: Modelled mean annual streamflow yield for the Upper Kromme River catchment for 1960–2018 under the current cover and IAP expansion scenarios, as predicted by four different models

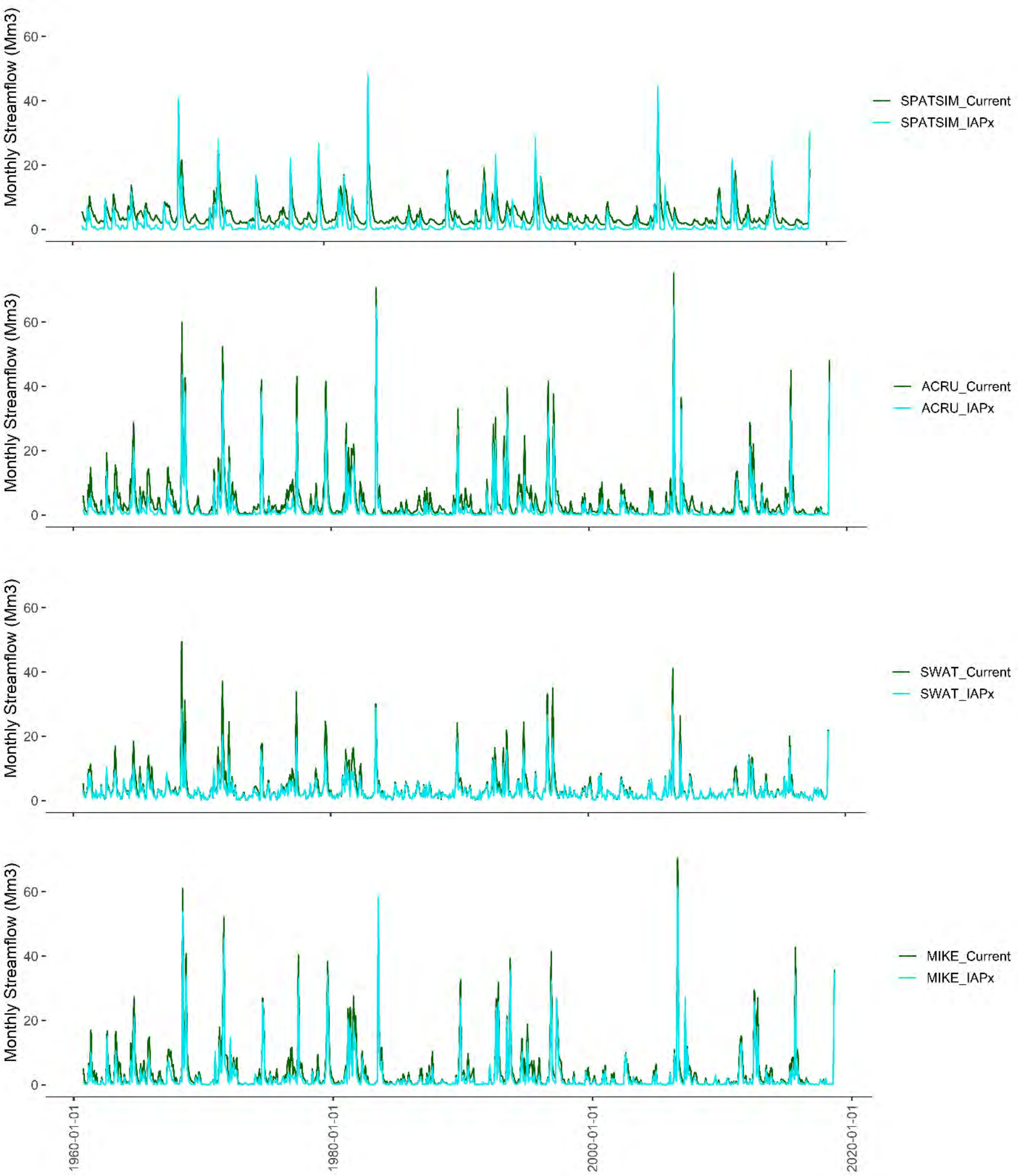


Figure 5.33: Modelled monthly hydrographs for the Upper Kromme River catchment, October 1960 to September 2018, for models built in four modelling tools for two land cover scenarios: current cover and IAP expansion (IAPx)

Table 5.17: Predicted changes in streamflow for the Upper Kromme River catchment with expansion of IAP cover (all clearing efforts cease) compared to the current scenario, using four different modelling tools

Statistics	**Absolute and relative CHANGE in modelled streamflow, October 1960 to September 2018, IAP expansion– current cover scenario**							
	SPATSIM		**ACRU4**		**SWAT2012**		**MIKE-SHEs**	
Annual stream yield (mm^3)								
Change in:								
Mean	-32	-59%	-24	-45%	-10	-21%	-15	-32%
Standard deviation	-3	-13%	-12	-30%	-11	-38%	-9	-23%
Minimum	-19	-93%	-5	-81%	0.5	5%	-0.7	-24%
Maximum	-50	-39%	-50	-31%	-41	-33%	-36	-25%
Monthly streamflow (mm^3)								
Change in:								
Mean	-2.7	-59%	-2.0	-45%	-0.8	-21%	-1.2	-32%
Standard deviation	0.5	13%	-1.6	-20%	-1.7	-32%	-1.1	-15%
Minimum	-1.2	-100%	-0.02	-49%	0.003	6%	-0.001	-8%
5th percentile	-1.6	-100%	-0.1	-76%	-0.05	-11%	-0.01	-22%
50th percentile	-2.7	-88%	-1.3	-77%	-0.2	-7%	-0.6	-55%
95th percentile	-3.4	-26%	-6.4	-36%	-3.1	-26%	-4.3	-26%
Maximum	14.0	42%	-10.1	-13%	-19.6	-40%	-8.9	-13%
Daily streamflow (cm)								
Change in:								
Mean			-0.8	-45%	-0.3	-21%	-0.5	-32%
Standard deviation			-1.1	-15%	-0.8	-21%	-0.6	-9%
Minimum			-0.01	-50%	0.00		0.00	
5th percentile			-0.03	-72%	-0.01	-12%	-0.001	-20%
50th percentile			-0.4	-79%	-0.1	-16%	-0.1	-61%
95th percentile			-2.4	-53%	-0.9	-20%	-2.2	-44%
Maximum			-19.0	-5%	-70.8	-32%	-19.8	-6%

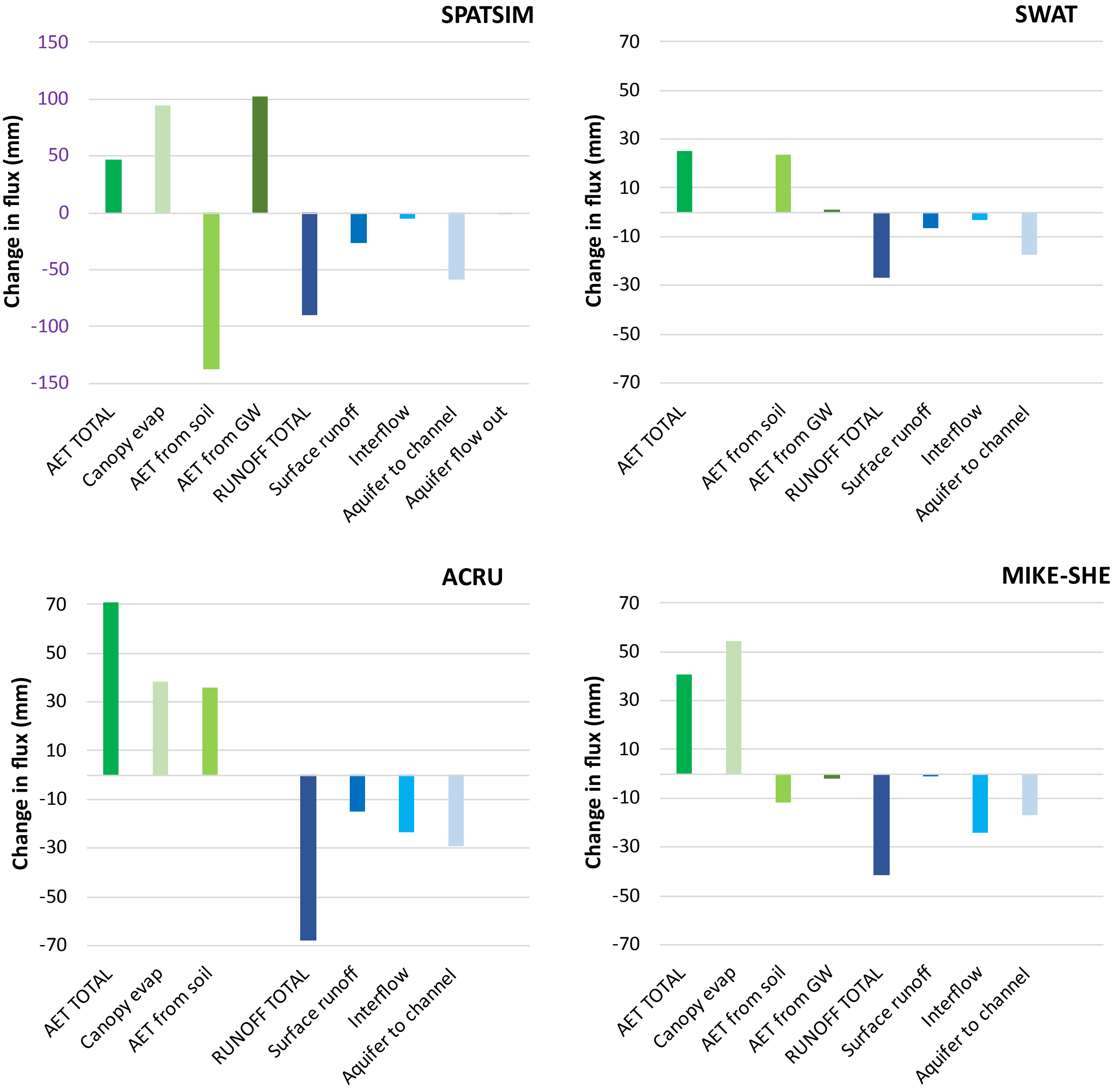


Figure 5.34: Predicted change in mean annual water balance fluxes for the Upper Kromme River catchment with an extreme increase in IAP cover, estimated using four different modelling tools

Note: Not all fluxes are modelled or output by all tools.

Table 5.18: Predicted change in mean annual water balance fluxes for the Upper Kromme River catchment with expansion of IAP cover (all clearing efforts cease) compared to the current scenario, estimated using four different modelling tools

Flux	**Absolute and relative CHANGE in modelled mean annual water balance components, October 1960 to September 2018, IAP expansion – current cover scenario** *(all fluxes given in mm over full catchment area)*											
	SPATSIM			**ACRU4**			**SWAT2012**			**MIKE-SHEs**		
	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*	mm	*Percentage*	*Percentage of change in AET or runoff*
AET total	**47**	***9%***		**74**	***15%***		**25**	***5%***		**41**	***8%***	
Farm dam evaporation	-0.05	-3%	*-0.11%*	-0.001	*-0.1%*	*-0.0001%*	0			0		
Canopy evaporation	94	*91%*	*200%*	38	*70%*	*51%*				54	*76%*	*134%*
AET from soil*	-138	*-40%*	*-294%*	36	*8%*	*49%*	24	*5%*	*96%*	-12	*-3%*	*-29%*
AET from GW*	102	*270%*	*217%*				1	*7%*	*4%*	-2	*-8%*	*-4%*
Palmiet wetland AET (subset)*	-11	*-68%*	*-23%*	(-3.4)	(-100%)	*(-5%)*	(-10)	(-100%)	*(-39%)*	(-3.1)	(-100%)	*(-7%)*
Runoff total	**-90**	***-59%***		**-68**	***-46%***		**-27**	***-21%***		**-42**	***-33%***	
Surface runoff[#]	-27	*-33%*	*30%*	-15	*-31%*	*22%*	-7	*-29%*	*24%*	-1	*-8%*	*2%*
Interflow[#]	-5	*-32%*	*5%*	-24	*-51%*	*35%*	-3	*-4%*	*11%*	-24	*-29%*	*58%*
Aquifer to channel[#]	-58	*-100%*	*65%*	-29	*-54%*	*43%*	-17	*-56%*	*64%*	-17	*-48%*	*40%*
Aquifer GW flow out of catchment	-0.008	*-82%*										
Storage change	43	*259%*		-6.2	*-76%*		1.9	*75%*		0.9	*165%*	

AET = Actual evapotranspiration; GW = Ground water; MIKE-SHEs = MIKE-SHE using simpler, more lumped algorithm options

Note:: Missing water balance components indicate that the tool does not save outputs of these components separately, although it may explicitly calculate the flux.

**Modelling tools differ in what is considered ET from soil vs GW and the outputs that can be exported. "AET from soil" includes water on the soil surface, and in the SWAT model, canopy interception is implicitly included in the value presented as "AET from soil" here.*

Palmiet wetland AET: In SPATSIM, wetlands were modelled water body units. These contributed separately to total AET (and storage). For the others, the wetland AET is a subset of the other AET values presented

[#] The interpretation of runoff source subdivisions differs somewhat across tools.

All models predicted notable increases in total AET with the IAP expansion, 5–15% increases in the catchment scale annual average, an added 25–74 mm, leading to decreased streamflow. Although an effort was made to parameterise the different vegetation types equivalently across models where possible (Appendix C3), differences in process representation in the tools resulted in different predicted changes in AET and the catchment water balance (Figure 5.34, Table 5.18) driving the differing magnitudes and patterns of predicted streamflow declines described above.

- Canopy interception had similar relative increases in the ACRU4 and MIKE-SHEs models, 70–76% increase in the average annual for the catchment, although magnitudes differed (38 vs 54 mm increase). The SPATSIM model predicted a much larger, 91% (94 mm) increase. Even between the ACRU4 and MIKE-SHEs models, these changes accounted for very different proportions of the overall increase in total AET. This was due to the interaction between canopy interception and soil moisture available for transpiration.
  - In both SPATSIM and MIKE-SHEs models, the modelled interception increase was so large that average annual evapotranspiration from soil was actually predicted to decrease. This meant that the total AET change was less than the predicted interception increase. Even though the IAP vegetation was parameterised for higher potential transpiration rates, the high canopy interception loss meant the soil was too dry for these rates to be achieved. This impact was large in the SPATSIM model, where AET from soil decreased 40%, but was much smaller in MIKE-SHEs, where AET from soil decrease by 3%.
  - In the ACRU4 model, the interception increase accounted for 51% of the total AET increase and an increase in ET from soil accounted for the remainder. The smaller magnitude interception increase, 38 mm, meant that there was soil moisture for more IAP transpiration. The ET from soil was predicted to increase by 8%, a much smaller relative increase compared to the 70% increase in interception, although the magnitudes of the predicted increases, 36 and 38 mm, were similar.
- SWAT2012 does not explicitly model canopy interception when run at a daily timestep. The average annual ET from soil for the catchment was predicted to increase by 5% (by 24 mm), which was much less than the other models, especially if this output is also implicitly including interception. It should be noted that, in the current cover scenario, the SWAT2012 model predicted much more ET from the palmiet wetlands than ACRU4 and MIKE, which partially accounts for the smaller difference in AET predicted when these were replaced with wattle.
- Predicted changes in vegetation transpiration from ground water storage also varied across models in both magnitude and direction.
  - In the MIKE-SHEs model, transpiration from ground water was predicted to decrease slightly (2 mm), likely due to the high canopy interception preventing recharge and reducing supply, similar to its impact on the ET from soil.
  - In contrast, the SPATSIM model, which also had high canopy interception, predicted a big increase in transpiration from ground water, counteracting the predicted decrease in ET from soil. This means there was sufficient ground water storage modelled to support the increase demand from IAP vegetation in the riparian areas. Differences in modelled soil percolation (after events exceeding the interception threshold) and ground water storage and outflow could allow this to occur in SPATSIM and not in MIKE-SHEs, even though both had soil moisture limited by high canopy interception.
  - The SWAT2012 model predicted a small increase in transpiration from ground water, but the majority (96%) of the total increase in average ET was due to an increase in ET drawn from the soil.

Average streamflow was predicted to decrease, primarily because of the increase average ET. However, in SPATSIM, there was also a notable increase in catchment water storage predicted for the time period compared to a net decrease in storage predicted in the current cover scenario. The reason for this requires further exploration. The wetland units in the upper catchment in the current scenario may have been the storage source that had a net loss. These were not present in the IAP expansion scenario.

The MIKE-SHEs model also predicted a small storage increase in the IAPx scenario compared to a small decrease in the current scenario, while SWAT2012 predicted small decreases in both cases, but less of a decrease in the IAPx case. The ACRU4 model predicted the opposite, a gain in storage in both cases, with a small gain in the IAPx scenario.

While all the contributing flows feeding streamflow were predicted to decrease in all models, the patterns of change again differed across the models:

- The SPATSIM and SWAT2012 models differed in their prediction of flow path contributions in the baseline condition (more surface flow and aquifer contribution in SPATSIM and more interflow in SWAT2012), yet predicted similarly dominant contributions from the decrease in average annual aquifer outflow to the channel, accounting for 64–65% of the total runoff drop. In both, the predicted decrease in average interflow was a minor contributor to the overall change (5–11%), while the decrease in surface flow was more important (24–30% of the streamflow change).
- The ACRU4 model also predicted that the decrease in average aquifer outflow would be the largest contributor to the drop in streamflow (43%), but predicted that the decrease in interflow would still be substantial (35%) and the surface flow decrease would be the smallest (22%).
- In contrast, the MIKE-SHEs model predicted that interflow was the dominant contributor to streamflow and also that the decrease in interflow would account for most of the streamflow decline (58%). The decrease in aquifer outflow was also a substantial contributor (40%), while the decrease in surface flow, a small contributor to overall flow in the first place, was only responsible for 2% of the change.

These differences in pattern reflect the differently modelled passage of water through soil and ground water layers in the different models and the access of the added IAP to different water sources. They also explain why the patterns of change in high and low flows differed across the models.

5.6 CASE STUDY OVERVIEW: MIDDLE LETABA RIVER CATCHMENT (B82A–D) LIMPOPO – IRRIGATION FROM FARM DAMS AND GROUND WATER, CHANNEL TRANSMISSION LOSS

5.6.1 Catchment description and modelling goals

Table 5.19: Middle Letaba Dam catchment and modelling overview

Catchment property	Description	Implication
Scale	1 805 km^2 Four quaternaries (B82A, B, C, D), catchment of the Middle Letaba Dam	
Climate	MAP 672 mm Summer rainfall Spatial rainfall gradient: estimated MAP ranges from ~1 300 mm in south-west highland to 440 mm in north-east lowland	Quaternaries capture some of the SE-NW gradient, but each includes some escarpment. If stormflow dominates, ideally model with subquaternary climate.
Runoff ratio	7%	
Topography	Scarps grading to rolling and near flat. Three main tributaries emerge from the escarpment in parallel with ridges between and converge in the lowlands. Mean slope: 12%	Expect most streamflow to originate in the highlands with losses in the drier flat areas
Soils and geology	Thin soil over fractured granite and gneiss in the highlands. Medium depth soil over thick (~30 m) regolith and weathered rock aquifer over fractured gneiss bedrock. Sandy alluvium surrounding river (~ 2 m) (Holland, 2011; Walker et al., 2018)	Surface flow from rocky highlands during summer storms likely significant. Weathered rock aquifer recharged in storms and supports baseflow. Bedloss feeds small riparian alluvial aquifer with “underflow” along the riverbed (Walker et al., 2018)
Vegetation	Dominated by arid lowveld woodland; significant irrigated (8% of catchment) and subsistence (10%) farming in lowlands; 6% of area is medium density residential.	Irrigation and irrigation systems are important to represent: many farm dams plus an estimated 35% of irrigation from ground water (Haasbroek et al., 2015)
Modelling		
Previous modelling	WRSM-Pitman built for DWS water supply reconciliation strategy (Haasbroek et al., 2015)	Input database and conceptual model reference point
Modelling goals / scenarios	Estimate the hydrological impact of not irrigating from ground water (would curtail overall irrigation in dry periods)	Model needs to represent irrigation from ground water specifically and dynamic ground water-surface water interaction.
Climate data	SAWS rain gauge and NCEP-CFSR station daily rain and ET demand: 1979-01-01 to 2011-09-30 (32.6 years)	**Model runs:** 1979-10-01 to 2011-12-31 **Output comparison (excluding warm-up):** 1982-10-01 to 2011-09-30 (29 years)
Streamflow data	DWS estimated inflow to Middle Letaba Dam: 1992-01-01 to 2008-12-31 (17 years)	**Calibration**: 1992-10-01 to 2008-09-30 (daily); October 1992 to September 2008 (monthly)

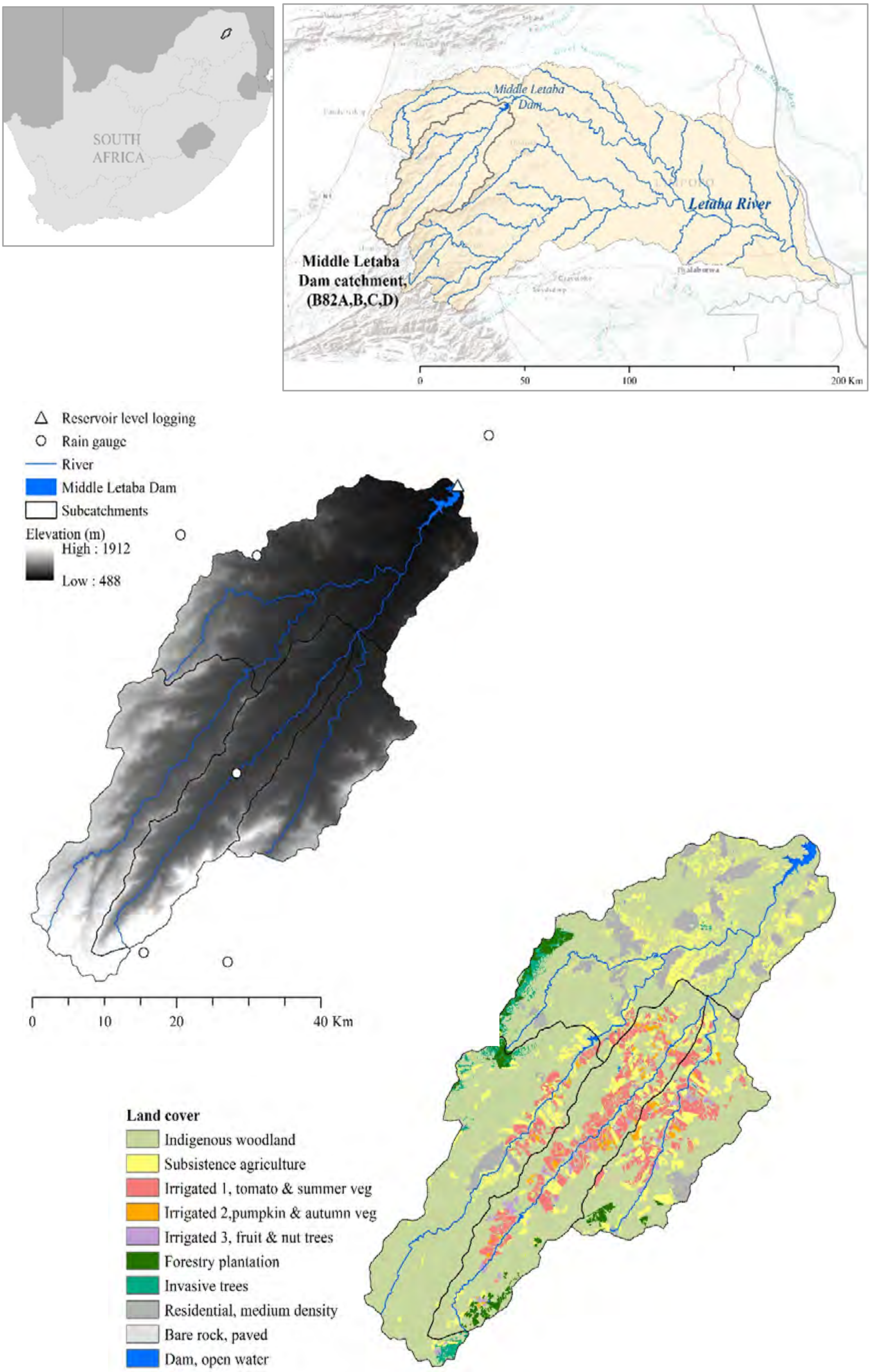


Figure 5.35: Location of the Middle Letaba River case study catchment (top), quaternary subcatchments and monitoring points (middle), and land cover distribution mapped for the baseline/current cover scenario (bottom)

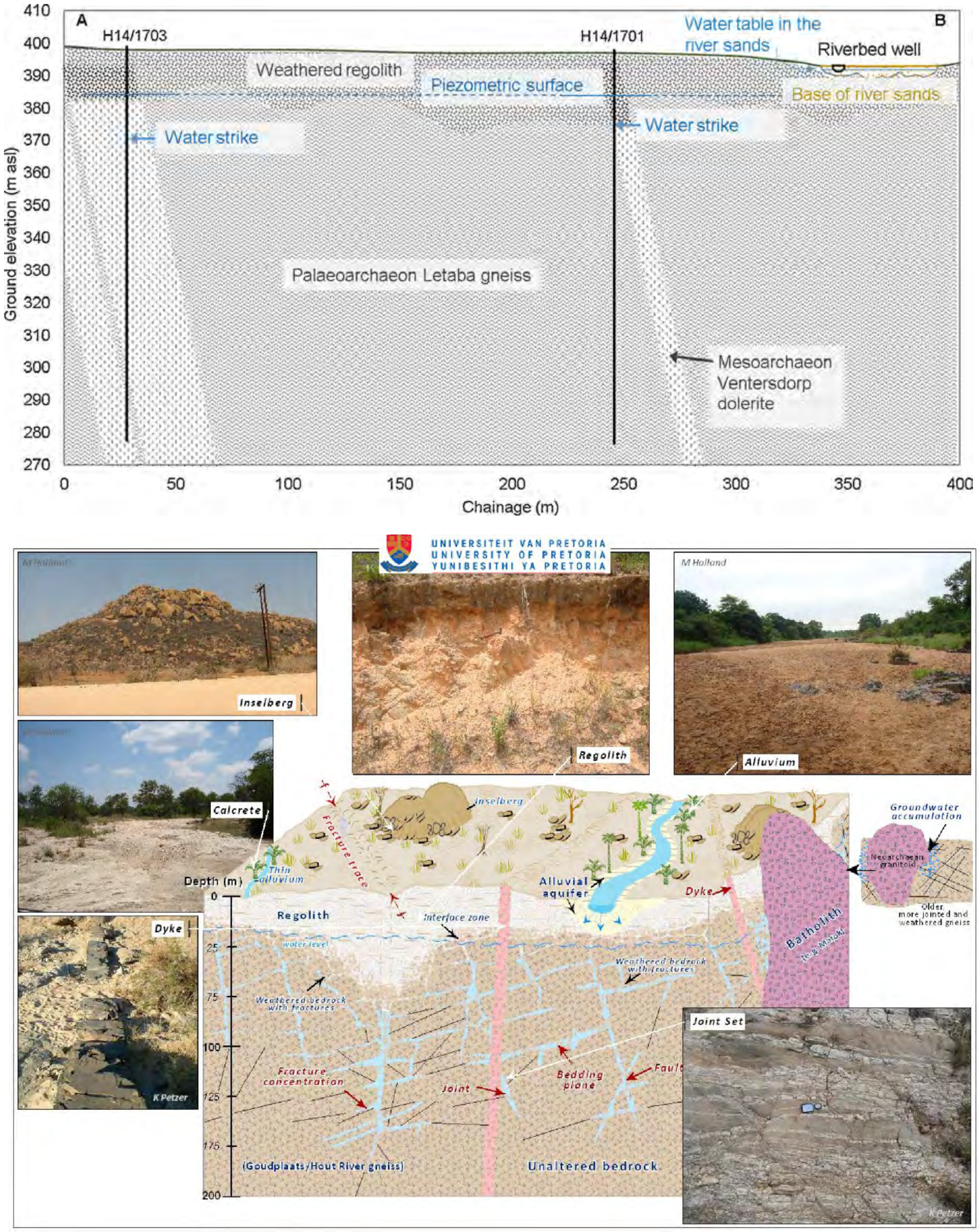


Figure 5.36: Conceptual models of vadose zone and aquifer layers in the region from Walker et al., 2018 (middle) and Holland 2011 (bottom) highlighting the weathered and fractured layer aquifers and riparian alluvial aquifer

5.6.2 Highlighted representation issue – representation of many small farm dams, particularly as an irrigation source

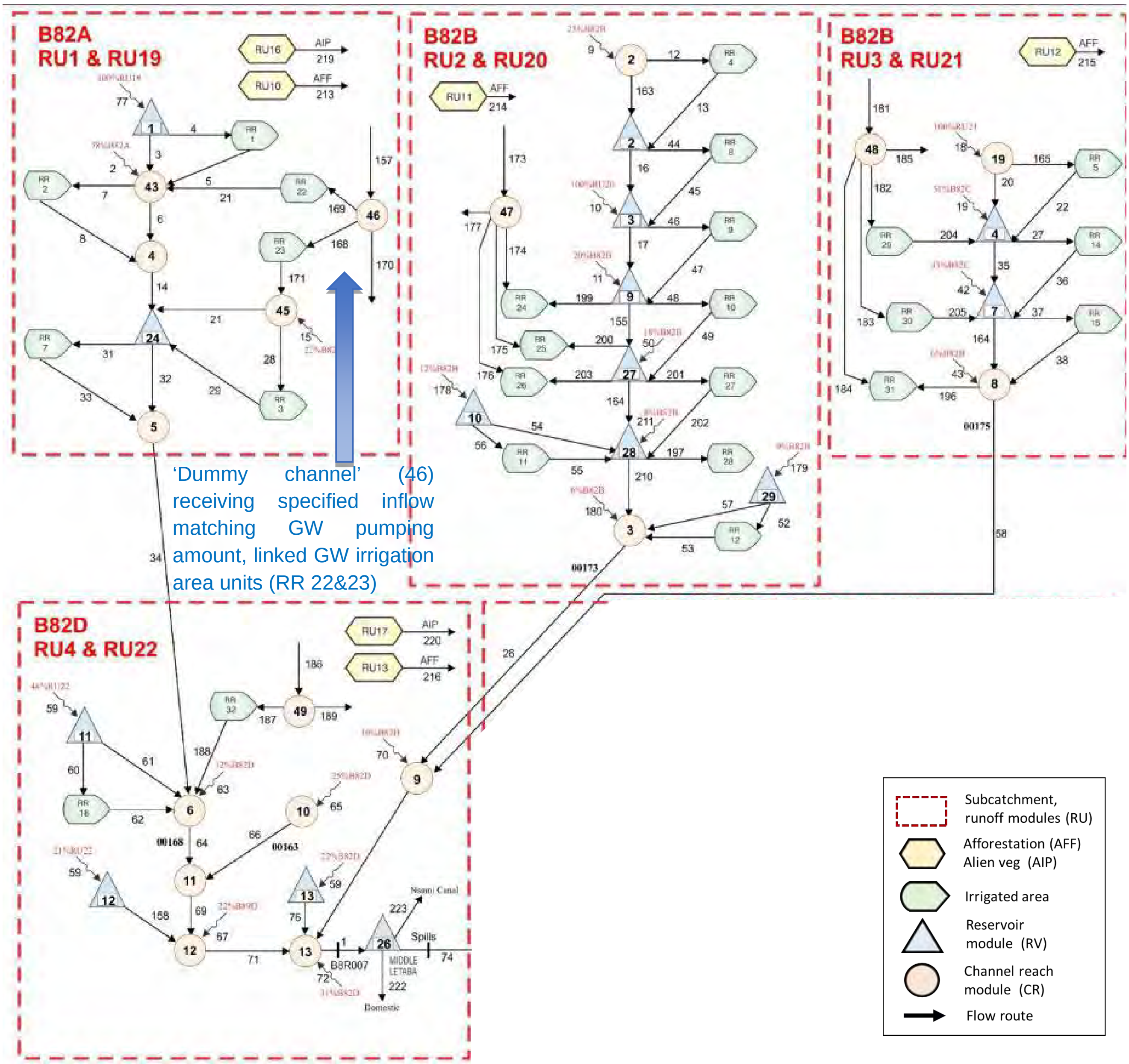
Commercial farmers in the Middle Letaba irrigate from a mix of sources, using mostly on-channel farm dams and run-of-river withdrawals when available, and switching to ground water withdrawals when surface water sources are insufficient (Haasbroek et al., 2015). There are many small farm dams in the catchment: the National Land Cover (NLC) dataset for 2018 (DEA, 2019) showed 150 separate open water areas. This was a relatively dry period. There are several larger dams on the main rivers in the central valleys of each quaternary and many small dams on tributary streams and drainage lines. The approaches available for including dam storages in models that can be used as irrigation sources differ notably across the different tools and influence decisions about subcatchment and HRU delineation. The lumped representation of many farm dams using fewer model waterbody units is a simpler process in the Pitman tools compared to the others. The inclusion of reservoirs, lumped or not, is most complex or data-intensive for the MIKE-SHE models if these are to be used for irrigation. These complexities limited what was completed in the time available for this case study.

WRSM-Pitman (Sami ground water)

The WRSM model of the Middle Letaba catchment by Haasbroek et al., 2015 (Figure 5.37) was set up with a relatively high level of detail in terms of separately represented irrigation areas, drawing from different sources and providing return flows to the main channels at different locations. The many small farm dams in each quaternary were lumped into several representative model dams ("reservoir modules"). In coarser-scale WRSM modelling, as done for the WR2012 assessment (Bailey and Pitman, 2015), all farm dams in a quaternary catchment are typically lumped into one or two reservoir modules. In this case, to more realistically capture surface source limitations, less lumping was done and many of the larger impoundments on the main channels were explicitly included. The most heavily farmed quaternary, B82B, has seven modelled dams: five in sequence along the main channel and two on smaller tributaries, each with an associated irrigated area module. Fourteen reservoir modules were included above the Middle Letaba Dam.

Because WRSM-Pitman allows each reservoir module to be fed by a user-selected proportion of a subcatchment or runoff module's runoff, in effect being fed by an internal subcatchment area within a runoff module, including many individual reservoir units does not necessarily require adding and parameterising more runoff modules in the model. However, to feed reservoir modules that represented dams on more upland tributary streams that were more proximal to the forestry plantations and alien invasives on the escarpments, an additional "runoff module" was included in each quaternary (Figure 5.37).

Irrigation modules in WRSM cannot contribute return flows upstream of the source from which they are irrigated. This means that areas irrigated by a farm dam are necessarily removed from its contributing catchment area, even if they are actually located upstream of the dam in reality. This restriction is not present in other tools. If the relevant irrigated area is large in relation to the dam's contributing catchment, this could lead to inaccurate dam inflow, particularly during large rainfall events, which produce surface flow. With many smaller dams and hence associated smaller irrigation areas linked in a sequence, this becomes less of a problem than it would be if all the small dams were lumped into one area with a large associated irrigation area that was not considered part of the contributing catchment of the lumped reservoir.



'Dummy channel' (46) receiving specified inflow matching GW pumping amount, linked GW irrigation area units (RR 22&23)

Figure 5.37: WRSM model structure for the Middle Letaba (Haasbroek at al., 2015) (Note: Red outlines indicate quaternary subcatchments, each represented with two "runoff modules" that are not shown as symbols in the network, but are named in red and their outflow routes into the reservoirs and channels labelled)

SPATSIM-Pitman (Hughes ground water)

SPATSIM-Pitman can include a single internal water storage dam per modelled subcatchment that can be used to feed irrigation. A user-input portion of the irrigated area in the subcatchment can be irrigated by the dam and a portion from river channel withdrawal. Similar to WRSM, the dam is fed by a user input proportion of the subcatchment runoff. This can be thought of as the proportion of the subcatchment area that is the contributing catchment for the farm dams being represented, assuming this area is representative of the average properties of the larger subcatchment. (If the subcatchment is relatively heterogeneous and the dams being represented are in a particular part, the runoff proportion and the catchment area proportion may not actually be a good match. The same would apply in WRSM.) If the contributing proportion was set to 100%, the dam would be close to the subcatchment outlet. However, the SPATSIM dam differs from the WRSM reservoir in that it is not on the channel network. It is not fed by channel flow from upstream subcatchments, only by runoff from the incremental subcatchment in which it is located.

A SPATSIM subcatchment can also have a reservoir unit, which is specifically located at its outlet on the channel network and so receives channel flow from upstream. However, the SPATSIM reservoir cannot feed irrigation. This can have implications for subcatchment delineation: they need to be of sufficient size to support the irrigation dam storages because any separated subcatchment upstream would not contribute.

To individually represent the 14 irrigation source reservoirs included in the WRSM model would require 14 subcatchments in SPATSIM. The dams that are actually downstream on the same channel would not receive overflows from those upstream in the model. The degree to which this is an issue worth considering depends on how often upper dams spill during periods when lower dams are not already full, such that the overflow from upstream effectively contributes to storage in the low dams. In dry periods, this would not be an issue, as dams may not be overtopping, and in very wet periods, all dams may be full. However, the times in between these extremes may be important. There was insufficient time in the project to explore this in detail, but a cursorial look at the WRSM model's output suggests that the importance may be limited and localised in this case study: only in B82A was the upper dam predicted to be spilling in more months than the lower dam on the same channel. Alternatively, all the farm dams in a quaternary could be lumped to have a SPATSIM model with only four subcatchments. The degree to which lumping the storages would lead to less restricted irrigation supplies at the catchment scale was not explored in this project.

ACRU4

The more modular structure of ACRU4 allows multiple dam units to be included within a subcatchment, with flexible arrangements with regard to their connections to channels and each other. However, explicit inclusion of more individual farm dams in ACRU4 would require a model set-up with more HRUs. The runoff of each HRU can only be routed to a single location – a channel, reservoir or subcatchment node – with the exception of "baseflow" outputs being routed to riparian HRU soils. The area feeding each modelled dam would need to be represented with one or more HRU routed to it, depending on the land cover distribution in its catchment and the degree to which this needs to be explicitly modelled. To balance the labour of manually setting up many ACRU4 HRUs, representing the spatial distribution of major land cover and topographic types, and representing the water storage network of the Middle Letaba catchment, a compromise was made to represent two lumped farm dams in each quaternary. For this, the reservoirs modelled in WRSM were grouped into those primarily fed by the upland "runoff modules" and those fed more by the main lowland "run-off modules" in each quaternary.

ArcSWAT2012

Like SPATSIM, SWAT2012 can only include one reservoir unit per subcatchment that can be used to feed irrigation. Unlike SPATSIM, this waterbody is necessarily located at the outlet of the subcatchment on the channel network. SWAT2012 can include other waterbodies internal to a subcatchment, termed "ponds", "depressions" and "wetlands", each of which have different inflow and outflow algorithms. However, these cannot feed irrigation. As such, separate subcatchments were delineated for the 14 dams represented in the WRSM model for explicit inclusion in the SWAT2012 model.

ArcSWAT2012 requires subcatchments to either be delineated from an input DEM in the tool's interface, which also automatically delineates and links the channel network and determines subcatchment connectivity, or for externally prepared subcatchment and channel reach shapefiles to be input with correctly prepared metadata indicating the linkages (which is potentially much more work). This can pose a hurdle for including model reservoirs that are a lumped representation of many smaller storages with distributed small catchment areas as there is not an obvious point in the topography that will delineate an appropriate contributing catchment area. In this case study, for the most part, obvious impoundments were visible in the aerial topography, which had similar contributing catchment areas to the units included in WRSM. In a few cases in which the WRSM reservoir units were primarily a lumped representation of many smaller storages on upland streams, a "flow accumulation" grid, calculated from the DEM, was used to pick a point in the relevant quaternary that would create a similar-sized catchment area to what had been assigned to the lumped reservoir module in WRSM.

MIKE-SHE (using simpler options and more complex, distributed options)

Like SWAT2012, inputs in MIKE-SHE are generally spatially explicit, which poses a challenge when trying to include a storage unit that is a lumped representation of many real small farm dams. As such, “dummy” subcatchment of a relevant size for the “dummy” reservoir would need to be delineated. The ease of finding an appropriately located and sized subcatchment will depend on the morphology and land cover distribution of the catchment. MIKE-SHE poses an additional challenge to representing farm dams that can be used for irrigation compared to SWAT2012, in that the most direct way to include them in a model would be to input explicit bathymetry and dam wall dimensions in the hydraulic channel module. MIKE-SHE models can include simple storage volume units either at the side of a channel reach receiving overflow, or directly on the channel. However, irrigation water cannot be drawn from these units, only from river reaches. There may be potential to include simple storages on the river that will flow back into the river when irrigation water draws it down, but this would require some testing to get it right. The other alternative would be to include explicit cross-sections that define the bathymetry of the storage and include the dam wall as a “structure” in the hydraulic model, so that the channel reach stores the appropriate amount of water. Synthetic cross-sections could be derived to give the same volume-area relationships as the storages used in the other tools. However, there was insufficient time in this project to come up with these and test them. (It should be noted that MIKE-Basins is a related tool designed to model managed water systems. However, its modelling of other catchment processes is highly simplified and very different to MIKE-SHE.)

5.6.3 Highlighted representation issue – irrigation from ground water when surface water supply is insufficient

Haasbroek et al., 2015 estimated that roughly one third of the irrigation in the Middle Letaba catchment is supplied by ground water pumping to make up for surface water supply shortfalls. Of the tools considered, only SWAT2012 and MIKE-SHE explicitly include irrigation from ground water and only MIKE-SHE is designed for irrigated areas to be dynamically supplied by multiple water sources. However, as described above, representing farm dam storages in MIKE-SHE is not straightforward. The Pitman tools allow ground water pumping withdrawals to be included in a model, but do not include irrigation drawn from ground water, whereas ACRU4 does not include ground water pumping at all. Workarounds for representing the case study irrigation system were discussed for all tools. However, several potential options were deemed to fall outside the scope of “typical use” of the tools. As such, none of the tools were an “easy fit” for this particular scenario, which is likely of common occurrence in much of the country.

The impacts of ground water pumping can differ to those of surface water withdrawal and can be important to represent explicitly. Pumping can allow for continued irrigation, even during times when there is little to no aquifer outflow into river channels. To some degree, this could be approximated in a model by adding more surface water storage capacity, from which most tools can easily irrigate. However, there may not be sufficient runoff modelled in the relevant locations using normal parameterisation. Surface water storages may also lose more water over time to evaporation than aquifer storage would. Pumping can reduce baseflow, and can draw down into aquifers at a faster rate than the water would otherwise drain into channels. Ground water withdrawals can also be drawn from aquifers too deep to feed streams in the catchment. To represent this in a model using additional surface water storage, rates of aquifer outflow into channels feeding “dummy” surface storages would need adjustment.

WRSM-Pitman (Sami ground water)

Each irrigation area can only receive water from one source in WRSM, a single channel or reservoir module. A comparison of irrigation demand with potential surface water supplies over time was done to estimate the amount of irrigation that would have had to come from ground water to maintain the observed agricultural production. In the model, ground water withdrawal demand rates were input for the main runoff module of each quaternary to match the expected ground water irrigation demand. The actual amount that would be withdrawn would be limited by the aquifer storage in the timestep. Ground water withdrawals are removed from the model in WRSM, as they are assumed to be used outside the catchment. To work around this, water was added to a “dummy channel” module, as would be done for a flow transfer from an external source, outside the modelled catchment. This amount was limited by the expected harvest potential of the aquifer. Specific ground water irrigation areas were added to the model, which were supplied by this “external source” dummy channel module (Figure 5.37). The size of these ground water irrigation areas was selected to match the estimated proportion of irrigation water use thought to come from ground water pumping (i.e. one third of the irrigated area).

A limitation of this approach is that the amount actually pumped from ground water in the model and the amount of water made available to the ground water irrigation areas are separate inputs. If the model ground water storage is too low to allow ground water pumping at a particular time, there should be no withdrawal, but this would not necessarily be included in the externally derived inflow timeseries. To prevent this, an iterative approach is needed to check the withdrawals achieved compared to the inflows input. This process would need to be redone if any relevant parameters or inputs are then changed
(i.e. the irrigated area, crop type, rainfall, etc.).

SPATSIM-Pitman (Hughes ground water)

SPATSIM, as with WRSM, only allows irrigation from a single source for a given irrigation area in a subcatchment. Each subcatchment can be assigned a total irrigation area, which can be portioned into area irrigated by the subcatchment’s dam unit and area irrigated from withdrawal from the channel. As in WRSM, SPATSIM ground water abstraction water is removed from the model. As such, a similar approach to WRSM would be needed for irrigation from ground water, in which a matching ground water withdrawal timeseries and external source water transfer input timeseries are established. However, the approach would differ somewhat in SPATSIM because there is only one channel module per subcatchment, which would need to receive the “external transfer ground water supply” and feed the runoff river irrigated area. In WRSM, a detached dummy channel could be used so that any excess water allocated (not used by the irrigated area) would leave the model. In SPATSIM, any excess not used in irrigation would stay in the model. In either case, an iterative process would need to be used to find the appropriate timeseries relevant to the irrigation demand and available aquifer storage over time.

ACRU4

ACRU4 does not include ground water withdrawals at all, and each irrigated area can only receive water from one source, channel or reservoir. An approach to attempt to represent irrigation from ground water in ACRU4 was discussed for this case study. An initial trial set-up for a single subcatchment was done (Figure 5.38). However, it was determined that the method would need significant testing and adjustment to perform as intended and was outside what could be considered the “typical use” of ACRU4. As such, it was not used in a full model of the Middle Letaba catchment, but is described here as the ideas may be useful to future developments.

In this trial “workaround” approach, an additional “dummy” dam was added to the subcatchment to represent aquifer water storage. A “dummy” riparian zone HRU was added to effectively route the baseflow outputs from all the HRUs in the subcatchment into the dam: flow is routed via the dummy riparian HRU, which is assigned parameters to promote drainage rather than ET. In this sense, this “dummy riparian HRU” acts like the vadose zone layer included in other tools, delaying recharge reaching the aquifer. The “aquifer dam” was given a maximum storage volume, matching the maximum aquifer storage volume, and a maximum seepage rate (which occurs when the dam is at its maximum storage) equivalent to the maximum aquifer outflow rate. Shape parameters were selected to minimise evaporative surface area, and the lowest allowed evaporation coefficients were assigned. However, evaporative losses cannot be completely eliminated. This is a shortcoming of the approach. In this case study, outflows from this “aquifer dam” would be routed to the channel upstream of the real surface water dams so that these would not be starved of baseflow.

The “aquifer dam” will only receive inflow from the contributing HRUs at the rate that they are predicted to produce baseflow in the model, controlled by a baseflow lagging parameter. Because storage may accrue over time in the aquifer dam, depending on the inflow versus outflow rates, there may be enough water stored to allow irrigation from ground water in excess of the amount of baseflow that would otherwise be modelled in the river. This is the desired conceptual outcome. It would be conceptually valid to decrease the baseflow lag from contributing HRUs compared to normal values applied because a lag is already being imposed through storage and seepage outflow in the aquifer dam. Finding appropriate values for HRU baseflow lag and “aquifer dam” seepage parameters would likely need to be a calibration exercise.

As with the Pitman tools, separate irrigated HRUs would be needed to represent irrigation from ground water (from the “aquifer dam”) and irrigation from surface water sources. This “aquifer dam” approach has a representation advantage over the WRSM and SPATSIM approaches in that irrigation would be curtailed internally by the model when the modelled ground water availability was low.

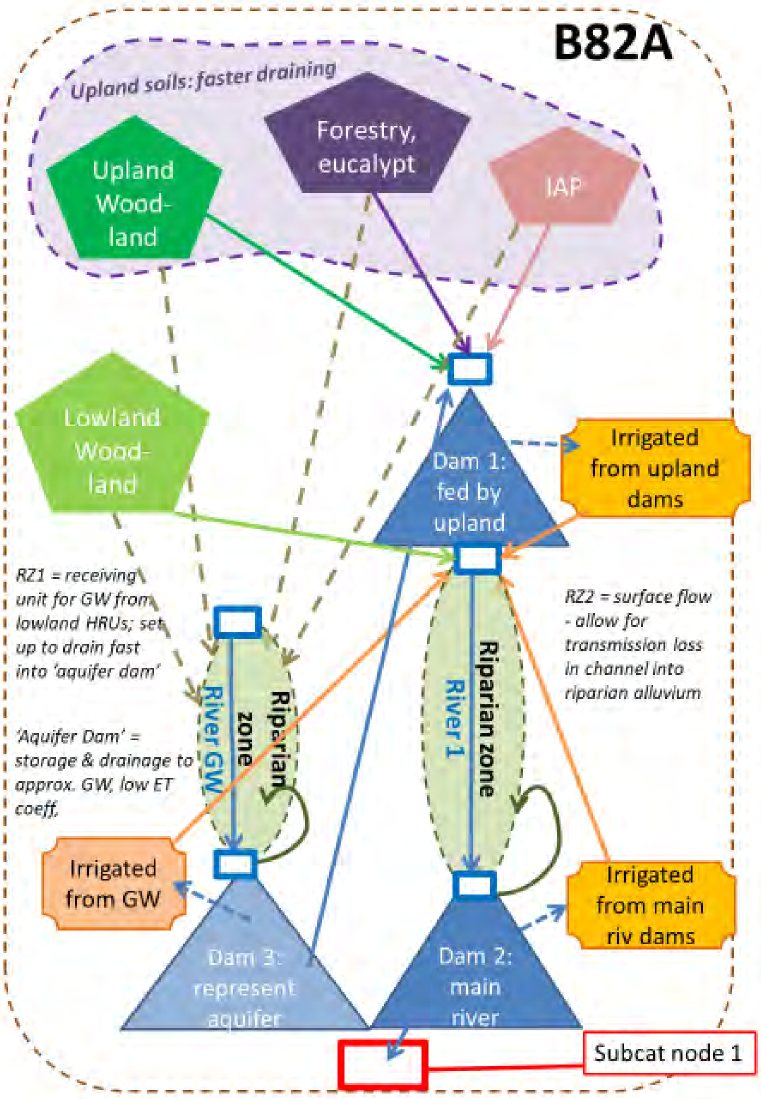


Figure 5.38: Proposed ACRU4 model structure shown for quaternary catchment B82A, showing the conceptual “aquifer dam” representation to simulate irrigation from ground water and the use of a riparian zone HRU to approximate channel bed transmission losses

ArcSWAT2012

ArcSWAT2012 allows irrigation from reservoirs, river withdrawals, ground water and external sources. The software appears to be designed for each irrigation area to be supplied by a single source, based on what is described in the documentation (Neitsch et al., 2011). If this approach is used, the same total area of ground water irrigation could be used as was assumed in the WRSM model. Using ArcSWAT2012, this would require the spatial selection of mapped irrigated areas to assign to a ground water irrigation land cover class in the model.

This approach was not used, however, because a relatively simple “workaround” was found to allow the irrigation of the same HRU from two sources in the model. Irrigation can be set up for an HRU with either an input application amount schedule (manual) or with irrigation amounts calculated by the model to maintain soil moisture above a certain threshold (automatic). It was found that a single HRU can be assigned both a manual irrigation set-up and an automatic irrigation set-up and that these can come from different water sources. In this case, the manual irrigation from surface water sources was coupled with automatic irrigation from ground water to only allow the ground water irrigation to be automatically modelled when surface water sources are depleted, curtailing the manual irrigation applied, causing the soil moisture to drop. The challenge of this method comes in determining the manual irrigation amounts. These were estimated from the local SAPWAT outputs provided by Haasbroek et al. (2015), as described in Appendix C4.

MIKE-SHE (all structure options)

MIKE-SHE, using any of the structural options, allows irrigated areas to be supplied by multiple different sources in an ordered sequence, so that when one source does not have sufficient supply available to meet the irrigation demand, the model will attempt to draw water from the next listed source if possible. This well represents what is done in practice in the Middle Letaba catchment and likely elsewhere, giving this tool a clear advantage for this type of application. Unfortunately, the difficulty in including the farm dams detracts from its potential usefulness in this case, given the scale and number of storages involved.

5.6.4 Highlighted representation issue – channel transmission loss

Channel transmission losses along the sandy riverbeds can be significant in the lowlands of this area, as described by Riddell et al. (2017) and Walker et al. (2018). The observed hydrograph and aerial photography show that channels are often dry or close to dry between flow peaks following summer storms, although riparian vegetation remains greener throughout prolonged dry periods. Walker et al. (2018) described a shallow water table in the riparian alluvial deposit recharged during flow events, with potential longitudinal flow in the subsurface following the river line. The modelling tools were found to differ notably in their approaches to representing channel transmission losses and where the water was routed once leaving the channel. There is no channel transmission loss algorithm in ACRU4, but it can be approximated using channel overflow. These differences meant that it would not be straightforward to purposefully set up a model to have a similar channel transmission loss to a model in another tool.

WRSM-Pitman (Sami ground water)

WRSM-Pitman can calculate channel transmission losses in two places: in the “runoff modules” and in the channel modules. Within the runoff module, which is essentially a subcatchment unit, the net exchange between ground water and an implicit channel in the module is calculated based on an estimation of their relative heads. This is part of the Sami ground water routine (Sami, 2015) and is calculated after the standard surface and subsurface runoff generation has been calculated. This determines the net outputs of the runoff module. Water recharging the runoff module aquifer in this way is available for evapotranspiration in the module’s riparian area and to contribute to aquifer outflow to the channel later on. This exchange with a conceptualised channel within the run-off module does not include flow in the model’s channel network. It does not include flows from upstream subcatchments, so essentially represents exchange with a tributary stream within an incremental subcatchment.

In addition, to address flow in the channel network, a channel bedloss rate in mm^3 per month can be added to channel modules. Values would be a function of the channel area (width, length) and conductivity. The method assumes that the channel is always losing, i.e. the ground water table is always below this channel, as the rate is not dynamic. Only flow in excess of the loss rate amount will flow out of the channel module downstream. The bedloss water, in this case, is removed from the model, which could be interpreted as evaporative loss or recharging an aquifer that does not feed streamflow there or elsewhere in the modelled domain. In the WRSM model of the Middle Letaba catchment, channel transmission loss rates were specified for the lower channel modules in B82A–C and all main channel modules in the downstream B82D, with values increasing downstream from 0.02 to 0.15 mm^3 per month (25% of the median monthly catchment outflow).

SPATSIM-Pitman (Hughes ground water)

Similar to WRSM, SPATSIM calculates net aquifer flow to the channel or channel loss to the aquifer at the subcatchment scale in a single calculation based on the estimated gradient of the ground water in relation to the channel (Hughes, 2004). Unlike WRSM, the exchange is calculated for a connected channel in the model, so that water that contributes to channel flow in upstream catchments may recharge the aquifer of a downstream subcatchment through channel transmission loss. This water is added to the subcatchment aquifer and can contribute to riparian zone ET and potentially aquifer outflow later on.

ACRU4

ACRU4 does not include an algorithm intended to estimate channel transmission losses. However, in cases like the Middle Letaba, in which the channel is wide and sandy, and likely to be losing flow most of the time, channel overflow onto special riparian zone or wetland HRUs may approximate the process. These HRUs are associated with a particular channel unit and a flow capacity is set, above which excess streamflow would be routed to the surface of the HRU where it can infiltrate or flow back into the channel. For the Middle Letaba scenario, riparian HRUs were intended to represent the sandy channel and immediate riparian vegetation, and the channel capacities were set to 0, meaning that all flow was routed onto the riparian HRU's surface with the potential to infiltrate. A potential issue with this approach would be when trying to also represent overbank flooding as a separate process, which would require setting a higher channel flow capacity. Channel transmission loss is not a threshold process that stops when flows are lower, so only a capacity of 0 is appropriate for this.

ArcSWAT2012

SWAT2012 includes an algorithm to calculate channel transmission loss when channel bed conductivity is specified. Each subcatchment has a main channel with explicit dimensions, so that bedloss is a function of the wetted area and the conductivity. Channel transmission loss water can be added to a bank storage unit or to the deep aquifer, which would have no further interaction in the model, except pumping. A proportional routing to each can be specified. Water from the bank storage can be routed back into the channel based on a specified recession constant. In theory, bank storage water is available for ET when there is a deficit in the soil profile. However, trials indicated that this may not be active in the version used, and there is no specific output of ET from bank storage that could be used to confirm this. As such, in the SWAT model of the Middle Letaba, a proportion of the bed loss was routed to the deep aquifer to approximate losses similar to the WRSM model.

MIKE-SHE using simpler options

In MIKE-SHE, when using the linear reservoir ground water representation, channel transmission loss is calculated similarly to SWAT: based on an input bed conductivity value and the wetted surface area in the MIKE-Hydro hydraulic model. The water is routed to the lowest subcatchment "baseflow reservoir", and can feed riparian zone ET and potentially contribute to flow back into the channel later. The difference in MIKE-SHE is that different reaches of river can be specified as losing reaches and have different conductivities, whereas in SWAT, properties are specified at the subcatchment scale. For the Middle Letaba, the lowland portions of each quaternary could be set up as losing reaches.

MIKE-SHE using more complex, distributed options

Similar to SPATSIM with Hughes ground water and WRSM with Sami ground water routines within the runoff modules, MIKE-SHE run with fully distributed, finite-difference ground water representation calculates the ground water-channel exchange based on the relative head elevations of the river and the aquifer in bordering grid cells, and the material conductivity. This means that the explicit channel depth in the model can be important for determining the direction of the exchange.

5.6.5 Modelling outcomes

Because relatively complex workarounds or adaptations are needed to represent this case study in all the tools, as described above, model-building and calibration was not completed in all the tools within the project timeline. The project team discussed potential structures, and climate, topography, soil, land cover and irrigation area inputs have mostly been compiled in the relevant formats for each tool and a priori parameter values chosen (Appendix C4). A decision was made to prioritise completing the ArcSWAT2012 model given the compromises it offered between process representation and input data requirements. MIKE-SHE offered the most realistic representation of irrigation practice. However, it required a large amount of data about the river channel and dam bathymetry that is not readily available, so that many assumptions would need to be made. The results of the calibrated SWAT2012 model (set-up described in Appendix C4) compared to the WRSM-Pitman model are presented below.

Model predictions vs observations

Flow duration curves and hydrographs for the calibration period are shown in figures 5.39 and 5.40, with statistics given in Table 5.20. For monthly streamflow predictions, both models achieved acceptable fits to the observed flow for most criteria, except for low flows: predicted mean monthly flows were within 1% (0.04 mm^3) of the observed flow, with NSE values of 0.96–0.97 for their monthly flow timeseries (Table 5.20). However, the statistics were dominated by the large peak in 2000. NSE values for log-transformed monthly flows were poor, -1.5 for WRSM and 0.17 for SWAT, showing that model fits were biased toward higher flow months. Nevertheless, smaller monthly peaks, important for water supply, were reasonably well captured in both.

Daily statistics for the SWAT2012 model were poor (NSE < 0), despite the closely matched average flow and reasonable frequency distribution (Table 5.20). The hydrographs revealed that this was in large part due to the mismatched timing of daily peaks between the modelled and observed flows, often a day difference. This may have to do with the observed data timeseries being derived from an approximated water balance for the Middle Letaba Dam rather than a weir and/or linked to the input rainfall data timing. It may also indicate that too much flow was predicted to come via faster pathways in the SWAT2012 model than is realistic.

Looking at the distribution of monthly flows in the calibration period, both models underestimated higher flows for the 90–98th percentiles, while the WRSM model slightly overestimated the 75th percentile and overestimated the median compared to the SWAT model, which generally slightly underestimated the mid-range flows. In terms of daily flows, the SWAT model generally underestimated flow above the median and overestimated median to low flows.

Table 5.20: Statistics for observed and modelled flow entering the Middle Letaba Dam for the calibration period

Statistic	Observed	WRSM	SWAT2012
Monthly streamflow yield (mm^3/month), January 1992 to December 2008			
Mean	6.98	6.95	7.02
difference vs observed		*-0.04*	*0.03*
percentage difference		*-0.5%*	*0.5%*
Standard deviation	42.05	44.13	44.48
Coefficient of variance	6.02	6.35	6.34
Minimum	0.00	0.00	0.00
5th percentile	0.01	0.00	0.02
25th percentile	0.21	0.23	0.19
50th percentile	0.61	0.71	0.54
75th percentile	1.86	1.90	1.50
95th percentile	17.8	14.8	10.1
Maximum	528	543	528
RMSE		7.32	8.27
MAE		2.47	2.42
NSE		0.97	0.96
NSE log		-1.55	0.17
R^2		0.97	0.97
Daily streamflow (cm), 1992-01-01 to 2008-12-31			
Mean	2.66		2.67
difference vs observed			*0.01*
percentage difference			0.5%
Standard deviation	31.96		40.40
Coefficient of variance	12.04		15.15
Minimum	0.00		0.00
5th percentile	0.00		0.00
25th percentile	0.00		0.03
50th percentile	0.03		0.10
75th percentile	0.43		0.30
95th percentile	4.76		3.23
Maximum	1528		2045
RMSE			38.53
MAE			3.22
NSE			-0.45
NSE log			-0.47
R^2			0.20

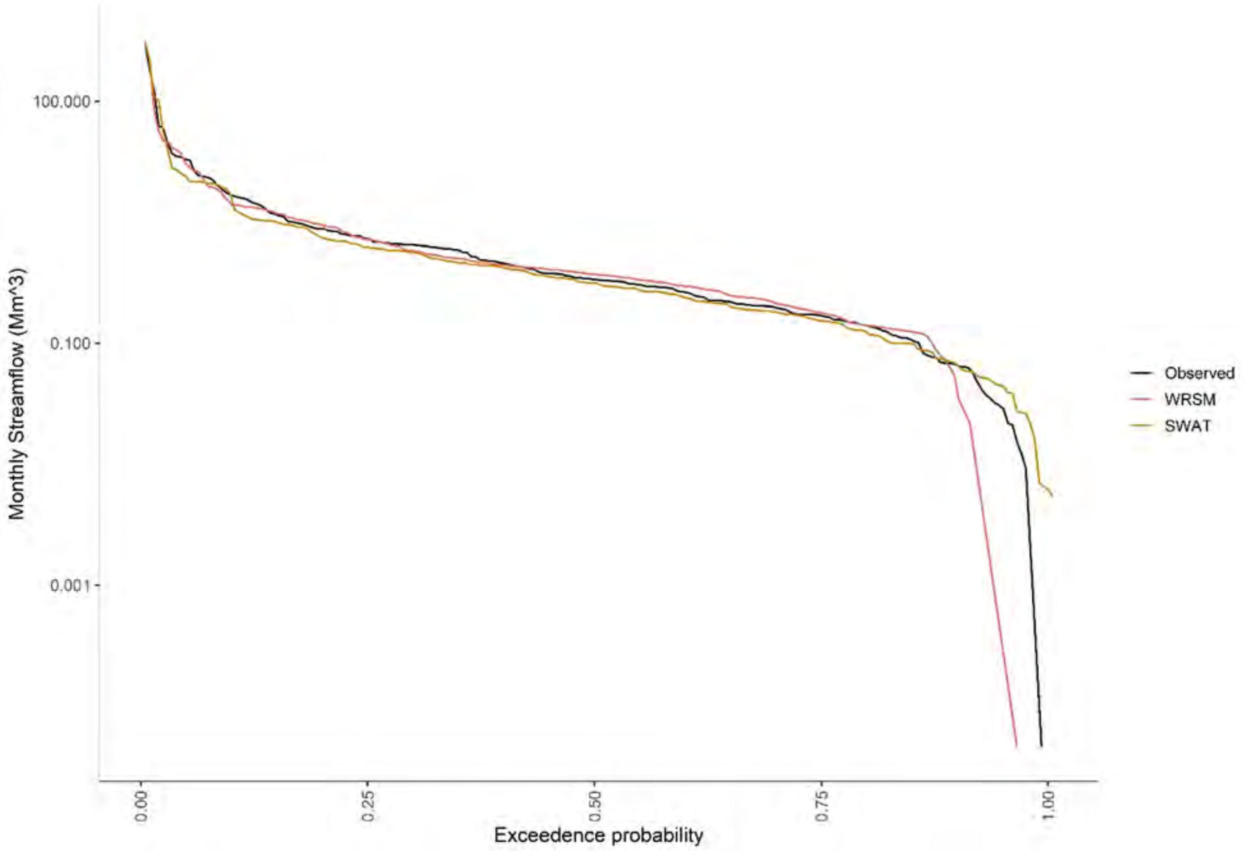


Figure 5.39: Observed and modelled monthly flow duration curves for modelled inflow into the Middle Letaba Dam, 1992–2008 (Note: Streamflow displayed on a log axis)

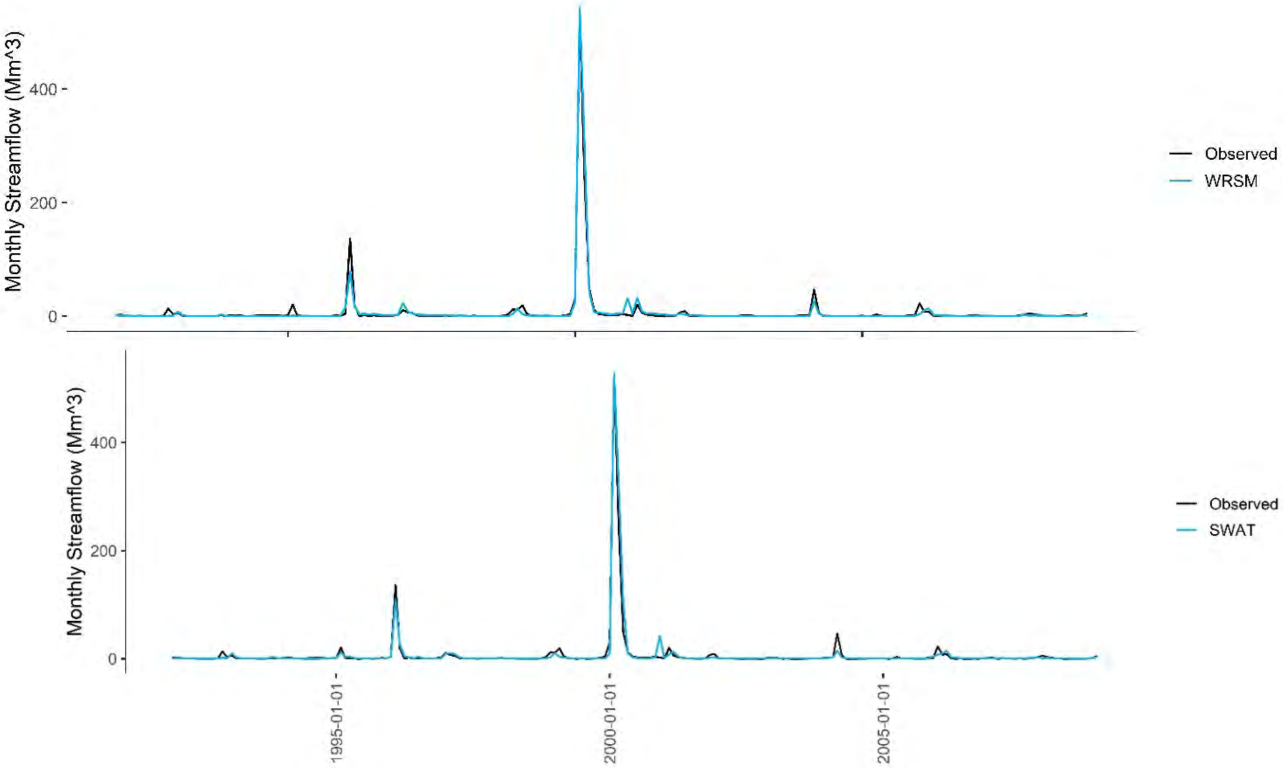


Figure 5.40: Observed and modelled monthly hydrographs of flow entering the Middle Letaba Dam, January 1992 to December 2008 calibration period, for models built in WRSM-Pitman and SWAT2012

Water balance comparison for current scenario (surface and ground water irrigation) models

The two models of the Middle Letaba catchment ended up with differing amounts of irrigation water applied. However, there were other key similarities in their predicted water balances. Despite efforts to parameterise the models comparatively (see Appendix C4), the model built in SWAT2012 predicted roughly half the average annual irrigation application than the WRSM model (14 mm vs 29 mm, scaled to the total catchment area). This was not only due to the irrigation scheduling instructions in the models, so was not simple to rectify. The same SWAT crop and irrigation set-up resulted in a similar irrigation application to the WRSM model prior to calibration, when the SWAT model was predicting much too much streamflow. The lower irrigation was, in part, due to greater modelled supply limitations in SWAT2012. However, the modelled proportions of surface water (63–67%) vs ground water (33–37%) from the total applied flow were similar across the two, despite the very different approaches: fixed areas for each source type in WRSM versus ground water only being drawn to address deficits in SWAT. In addition, both models predicted similar average proportional contributions from surface flow (57–60%), interflow (20–23%), and aquifer outflow (19%) to total runoff, potentially suggesting similar process representation.

The two models predicted fairly similar amounts of runoff, with modelled runoff ratios of 5–6%. However, the runoff predictions were more divergent for the full run period (1983–211) than they had been for the calibration period (1992–2008). The SWAT2012 model predicted less AET and more runoff than the WRSM. Interestingly, although twice as much irrigation water was applied, the modelled ET from the irrigated areas in WRSM was only 20% greater than that modelled in SWAT, potentially indicating more over-irrigation and return flow in the WRSM set-up.

Model predictions with a shift in water management: no irrigation from ground water

When used to estimate the impact of disallowing ground water pumping in the catchment, the two models both predicted relatively small changes (<2%) to mean annual runoff in the catchment (Gifure 5.41 and Table 5.21). However, they differed in the predicted direction of change, the distribution of predicted change across wet and dry times, and the predicted impacts on the water balance (Figure 5.42 and Table 5.22), all highlighting differences in process representation.

The WRSM model predicted a 0.1% (0.03 mm^3) increase in mean annual flow if irrigation from ground water were to stop. The model predicted an increase in median and below-median monthly flows and annual yields, with greater increases predicted for lower flows, while higher flows (i.e. 75th to 98th percentiles) were predicted to decrease, although a slight increase was predicted for the maximum monthly flow. The model predicted a 15% drop in the average annual amount of irrigation water applied (-4.5 mm at the catchment scale), with the total amount of surface water being applied increasing, but not enough to make up for the ground water application. Average total AET was predicted to drop by an amount similar to the drop in ground water irrigation (10 mm), accompanied by a small increase in surface runoff and aquifer outflow, while interflow was predicted to decrease slightly. The aquifer outflow was expected to increase, with withdrawals ceasing. However, the small impact on aquifer outflow to the channels is likely because aquifer levels were often lower than the outflow threshold, even without the irrigation withdrawal.

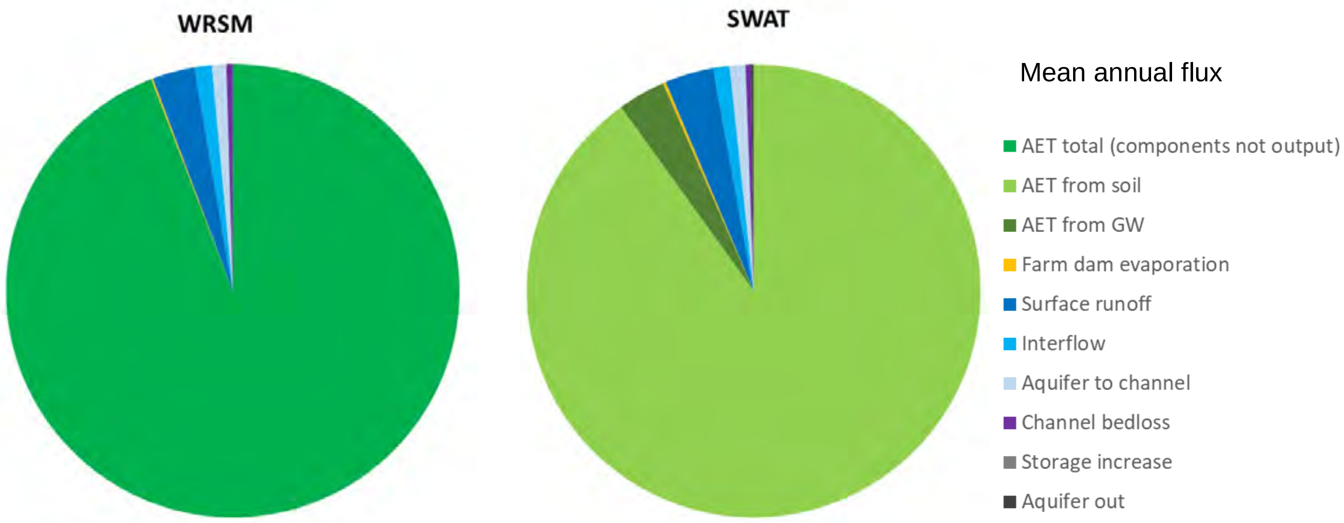


Figure 5.41: Modelled mean annual outgoing fluxes for the Middle Letaba catchment for 1982-10-01 to 2011-09-30, predicted using WRSM-Pitman and SWAT2012 (Note: Not all fluxes are modelled or output by all tools)

Table 5.21: Modelled mean annual water balances for the Middle Letaba catchment for 1982-10-01 to 2011-09-30 (all fluxes are given in mm over the full catchment area)

	WRSM			**SWAT2012**		
Mean annual flux	mm	*Percentage of precipitation*	*Percentage of general flux*	mm	*Percentage of precipitation*	*Percentage of general flux*
Precipitation	**634**			**634**		
Irrigation applied	**29**	***5%***		**14**	***2%***	
Irrigation from SW	20	*3%*	*67%*	9	*1%*	*63%*
Irrigation from GW	10	*2%*	*33%*	5	*1%*	*37%*
AET total	**608**	***96%***		**594**	***94%***	
Farm dam evaporation	0.8	*0.1%*	*0.1%*	1	*0.2%*	*0.2%*
AET from soil				572	*90%*	*96%*
AET from GW				22	*3%*	*4%*
(AET from irrigated)	64	*10%*	*10.5%*	50	*8%*	*8%*
Runoff all (NET)	**34**	***5.4%***		**37**	***5.8%***	
Surface runoff	20	*3%*	*57%*	22	*3%*	*60%*
Interflow	8	*1%*	*23%*	7	*1%*	*20%*
Aquifer to channel	7	*1%*	*19%*	7	*1%*	*19%*
Channel bedloss	*3.0*	*0.5%*		*2.4*	*0.4%*	
Aquifer GW flow out/ inaccessible	0	*0%*		1.2	*0.2%*	
Storage change	-0.29	*0.05%*		-0.1	*0.01%*	
Soil storage change	-0.27	*0.04%*	*94%*	0.1	*0.02%*	*-185%*
Aquifer storage change	-0.02	*0.002%*	*5%*	-0.2	*0.03%*	*290%*
Reservoir storage change	-0.002	*0.0002%*	*1%*	0.004	*0.001%*	*-6%*

Table 5.22: Model predicted changes in streamflow for the Middle Letaba catchment under different irrigation scenarios: switching from surface water and ground water irrigation to surface water only, and switching from surface water irrigation to no irrigation at all

Statistic	**Changes in modelled streamflow, October 1982 to September 2018**							
	Surface water irrigation only vs surface and ground water				**No irrigation vs surface water irrigation only**			
	WRSM		**SWAT2012**		**WRSM**		**SWAT2012**	
Annual stream yield (mm^3)								
Change in:								
Mean	0.03	0.1%	-1.13	-1.7%	55.2	90%	10.5	16%
Standard deviation	-0.19	-0.1%	1.73	1.0%	8.0	4.6%	0.08	0.04%
Minimum	1.3	97%	-0.5	-13%	29.1	1120%	4.2	138%
Maximum	0.9	0.1%	5.9	0.6%	81.5	9%	8.7	0.9%
Monthly streamflow (mm^3)								
Change in:								
Mean	0.003	0.1%	-0.09	-1.7%	4.60	90%	0.88	16%
Standard deviation	0.27	0.8%	0.37	1.1%	-0.05	-0.1%	-0.25	-0.7%
Minimum	0.00	0%	0.0001	8%	1.44	*	-0.0001	-8%
5th percentile	0.12	*	-0.005	-16%	2.20	1833%	0.03	108%
50th percentile	0.07	9%	-0.11	-17%	4.47	508%	0.63	126%
95th percentile	-0.47	-4%	-0.21	-1.7%	6.65	54%	3.23	27%
Maximum	4.67	0.9%	8.75	1.7%	1.92	0.4%	-3.47	-0.6%
Daily streamflow (cm)								
Change in:								
Mean			-0.035	-1.7%			0.33	16%
Standard deviation			0.18	0.5%			0.01	0.03%
Minimum			0.000	0%			0.000	0%
5th percentile			0.000	0%			0.000	0%
50th percentile			-0.03	-24%			0.16	198%
95th percentile			0.07	2.7%			0.60	23%
Maximum			13.0	0.6%			-2.00	-0.1%

In contrast to the WRSM model's predictions, the SWAT2012 model predicted a small decrease (1.13 mm^3, 1.7%) in average annual outflow if ground water pumping were to stop. The decrease in predicted average total irrigation applied was similar to WRSM (close to 4 mm). The model predicted a general decrease in flow for low- to high-flow days, with the very highest daily flows increasing slightly. This pattern carried through to small increases in the highest flow months and years, with decreases in flow predicted for the rest.

This predicted pattern of change was accompanied by a modelled increase in average AET, driven by an increase in AET withdrawal from ground water, given that there was more ground water available without pumping (Figure 5.42). AET drawn from soil was predicted to decrease slightly, likely to due to the decrease in overall irrigation. Surface runoff, interflow and aquifer outflow to the channel were all predicted to decrease slightly, presumably because some of this had been artificially fuelled by the extra irrigation when ground water irrigation was included. Although pumping stopped so that the ground water table could be higher, added modelled AET in the riparian zone appeared to have reduced it so that a decrease in aquifer outflow to the channel was predicted. All these changes are of relatively small magnitudes (<1 mm at the catchment scale).

Model predictions with a shift in water management: no irrigation at all

When these two models were run with no irrigation at all, both predicted an increase in average annual runoff (Figure 5.42 and Table 5.22). Although only 8% of the catchment area is under commercial irrigation, the amounts of irrigation water predicted to be applied were 40–80% of the runoff modelled for the catchment. Because the amount of irrigation being applied in the WRSM models was greater than that applied in the SWAT2012 model, the change was expected to be bigger in WRSM. In addition to this, the patterns of predicted changes and the water balance responses differed between the models. In WRSM, the modelled increase in streamflow when moving from the surface water irrigation scenario to the no-irrigation scenario was slightly greater than the decrease in irrigation water applied. This was, in a large part, because the dams were fuller during wet events, as there were no withdrawals, and so spilled more frequently. In the SWAT2012 model, in contrast, the predicted change in runoff (5.9 mm) was actually a bit smaller than the amount of irrigation that was stopped (10 mm). This was, in part, because of the predicted increases in channel transmission loss, soil and aquifer storage increases and evaporation off the fuller farm dams. In addition, ET from the crop areas did not decrease as much.

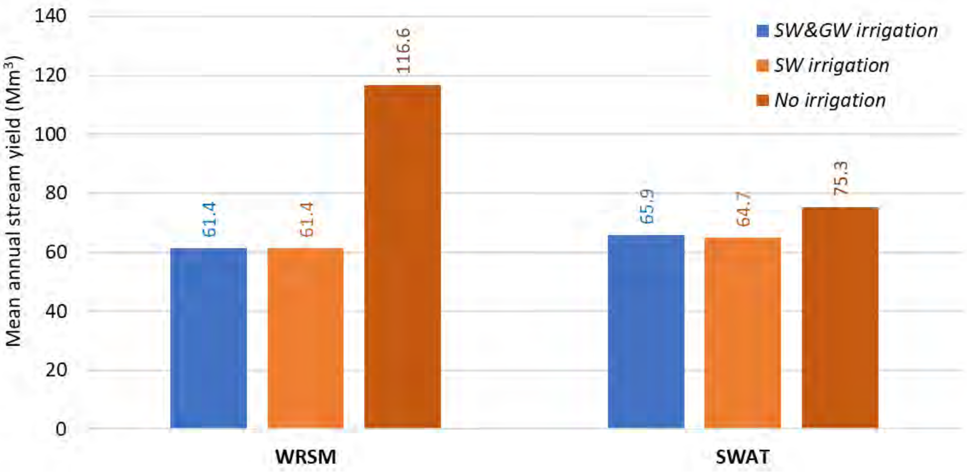
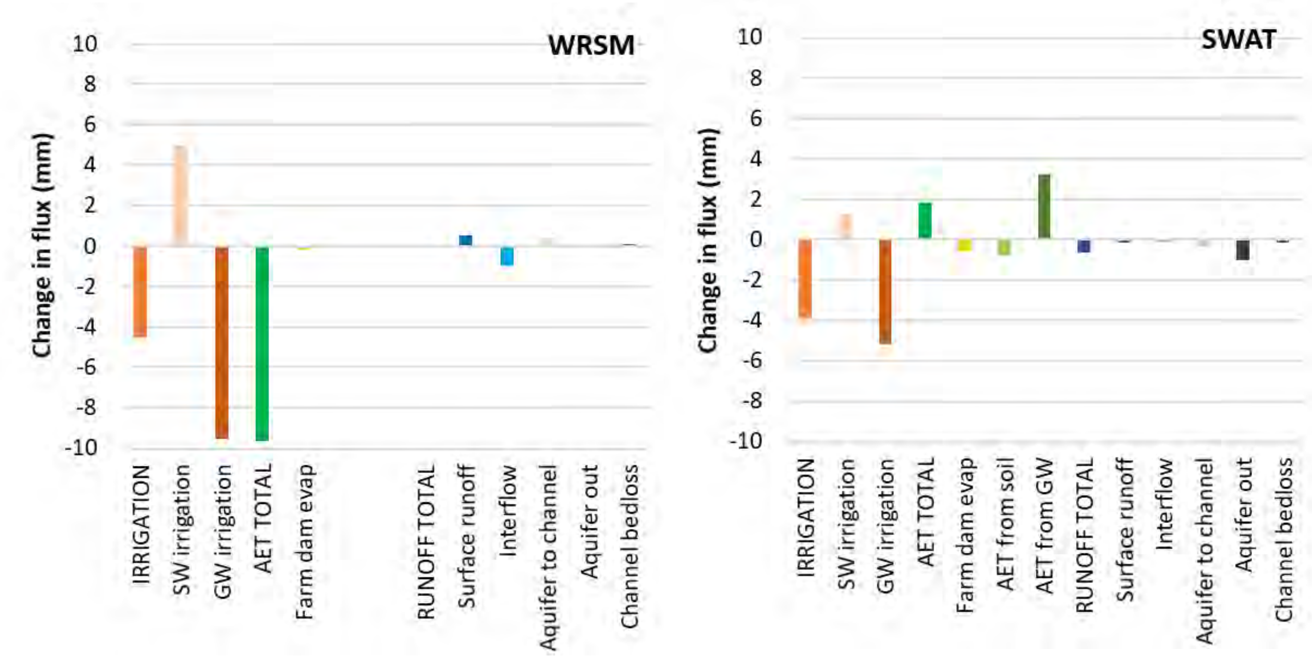


Figure 5.42: Modelled mean annual streamflow yield for the Middle Letaba catchment,1982–2011, under three irrigation scenarios (surface and ground water fed, surface water only, no irrigation)

Switching from surface water and groundwater irrigation to surface water only



Switching from surface water irrigation to no irrigation

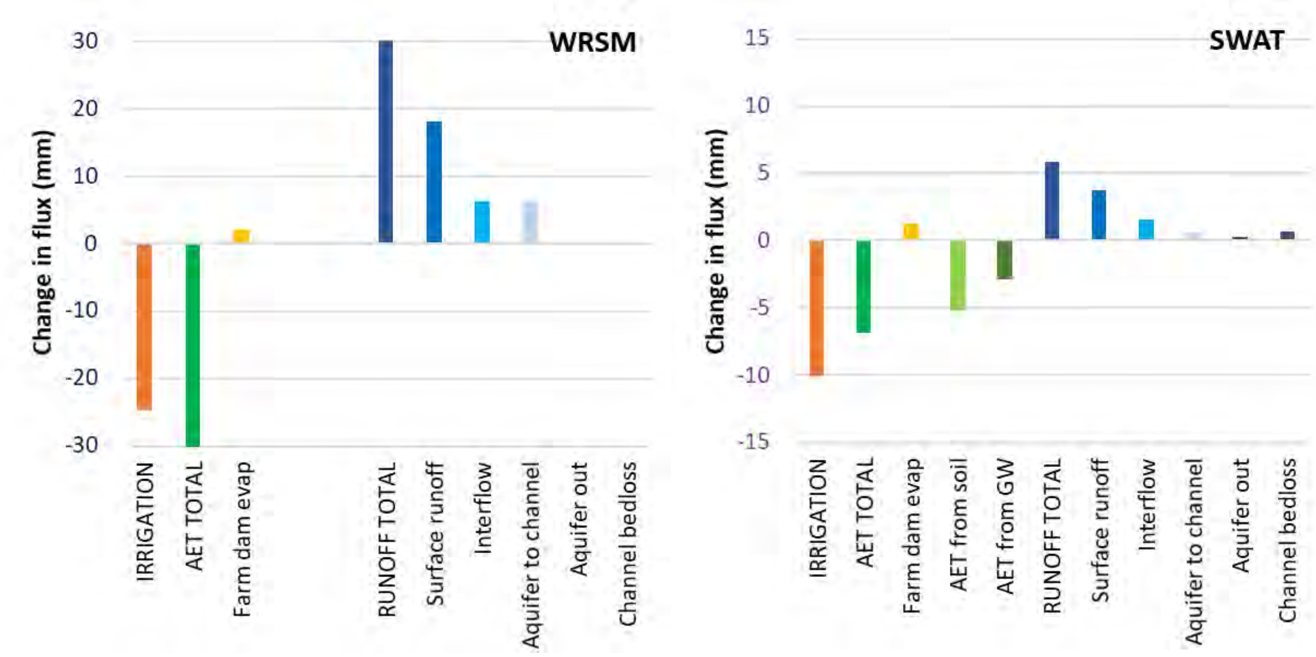


Figure 5.43: Predicted change in mean annual water balance fluxes for the Middle Letaba catchment under different irrigation scenarios using two different models (different axes' scales highlighted)

Table 5.23: Predicted change in mean annual water balance fluxes for the Middle Letaba catchment under different irrigation scenarios using different models

Mean annual flux	**CHANGE in modelled water balance components, October 2006 to September 2018** *(All fluxes given in mm over the full catchment area)*											
	Surface water irrigation only vs surface and ground water						**No irrigation vs surface water irrigation only**					
	WRSM			**SWAT2012**			**WRSM**			**SWAT2012**		
	mm	*Percentage*	*Percentage of change in flux*	mm	*Percentage*	*Percentage of change in flux*	mm	*Percentage*	*Percentage of change in flux*	mm	*Percentage*	*Percentage of change in flux*
Irrigation applied	**-4.5**	***-15%***		**-3.9**	***-28%***		**-24.7**	***-100%***		**-10.1**	***-100%***	
Irrigation from surface water	5.0	*25%*	*-111%*	1.3	*14%*	*-32%*	-24.7	*-100%*	*100%*	-10.1	*-100%*	*100%*
Irrigation from ground water	-9.5	*-100%*	*211%*	-5.1	*-100%*	*132%*						
AET total	**-10**	***-2%***		**1.9**	***0.3%***		**-31**	***-5%***		**-6.9**	***-1.2%***	
Farm dam evaporation	-0.2	*-20%*	*1.7%*	-0.6	*-45%*	*-30%*	2.0	*313%*	*-6.6%*	1.2	*180%*	*-18%*
Canopy evaporation												
AET from soil				-0.8	*30%*	*-44%*				-5.2	*-169%*	*76%*
AET from ground water				3.2	*15%*	*174%*				-2.9	*-12%*	*42%*
(AET from irrigated)	-4.2	*-7%*	*44%*	0.4	*1%*	*24%*	-31.6	*-53%*	*103%*	-7.1	*-14%*	*103%*
Runoff all (NET)	**0.02**	***0.1%***		**-0.6**	***-1.7%***		**30.57**	***89.8%***		**5.9**	***16.3%***	
Surface runoff	0.5	*3%*	*2962%*	-0.2	*-1%*	*26%*	18.0	*90%*	*59%*	3.8	*17%*	*64%*
Interflow	-1.0	*-12%*	*-5176%*	-0.1	*-1%*	*12%*	6.3	*90%*	*20%*	1.5	*21%*	*26%*
Aquifer to channel	0.4	*7%*	*2314%*	-0.4	*-5%*	*62%*	6.3	*90%*	*21%*	0.5	*8%*	*9%*
Channel bedloss	*0.1*	*2.4%*		*-0.1*	*-5.3%*		*0.0*	*0.7%*		*0.7*	*28.5%*	
Aquifer ground water flow out	0	*0%*		-1.0	*-85%*		0	*0%*		0.3	*134%*	
Storage change	-0.02	*5.5%*		-0.07	*113%*		0.00	*0.0%*		0.13	*-96%*	
Soil storage change	0.00	*0.0%*		0.02	*18%*	*100%*	0.00	*0.0%*		0.13	*94%*	*100%*
Aquifer storage change	-0.02	*112%*	*108%*	-0.09	*49%*	*-425%*	0.00	*0%*		0.00	*1%*	*-2%*
Reservoir storage change	0.001	*-87%*	*-8%*	-0.002	*-67%*	*-11%*	0.000	*0%*		0.001	*71%*	*1%*

The differences in the scenario response predictions of these models were due to different representations of processes for which there is insufficient information available to determine which model is more accurate. For example, the SWAT2012 model predicted that the impact of reducing ground water pumping would be compensated by an increase in ET in riparian areas given greater access to subsurface water. This feedback could also be modelled in WRSM, given its riparian zone in the runoff module that can access ground water. However, the differences in algorithms and parameterisations made the two predict this response differently. Additional data would be needed to discern which is more realistic.

5.7 DISCUSSION

The process of designing models for the case studies across the set of modelling tools brought up various process representation, structure and interface differences of importance, as described in the "highlighted representation issue" sections. The results of running these models quantitatively illustrated the impacts of these differences on modelled streamflow, water balance components and catchment responses to land cover and water abstraction change scenarios. Predictions across models were in agreement in the broadest senses: agreeing on the direction of streamflow change with a land cover change, or agreeing on a major difference across two different catchments. For example, all predicted that a greater proportion of rainfall will become surface runoff in the Upper Berg River than in the Mistley, Upper Kromme River, or Middle Letaba catchments. However, in most cases, it was found that the models had important differences in the predicted water balance component compositions, leading to differing patterns of streamflow prediction errors and predicted response changes. This variation in outcomes demonstrated that different modelling exercises, even when provided with the same information and data, could lead to some differing decisions in the applied contexts. These issues could be addressed by using more data and information on other water balance fluxes to better constrain model process representation, uncertainty analyses and multi-model trials.

5.7.1 Streamflow prediction and baseline water balances, across tools and case studies

The exercise illustrated that it was not the differences between the software tools alone that drove differences in predictions for the same catchment. It was a combination of the algorithms and structures imposed by the tools, the available data and the many structure and parameter decisions made by the user. For the most part, models built using different tools did not produce outputs that differed from one another, or from the observed data, in the same way systematically across case studies. For example, the ACRU4 model of the Mistley catchment underpredicted median flows and overpredicted high and low flows, while the Berg River catchment ACRU4 model overpredicted median to high flows. The SPATSIM Mistley model underpredicted high flows and overpredicted low flows, while the SPATSIM Berg River catchment model underpredicted low flows.

Differences in performance patterns across the hydrograph among models could be linked to differences in predicted magnitudes and relative contributions across flow paths. These occurred, despite efforts to set up and parameterise the models equivalently, because the model water balance analyses were mostly done post-hoc. For the Mistley case study, all the models underpredicted mean flow, with the SWAT2012 model's mean coming closest to the observed flow. Models built in SWAT2012 and SPATSIM matched the higher flows better than other models did, while the MIKE-SHEs and ACRU4 models better represented the lower flows. This corresponded to differences in modelled water balance composition: the SWAT2012 and SPATSIM models predicted that interflow dominated runoff on average, followed by surface flow, while the MIKE-SHEs and ACRU4 models' predicted aquifer outflow was the largest contributor, followed by interflow. None of the models met all performance targets, suggesting that a realistic description of the flow paths had not actually been found. Better performance was achieved across the set for the Berg River case study. The MIKE-SHEc model had the closest mean to the observed flow and predicted the greatest dominance of surface flow of the set. The model built with ACRU4 had the greatest overprediction of the mean, but had the best statistics of daily flow fit in the set (R^2, NSE of flow and logged flow). The ACRU4 model fit statistics were only slightly better than those of the MIKE-SHEc model, but the distribution of the runoff's contributions was notably different, with ACRU4 having the greatest predicted ground water contribution of the set.

As could be expected given their physical properties, modelled water balances differed across the four catchments in consistent ways across the models and tools. Comparing models built with the same tool, for each of the tools, a far greater proportion of precipitation became ET in the Mistley and Middle Letaba than in the Upper Berg River, with the Upper Kromme River falling in the middle. Across models, Mistley had a greater proportional (not absolute) aquifer outflow contribution to runoff than the Berg River, and the Berg River had greater proportional surface flow contributions than the Mistley. Across tools, the Letaba also had a higher proportional surface flow contribution than the Mistley, consistent with the steep escarpment terrain driving flash flows in summer storms. The Kromme River catchment saw the most variable runoff source balance predictions across the different models, but generally had the most equal predicted split of surface flow, interflow and aquifer contributions of all the case study catchments.

There were no obvious water balance patterns that were notably consistent for models built with a given tool across the case studies. Models built in SWAT2012 had the highest modelled interflow contribution of the set for the Mistley, Berg and Kromme River scenarios, and also overpredicted flows around the median in these cases, but this was not the case for the Letaba model. For the Berg River case study, the SWAT2012 model was the only one that did not predict surface flow dominance, although the SWAT2012 model of the Letaba did. The ACRU4 models generally had larger aquifer outflow ("baseflow") contributions than the other models, with the exception of SPATSIM predicting a similar contribution for the Kromme River. This did not translate to the ACRU4 models having the highest low flows of the set, as low flows were supported by more, and likely slower draining, interflow in other models.

As described in section 4.7.5, the classification of flow paths used in this study cannot be considered to be strictly equivalent across the tools given their structural and algorithm differences. Seemingly large departures across models may not be as significant when translated into predicting the resulting pattern of streamflow. One tool's fast interflow could be another tool's surface flow, for example. However, these differences should be understood by users when model outputs of surface flow, interflow and aquifer outflow's contributions are specifically needed for the modelling application, such as when modelling is linked to erosion and water quality studies or ground water management, for example.

Table 5.24: Case study modelling performance and prediction overview summary

Case study	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**	**MIKE-SHEc**
Mistley, uMvoti, KwaZulu-Natal ***Scenario: 12% of catchment, eucalyptus to riparian wetland***						
Error in mean	-12%	-17%	-16%	**-2%**	-14%	
NSE monthly	0.23	0.56	0.18	**0.59**	0.36	
NSE log monthly	-0.20	0.37	0.39	-0.02	**0.41**	
Runoff contributions	interflow > aquifer > surface	interflow > surface > aquifer	aquifer > interflow > surface	interflow > surface > aquifer	aquifer > interflow > surface	
Scenario: MAR change	*+22%*	*+24%*	*+40%*	*+4%*	*+34%*	

Case study	**WRSM-Pitman**	**SPATSIM-Pitman**	**ACRU4**	**SWAT2012**	**MIKE-SHEs**	**MIKE-SHEc**
Upper Berg, Western Cape ***Scenario 1: 8% of catchment, upland pines to fynbos,*** ***Scenario 2: upland pines to riparian pine***						
Error in mean	12%	7%	18%	7%		**-4%**
NSE monthly	0.87	0.90	0.89	**0.94**		0.92
NSE log monthly	0.90	**0.90**	0.90	0.88		0.89
Runoff contributions	surface > interflow > aquifer	surface > interflow > aquifer	surface > interflow > aquifer	interflow > surface > aquifer		surface > interflow > aquifer
Scenario 1: MAR change	*+7.1%*	*+1.3%*	*+0.8%*	*+0.1%*		*+1.1%*
Scenario 2: MAR change	*-1.0%*	*-0.4%*	*-0.4%*	*-0.5%*		*-0.8%*
Upper Kromme River, Eastern Cape ***Scenario: 58% of catchment, fynbos and wetland to wattle and pine***						
Error in mean		*17%*	*14%*	***-2%***	*-3%*	
NSE monthly		0.55	0.85	0.65	**0.86**	
NSE log monthly		0.06	**0.66**	0.49	0.48	
Runoff contributions		surface > aquifer > interflow	aquifer > surface > interflow	interflow > aquifer > surface	interflow > aquifer > surface	
Scenario: MAR change		*-59%*	*-45%*	*-21%*	*-32%*	
Middle Letaba, Limpopo ***Scenario 1: 8% of catchment, surface water and ground water irrigation to surface water only*** ***Scenario 2: Surface water irrigation to no irrigation***						
Error in mean	***-0.5%***			***0.5%***		
NSE monthly	**0.97**			0.96		
NSE log monthly	-1.55			**0.17**		
Runoff contributions	surface > interflow > aquifer			surface > interflow > aquifer		
Scenario 1: MAR change	*+0.1%*			*-1.7%*		
Scenario 2: MAR change	*+90%*			*+16%*		

A shaded cell for a performance statistic value indicates that it met acceptability targets (Error in mean ≤15%, NSE ≥ 0.6), ***bold*** *text indicates the highest performance in the set of models for that statistic.*

5.7.2 Predicted change in streamflow and contributing fluxes due to land cover change, across tools and case studies

Given their differences in process representation shown in the baseline water balances, it was not surprising that models differed notably in their predictions of change when alternative land cover scenarios were applied. Some differences in change prediction were consistent for models built with a different tool, but most were not. The models built with SWAT2012 predicted much smaller changes with tree clearing than the other models across the case studies, and also predicted a smaller change in runoff with a decrease in irrigation. However, for the Mistley case study, the ACRU4 model predicted the most change with plantation clearing. For the Berg River catchment, the WRSM model predicted the most change with alien clearing. For the Kromme River catchment, the SPATSIM model predicted the most change with alien invasion expansion. For the Mistley case study, the two models built with the Pitman tools predicted relatively similar amounts of change (22–24% increase). However, for upland IAP clearing in the Berg River catchment, the SPATSIM model predicted a much smaller change in mean flow compared with the WRSM model (1.3% vs 7.1%), instead predicting more consistent degrees of change to the ACRU4 and MIKE-SHEs models (0.8–1.1%). For the case of exchanging upland IAPs for riparian IAPs in the Berg River catchment, WRSM again predicted the most change (1%), followed by MIKE-SHEs (0.8%), with SPATSIM, ACRU4 and SWAT2012 predicting relatively similar mean changes (0.4–0.5%)

Predicted streamflow changes associated with the scenarios were explained by differing water balance changes across models. Again, these were not necessarily consistent for models built with a given tool across case studies for the most part. However, models built with SPATSIM-Pitman had the highest predicted canopy interception of those outputting canopy interception, and predicted the largest change in canopy interception with vegetation change scenarios. The predicted decrease in canopy interception predicted in the SPATSIM model resulted in a compensating increase in predicted ET from soil due to the increased water availability, generally not predicted in other models. However, it is likely that the major role of canopy interception in these SPATISM models was less to do with the tool's algorithms than the parameterisation used (see appendices C1–C4). In the ACRU4 Mistley model, canopy interception change with tree removal did not dominate the predicted ET change. However, it did dominate in the ACRU4 Berg model. The MIKE-SHEc and MIKE-SHEs canopy interception algorithms are the same, but use different timesteps. Canopy interception dominated the predicted change for the MIKE-SHEs Mistley and Kromme River models, but did not do so for the MIKE-SHEc Berg River model. It is not known which model was more accurate, but these results highlight the importance of understanding canopy interception, and attention is needed in its parameterisation.

In the Mistley, Berg, and Kromme River case studies, the models built in ACRU4 predicted that the streamflow changes due to changes in land cover were dominated by changes in aquifer outflow ("baseflow" output). For the Mistley case study, this was also the case for the SPATSIM, SWAT2012 and MIKE-SHEs models, but it was not the case for the other models of the Berg or Kromme River. This highlights the differences in runoff generation, infiltration and percolation calculations across the tools, despite efforts to input similar soil property parameters.

The models built in SWAT2012 predicted smaller amounts of change than all the other models for the Mistley plantation clearing in wetlands and buffers, the Berg River upland invasive pine clearings, the Kromme IAP expansion and the Letaba reductions in abstraction and irrigation. This was, in part, due to the way vegetation water use across different vegetation types was parameterised in the tool and, in part, due to the models' consideration of subsurface flow connectivity and vegetation access to ground water. In the Mistley case study, the full Penman-Monteith method was applied in SWAT2012, using LAI and stomatal conductance rather than ET coefficients (crop factors). In the Berg and Kromme River case studies, reference PET was used, so the model calculated a crop factor from the LAI values used. SWAT2012 caps this crop factor at 1, while higher values were used in other tools. However, outputs showed that smaller differences in vegetation-type ET demand was not the only reason for the smaller change prediction.

When treed cover was cleared, the SWAT2012 models predicted increased ground water recharge and availability, which resulted in increased AET from ground water through dry periods. This compensated for the lower maximum AET rates of the new vegetation. This was also seen in the Letaba when ground water pumping was stopped. A similar pattern was predicted by the Mistley MIKE-SHEs model, but to a smaller degree. In the Berg River, the SWAT2012 model predicted larger, more similar changes to other models when comparing the case of pines in the riparian area versus the uplands. This was because the riparian pines being removed were less often predicted to be water-stressed. Without alternative data to confirm these process patterns, it is difficult to know whether or not this predicted compensation impact of riparian vegetation modelled by SWAT2012 is more or less realistic to what is modelled by the other tools.

This exercise highlighted the importance of consulting the predicted water balance in greater detail during the model-building process and has means to validate it. Operationalising this is facilitated to very different degrees across the different software tools, described in sections 4.7.5 and 4.7.6.

5.7.3 Model-building and process representation challenges

When building models for the case study catchments using the different modelling tools, a variety of challenges were encountered, which were applied to one or more of the tools. Some of these were primarily due to the process conceptualisation strategies in the tools, while others were linked more to the software interface and ways that inputs are added and outputs exported. These interface hurdles could also result in process representation issues. For example, labour- and time-intensive set-ups of modelling units in the software drives users towards more spatially lumped representation, which may be more or less appropriate in different cases. These representation and interface challenges led to further refinement of the structural review sections. The practical implications of tools' structural differences, such as not including subsurface flow between subcatchments, became clearer when trying to make model set-up decisions for the case studies.

Documenting the model set-up decisions (appendices C1–C4), such as if and how to simplify land cover and soil types or how these should be parameterised, highlighted the large number of decisions that would be user-dependent, even when using a single tool. It was clear that decisions could easily be made differently by a different user and still be rationalised based on the information available about the case study. Some parameter value choices could come directly from the catchment property data available, but many did not have direct equivalence in scale or meaning to the available information, and so interpretation was needed. This project did not include time to experiment with different model structures within the same tool for a given case study, something that the modelathon activity would help explore.

CHAPTER 6: CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

6.1 MODELLING TOOL REVIEW

This project accomplished its primary objectives in comparing the focus set of commonly modelling tools on a range of levels and using a variety of approaches and initiating a guidance- and information-sharing platform for model users.

The five modelling tools, WRSM-Pitman, SPATSIM-Pitman, ACRU4, SWAT2012 and MIKE-SHE, are commonly used in the same application contexts as each other and share many basic capabilities and high-level approaches. However, they were also found to differ substantially in many ways that will have different implications in different contexts. There were some obvious differences in terms of having or lacking the capability to explicitly model a certain process (as summarised in Table 4.3). For example, the Pitman-based tools calculate flows on a monthly timestep and are not appropriate for evaluating flood peaks. ACRU4 does not include ground water pumping. SWAT2012 cannot model overbank flooding into a wetland on a main channel. MIKE-SHE does not have a straightforward way to represent many small farm dams used for irrigation. There were also less obvious differences in terms of how certain processes were represented across the tools, in particular, the handling of interflow and ground water flows and landscape connectivity.

When applying the different tools to application cases, all were fairly well suited to change in forestry plantation cover or change in IAP cover. No one modelling tool stood out as having consistently better or worse performance, or systematically over- or underpredicting parts of the hydrograph across multiple case studies.

An important finding in this project is that, for most of the tools, it is time-consuming and not straightforward to obtain catchment-scale (and other scale) outputs of various water balance fluxes, such as canopy interception or aquifer outflow’s contribution to streamflow. At the same time, the case study exercise demonstrated that it can be highly important to assess these and determine if the modelled water balance is realistic before extending the model to alternative scenarios. In the case study modelling exercises, even when models across the different tools achieved fairly similar baseline streamflow predictions, they could diverge notably when modelling an alternative scenario. This was because a different balance of processes had been underlying the baseline case. While this was found using models built with different tools, it is essentially the same problem as equifinality across alternative baseline parameter sets for a single model structure: the different sets may perform equally well in the baseline, but would lead to differing outputs under a change scenario.

The intention of this project was to assess water balances across the different tools during calibration to see if models predicting equivalent balances of processes can be built across the different tools. However, the technical difficulty of extracting and processing these meant that it became a parallel workstream and the assessment was done post-hoc. It is not likely to be common practice to assess modelled water balances in the way done during this study, not only because it is challenging, but also because there is often no other data (ground water levels, measured ET) or information to compare it to.

Generic model approach lessons that were reiterated throughout this project were the following:

- Every catchment modelling project will entail a compromise of one sort or another, so the priorities of the exercise should be discussed and identified before model building starts. These will likely need to be revisited and refined during the process. This not only applies to process representation, but also to the practicalities of applying a tool and processing output. For example, one tool may be easier to learn and faster to run, but may take much more external post-processing to obtain the needed outputs.

- One should establish as much of a conceptual model of internal catchment processes as possible. Ideally, data regarding internal catchment fluxes, such as ground water recharge or AET, will allow an assessment of model realism. This is needed as different model structures can arrive at similar streamflow predictions, especially for complex, highly parameterised systems.
- Given the conceptual model, the available information and goals of the modelling study, one should identify the desired model outputs (other than streamflow) for the exercise, as not all tools can easily output all fluxes at all spatial scales. In some cases, these can be back-calculated from the outputs.
- The delineation of subcatchments and other separately modelled units have a variety of implications for process representation, so most modelling tools can determine the spatial distribution of climate input and flow connectivity. Mapping out the model structure externally to the modelling tool interface, even if the tool can automate model unit generation, can assist in understanding and interrogating the surface and subsurface flow connections that are possible in the model compared to the conceptual model of the catchment.
- Even when parameter values are intended to be physically measured properties or directly tied to these, the scale at which they are applied and the algorithms used in different tools can mean that the same value may not result in the same process representation in different model structures within a tool or across tools. Exact field-measured or literature values may not always be appropriate when used directly. This further highlights the need to evaluate a model’s internal process predictions and water balance composition.

In terms of selecting tools given the particular needs of a modelling project, there are many issues to consider, and workarounds and compromises possible so that there would never be a single best answer. However, if some specific processes or features are critical to a project, some tools may offer an easier road than others as identified in this project. Examples include the following:

- If the explicit representation of multiple vegetation types beyond tree plantations, IAPs, irrigated areas, impervious areas and wetlands is important for the modelling exercise, the Pitman tools will not be straightforward to apply compared to other tools.
- If it is important to specify a particular vegetation type in the riparian zone, the SPATSIM-Pitman offers less direct approaches to handle this than the other tools.
- If clearly distinguishing interflow from surface runoff and aquifer outflows are important, ACRU4 would be a more difficult tool than the others to achieve this. Depending on how an ACRU4 model is parameterised, interflow may be included in one or more of the tool’s calculated flows: delayed-stormflow, baseflow and saturated overland flow.
- If regional ground water flow is likely to be important, SPATSIM, WRSM and MIKE-SHEc are designed to explicitly include this. In SWAT2012 and MIKE-SHEs set-ups, ground water flow leaving the catchment can be implicitly included by routing some recharge to “dead storage”.
- If representing channel transmission loss is important, ACRU4 and WRSM may pose more representation challenges than the other models. ACRU4 does not explicitly include channel transmission losses. A workaround can be applied, using channel overflow onto an associated riparian HRU. This is a high-flow threshold process, rather than one continuing at low flows, but the riparian HRU could be parameterised to represent the channel plus riparian vegetation and have an overflow threshold of 0 cm. However, this would take careful adjustment to get right. WRSM includes channel transmission losses, but the water is assumed to leave the model and is not available.
- If there are many small farm dams in a catchment that store a significant amount of water compared to predicted runoff, it will be more challenging to include these in SWAT and MIKE-SHE than with the other tools. Including them in ACRU4 would entail establishing separate HRUs both upstream and downstream, while including them in a SPATSIM or WRSM model entails less additional complexity.
- If irrigation is to be included, different tools allow irrigation to be drawn from different sources: rivers, dams and external inputs in WRSM, SPATSIM and ACRU; rivers, ground water and external sources in MIKE-SHE; and rivers, dams, ground water and external sources in SWAT.

The guidance material includes information about the user interface challenges in each tool as described above, potentially to help inform tool selection, but more to provide strategies for more effective use.

For example, cautionary tales about checking and rechecking the unit the relationships specified in ACRU4 set-ups or being sure to review the default parameters being applied in SWAT2012.

This project clearly highlighted the ongoing need for environmental data collection of various kinds and data availability to enable the more accurate and appropriate use of models. Beyond maintaining and enhancing climate data collection, particularly across elevation gradients, and the streamflow gauging network, a critical gap is soil and aquifer property data. A review of how to translate this data into appropriate model parameter values for different modelling tools is also needed. Relatively speaking for the continent, South Africa has reasonably readily available national-scale databases of various biophysical parameters and process estimations that can be used to inform modelling: the ACRU “compoveg” vegetation parameters database, the ARC’s landtypes and AutoSoils and the South African Atlas of Agrohydrology and Climatology (Lynch, 2003; Schultze, 2007), Groundwater Resource Assessment (GRA) II (DWS, 2006), the Water Resources of South Africa 2012 Study (Bailey and Pitman, 2015), NLC datasets (DEA, 2019) and the national geology maps of the Council for Geosciences. In some cases, these databases were developed in concert with a South African modelling tool and have some correspondence to the tool’s parameterisation. However, this is not always the case, and these databases may need revisiting in light of new data sources and modelling tools.

6.2 HYDROLOGICAL MODELLING WIKI SITE

The findings of the review were synthesised into the initial content of a wiki website, HydroModel wiki South Africa (https://hydromodel-sa-wiki.saeon.ac.za/). The project team members build the site using MediaWiki online software and it is freely hosted on SAEON’s servers. The site is intended to be a living resource that the modelling community can continually update. It is aimed at both those relatively new to modelling and those who are already experienced in it, but may be interested in trying different tools for different applications and/or developing tools. As such, the information is presented at differing levels of summary and detail, so hopefully users can find the level they are looking for. The material covers similarities and differences between the tools in terms of process representation and user experience with a focus on implications for common use cases or use settings.

Pages are organised into a few general content types in a navigation bar that is always visible. Pages listed in this bar are, in turn, linked to pages on more specific topics. The site has a search function and cross-linking between pages to help users navigation through the material.

The main topic groupings and pages are as follows:

- **Site introduction:** Main page, wiki scope, content team, discussion page instructions
- **Background:** Terminology, modelling process overview, model types and tools
- **Modelling tool intercomparison:** Capabilities overview, model units and connections, process representation, water balance outputs, user interfaces, documentation and support, specific use cases
- **Resource links:** Tool documentation, data sources, intercomparison study project report

As the model user survey highlighted, there are many factors that influence what tool a modeller may use, and learning curves prevent users from jumping between many tools. While 95% of survey responders had been exposed to several modelling tools, only 28% indicated using more than one tool regularly and “prior use” of a tool was the most frequently selected factor driving users’ tool selection. As such, part of the intent of the site is to provide suggestions for using any of the common tools in a given context: things to consider in model set-up, ways of implicitly representing processes that a tool cannot represent explicitly, etc. With the diversity of applications, scales and settings across which catchment-scale models are used, the goal was not to be exhaustive during the current project, but rather to establish a framework and platform for sharing this information.

The site has been set up so that additional editors, with full access to edit the site, can be established, and general users can comment and suggest content edits and additions via discussion pages, rather than freely editing all site content. Much of the envisioned initial content has been put on the site. The initial content will be finalised after review from the project reference group and additional project advisors, to be ready for public launch in September 2021.

6.3 RECOMMENDATIONS FOR FURTHER WORK

There were activities envisioned in the inception phase of this project that proved to be overly ambitious, but would be useful next steps:

- Implementing a refined version of the case study modelling exercise across tools in which models are built and calibrated against not only catchment outlet streamflow, but also other indicators of the underlying balance of fluxes, i.e. ground water-level data, soil moisture data and/or measured AET.
- Running one or more modelathon activities to further explore the variability or similarities across modelling tools and across users. The catchment case study for the activity should ideally be one with additional water balance observational data to use in assessing the water balance outcomes after they have been modelled against streamflow.

The case studies explored in this project were necessarily limited, and it would be useful to give similar depth consideration to other use case types, particularly the following:

- Modelling alternative climate scenarios for the same catchments using multiple tools
- Modelling large reservoirs and/or transfer schemes explicitly with various release schedules, etc., using multiple tools.

Climate change studies and reservoir planning were the next most frequently cited use of catchment models across the survey respondents. In addition, there were many model structural alternatives and trade-offs identified during the case study modelling exercise that it would be instructive to test: particularly the impact of spatially averaging climate for larger model landscape units or breaking up the landscape more to allow more spatially distributed rain input.

This project highlighted the need for additional checks on the modelled water balance outside of just streamflow. In data-limited cases, remote sensing products could assist. Locally adapted research and method development for operationalising this (i.e. strategies to this data given the input and output variables, scales and formats of the commonly used modelling tools) is needed. It would be valuable content to add to the wiki as well. In addition, during this project, a lot of R-code was created to assist in processing model outputs from the various modelling tools. A helpful addition would be to revise these codes to be more generic or transferable and make them available for download on the wiki. If further development work is supported for the South African modelling software tools, improving the ease of accessing various water balance outputs and the ease of setting up sensitivity analyses and parameter exploration batch runs would be valuable.

A follow-on from this project that will also be vital to its impact is to further engage the modelling community regarding the findings and to formally establish a group of content moderators for the wiki site to join the project team in maintaining and updating it. Although some of the community engagements initially planned for this project could not be completed, the project is well timed with the initiative to establish a formal hydrological sciences society and revitalise a community of practice. This will provide a platform through which the wiki site can be publicised, the modelathon activity more simply organised and volunteer wiki content managers found.

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APPENDIX A: REPRESENTATION OF MAJOR CATCHMENT PROCESSES COMPARED ACROSS MODELLING TOOLS

For each of the main catchment processes listed below, salient differences in process representation algorithms across the modelling tools are summarised, followed by tables describing the relevant algorithms used in each tool. An effort has been made to describe algorithms in similar terms for all the tools to aid comparison (see Terminology description in Section 3.2 of the main report). The process algorithms are relevant to the spatial and temporal discretisation differences in the tools described in Section 4.4 of the main report and not covered in depth again here.

Catchment processes covered:

- Rainfall
- Atmospheric demand for evapotranspiration and total actual evapotranspiration
- Canopy interception: storage and evaporation
- Soil infiltration and soil bypass flows (macropore flow and flow in shrink-swell cracks)
- Surface runoff generation and routing
- Evapotranspiration withdrawal from soil moisture and ground water
- Soil and vadose zone water distribution and storage vs percolation to ground water (ground water recharge)
- Interflow (lateral flow, shallow subsurface flow)
- Ground water storage, flow, capillary rise and exchange with channels
- Channel flow and overbank flooding

MIKE-SHE includes more diverse discretisation and algorithm options than the other tools. To describe process representation in comparison to the other tools, two approaches for setting up a model in MIKE-SHE are summarised here, referred to as “simple” and “complex”. The “simple” approach is more semi-distributed and uses more conceptual algorithms, while the “complex” approach is fully distributed and uses the more physics-based algorithms. These are further described in **section 4.3.1** in the main report.

ABBREVIATIONS USED IN PROCESS ALGORITHM TABLES

↑ = increase; ↓ = decrease
min = minimum; **max** = maximum; **ave** = average
func = function
calc = calculate
coeff = coefficient
subcat = subcatchment
HRU = hydrologic response unit
DEM = digital elevation model
evap = evaporation
ET = evapotranspiration
PET = potential ET; **AET** = actual ET
CI = canopy interception
E_p = plant transpiration
E_s = soil evaporation
LAI = Leaf Area Index

SW = surface water
RO = runoff
SRO = surface runoff
IR = infiltration rate
SM = soil moisture
SAT = saturation SM
FC = field capacity SM
WP = wilting point SM
AWC = soil available water holding capacity (AWC = FC – WP)
IR = infiltration rate
MPF = macropore flow
K = hydraulic conductivity; **K_{sat}** = saturated K
GW = ground water
grad = gradient (ground water gradient)

A1: RAINFALL

In all tools, rainfall is a user input, but differences exist in terms of timesteps and spatial discretisation (see 4 in main report). The spatial unit for a rainfall input determines how available observation datasets need to be processed. To get spatially averaged rainfall for a unit, point-based gauge data will need interpolation. Spatial rainfall distribution surfaces from gauge data, other spatial co-variates and/or satellite estimates can also be used.

Averaging rainfall across large areas can impact on process calculations and predicted water balance, particularly when there is high spatial diversity in rainfall and quantities are close to thresholds that would allow for a particular process to occur, i.e. exceed canopy interception and reach the soil; exceed the infiltration rate and create runoff.

- Both **Pitman** models use monthly rainfall inputs, which are internally distributed into four periods. However, **SPATSIM-Pitman** allows the user to control this distribution with a parameter, while the distribution pattern is fixed in **WRSM-Pitman**. This will impact on the calculation of threshold-controlled processes.
- **SPATSIM-Pitman and SWAT** apply an input rainfall time series for the area of a subcatchment: all internal units receive the same rainfall.
- **WRSM-Pitman** applies a rainfall input per runoff module, which is similar to a subcatchment. However, associated special land and water area modules (i.e. irrigated areas, plantations, alien vegetation stands, mines, wetlands, reservoirs, etc.) can be assigned different rainfall inputs.
- **ACRU4** allows a different rainfall input for each HRU in the model if desired.
- **MIKE-SHE** has the greatest flexibility in the rainfall inputs: spatially averaged inputs can be given for user-defined zones, which can line up with HRUs, subcatchments or be independent (e.g. using isohyets that do not need to line up with land cover or subcatchment boundaries). Gridded rainfall timeseries data cubes can also be directly input. The model internally finds appropriate rainfall for each model grid cell based on the inputs. For other tools, this pre-processing to get inputs for modelled units would need to be done externally by the user.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple Semi-distributed, more conceptual	MIKE-SHE complex Distributed, more physical
Rainfall	Monthly time-series of rainfall input by user for each module. Model internally divides month into four periods to account for intensity patterns, allocating less rain in first and last vs. middle two.	Monthly time-series of rainfall input by user for each subcatchment Model internally divides month into four periods to account for intensity patterns. Distribution across periods is a function of an input parameter.	Daily time-series of rainfall input by user for each subcatchment or individual HRU *OPTION: In-built function to estimate daily series from monthly + parameters (Fourier analysis)*	Time-series (subdaily, daily, monthly options) of rainfall input by user for each subcatchment *OPTION: In-built weather generator - estimate daily series from monthly + parameters, subdaily from daily and fill gaps*	Time-series (flexible timestep options) of rainfall input by user for user-defined polygons, not forced to align with other zones OR Input as data-cube: time-series of gridded rainfall data Model internally finds value for each calculated grid cell and timestep (spatial and temporal averaging where needed)	

A2: ATMOSPHERIC DEMAND FOR EVAPOTRANSPIRATION AND TOTAL ACTUAL EVAPOTRANSPIRATION

The tools differ in the input value that is used to consider the atmospheric demand for ET in the calculation of AET:

- **WRSM-Pitman, SPATSIM-Pitman and ACRU4** typically use pan evaporation inputs, an open water reference, vs **SWAT2012 and MIKE-SHE,** which use PET for a reference vegetated surface (maximum ET for the climate conditions estimated for well-watered grass, standardised United Nations Food and Agriculture Organisation (FAO) method) as the input.
  - The Pitman tools call for S-pan data, while ACRU calls for A-pan data. Conversion factors can be applied to move between pan types and potentially estimate an equivalent reference vegetation PET.
- **SWAT2012** differs from the others in that it internally calculates PET from user-input climate data with three algorithm options. The algorithm used depends on the climate data available: the minimum input is minimum and maximum temperature time-series. The Penman-Monteith algorithm differs in that PET for the vegetation being modelled (maximum ET given the weather conditions, assuming no water limitation) is calculated directly, rather than first calculating PET for a grass reference to be later adjusted. This has some implications for other process calculations that would otherwise use the reference PET, discussed below.
- **MIKE-SHE** requires the reference PET be input by the user directly, but it could be calculated by the user externally using the same methods and data as SWAT applies internally.

The tools differ in how the reference value is adjusted to estimate the PET (or maximum ET) for the specific cover type being modelled:

- **SPATSIM-Pitman** differs from the other models in that it does not adjust the input pan value, assuming the vegetation could achieve this ET if not water limited. However, a pan factor adjustment, as applied within WRSM-Pitman, could easily be applied by the user externally to the model to make the inputs equivalent.
- The others modify the reference PET using a function of LAI (**SWAT2012, ACRU4 option**) or a coefficient (**WRSM-Pitman, ACRU4 option, MIKE-SHE** – *Note: Coefficients for each will be different because of the difference reference*).

The differences mean that reference PET inputs and coefficients from a model built using one of the tools are not directly transportable to another tool and would need conversion.

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Atmospheric demand for ET *(reference surface PET)*	Monthly pan evaporation values (long-term averages, not time-series) input by user for each module. Evaporation pan factors used to calculate a PET for module's specific land cover.	***OPTIONS*** **Monthly averages:** Monthly pan evaporation values (long-term averages, not time-series) input by user for each module. **Monthly time-series:** Monthly time-series input by user for each subcatchment.	Daily time-series of A-pan evaporation input by user for each subcatchment or individual HRU. Crop coefficients used to calculate a PET for HRU's specific land cover.	Time-series (subdaily, daily, monthly options) of climate data input by user for each subcatchment Model estimates PET. ***OPTIONS*** ***Hargreaves et al., 1985:*** *Minimum and maximum temperature for reference PET; LAI to calculate PET for HRU's specific land cover* ***Priestly & Taylor 1972:*** *As above, plus solar radiation and relative humidity* ***Penman-Monteith 1965:*** *All climate data above plus wind speed; stomatal conductance to calculatc PET for HRU's specific land cover*	Time-series (flexible timestep) PET for reference vegetation input by user for polygons, not forced to align with other zones OR Input as data-cube: time-series of gridded data Model internally finds value for each calculated grid cell and timestep (spatial and temporal averaging where needed) Crop coefficients used to calculate the PET for the specific land cover type (input land cover polygons with linked coefficients).	
AET *(components covered below)*	Draw from available storages: 1. Canopy interception: evaporation 2. Soil: transpiration and evaporation 3. Ground water: transpiration		Draw from available storages in sequence up to reference PET as maximum possible total AET:	Draw from available storages in sequence up to reference PET as maximum possible total AET:	Draw from available storages in sequence up to (reference PET * crop coefficient) as maximum possible total AET:	Draw from available storages in sequence up to (reference PET * crop coefficient) as maximum possible total AET:

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
	ET from canopy interception does not impact on the total ET from soil and ground water. ET from soil is limited to PET as a maximum. Transpiration from ground water only occurs when ET from soil < PET		1. Canopy interception: evaporation 2. Soil: transpiration and evaporation 3. (option) Vadose zone: transpiration Vadose zone includes capillary rise from ground water	1. Canopy interception: evaporation *(only with Green-Ampt infiltration option)* 2. Soil: transpiration and evaporation Soil includes capillary rise from ground water	1. Canopy interception: evaporation 2. Surface ponding: evaporation 3. Soil: transpiration and evaporation 4. Ground water: transpiration	1. Canopy interception 2. Surface ponding: evaporation 3. Soil: transpiration and evaporation 4. Ground water: transpiration Soil includes capillary rise from ground water.

The tools differ in the spatial and temporal scale at which the atmospheric ET demand reference is input in the same way as described for rainfall above. Impacts of this on data processing and potentially on model outputs are similar to those mentioned for rainfall. However, spatial and temporal generalisations for reference PET are likely to have a lesser impact due to less spatial and temporal variability compared to rainfall.

- **Pitman** tools use monthly inputs vs daily or subdaily inputs of the others. **WRSM-Pitman** uses fixed monthly average pan evaporation, meaning no inter-annual variability in monthly PET, while **SPATSIM-Pitman** allows monthly time-series to be input.

Total AET from a vegetated surface can include evaporation from canopy interception, evaporation of water in and on the soil, and plant transpiration drawn from the soil and potentially aquifer layers. The modelling tools are relatively similar in representing ET occurring from most of these stores when water is present, with rates generally driven by atmospheric demand and curtailed by water availability (*see table above and component processes in sections below*).

However, the tools differ in whether or not they explicitly include ET drawn from certain sources:

- **SWAT2012**, when using the **SCS-CN method** option for calculating runoff generation and infiltration from rain events, does not explicitly calculate **canopy interception storage and evaporation.** Rainfall that does not become surface runoff is assumed to infiltrate. Canopy interception ET would have to be implicitly included in the ET from soil to achieve an appropriate water balance. This could influence parameters controlling ET (vegetation canopy resistance or LAI, soil texture used to calculate the SAT, FC and WP soil moisture) to allow for this additional ET from the soil to compensate.
- **SWAT2012** and **ACRU4** do not explicitly include **ET withdrawals from ground water** aquifers, while the Pitman models and MIKE-SHE do. However, in SWAT2012, capillary rise from ground water into the soil profile can result in deep- rooted vegetation ET being sourced from water that had previously been in the ground water store. In the default ACRU4 set-up, once water percolates from the lower soil layer, it is no longer available for ET. An optional routine adds a vadose zone (“intermediate” zone) layer below the standard soil layers, which is accessible to deep-rooted vegetation. This zone can receive capillary rise from ground water below, similar to SWAT2012.
- **MIKE-SHE** is the only tool considered that explicitly calculates **evaporation from surface ponding**. This would only become important for flat terrain, low infiltration terrain or areas with high detention storage. This could be accounted for in other ways in other tools: soil water retention, a wetland routine, etc.

Tools also differ in their approach to considering the overall atmospheric ET demand when drawing from the different sources:

- **Pitman** tools limit the total ET that can be drawn from soil and ground water to the PET being applied (pan evaporation in SPATSIM-Pitman and adjusted pan evaporation in WRSM-Pitman). However, the total amount of ET from **canopy interception** calculated is not linked to, or limited by, the monthly PET demand. Evaporation from CI does not influence the total ET allowed from the soil and ground water in the month’s timestep. This could mean that the total AET (from CI + soil + ground water) calculated for a very wet period could end up being greater than the PET. In relatively dry South African conditions, this is not likely to be a major concern in most catchments.
- **ACRU4, SWAT2012** and **MIKE-SHE** draw from different stores in an ordered sequence, stopping any further ET if a maximum allowed total AET (determined based on the reference PET) has been reached for the timestep.
  - **ACRU4** and **SWAT2012** limit maximum total AET to the reference PET. CI evaporation can occur up to the reference PET rate for the day if water is available. However, the maximum rate

for ET from soils uses an adjustment for the specific cover type (coefficient or LAI function) applied to reference PET. This means that the total AET could only reach full reference PET if it all comes from canopy interception. It is possible that the total AET calculated could be above the PET for the vegetation type in a warm-wet period when there is both CI and non-water-limited ET from soil.

- **MIKE-SHE** limits the total AET (all sources) for a time-step to the PET of the specific vegetation cover of the modelled unit (ref PET * crop coefficient).

The different limits to total AET applied by the tools are only likely to create output differences when conditions are very wet for prolonged periods when ET is not water limited.

A3: CANOPY INTERCEPTION: STORAGE AND EVAPORATION

- **Pitman** tools calculate monthly CI evaporation as a function of rainfall, without considering PET demand, given the monthly timestep and the fact that the rain would be the biggest driver. However, areas with high canopy storage potential could have different CI evaporation for the same rainfall in different seasons due to differing atmospheric demand.
  - **SPATSIM Pitman** accounts for this by allowing the CI parameter to vary seasonally, while WRSM-Pitman holds this constant.
- **ACRU4, SWAT2012 using the Green-Ampt method** and **MIKE-SHE** all allow CI storage to accumulate to a maximum before throughfall with the stored water evaporating at a rate driven by the PET.
  - All three use **LAI to calculate CI storage**, but use different equations. The user inputs and coefficients differ between the models, although both **SWAT2012** and **MIKE-SHE** assume a **linear** relationship between LAI and maximum CI storage, such that if the timesteps were the same, corresponding parameter values could be calculated for the two. The **ACRU4** method uses the **empirical power function** of LAI and rain, with no additional user input coefficients required.

    Tools differ in the rate of evaporation from the store: **ACRU4** uses the pan reference, **SWAT2012** uses standard grass surface reference PET (or the vegetation-specific one if the Penman-Monteith calculation is applied), **MIKE-SHE** uses the PET for the land unit's vegetation type (ref PET * crop coefficient)

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM-Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Canopy interception: **storage and evaporation**	CI evaporation for a month is an empirical, exponential function of maximum daily CI (input) and month's rain. (CI input parameter is constant) Month's rain in excess of CI evaporation reaches soil as throughfall. No CI storage carry-over between months.	CI evaporation for a month is an empirical, exponential function of maximum daily CI (input) and month's rain. (CI input parameter can vary seasonally) Month's rain in excess of CI evaporation reaches soil as throughfall. No CI storage carry-over between months.	***OPTIONS*** **User input:** Input maximum daily CI storage by month. Day's rain intercepted until CI store is full. **LAI function:** CI storage for a day is an empirical power function of LAI (can vary monthly) and day's rain. Day's rain in excess of CI reaches soil as throughfall. Maximum CI evaporation = reference PET Remaining CI store carries over to the next day.	***OPTIONS*** **SCS-CN**: Does not consider CI separately; part of "initial abstraction" **Green-Ampt:** Maximum CI storage for timestep is a linear function of maximum CI store (input) and timestep LAI vs. max LAI Timestep rain intercepted until CI store is full, excess reaches soil as throughfall. Maximum CI evaporation = reference PET Remaining CI store carries over to next timestep.	Maximum CI storage for timestep = CI coefficient * LAI for timestep. (LAI can vary daily). Coefficient represents a depth of CI storage on the leaf area. Timestep's rain intercepted until CI store is full, excess reaches soil as throughfall. Maximum CI evaporation = (reference PET * crop coefficient) Remaining CI store carries over to next timestep	

A4: SOIL INFILTRATION AND SOIL BYPASS FLOWS (MACROPORE FLOW AND FLOW IN SHRINK-SWELL CRACKS)

Some of the tools can explicitly represent bypass flows in which water moves quickly from the soil surface to a subsurface layer, such as through macropores or cracks formed when shrink-swell soils (high clay content, vertisols) dry. The pathways included and the algorithm approaches differ notably:

- **Pitman** tools do not explicitly calculate any soil bypass flows.
- **ACRU4** and **SWAT2012** can simulate flow in **cracked soils**, but not macropore flow. The two tools differ in the crack flow algorithms.
    - **ACRU4** calculates crack flow **before infiltration** as a proportion of throughfall going directly into the cracks and therefore added to the subsoil layer. It is **not threshold** initiated. Not being limited to dry soils, the algorithm could be used to represent macropore flow as well.
    - **SWAT2012** calculates crack flow **after infiltration** so that water not infiltrated fills cracks before surface runoff is generated. It is **threshold initiated**: it only occurs when antecedent soil conditions are **drier than field capacity**, with increasing crack volume with decreasing soil moisture.
- **MIKE-SHE** can simulate **macropore flow** with different levels of detail, but does not specifically account for cracking soils. It is **threshold initiated**: it only occurs when soils become **wetter than a limit** and increases with increasing soil moisture.

If bypass flows are significant in the modelled area and are not explicitly accounted for in models, they may be implicitly considered in soil infiltration and percolation calculations by adjusting parameters to increase flow through the upper layers. In this approach, the flow increases would not be triggered by the same threshold events as the bypass flow would be, but may improve the water balance when averaged over longer time periods.

The tools use similar soil properties (conductivity, porosity, retention curves or levels like FC and WP) to calculate infiltration, and some use similar algorithms. However, the exact algorithms and parameters differ and are linked to calculation timesteps and soil layering included in a model set-up (main report section 4)

- **Pitman** tools use a triangular infiltration distribution and rainfall to find a month’s infiltration rate. When a month’s rain is less than an input low limit, all will infiltrate. An input maximum rate is reached at an input upper rainfall limit. **SPATSIM-Pitman** differs from WRSM in that the **low limit can vary seasonally**.
- **ACRU4** and **SWAT2012** both have daily infiltration routines based on the **SCS-CN method** in which a storage parameter (a function of the CN parameter) is used in a non-linear equation to determine how much rainfall will become runoff, and the rest infiltrates (“initial abstraction”). **ACRU4** uses an adjusted version of the method in which the storage parameter is calculated from the soil moisture deficit and no empirical CN parameter is needed. In **SWAT**, this infiltrated “initial abstraction” amount includes canopy interception as mentioned above.
- **SWAT2012** and **MIKE-SHE** both include **Green-Ampt**-based infiltration routines, which require subdaily inputs, soil saturated conductivity, wetting front matric potential and field capacity. SWAT internally calculates the parameters from input soil texture properties, while in MIKE-SHE, the user finds or calculates them.
- **MIKE-SHE** includes a simplified approach with a single soil infiltration rate input by the user and an optional surface water depth threshold for infiltration.

All tools find an infiltration rate for the timestep and, if throughfall (or rainfall) is less, all will infiltrate. In all, once soil becomes saturated, infiltration stops. When using similar timesteps, these shared threshold types may make it possible to find parameter sets in each structure that produce somewhat similar infiltration patterns.

However, the **Green-Ampt** method increases infiltration when soils are very dry vs infiltration calculated using the same conductivity and retention in other algorithms. Parameter adjustment to increase infiltration with the other algorithms would increase it in both drier and wetter periods prior to saturation.

Process	WRSM-Pitman (Sami GW)	SPATSIM-Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more
Bypass flows through soil: macropore flow and shrink-swell soil cracks *(fast passage from soil surface to deeper subsurface layers)*	(Not explicitly represented – implicit in infiltration calculation)		*Optional algorithm for* ***shrink-swell soil cracks***. Fixed percentage of throughfall (0–10%) is directly allocated to cracks, before calculating soil infiltration vs. surface runoff. This percentage is fixed, set by crack index (0–3) user input, based on percentage clay. Crack water is added directly into subsoil horizon, until subsoil SM = SAT.	*Optional algorithm for* ***shrink-swell soil cracks*** Soil infiltration vs surface runoff is calculated, then surface water is diverted to fill crack volume. If the SRO initially calculated ≤ crack volume, there is no SRO leaving HRU. Crack volume per layer is an empirical function of maximum crack volume percentage for profile (input), SM vs. FC for layer (SM ≥ FC, crack volume =0), layer thickness. Crack water added to soil layers until layer SM = FC, starting from bottom layer moving up. (If water remains, add until layer SM = SAT, bottom to top)	*Optional algorithm for* ***macropore flow (MPF)*** **Simple macropore flow (+ two-layer water balance soils method):** A percentage of throughfall is directly routed as MPF into the interflow reservoir, before soil infiltration is calculated. The percentage of throughfall going to MPF is an empirical function of maximum percentage to MPF (input), SM in upper and lower layers, SM limit for MPF to start decreasing (input, often FC), minimum SM limit below which no MPF occurs (input, often WP) If SM in either of the layer ≤ minimum limit, no MPF.	*Optional algorithm for* ***macropore flow*** ***OPTIONS*** **Simple macropore flow (+ Richards or gravity flow soils method):** As described left – “upper layer” is 10 cm depth, “lower layer” is 50 cm depth. **Full macropore flow (+ Richards or gravity flow soils method):** Soil matrix water enters the macropore system when matrix potential exceeds a threshold (input). Flow through the macropore system, and between macropores and soil matrix is calculated using physical Darcy-Richard’s equations assuming gravity flow (no retention curve), as functions of macropore porosity, K_{sat} of macropores,

Process	WRSM-Pitman (Sami GW)	SPATSIM-Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more
				Option: Percentage of crack water passes directly soil) as an empirical to aquifer (before fill function of crack water in lowest layer, depth of lowest layer	If SM in both layers ≥ limit for MPF to decrease, the maximum percentage of the throughfall will go to MPF.	conductivity exponent (tortuosity, pore size), transfer coefficient
Infiltration into soil moisture store	Percentage impervious area in subcatchment = percentage throughfall automatically becoming surface runoff and not available for infiltration. Month's infiltration rate (IR) is a function of month's rain and subcatchment's minimum, average and maximum infiltration (Zmin, Zave, Zmax). The Z inputs describe an infiltration distribution curve:	Percentage impervious area in subcatchment = percentage throughfall automatically becoming surface runoff and not available for infiltration. Month's infiltration rate is a function of month's rain and subcatchment's minimum, average and maximum infiltration (Zmin, Zave, Zmax).	Percentage impervious in HRU and percentage connected to drainage are input. No infiltration on impervious: runoff from disconnected portion is added to the throughfall on the pervious surface Percentage of throughfall may be diverted to soil cracks first. **Modified SCS-CN:** *No curve number used* Infiltration = throughfall – storm runoff for day.	Percentage impervious in HRU and percentage connected to drainage: modify CN (used below) ***OPTIONS*** **SCS- CN** Infiltration = rain – storm runoff for day. The runoff is an empirical power function of day's rain, day's maximum "retention" (S, calculated from CN and SM), "initial abstraction" (ia; fixed proportion of S)	Input impervious zones assigned user-specified infiltration rates (can be 0), regardless of soils below. Available surface water = ponding left from previous timestep – evaporation + timestep throughfall – macropore diversion (if applied)	

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM-Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more**
	When rain < Zmin, all infiltrates When rain > Zmax, subcatchment infiltration = Zave (After impervious runoff): If month's remaining throughfall ≤ IR, all infiltrates Once profile's SM = SAT, no further infiltration.	The Z inputs describe an infiltration distribution curve: When rain < Zmin, all infiltrates; When rain > Zmax, subcatchment infiltration = Zave (Zmin can vary seasonally.) (After impervious runoff): If month's remaining throughfall ≤ IR, all infiltrates Once profile's SM = SAT, no further infiltration.	The runoff is an empirical power function of day's throughfall, day's maximum "retention" (S; calculated as SM – SAT deficit for a specified depth), "initial abstraction" (ia; proportion of S that can vary monthly). If day's throughfall ≤ ia, all infiltrates. Once profile's SM = SAT, no further infiltration.	If day's rain ≤ ia, all infiltrates. **Green-Ampt Mein-Larson (only subdaily)**: Maximum infiltration rate for timestep is a function of effective K (function of: K_{sat} for top layer and CN), wetting front (WF) matric potential (function of soil profile texture and porosity), ΔSM across WF (function of SM vs FC for profile). If timestep throughfall ≤ maximum IR, all infiltrates ***All methods:*** Once profile's SM = SAT, no further infiltration.	***OPTIONS*** **Two-layer water balance (2LWB):** Maximum infiltration rate = K_{sat} for profile. When surface water < threshold (optional input), no infiltration (can evaporate). **2LWB + Green-Ampt:** Maximum infiltration rate for timestep is a function of K_{sat} for profile, wetting front matric potential, ΔSM across WF (function of SM vs FC for profile).	***OPTIONS*** **Richard's equation:** Maximum infiltration rate calculated using Darcy-Richards, a function of surface water depth, unsaturated K (function of: K_{sat} and SM for top layer), pressure head (function of: SM and SM retention curve for top layer) **Gravity flow (GF):** Maximum infiltration rate = K_{sat} for top layer. **GF + Green-Ampt:** Maximum infiltration rate for timestep is a function of K_{sat} for top layer, wetting front) matric potential, ΔSM across WF (func of SM vs FC for profile).
					All methods: If timestep throughfall ≤ maximum IR, all infiltrates Once profile's SM = SAT, no further infiltration.	

A5: SURFACE RUN-OFF GENERATION AND ROUTING

The tools differ in handling water on the land surface that does not immediately infiltrate. What of this will become runoff and surface runoff in particular? MIKE-SHE is the most notably different from the others.

- In both **Pitman tools, ACRU4** and **SWAT2012**, water reaching the soil surface that does not infiltrate in the timestep becomes runoff. Some of this runoff water may be lagged in leaving the land unit and reaching a river channel, but it is not available for infiltration or evaporation in subsequent timesteps once it is allocated to the runoff store, even when the outflow is delayed.
  - The **Pitman tools** consider water that becomes runoff because the month's rainfall exceeded the infiltration rate to be surface runoff, or runoff following a quicker flow path: all of it leaves the subcatchment or module area in the same month. If the month's rainfall did not exceed the infiltration rate, but some does not infiltrate because the soil reached saturation, the excess is considered part of the shallow subsurface flow, or interflow, which is lagged.
  - **ACRU4** and **SWAT2012** use similar approaches to estimate runoff created on a rain day, but differ in what is considered surface runoff. Both divide throughfall (or rainfall) into infiltration and runoff on the day (or timestep) it arrives. Both apply a lag function to the available runoff volume (includes lagged runoff from previous days) to determine how much leaves the HRU each day (or timestep). They differ because **SWAT2012 considers all of this runoff to be surface runoff**, and the algorithm for lagging it is appropriate for this assumption, while **ACRU does not** assume all will be surface flow:
    - **ACRU4** lags the runoff by assuming a fixed fraction of the store leaves in a day. The runoff that leaves the same day it is produced could be surface flow, but could include fast shallow subsurface flow. The delayed portion is referred to as "interflow".
    - **SWAT2012**, because it considers this as surface runoff, **lags using land surface properties in Manning's equation** with an additional lag coefficient. Unlike ACRU4, interflow runoff can be generated from soil moisture in a later routine in SWAT2012 (see below).
- In **MIKE-SHE,** unlike in the other tools, surface water on a land unit that does not flow off the unit in a timestep is subject to **infiltration and evaporation in subsequent timesteps**. Surface water that does not infiltrate may take more than one timestep to leave the land unit, depending on the surface flow rate calculated. MIKE-SHE can include **detention storage**: a threshold depth of water on the land unit surface that needs to accumulate before surface runoff can be generated. Surface water below this threshold will remain on the land unit and can infiltrate or evaporate over time.
  - Similar to SWAT2012, MIKE-SHE can use **surface properties** and Manning's equation, or a finite difference diffusive wave approximation of Saint Venant equations, to calculate the **flow rate of the surface runoff**.

These differences in what is considered **surface runoff vs interflow** and how this is calculated in a model also influence how model infiltration is viewed conceptually. **In ACRU4, the water that becomes interflow does not infiltrate or pass via model soil layers**. A *smaller* infiltration rate and a *greater* runoff lag coefficient would produce more interflow in ACRU4, while a *greater* infiltration rate and adjusted soil properties would be needed to achieve this in the other tools.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Surface runoff generation and routing across landscape unit	Percentage impervious area in subcatchment = percentage throughfall automatically becoming surface runoff. If the month's throughfall > month's infiltration rate, the excess becomes SRO. All SRO leaves the runoff module in the same month it is generated	Percentage impervious area in subcatchment = percentage throughfall automatically becoming surface runoff. If the month's throughfall > month's infiltration rate, the excess becomes SRO. All SRO leaves the subcatchment in the same month it is generated.	Rainfall on percentage of HRU impervious connected to drainage becomes SRO leaving HRU on the day. **Modified SCS-CN:** *Note: Calculate "stormflow" RO, which can be surface and shallow subsurface RO.* Storm runoff for the day is an empirical function of the day's throughfall, the day's maximum "retention" (S; calculated as SM – SAT deficit for a specified depth), "initial abstraction" (ia; proportion of S that can vary monthly). Storm RO lagged, function of "stormflow store" (day's storm RO + remaining from previous day), lag coefficient (fraction released per day)	***OPTIONS:*** **SCS- CN** *"Stormflow" RO assumed to be surface RO.* SRO is an empirical function of the day's rain, the day's maximum "retention" (S, calculated from CN and SM), "initial abstraction" (ia; fixed proportion of S) **Green-Ampt Mein-Larson (only subdaily)**: SRO = throughfall – infiltration (see above) ***All methods:*** SRO lagged assuming tributary channel flow, outflow calculated as a function of SRO available (day's SRO + remaining from previous day), lag coefficient, time of concentration (ToC; calculated using Manning's equation, given slope and	SRO = surface water – detention storage for timestep, summed for all grid cells in an overland flow zone (HRU) SRO routed out of the zone using Manning's equation, function of zone SRO depth, slope length for zone, gradient for zone, roughness for zone .	SRO = surface water – detention storage for timestep, for each grid cell. SRO is routed from grid cell to grid cell using a finite difference diffusive wave approximation of Saint Venant equations, a function of cell SRO depths, water surface slope between cells (SRO depth and topography), roughness parameters (uniform, zonal or distributed grid input)

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
			Lag includes leaving HRU and landscape to channel. *Storm RO reaching channel on the same day is labelled "quickflow", vs delayed "interflow".*	roughness parameters, applied to longest flow path in subcatchment, as determined from an input DEM). Lag includes leaving HRU and landscape to channel.		
Surface runoff routing across subcatchment to river channel	Runoff modules are linked by the user to channel modules. Channel module may receive outflow from several other modules. SRO leaves the runoff module in the same month it is generated.	Runoff is routed to the river channel within the subcatchment. All SRO is added to the subcatchment river channel in the same month it is generated	**Simple parallel routing:** SRO/"storm" RO leaving each HRU is added to the subcatchment channel. Lagging described above: proportional lag parameter and SRO from impervious connected to drainage areas in HRU is not lagged. Lag includes leaving HRU and landscape to channel.	***OPTIONS:*** **Simple parallel routing:** SRO leaving each HRU is added to the subcatchment's main channel. Lagging described above: Manning's equation. Lag includes leaving HRU and landscape to channel. Can include "transmission loss": treat SRO routing as a tributary channel. Loss volume is added to shallow aquifer ground water, calculated as a function	***OPTIONS:*** **Simple parallel routing:** SRO leaving each overland flow zone is added to subcatchment channel. Flow of SRO across and out of zone described above: Manning's equation. In this option, it would include landscape to channel. **Catena series routing:** SRO is routed a across user-specified catena of overland flow zones within a subcatchment.	SRO is routed from grid cell to grid cell using a finite difference diffusive wave approximation of Saint Venant equations, a function of cell SRO depths, water surface slope between cells (SRO depth and topography), roughness parameters (uniform, zonal or distributed grid input) As it is routed from cell to cell, the SRO can go into detention storage, infiltrate, evaporate or remain SRO. SRO that is produced in, or flows across, grid cells bordering the river

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
				of SRO longest flow path length, tributary channel width, tributary bed conductivity, flow duration (Manning's equation) **Floodplain unit routing:** Divide subcatchment into two units: "floodplain" and "upland", to classify HRUs. A proportion of SRO leaving each upland HRU is added to the surface of the floodplain HRUs (can infiltrate, become SRO). The remainder goes to subcatchment channel. SRO leaving floodplain HRUs goes to subcatchment channel.	Flow of SRO across and out of zone described above: Manning's equation. SRO leaving a zone is added to the surface water of the next zone downslope (can go into detention storage, infiltrate, evaporate, become SRO). SRO leaving most of the downslope zone in the subcatchment enters the channel.	channel will be added to the channel if the water surface elevation on these riparian cells is higher than the water level in the river.

The tools also differ in how modelled **surface runoff is routed across the landscape**. The importance of these differences will depend on how important surface runoff (i.e. vs interflow and baseflow) is to the overall streamflow generation and water balance.

Routing approaches reflect the spatial discretisation of the model structure and how the modelled surface runoff is conceptualised:

- **Pitman tools, ACRU4, SWAT2012 (simple option)** and **MIKE-SHE simple** can all route surface runoff generated on a land unit **directly to the river channel** of the associated subcatchment. The nature of the flow path that the runoff would have to take from the place it is generated to the river channel would be conceptualised in the lagging routine and parameters, but the amount of surface runoff actually reaching the channel would not be changed during this routing, just the timing.
  - In the **Pitman tools** the land unit for which the runoff quality is calculated is an entire subcatchment. Infiltration that may occur along the flow path would be implicitly considered in the subcatchment-scale runoff generation algorithm, so does not need to be separately considered. Because of the monthly timestep, no lagging is required for surface runoff.
  - In the other tools, and for special modules in WRSM-Pitman that are individually modelled, the spatial unit for surface runoff generation is an HRU or zone within a larger subcatchment. In the simpler options, **parallel routing of HRU runoff** is applied, meaning that the surface **runoff from each HRU is routed to the subcatchment river channel separately**. The properties of the pathway between the particular HRU and the channel can be considered in the various parameters linked to routing from that HRU. However, infiltration losses of surface runoff that may occur along the path between this unit and the river channel would not be explicitly considered. The importance of this will depend on the landscape being modelled:
    - In some landscapes, this may not be important: the surface runoff, even from uplands, may generally flow in concentrated rills or ephemeral drainage lines and/or the lowland areas crossed may be saturated so that transmission losses are minimal.
    - There are cases where surface runoff generated in an upland area is likely to have losses on its pathway to a modelled channel, such as more arid landscapes with often unsaturated toe slopes and floodplains. When parallel routing is used, surface runoff transmission losses could be implicitly accounted for in the surface runoff generation calculation for upland HRUs through parameter adjustments (i.e. increasing infiltration). This could improve the modelled hydrograph and potentially the water balance at the catchment scale, but shows incorrect processes at the HRU scale. The approach would also not respond to the variation in conditions of the downslope units (i.e. periodic saturation) that would determine the transmission loss.
- **SWAT2012** and **MIKE-SHE** both provide options for routing surface runoff across the landscape in a more spatially explicit way, **routing surface flows in a downslope series (catena)** of land units (HRUs, zones, grid cells). The specific approaches differ as follows:
  - **SWAT2012** provides a simple approach in which upland and floodplain land units are mapped within a subcatchment and HRUs are assigned to one or other class based on their spatial location. A user-specified proportion of the runoff from upland units will be routed onto the surface of the floodplain units. Determining this parameterisation would be more or less an empirical fitting exercise.
  - **MIKE-SHE simple** using a simplified overland flow option routes runoff from one zone to the next. The properties of the zone determine the flow rate off one zone and onto the next. Inflowing surface runoff could infiltrate or evaporate if it is detained in the next zone.
  - **MIKE-SHE complex** will route surface flow from cell to cell across the gridded model domain. Topography is explicitly included so that flow would concentrate in depressions and follow drainage lines. This method is very computationally intensive.

A6: ET WITHDRAWAL FROM SOIL MOISTURE AND GROUND WATER

In all tools, the actual ET withdrawal from the soil is reduced from its potential maximum given the atmospheric demand and cover type (PET) based on the available soil moisture in the root zone and the soil moisture retention properties of the soils. (Tools differ in the way the maximum PET demand to be applied in this calculation is derived, and how evaporation from canopy interception and surface ponding effects' demand for ET from the soil is derived, as described above and shown in the table below.)

ACRU4, SWAT2012 and **MIKE-SHE complex** calculate **plant transpiration and soil ET as separate**, but linked quantities, while the Pitman tools and MIKE-SHE simple calculate them together as a single quantity. This could influence the total amount of ET calculated because the soil evaporation tends to occur from shallower in the soil than transpiration and so will face different soil moisture restrictions. The **division of the PET demand between soil evaporation and transpiration is a function of LAI** in all three tools, as an indication of the vegetation density and soil shading, although algorithms differed. When there is a lot of bare soil, the ET from soil would be different from dense vegetation given the same climate and soil moisture, and the response to changes in soil moisture would be a different shape. This would need to be implicitly accounted for in the combined ET calculation approach through the ET vs SM relationship parameterisation.

ACRU4, SWAT2012 and **MIKE-SHE complex** divide the ET withdrawals across **multiple soil layers in the root zone**, while the Pitman tools and MIKE-SHE simple calculate ET withdrawals from a single root zone layer. **Root distribution functions** are used to distribute the transpiration demand in all three tools, but their forms differ.

Tools differ in the **basic shape of the decline of transpiration or ET with declining soil moisture** and how this shape is defined:

- **SM threshold for max ET:**
  - In **SWAT2012** and **MIKE-SHE**, maximum transpiration occurs when soil moisture is above **field capacity**. SWAT and MIKE-SHE also assume maximum soil evaporation at field capacity.
  - In the **Pitman** tools, maximum monthly ET occurs when monthly soil moisture is at **saturation**.
  - In **ACRU4**, maximum transpiration occurs when soil moisture is above a user-defined **stress limit** (typically less than field capacity) for the vegetation cover, while maximum soil moisture occurs at a different user-specified limit. In the MIKE-SHE simple option, maximum ET from soil similarly occurs when soil moisture is above an input stress limit for the vegetation type.
- **SM threshold for no ET:**
  - In **ACRU4, SWAT2012** and **MIKE-SHE**, transpiration stops when soil moisture reaches the **wilting point**, while soil evaporation can continue at soil moistures below wilting point, although at very low rates. In the simpler MIKE-SHE option that calculates combined ET, ET withdrawal stops at the wilting point.
  - In **MIKE-SHE, soil evaporation** stops at a defined **residual soil moisture** limit.
  - In the **Pitman tools**, which calculate combined ET (monthly at a subcatchment scale), ET can continue to subcatchment-scale soil moisture levels **lower than the wilting point, potentially to 0,** depending on parameterisation for the subcatchment land cover.
- **Shape of decline in ET from maximum to 0 with decreasing SM between the upper and lower thresholds:**
  - **ACRU4** applies a **linear decline in transpiration** and an **exponential decline in soil evaporation.** ACRU4 can apply a linear decline in transpiration above field capacity to represent **water logging** impacts on roots. Other tools do not account for this.
  - The **Pitman tools** and **MIKE-SHE simple** apply a **linear decline in ET.**

  - **SWAT2012** and **MIKE-SHE complex** apply an **exponential decline in transpiration.** SWAT applies an **exponential decline in soil evaporation,** while MIKE-SHE applies a stepped decline function with portions of different slopes (slopes are steep below field capacity and then level off, approximating exponential).

All tools included some mechanism for the ET demand to potentially be met by ground water or water that was previously ground water and entered the normally unsaturated soil zone through capillary rise.

- **Pitman tools** and **MIKE-SHE** calculate ET withdrawals directly from ground water aquifers. In the case of MIKE-SHE, this occurs when the dynamic water table rises into the root zone.
- **ACRU4, SWAT2012** and **MIKE-SHE** (both approaches) simulate **capillary rise** from ground water into the root zone. All tools do the following:
  - In **ACRU4,** capillary rise is only applied in an optional vadose zone (“intermediate zone”) routine. Ground water is withdrawn from the aquifer below to maintain the vadose zone moisture profile, as being mostly a field capacity with a capillary fringe at the bottom in which moisture increases to saturation over the input fringe thickness. Deep-rooted vegetation can transpire using the moisture in this layer when the ET demand is not met from the soil layers above.
  - **MIKE-SHE simple** has a similar approach in that water is removed from the underlying aquifer to maintain the root zone soil moisture at **field capacity**.
  - **MIKE-SHE complex** calculates capillary rise based on the pressure differential between the layers just above and below the water table.
  - **SWAT2012** applies a different approach in which capillary rise is calculated as **a function of the ET demand** defined by an input vegetation-specific coefficient.

Pitman tools and **MIKE-SHE simple** restrict the ground water access, for direct ET withdrawal (Pitman) or capillary rise (MIKE-SHE), to a **defined lowland or riparian zone** within the subcatchment. In the other tools, this can occur anywhere in the landscape, depending on the root depth vs the water table.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
ET withdrawal from soil: plant transpiration (E_t) and evaporation of soil water (E_s)	ET is reduced from a maximum ET if SM is limiting. *Transpiration (E_t) and soil evaporation (E_s) are calculated as one.* $E_t + E_s$ for month is a linear function of the month's PET (pan evaporation *pan factor) Month's SM vs SAT Evaporation storage decay constant When SM = SAT, E_t+E_s = PET When SM < SAT linear $E_t + E_s$↓ with ↓SM Decay constant (R) determines ET vs SM slope at different PET: When R = 0, $E_t + E_s = 0$ at SM = 0, *ET at very low SM.* When R = 1, slope = (maximum PET of all months) / SAT.	ET is reduced from a maximum ET if SM is limiting. *Transpiration (E_t) and soil evaporation (E_s) are calculated as one.* E_t+E_s for month is a linear function of the month's PET (pan evaporation) Month's SM vs SAT Evaporation storage decay constant When SM = SAT, E_t+E_s = PET When SM < SAT linear $E_p + E_s$↓ with ↓SM Decay constant (R) determines ET vs SM slope at different PET: When R = 0, $E_t + E_s = 0$ at SM = 0, *ET at very low SM.* When R = 1, slope = (maximum PET of all months) / SAT.	ET is reduced from a maximum ET if SM is limiting. Maximum ($E_t + E_s$) for day = (reference PET – CI evaporation) *crop coefficient Maximum ($E_t + E_s$) then split into maximum E_t and maximum E_s as a function of crop coefficient or LAI (both can vary monthly) **E_t**: Maximum E_t split across two soil layers using root distribution parameter. E_t from layer is a function of day's maximum E_p for layer, day's SM in layer, WP and FC for layer, water stress SM for vegetation. When SM ≤ WP, $E_t = 0$.	ET is reduced from a maximum ET if SM is limiting. **E_t**: ***Maximum E_t OPTIONS*** *(see PET methods above)* **Penman-Monteith:** Maximum E_t is a function of weather and canopy resistance – CI evaporation **Other ref PET methods:** When LAI > 3.0: Maximum E_t = reference PET – CI evaporation When LAI < 3.0: Maximum E_t = (reference PET – CI evaporation) *LAI/3 Maximum E_t split across root zone soil layers using a distribution parameter. Compensation coefficient can allow redistribution when SM is limiting.	ET is reduced from a maximum ET if SM is limiting. *Transpiration (E_t) and soil evaporation (E_s) are calculated as one.* **Two-layer soil water balance method + linear reservoir ground water:** Maximum ($E_t + E_s$) in timestep = (reference PET * crop coefficient) – CI evaporation – evaporation from ponding $E_t + E_s$ is drawn from the upper soil layer, which is defined by the ET extinction depth = root depth + capillary fringe (root depth can vary daily, changing layer) $E_t + E_s$ is a function of timestep maximum ($E_t + E_s$) timestep SM for layer WP of layer water stress SM for vegetation	ET is reduced from a maximum ET if SM is limiting. **Kristensen and Jensen ET method:** Maximum ($E_t + E_s$) in timestep = (reference PET * crop coefficient) – CI evaporation – evaporation from ponding Maximum ($E_t + E_s$) then split into maximum E_t and maximum E_s as a function of day's LAI and empirical parameters (c1, c2) **E_t:** Maximum E_t split across root zone soil layers using a distribution parameter. (root depth can vary daily.) E_t from layer is a function of timestep maximum E_t layer, timestep SM in layer,

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
	ET stops at higher SM values when PET is lower.	*ET stops at higher SM values when PET is lower.*	When WP < SM < stress limit, linear E_t↓ with ↓SM. When stress limit < SM ≤ FC, E_t = maximum E_t (layer). When SM > FC, linear E_t↓ with ↑SM (water logging) **E_s**: Maximum E_s can be reduced by a cover factor. E_s, from upper layer only, is a function of day's maximum E_s for layer, day's SM in layer, stage limit SM (function of texture) When SM ≥ stage limit, E_s = max E_s When SM < stage limit, exponential E_s↓ with ↓SM	E_t from layer is a function of timestep maximum E_t layer, timestep SM in layer, AWC (FC – WP) in layer When SM ≤ WP, E_t = 0. (SM – WP) < 0.25 *AWC, exponential E_t↓ with ↓SM (SM – WP) ≥ 0.25* AWC, E_t = maximum E_t for layer **E_s**: Maximum E_s is a function of reference PET – CI evaporation, E_t for timestep cover index (function of LAI) Maximum E_s distributed across layers in top 100 mm using parameter. No compensation for SM limitation across layers. E_s for layer is a function of timestep maximum E_s layer,	When SM ≤ WP, ($E_t + E_s$) = 0. When WP< SM < stress limit, linear ($E_t + E_s$)↓ with↓SM When SM > stress limit, $E_t + E_s$ = maximum ($E_t + E_s$)	FC and WP of root zone, c3 empirical parameter When SM ≤ WP, E_t = 0. WP < SM < FC, exponential E_t↓ with ↓SM based on c3. When SM ≥ FC, E_t = maximum E_t **E_s**: Maximum E_s for timestep = (reference PET * crop coefficient) – CI evaporation – evaporation from ponding E_s topsoil layer only (user defines layer depths). E_s for timestep is a function of timestep maximum E_s, timestep E_t, timestep SM in layer, AWC, FC, WP and residual SM for layer, day's LAI, c1, c2 empirical parameter (same as above)

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
				timestep SM in layer, FC and WP for layer When SM ≥ FC E_s = maximum E_s for layer When SM < FC, exponential E_s↓ with ↓SM		When SM ≤ residual SM, E_s = 0 When residual. < SM <WP, linear E_s↓ with ↓SM When WP ≤ SM and (SM – WP) ≤ 0.5*AWC E_s = c2 * maximum E_s When (SM – WP) > 0.5*AWC and SM < FC linear E_s↓ with ↓SM down to E_s = c2 * maximum E_s with slope determined by LAI, $E_{t,}$ maximum E_s

In all cases, the amount of water withdrawn from the ground water store is driven by soil moisture deficit and/or ET demand, but it is limited by the amount stored in the aquifer at the timestep, and the aquifer properties. The approaches to this calculation differ between tools:

- **ACRU4** applies a **maximum capillary yield rate**, but **no ground water storage threshold** below which capillary rise stops.
- **MIKE-SHE complex** calculates capillary rise from storages and properties of layers above and below the water table, which change as the water table fluctuates. ET from layers below the water table is driven by the ET demand and will decline as the water table drops.
- **Pitman tools, SWAT2012** and **MIKE-SHE simple** have **ground water storage thresholds** below which ET from ground water or capillary rise stops, but use different approaches to determine a maximum rate, when the maximum can occur, and a distribution of rates below this:
  - In the **Pitman tools** and **SWAT2012**, the maximum ET or capillary rise from ground water is defined by the **ET demand** or a function of it. This maximum will occur when the ground water storage is **at or above some upper ground water storage threshold** and declines below this until the lower ground water storage threshold.
    - In **WRSM-Pitman,** maximum ET from ground water only occurs when the aquifer is **full to capacity,** and **declines linearly with decreasing ground water storage**.
    - In **SPATSIM-Pitman,** maximum ET from ground water occurs when the conceptual ground water wedge has a **positive slope towards the river** channel (function of ground water storage, aquifer properties, subcatchment shape and drainage pattern properties), which may occur below “full capacity”. ET from ground water **declines linearly with decreasing ground water slope**.
    - In **SWAT2012,** maximum capillary rise will occur when the ground water storage can meet the demand without pushing the aquifer ground water storage below a certain **minimum storage threshold,** and the rate **declines linearly with decreasing ground water storage.**
  - In **MIKE-SHE simple**, the maximum capillary rise is determined by the **soil moisture deficit,** but there is no **defined threshold of aquifer ground water storage** at which this maximum rate would be achieved. The ground water available for the capillary rise is a function of aquifer storage, the aquifer outflow recession constant and a fixed percentage of the outflow allowed to contribute to soil moisture (diverted from baseflow). In effect, the baseflow is reduced rather than the aquifer store, which produces the same outflow, regardless of capillary rise demand and diversion.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
ET withdrawal from ground water aquifers ***(including capillary rise)***	Assume monthly subcatchment ET from soil < PET for month, always demand for additional ET from ground water ET from ground water is restricted to the riparian zone in the subcatchment (user input area). Maximum ET from ground water = riparian area * [(pan evap * vegetation factor) – rainfall] for month ET from ground water is a function of maximum ET from ground water, ground water storage, aquifer capacity, aquifer static water level (SWL) When ground water storage ≤ SWL, ET from ground water = 0 When SWL<GW < capacity	Assume monthly subcatchment ET from soil < PET for month, always demand for additional ET from ground water ET from ground water is restricted to the riparian zone in the subcatchment (input percentage of drainage slope; see ground water section 9 below). Maximum ET from ground water = riparian area * (pan evaporation – rainfall] for month ET from ground water is a function of maximum ET from ground water, lower ground water wedge gradient (function of ground water storage and aquifer properties), ground water gradient at aquifer resting water level (RWL)	ET withdrawal *directly* from ground water aquifer is not considered. Capillary rise from ground water optionally added. (ET demand met by water previously in ground water store) **Optional “intermediate zone” (vadose zone):** An optional routine adds a vadose zone (VZ) layer below the lower soil layer. It has a user input thickness, ST, FC and WP moisture levels, and capillary fringe (CF) properties (depth, yield). VZ SM above CF = FC, unless there are ET withdrawals. Vegetation can have root depths extending into this zone: when E_t from soil < maximum E_t for the day, the remaining demand is met from the VZ.	ET withdrawal directly from ground water aquifer is not considered. Capillary rise from ground water is calculated. (ET demand is met by water previously in ground water store) Capillary rise of water from the shallow ground water aquifer into the soil profile replenishes SM as E_t is withdrawn. Maximum capacity rise = maximum E_t * capacity rise coefficient Capacity rise is a function of maximum capacity rise, ground water storage, ground water store limit for rise When ground water storage < limit, capacity rise = 0 When limit < ground water < (limit +	ET withdrawal directly from ground water aquifer is not considered. Capillary rise from ground water can be added in low-lying areas. (ET demand met by water previously in ground water store.) **Two-layer soil water balance method +** **linear reservoir ground water:** Capillary rise restricted to lowland or riparian areas (defined by lowest interflow zone mapped in subcatchment – *see ground water sections below*) Capillary rise calculated when SM < FC for upper layer (root zone) Maximum capillary rise = fixed percentage of aquifer outflow for	When root depth extends into the saturated zon), ET from ground water will be calculated. Capillary rise from ground water is also calculated. (ET demand met by water previously in ground water store.) **Kristensen and Jensen ET +** **Richard’s equation soil + 3D finite difference ground water:** *(See calculation methods for E_t from soil above)* The ground water table depth is dynamic and can rise into the root zone. When this occurs, E_t demand allocated to soil layers that have become part of the SZ will met from the ground water. Capillary rise from the ground water table into

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
	Linear ↓ ET from ground water with ↓GW storage When ground water storage = capacity, ET from ground water = maximum ET from ground water	When gradient ≤ RWL, gradient ET from ground water = 0 When RWL < gradient < 0, linear ↓ET from ground water with ↓lower wedge gradient When grad > 0, ET from ground water = maximum ET from ground water	VZ SM above CF is replenished up to FC by water drawn from the ground water aquifer store at the capillary yield rate. This can allow continued E_t	maximum capacity rise), capacity rise = (ground water – limit) When ground water storage ≥ limit, capacity rise = maximum capacity rise ***Channel bank storage water** can also enter soil profile of riparian HRUs to meet ET demand (see channel section below)*	timestep (*see ground water sections below for calculation*) When ground water < threshold, aquifer outflow, including capacity rise = 0 Water diverted from aquifer outflow until SM = FC or maximum capacity rise quantity reached.	the soil layer above it is calculated based on soil matrix potential differences between underlying and overlying units, gravity and conductivity.

A7: SOIL AND VADOSE ZONE WATER DISTRIBUTION AND STORAGE VS PERCOLATION TO GROUND WATER (GROUND WATER RECHARGE)

All tools and options differ in how the subsurface is divided into vertical units for modelling water movement through unsaturated and saturated layers, which dictated the nature of their calculation routines.

- **SPATSIM-Pitman** had the fewest calculation layers: one soil layer and one ground water aquifer.
- **ACRU4** additionally divided up the root zone soil into two layers above the ground water aquifer (although a vadose zone option can be activated).
- **WRSM-Pitman, SWAT2012 (potentially ACRU4)** and **MIKE-SHE simple** can include a parameterised **vadose zone** between the root zone and the ground water aquifer, which serves to lag water predicted to leave the bottom of the root zone in reaching the ground water aquifer. These tools differed in how the overlying root zone soils are represented, one layer in WRSM-Pitman and MIKE-SHE simple vs. up to 10 layers in SWAT (user defined), and the governing equations for outflow of the vadose zone to ground water:
  - **WRSM-Pitman:** Power function with thresholds
  - **SWAT2012:** Linear reservoir type with no threshold limits
  - **MIKE-SHE simple**: Simple FC threshold for downward flow from the lower soil layer into the interflow reservoir, also conceptually part of the “vadose zone”, and has a linear reservoir outflow algorithm to determine outflow
- **MIKE-SHE complex** allows users to define layers of different material types in the subsurface. The user does need to classify typically unsaturated zones from the more typically saturated zones. The model adjusts the boundary as the water table moves. The presence, thickness and conductivity of a vadose zone between the root zone layers and the ground water table is automatically and dynamically calculated.

When more layers are included, these can be parameterised with more direct reference to the changing physical soil and sediment properties with depth, while this needs to be implicitly considered in larger lumped layers. However, detailed subsurface data is often not available, making parameterisation a calibration exercise, which is simpler when the number of free parameters is constrained.

When no vadose zone is explicitly included, its impact on delaying ground water recharge can be represented by the parameters used to control the rate of outflow from the root zone soil (i.e. the ground water recharge power function coefficient in SPATSIM-Pitman and the maximum recharge rate K_{sat} parameter in ACRU).

Across all tools, the **field capacity** of unsaturated layers creates thresholds for downward water movement, while only ACRU4 and MIKE-SHE calculate the vertical redistribution of water when moisture levels are below field capacity. Tools differed in how percolation rates respond to the amount of water available above this threshold in the given layer:

- **Pitman tools: Exponential** decrease
- **ACRU4, SWAT2012** and **MIKE-SHE simple options: Linear** decrease, with ACRU4 and SWAT2012 enforcing a maximum rate representing conductivity (in SWAT, this is in the soil, not the vadose zone)

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Soil and vadose zone water distribution and storage vs. percolation to ground water (ground water recharge)	*One root zone soil moisture store, a vadose zone, one aquifer ground water store* Percolation from soil to VZ is a power function of SM in month vs. SAT and FC. Maximum percolation rate (input) Power function coefficient Maximum VZ store capacity Until VZ storage = capacity: When SM < FC, percolation to VZ = 0 When FC ≤ SM < SAT, exponential ↓percolation with ↓SM (defined by coefficient) When SM = SAT, percolation to VZ = maximum rate. Percolation to VZ in excess of VZ capacity, added to recharge.	*One root zone soil moisture store, one aquifer ground water store. No vadose zone.* Ground water recharge from soil is a function of SM in month vs. SAT and FC Maximum recharge rate(input) Power function coefficient When SM < FC, recharge = 0 When FC ≤ SM < SAT, exponential ↓recharge with ↓SM (defined by coefficient) When SM = SAT, recharge = maximum rate	*Two root zone soil layers (upper layer (UL) and lower layer (LL)), one aquifer ground water store* Percolation UL to LL: When $SM_{UL} > FC_{UL}$, percolation to LL = $(SM_{UL} – FC_{UL})$ When $SM_{UL} ≤ FC_{UL}$, water redistribution between UL and LL is a function of the ratio of SM deficits (vs FC) between layers. Daily percentage unsaturated SM redistribution limits (maximum 2% downward, maximum 1% upward) Ground water recharge (percolation from LL to aquifer ground water store): Maximum recharge rate = K_{sat} When $SM_{LL} ≤ FC_{LL}$, recharge = 0	*Maximum 10 soil layers, a vadose zone, two aquifer ground water stores (shallow and deep)* Percolation between layers only when $SM_{UL} > FC_{UL}$, then percolation to LL = minimum [$(SM_{UL} – FC_{UL})$, K_{sat}] Percolation out of the lowest layer in the profile enters VZ. (May include crack bypass flow, see above.) Ground water recharge (percolation from VZ to aquifer ground water store) is a function of VZ storage and lag parameter (linear reservoir, no thresholds) Recharge divided into shallow and deep aquifer by fixed recharge ratio	**Two-layer soil water balance method + linear reservoir ground water:** *One root zone soil moisture store, a vadose zone, one interflow reservoir (IFR), two aquifer ground water stores* UL = ET extinction depth = root depth + capillary fringe. LL (VZ): Bottom of UL to the ground water table. Percolation UL to VZ, only when $SM_{UL} > FC_{UL}$ Percolation to VZ = $(SM_{UL} – FC_{UL})$ Percolation VZ to IFR only when $SM_{VZ} > FC_{VZ}$ Percolation to IFR = $(SM_{VZ} – FC_{VZ})$ Ground water recharge (percolation from IFR to aquifer ground water store) function of IFR storage and vertical vs.	*User-determined subsurface layers for unsaturated zone and saturated zone* ***OPTIONS:*** **Richard's equation UZ:** Redistribute water between the 3D cell volumes above the water table using hydraulic conductivity (K, function of K_{sat} and SM), pressure head (function of soil moisture retention curve and SM) **Gravity flow UZ:** Percolation between layers only when $SM_{UL} > FC_{UL}$, then percolation to LL = minimum [$(SM_{UL} –FC_{UL})$, K] K: Function of K_{sat} and SM water leaving lowest layer enters ground water (SZ) and ground water table depth changes.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
	Ground water recharge (percolation from VZ to aquifer ground water store) is a power function of VZ storage vs. maximum VZ capacity Moving average recharge for month vs. mean monthly recharge (input) Maximum ground water aquifer capacity Ground water recharge in excess of aquifer capacity, added to interflow		When $SM_{LL} > FC_{LL}$, recharge = minimum [(SM_{LL} - FC_{LL}), maximum recharge rate] **Optional "intermediate zone" (vadose zone):** *See ET from ground water above)* VZ receives percolation from LL as calculated above and then VZ SM > FC recharges ground water	**OPTION: Perched water table** in soil profile by defining impervious layer. Percolation from lowest soil layer reduced as a function of depth to impervious.	horizontal flow rate constants (linear reservoir with two outlets) Recharge divided between aquifers by fixed recharge ratio.	**For both UZ methods + 3D finite difference ground water:** Dynamic ground water table can rise into UZ removing layers or parts of layers from SM calculation.

A8: INTERFLOW (LATERAL FLOW, SHALLOW SUBSURFACE FLOW)

All tools can represent some flow contribution to the river channel that reaches the channel more slowly than surface runoff and more quickly than aquifer outflow in response to rainfall, although different approaches are used to estimate the quantity and rate:

- **SWAT2012** and **MIKE-SHE complex** take a mechanistic approach, requiring the input soil profile to contain layers with low conductivity, so that soil moisture accumulates faster than it can drain vertically, invoking lateral flow calculations when moisture levels are above field capacity.
- **MIKE-SHE simple** also explicitly represents interflow generation as a balance of vertical vs. horizontal drainage rates using a linear reservoir with two outlets (ground water recharge and interflow). The **Pitman tools** also draw interflow from the same soil moisture store layer that is simultaneously recharging the aquifer.
- **ACRU4** lumps the calculation of surface runoff and shallow subsurface runoff generation into a single stormflow runoff quantity estimated by the modified SCS-CN algorithm approach. As interflow can be conceived as moving too quickly to a stream channel to be subject to much ET withdrawal, the fact that the interflow water never enters the soil layers in this method should not impact on the estimation of other processes very much. This approach does not allow for different thresholds to impact interflow to those impacting surface runoff generation.
- **The Pitman tools**, due to their monthly timestep and subcatchment scale, calculate interflow from the soil moisture (water that previously infiltrated), as well as water not given the chance to infiltrate due to saturation of the moisture store. This is not the same as saturation excess runoff, which is produced during the course of an individual rainfall event and would result in surface runoff, instead it reflects the wet conditions in the catchment over a month that would result in shallow subsurface flow.

The interflow quantities generated from a modelled land unit would take time to reach the channel.

- **The Pitman tools, ACRU4** and **SWAT2012** lag the calculated interflow amount to the channel, without opportunities for losses to ground water or ET on the flow path. This means that if these actually occur, they would need to be accounted for in parameters that generate the interflow quantity. The lagging parameters in these approaches do not respond to the conditions elsewhere along the flow path that could influence the quantity arriving at the river.
- **MIKE-SHE (both options) routes the interflow across the landscape** so that it can be influenced by conditions of other model units along the flow path. With the simple options, interflow can move through a series of interflow reservoirs before reaching the river, with the possibility for some of the interflow generated in uplands to become ground water recharge or be detained due to reservoir storage flow thresholds along its route. Only in MIKE-SHE's distributed approach would water that starts to move laterally as interflow also potentially be vulnerable to ET withdrawals on its flow path to the river.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
Interflow (lateral flow, shallow sub-surface flow)	Interflow runoff for the month comes from: 1. Any of the month's throughfall that does not infiltrate because soil moisture reaches saturation (SM = SAT) becomes interflow. 2. Interflow generated from the soil store as a power function of SM in month vs SAT and FC Maximum interflow rate (input) power function coefficient When SM < FC, Interflow = 0 When FC ≤ SM < SAT, exponential ↓interflow with ↓SM (defined by coefficient) When SM = SAT, interflow = maximum rate. 3. When potential ground water recharge exceeds aquifer capacity, the excess is added to interflow.	Interflow runoff for the month comes from: 1. Any of the month's throughfall that does not infiltrate because soil moisture reaches saturation (SM = SAT) becomes interflow. 2. Interflow generated from the soil store as a power function of SM in month vs. SAT and FC Maximum interflow rate (input) power function coefficient When SM < FC, Interflow = 0 When FC ≤ SM < SAT, exponential ↓interflow with ↓SM (defined by coefficient) When SM = SAT, interflow = maximum rate.	Interflow is estimated as part of the "stormflow" calculation using the modified SCS-CN method (function of rain and antecedent SM, *see above*) The "stormflow" is differentiated into "quickflow" and "interflow" using a lag coefficient: "quickflow" is the fraction reaching the channel on the day of generation; "interflow" is the remainder lagged to successive days	Interflow is only calculated when a perched water table develops in the soil profile so that there is drainable SM > FC that cannot percolate vertically in the timestep. The interflow amount available is routed with a kinematic storage model (Sloan and Moor, 1984l): assume conceptual 2D cross-section down hillslope with given thickness (function of interflow volume and drainable porosity SAT – FC), slope length, gradient, K_{sat} Calculate flow across boundary out of HRU into main channel. Outflow volume crossing boundary can be lagged additionally to represent a longer flow path in a larger catchment, using a travel time parameter	**Simple linear reservoir ground water routing method:** Water percolating out of the soil layers (SM > FC) is input into an interflow reservoir above one or more ground water aquifer stores (*see above*). The IFR acts as a linear reservoir with two outflows: horizontal to the next interflow reservoir in a catena or to the channel, and vertical to the ground water reservoir, each with a lag coefficient and potential outflow threshold. Interflow vs ground water recharge is a function of IFR storage and lag coefficients. Several IFR stores can be defined in a catena series in a subcatchment: lateral flow will be routed	**3D finite-difference ground water:** Lateral flow between grid cells is not calculated for unsaturated zones (only redistributed vertically – no interflow). Perched water tables can develop in the 3D subsurface model grid, depending on horizontal and vertical transmissivity and K_{sat} values assigned to different layers and the water received. Depending on the resulting head gradients, this can result in lateral subsurface flow occurring above the regional ground water table (hence interflow), that reaches the channel network.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
	Interflow produced in a month is lagged leaving the runoff module using the Muskingum equation (one lag parameter).	Interflow produced in a month is lagged leaving the runoff module using the Muskingum equation (one lag parameter).			between them with opportunity for ground water recharge on the route to the channel.	

A9: GROUND WATER REGIONAL FLOW, EXCHANGE WITH CHANNELS AND CAPILLARY RISE

The importance of the details of a model's ground water representation depends on the importance of ground water outflow in the hydrograph, the degree of regional ground water flow in the area, the importance of ground water pumping, and how dynamic the ground water-surface water (GW-SW) exchange is with changes in ground water level. Tool representation of capillary rise from ground water to the vadose zone or soil layers is given in the last table in this section, but is most relevant to meeting ET demands, and is further described above.

Both **Pitman tools** and **MIKE-SHE complex** can represent **regional ground water flow** by calculating ground water exchanges between neighbouring subcatchments. **ACRU4, SWAT2012** and **MIKE-SHE simple** do not allow ground water to flow between subcatchments, so no regional ground water flow can be included.

The tools differ in which potential **exchanges of water between aquifers and river channels** can be included and how these flows are calculated:

- Both **Pitman tools** and **MIKE-SHE complex** allow for the **two-way dynamic exchange** of water between aquifer storage units and river channels governed by estimations of relative head.
    - Both **SPATSIM-Pitman** and **MIKE-SHE complex** approximate the **ground water gradient** with respect to the channel in **riparian aquifer units** and **apply Darcy's Law** using aquifer and riverbed conductivity. If the water table is above (slopes towards) the channel, ground water will flow into the channel. If the water table is below or slopes away from the channel, the river can input water into the neighbouring aquifer units.
        - In **MIKE-SHE complex,** the riparian aquifer units are the grid cells bordering the channel. The river water level is explicitly modelled and relative elevations are considered.
        - In **SPATSIM-Pitman,** the riparian aquifer unit is the lower slope segment of a conceptual ground water wedge for the subcatchment. The relative channel elevation is considered, not the channel water level, when determining if ground water will outflow in the month. Channel losses are calculated for the incremental subcatchment and inflow is calculated from those upstream.
    - **WRSM-Pitman** estimates the aquifer vs. channel relative head gradient at the subcatchment (runoff module)-scale, not for a riparian zone specifically. Flow in either direction is an **exponential function** of this gradient. The water level in the river is conceptually considered by estimating surface water head as runoff or the subcatchment area. For a downstream subcatchment, this does **not include runoff from upstream subcatchments**. For the latter, additional transmission losses can be added to channel modules, but these are not added to an aquifer unit.
- **SWAT2012** can calculate both aquifer-to-channel and channel-to-aquifer exchanges at the subcatchment scale, but there is not a two-way exchange between one aquifer and channel unit pair:
    - A subcatchment's **shallow aquifer outflows to the main channel** when it is above a threshold storage using a **non-linear storage-outflow function**, regardless of the amount pre-existing channel flow.
    - A subcatchment's **main channel can lose water to the deep aquifer and bank storage.**
    - If channel losses were added to the shallow aquifer, the water would be distributed across the subcatchment-scale unit. Instead, a separate bank storage unit is included that interacts with the channel and riparian HRU soil. Bank storage outflows back into the channel with a **non-linear storage-outflow function**. Bank storage can be drawn upon to meet ET demand in riparian HRUs. Water entering the deep aquifer unit is essentially no longer active, except for pumping. It does not discharge to the channel.

- **MIKE-SHE simple** can calculate both aquifer-to-channel and channel-to-aquifer exchanges at the subcatchment scale, given certain input choices. The user can define multiple connected channel branches in a single subcatchment, and branches are predetermined by the user to be losing or gaining – the ***direction of the exchange is not dynamic***. By including both types of branches, both exchanges are possible in a subcatchment. Like SWAT2012, there is not a two-way exchange between one aquifer and channel unit pair.
  - **Aquifer flow into a gaining channel branch:** MIKE-SHE allows for multiple aquifer units (user-determined number) within a subcatchment, each with a **threshold storage for outflow and linear storage-outflow function**. *Note: The combination of multiple linear reservoirs with different recession parameters results in non-linear total aquifer outflow*. The exchange is calculated regardless of the water level in the river.
  - **Channel loss from a losing branch to subcatchment aquifers:** Transmission losses are a function of the channel-wetted perimeter and length, head (depth of water in the channel) and the bed conductivity. The exchange is calculated regardless of the aquifer storage.
- **ACRU4** only includes **one direction of exchange** from HRU-scale aquifer units into channels (or potentially into riparian HRU soils). There is **no flow from the channel directly into aquifer units** in the tool. For aquifer unit outflow to the channel, a **non-linear storage-outflow function with no thresholds** is applied. There is no additional lagging or routing, so outflow parameterisation should also be relevant to the distance from the HRU to the channel (or riparian HRU).

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple semi-distributed, more conceptual**	**MIKE-SHE complex distributed, more physical**
Ground water storage and flow between aquifer units	*One aquifer ground water store per runoff module.* Ground water outflow to aquifer of downslope runoff module only when ground water storage > threshold (static water level) Ground water flow calculated using Darcy's Law, function of transmissivity (input) ground water gradient Ground water gradient is a function of maximum gradient (input), ground water storage vs. SWL and maximum storage capacity. When ground water storage = capacity, ground water gradient = maximum gradient	*One aquifer ground water store per subcatchment* Ground water outflow to aquifer of downslope subcatchment only when ground water storage > threshold (resting water level, RWL) Maximum ground water flow calculated using Darcy's Law, function of transmissivity (input) regional ground water gradient (input) slope width (function of subcatchment size and drainage density) Flow is function of maximum ground water flow, lower ground water wedge gradient (function of ground water storage and aquifer properties) Ground water gradient at aquifer's resting water level.	*One aquifer ground water store per HRU* Ground water flow between HRUs or subcatchments not calculated, *unless applying option below* **Optional riparian zone HRU + routing:** One HRU in a subcatchment is specified as the riparian zone. The aquifer outflow of all other HRUs, calculated as for outflow to the channel (see table below) within a subcatchment is routed to the ***soil*** of the riparian zone's HRU.	*Two aquifer ground water stores per subcatchment: shallow unconfined and deep confined. Both aquifers recharged by all HRUs in subcachmentt.* Ground water flow between subcatchments not calculated	**Simple linear reservoir ground water routing method:** *One or more aquifer ground water stores per subcatchment. Aquifers recharged from overlying interflow reservoirs (mapped polygons) in subcatchment.* Ground water flow between aquifer units not calculated (within or between subcatchments)	**Distributed, finite element subsurface modelling:** *3D gridded subsurface zone.* Ground water flow is calculated between cells in 3D using pressure heads and vertical and horizontal K of user input layers. Ground water can flow in any direction in the model domain.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
	When SWL < GW storage < capacity, Linear↓gradient with ↓GW storage When storage = SWL gradient = 0 (no outflow)	When lower gradient > 0, ground water flow = maximum ground water flow When RWL < gradient < 0, linear ↓GW flow with ↓lower gradient When lower gradient ≤ RWL, ground water flow = 0				
Ground water exchange with channels (GW-SW interaction: aquifer outflow and channel transmission loss)	*One aquifer ground water store per runoff module* Two-way ground water channel exchange calculated. Flow direction determined by ground water head vs surface water head. Ground water head = Ground water storage – SWL store (store at river elevation) Surface water head = runoff/subcatchment area When ground water head > surface water head, aquifer outflow to runoff module outlet	*One aquifer ground water store per subcatchment* Two-way ground water channel exchange calculated. Flow direction determined by subcatchment ground water gradient to channel. Ground water gradient calculated from “wedge” shape, function of drainage slope width (ridge to channel, function of drainage density), ground water storage and storativity. Wedge has two sections: upper 60% (ridge to inflection	*One aquifer ground water store per HRU* One-way ground water to channel exchange calculated. No channel transmission loss to ground water. Aquifer outflow to channel = proportion of ground water storage. This proportion is a power function of Ground water release coefficient (input), Ground water storage on the previous day *(not a linear reservoir)* HRU aquifer outflow is added to channel the	*Two aquifer ground water stores per subcatchment: shallow unconfined and deep confined* **Shallow aquifer:** One-way ground water to main channel exchange calculated. No main channel loss to shallow ground water. Tributary channel (= SRO landscape routing) loss to shallow aquifer described above. Aquifer outflow to channel only if ground water storage ≥ threshold. Flow is an exponential function: Ground water	**Simple linear reservoir ground water routing method:** *One or more aquifer ground water stores per subcatchment.* Multiple channel branches allowed per subcatchment. For each branch: one-way ground water to channel or channel to ground water exchange calculated (branches classed as losing or gaining by user). **Gaining branches:** Each aquifer in subcatchment outflows to gaining channels only if ground wataer storage ≥ threshold	**Distributed, finite element subsurface modelling:** *3D gridded subsurface zone.* Two-way ground water-channel exchange calculated. Flow direction determined by ground water head vs channel head at each node. Ground water flow is calculated between 3D cells using pressure heads, and vertical and horizontal K of layers. Ground water can flow in any direction. If a gradient develops towards a channel element, and

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
	When ground water head < surface water head, portion of runoff added to aquifer ground water store. Flow (either direction) is an exponential function of maximum flow rate (input), GW-SW head difference, power parameter (input) (Note: Can also calculate transmission loss in a channel module, but not linked to any ground water store.)	point) lower 40% (inflection point to channel). Darcy's law used to calculate section exchanges. When lower ground water gradient > 0 (towards channel), aquifer outflow to channel, flow calculated with Darcy's law. When lower ground water gradient < 0 (away from channel), channel loss to lower ground water, flow calculated as power function of ground water gradient vs. RWL. Maximum transmission loss, month's runoff vs. maximum (subcatchment and upstream of subcatchment)	same-day generated outflow (not lagged) **Optional riparian zone HRU + routing:** One HRU in a subcatchment is specified as riparian. The aquifer outflow of all other HRUs, calculated as for the outflow to the channel, is routed to the soil of the riparian-zone HRU.	storage and recession constant **Deep aquifer:** One-way channel to ground water. No deep aquifer outflow. Main channel loss only when no ground water to channel. Flow is a function of flow travel time (Manning's equation), channel length, wetted perimeter, bed conductivity, fraction of loss to ground water vs. bank store. *(**Bank store:** Release to channel and riparian soil)*	Flow is a function of ground water storage and recession constant. Flow is divided between branches using length. Each aquifer's outflow is added to the channel in the timestep generated (not lagged) **Losing branches:** Channel loss to aquifer is a function of channel water depth, wetted perimeter, bed conductivity	ground water table in cells bordering channel is higher than the channel water elevation, ground water inputs to the channel. If the ground water table in cells bordering the river channel is below the channel, the channel can lose to ground water. Flow (either direction) is a function of head difference between riparian ground water and channel water, aquifer K_{sat}, bed conductivity
Capillary rise (flow from ground water into vadose zone or soil)	*(Not explicitly calculated – implicit in monthly AET and recharge, ET direct from ground water can be modelled)*	*(Not explicitly calculated – implicit in monthly AET and recharge, ET direct from ground water can be modelled)*	Capillary rise from ground water is only calculated with the optional vadose zone representation.	Capillary rise from ground water is calculated as a function of ET demand, not only SM deficit.	Capillary rise from ground water can be added in low-lying areas.	**Richard's equation soil + 3D finite difference ground water:** Capillary rise from the ground water table (saturated zone)

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
			Optional “intermediate zone” (vadose zone): An optional routine adds a vadose zone below the lower soil layer. It has a user input thickness, ST, FC and WP moisture levels, and capillary fringe properties (depth, yield). VZ SM above CF = FC, unless there are ET withdrawals. VZ SM within CF: bottom 10% CF = SAT, upper 90% CF = linear transition SAT to VZ SM VZ SM above CF is replenished up to FC by water drawn from the ground water aquifer store at the capillary yield rate.	Capillary rise of water from the shallow ground water aquifer into the soil profile replenishes SM as E_t is withdrawn. Maximum capacity rise = maximum E_t * capacity rise coefficient Capacity rise is a function of maximum capacity rise, ground water storage, aquifer threshold for capacity rise When GW < threshold, capacity rise = 0 When threshold < ground water < (threshold + maximum capacity rise), capacity rise = (ground water – threshold) When ground water ≥ threshold, capacity rise = maximum capacity rise	**Two-layer soil water balance method + linear reservoir ground water:** Capillary rise restricted to lowland or riparian areas (defined by lowest interflow zone mapped in subcatchment – *see table below*) Capillary rise is calculated when SM < FC for upper soil layer (root zone) Maximum capillary rise = fixed percentage of aquifer outflow for timestep (*see table below for calculation*) When ground water < threshold, aquifer outflow, including capacity rise = 0 Water is diverted from aquifer outflow until upper soil layer SM = FC or maximum capacity rise quantity is reached.	into the soil layer above it (unsaturated zone) is calculated on a cell-by-cell basis based on the matrix potential differences between underlying and overlying 3D cells, gravity and conductivity.

Process	WRSM-Pitman (Sami GW)	SPATSIM Pitman (Hughes GW)	ACRU4	SWAT2012	MIKE-SHE simple semi-distributed, more conceptual	MIKE-SHE complex distributed, more physical
				Bank storage (from channel transmission loss) can also contribute to riparian HRU soil. Calculation follows the same form as above.		

A10: CHANNEL FLOW AND OVERBANK FLOODING

All the tools differ to some degree in the arrangement of channel model units in a model set-up:

- **SPATSIM-Pitman** and **SWAT2012** set-ups have one main channel unit per subcatchment.
- **WRSM-Pitman, ACRU4** and **MIKE-SHE** allow for multiple channel units to be included in a subcatchment, allowing a variety of connections to other model units in a network.

A few tools have similar approaches to routing flow through channel elements, applying some variation of the Muskingum method's kinematic routing, with WRSM-Pitman and MIK-SHE using different approaches. Some Muskingum methods and MIKE-SHE's hydraulic routing require inputs of channel dimensions and roughness.

- **WRSM-Pitman,** as it uses a monthly timestep, does not include any routing calculation to lag flows through a channel module: outflow in a timestep equals the inflow minus withdrawals and diversions. (Within the runoff module, interflow is lagged to the module's outlet.)
- **SPATSIM-Pitman, ACRU4** and **SWAT2012**, can apply variants of the Muskingum method's kinematic routing through channel units, allowing some of the inflow to be attenuated.
  - **SPATSIM-Pitman**, by default, does not lag flow entering the subcatchment channel due to the monthly timestep, but an option to introduce a lag exists to handle large subcatchments that may take longer than a month to drain. The Muskingum equation is applied with no weighting factor (weighting factor, x = 0), implying no flood wave.
  - **ACRU4,** by default, does not route flows either, assuming that the water entering the channel leaves on the same day, but there is an option to explicitly route water through channel units. This is done at a daily timestep applying the Muskingum equation, including the weighting factor (0). The flow lag time (K) and the flood wave weighting factor (x) can be input by the user or calculated using the Muskingum Cunge method that uses Manning's equation to estimate flow velocity. For this, ACRU requires inputs of channel dimensions.
- **MIKE-SHE** is coupled with a hydraulic model, MIKE-Hydro River. The river channel network is made up of points (nodes) at which channel cross-sections are input by the user with explicit elevations so that the channel slope for the reach between the cross-sections can be derived and also so that the elevation of the water surface can be compared to the water elevation on the land surface for overland flow and to the ground water table elevation for model grid cells bordering the channel. The exchange of water between the land surface, ground water and the channel is calculated based on elevation gradients and bed material conductivity. Channel flow, water height and spatial extent are calculated using the Saint-Venant equations, conserving mass and momentum. The flow routing timestep needed for model stability depends on the distance between defined cross-sections, but is generally in the order of minutes or seconds. If daily routing or no routing is appropriate for the catchment size and subdaily peaks are not needed, channel flow can be simplified to reduce the computation burden, either not lagged or routed using Muskingum or Muskingum-Cunge methods.

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple Semi-distributed, more conceptual**	**MIKE-SHE complex Distributed, more physical**
Channel flow	*Flexible number of channel modules in a network.* Channel module receives inflow from up to 10 routes from other modules (runoff modules, special areas, reservoirs, channels) Transmission loss is a function of maximum loss rate (input) channel inflow When inflow ≤ maximum loss, loss = inflow and outflow = 0 When inflow > maximum loss, loss = maximum and outflow = inflow – loss Losses removed from model. Evaporation loss not considered. Only have overbank flooding with a wetland *(see wetland section)*	*One channel unit per subcatchment* Channel receives SRO, interflow and aquifer outflow from the subcatchment, channel outflow from any upstream subcatchments Transmission loss to subcatchment aquifer *(see calculation in ground water section)* Evaporation loss not considered. Only have overbank flooding with a wetland *(see wetland section).* Channel outflow to downstream subcatchment, assume exit in the month (no routing). **Optional lagging:** For large subcatchments (> month to drain), outflow calculated with Muskingum equation	*Flexible number of channel units per subcatchment. Headwater subcatchment does not need a channel. Downstream subcatchments need channel to route inflow from upstream. Can add multiple for linking riparian, wetland and reservoir units.* Channel receives outflow from linked subcat HRUs, channel outflow from upstream channels. No transmission or evaporation losses calculated. Only have overbank flooding with special riparian and wetland HRUs *(see wetland sectio..)* Channel outflow calculated with Muskingum equation, function of weight factor, inflow, storage,	*One main channel unit per subcatchment (and representation of tributaries in routing HRU runoff to main channel – see SRO routing section)* Channel receives routed outflow from linked subcatchment HRUs, channel outflow from upstream channels. Transmission loss to bank store and aquifer *(see calculation in ground water section)* Evaporation loss is a function of PET, flow duration, channel length and width, and evaporation coefficient. No overbank flood exchange with HRUs. *(wetland on channel – see wetland section).* Channel outflow calculated with Muskingum equation,	*Flexible number of channel branches per subcatchment. Branches have spatial calculation nodes with input cross-sections.* Branch nodes receive overland flow from subcatchment surface zones, interflow and aquifer outflow (distributed across channel nodes in subcatchment), flow from upstream node, direct rainfall (optional). User classifies branches as losing or gaining *(see calculation in ground water section.)* Evaporation loss is a function of PET and open water surface. Overbank flooding onto surrounding area if node cross-section water elevation > topography.	*Flexible number of channel branches. Branches have spatial calculation nodes with input cross-sections. Nodes linked to surface and subsurface grid cells.* Branch nodes receive overland and subsurface flows from neighbouring cells, outflow from upstream node, direct rainfall (optional). Transmission loss to neighbouring aquifer units *(see calculation in ground water section).* Evaporation loss is a function of PET and open water surface. Overbank flooding onto surrounding area if node cross-section water elevation > topography. Water joins surface processes calculation.

Process	**WRSM-Pitman (Sami GW)**	**SPATSIM Pitman (Hughes GW)**	**ACRU4**	**SWAT2012**	**MIKE-SHE simple Semi-distributed, more conceptual**	**MIKE-SHE complex Distributed, more physical**
	No lagging: Outflow leaves in the timestep of the inflow (after losses and withdrawals, diversions are calculated). Outflow can be routed to reservoirs, other channels modules, model outlet.	with weight factor = 0 (reservoir type, no waves), a function of the previous month's outflow, current and previous runoff, lag time (input). Remainder added to the next month's channel water.	lag time (either user-input parameters, or derived from input channel dimensions and roughness).	function of weight factor, inflow, storage, lag time (derived from input channel dimensions and roughness, shape includes main channel and wide rougher floodplain).	Water joins surface processes calculation. Flow between nodes calculated using hydraulic Saint Venant equations, function of inflow, channel + floodplain cross-sections, slope and roughness.	Flow between nodes calculated using hydraulic Saint Venant equations, function of inflow, channel + floodplain cross-sections, slope and roughness.

APPENDIX B: WETLAND REPRESENTATION ACROSS MODELLING TOOLS

INTRODUCTION

Assessing the approach to wetland representation in a modelling tool is important for reliably modelling a catchment with significant wetlands and appropriately considering the wetland's influence on the catchment hydrology. Wetland representation refers to how well a simulated wetland describes and includes the characteristics, processes and function of a physical wetland. Assessments of wetland representation in models can be conceptual and quantitative.

Using the national classification system of wetlands and other aquatic ecosystems in South Africa (Ollis et al., 2013), general information about hydrological processes and water movement for many mapped and classified wetlands is available. The fourth level of classification in this system defines wetland hydrogeomorphic units and has been used in other hydrological studies (Maherry et al., 2017; Tanner et al., 2019; Rivers-Moore et al., 2020). This serves as a standard and comparable starting point for describing a given wetland, but if the situation allows, this information can be supplemented with information from local monitoring.

In most catchment hydrological models, a wetland is considered to be a depression that forms a water storage unit regulated by a water balance of temporally variable inflows and outflows (Rahman et al., 2016). Potential differences between wetlands and how they are simulated can be as follows:

- The location relative to the river network: riparian vs geographically isolated wetland
- The wetland's dependence on the surrounding topography
- The inflows and outflows of the wetland water balance: interactions with surface and ground water flows in the surrounding catchment
- The type of water storage: landmass with vegetation and soils or only an open water body (i.e. treated like a lake or a dam), and the geometry of the "wetland unit"
- The spatiotemporal scale of the storage

TYPES OF WETLANDS CONCEPTUALISED IN MODELLING TOOLS

The modelling tools reviewed differ in the wetland type(s) they can represent with their conceptualised "wetland module" or other means of representation. A summary is presented in Table B1. In MIKE-SHE, there is not a special wetland unit. The model needs to be set up to create a saturated area through the topography, soil and aquifer inputs, and the vegetation can be appropriately parameterised. In some tools, an alternative wetland type can be implied by modifying the set-up of the wetland unit in the catchment and how water is routed. For example, the "wetland HRU" in ACRU4 was designed to represent riparian wetlands. However, geographically isolated wetlands can be represented by splitting a catchment into several subcatchments, so that wetland units in upper subcatchments can act as geographically isolated wetlands (Gray, 2011).

All modelling tools, except for SWAT2012, can conceptualise wetlands as riparian wetlands. The SWAT2012 wetland unit is modelled within a subcatchment, but is not associated with the river channel and cannot receive any channel flows from upstream subcatchments. A riparian wetland can be modelled using modified versions of SWAT available from independent researchers. For example, Rahman et al. (2016) developed a version of SWAT with riparian wetlands by changing the internal mechanisms of the model to allow the wetland to receive water from the river.

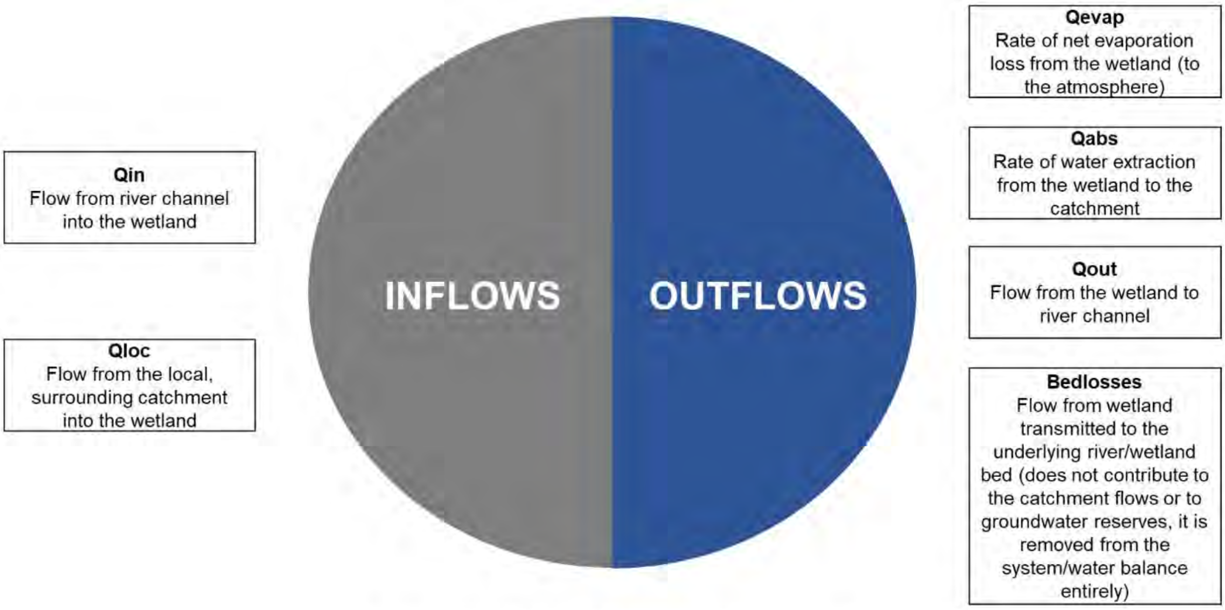
Table B1: Wetland types, storages and scales conceptualised in different modelling tools

Description	ACRU4	WRSM-Pitman	SPATSIM-Pitman	SWAT2012	MIKE-SHE
Wetland type	Riparian	Riparian	Riparian	Geographically isolated wetland	Riparian, geographically isolated wetlands
Storage or cover type	Land mass	Open water body	Hybrid	Open water body	Hybrid
Regulation process	Threshold process for channel overflow, soil water budgeting and routing for wetland outflow	Threshold relationships between the main channel, and wetland storage level and inflow rate	Threshold relationships and exponential functions between upstream river flows, and wetland storage and hydraulic properties; attempts to reproduce inundation hysteresis	Water availability in the surrounding subcatchment: receives a portion of the surface and subsurface runoff produced; storage exceedance controls outflow	Surface and subsurface water level gradients between cells
Spatial unit	HRU within a subcatchment	Attached to a channel module in a network	Unit at subcatchment outlet, on channel	Unit within a subcatchment	Grid cells
Temporal scale	Daily	Monthly	Monthly	Daily	Daily

WETLAND WATER BALANCE CONCEPTS

The inflows and outflows of the simulated wetland water balance in each tool are summarised in Figure B1. Most of the simulated wetlands receive surface flow and rainfall as the main inflows. Most do not receive direct ground water flow, but ground water can contribute indirectly by contributing to channel flows that then feed the model wetland. SWAT2012 and MIKE-SHE wetlands have a separate inflow of ground water, and ACRU4 includes this for its “riparian” HRU. In these tools, the wetlands can contribute to ground water through seepage losses or percolation to a “baseflow reservoir”. WRSM-Pitman and SPATSIM do not have direct ground water inflows or outflows. All tools can account for water losses through water surface evaporation, while ACRU4 and MIKE-SHE include ET from vegetated surfaces explicitly represented for the wetland.

WRSM-Pitman – wetland water balance



Qin
Flow from river channel into the wetland

Qloc
Flow from the local, surrounding catchment into the wetland

Qevap
Rate of net evaporation loss from the wetland (to the atmosphere)

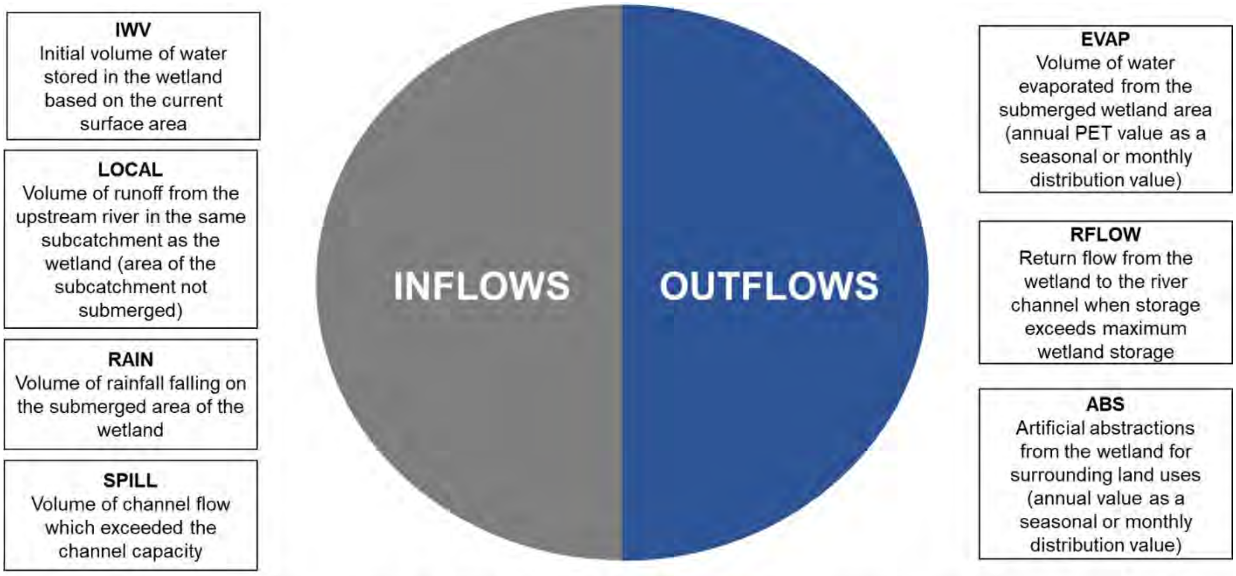
Qabs
Rate of water extraction from the wetland to the catchment

Qout
Flow from the wetland to river channel

Bedlosses
Flow from wetland transmitted to the underlying river/wetland bed (does not contribute to the catchment flows or to groundwater reserves, it is removed from the system/water balance entirely)

S2, storage in the wetland at the end of the month
= S1, initial storage at the start of the month + Qin + Qloc – Qevap – Qabs – Qout - bedlosses

SPATSIM-Pitman – wetland water balance



IWV
Initial volume of water stored in the wetland based on the current surface area

LOCAL
Volume of runoff from the upstream river in the same subcatchment as the wetland (area of the subcatchment not submerged)

RAIN
Volume of rainfall falling on the submerged area of the wetland

SPILL
Volume of channel flow which exceeded the channel capacity

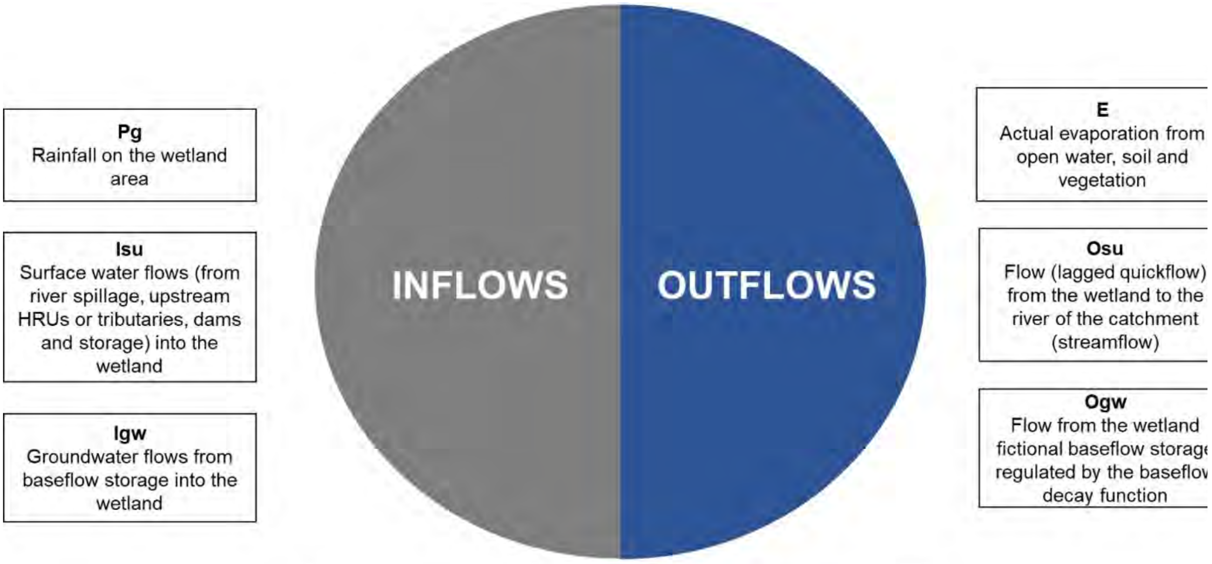
EVAP
Volume of water evaporated from the submerged wetland area (annual PET value as a seasonal or monthly distribution value)

RFLOW
Return flow from the wetland to the river channel when storage exceeds maximum wetland storage

ABS
Artificial abstractions from the wetland for surrounding land uses (annual value as a seasonal or monthly distribution value)

WV, wetland volume at the end of the month
= IVW + LOCAL + RAIN + SPILL – EVAP – RFLOW - ABS

ACRU4 – wetland water balance



Pg
Rainfall on the wetland area

Isu
Surface water flows (from river spillage, upstream HRUs or tributaries, dams and storage) into the wetland

Igw
Groundwater flows from baseflow storage into the wetland

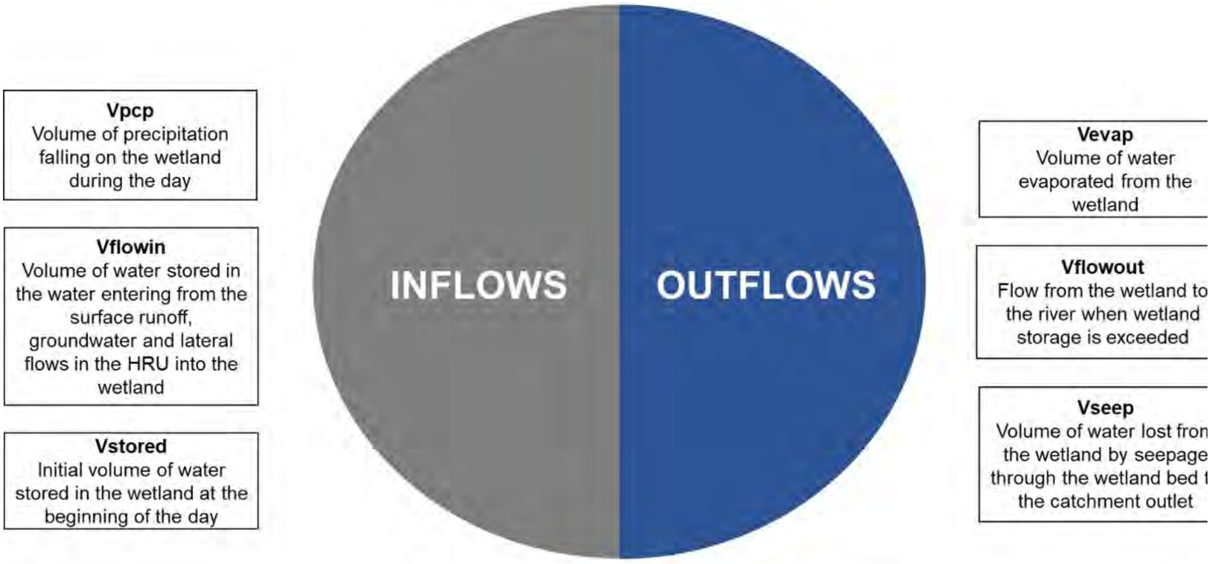
E
Actual evaporation from open water, soil and vegetation

Osu
Flow (lagged quickflow) from the wetland to the river of the catchment (streamflow)

Ogw
Flow from the wetland fictional baseflow storag regulated by the baseflov decay function

ΔS, daily change in storage
= Pg + Isu + Igw – E – Osu - Ogw

SWAT2012 – wetland water balance



Vpcp
Volume of precipitation falling on the wetland during the day

Vflowin
Volume of water stored in the water entering from the surface runoff, groundwater and lateral flows in the HRU into the wetland

Vstored
Initial volume of water stored in the wetland at the beginning of the day

Vevap
Volume of water evaporated from the wetland

Vflowout
Flow from the wetland to the river when wetland storage is exceeded

Vseep
Volume of water lost fron the wetland by seepage through the wetland bed t the catchment outlet

V, volume of water in the wetland at the end of the day
= Vstored at the start of the day + Vflowin + Vpcp – Vflowout – Vevap - Vseep

MIKE-SHE – wetland water balance

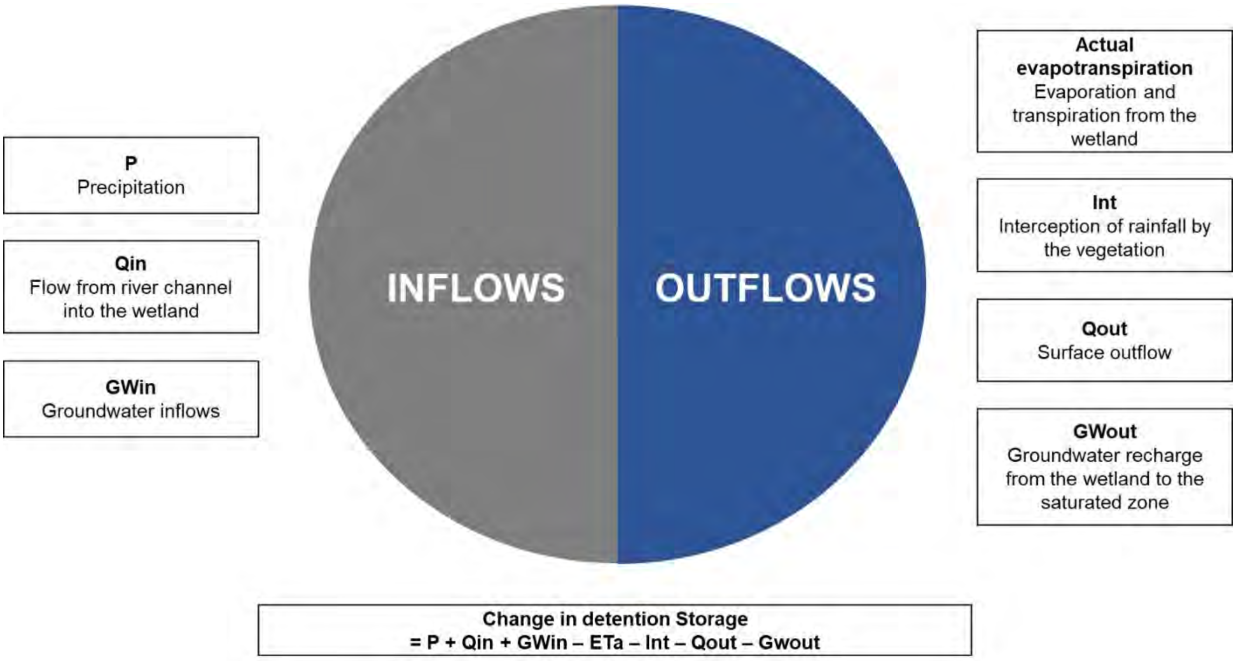


Figure B1: The water balance inflows and outflows of the modelling tools

INTERACTIONS CONTROLLING THE WETLAND'S ACCESS TO WATER

The interactions that the simulated wetland has with different modelled components of the catchment controls the wetland's access to water. The interactions are either unidirectional (going in one direction and downstream only) or bidirectional (able to go back and forth between the source and destination of the water). Figure B2 illustrates this in terms of water routing between the wetland and surface water. The wetland's interactions with ground water can be uni- or bidirectional, as well vertical and horizontal. Figure B3 illustrates the potential water flow pathways. Vertically, water can move upwards or downwards between the water stored, soil, subsurface materials and ground water reserves of the wetland unit itself. Horizontally, water can move between the wetland and the surrounding land units. The dashed red lines in Figure B3 indicate water moving bidirectionally from and to the wetland.

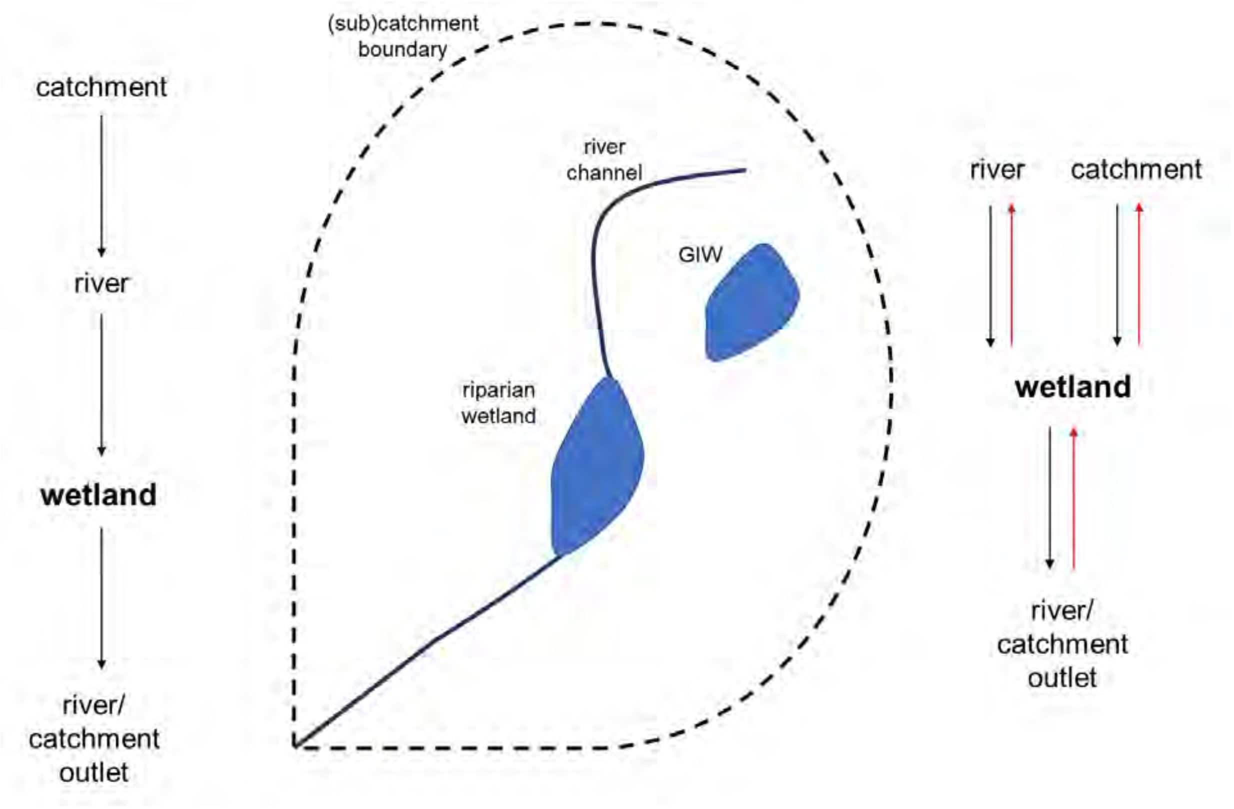


Figure B2: A simple model of uni- and bidirectional water movement between the simulated wetlands, surface water and ground water

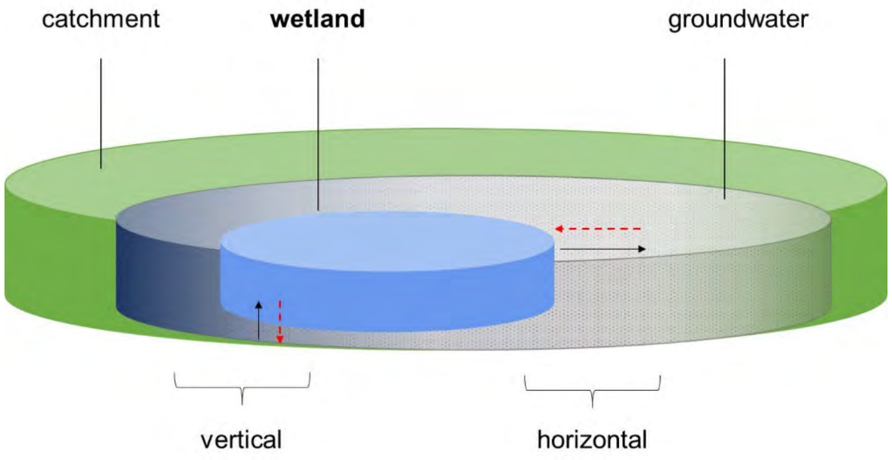


Figure B3: A simple model of water movement between a simulated wetland and ground water

The movement of water between the catchment and the wetland is presented in Table B2. Each modelling tool has a specific way of routing water to and through the river network. Water flow pathways show the potential influence of the wetland on retaining and releasing water. The direct inflows into the wetland may include surface water, ground water or both. If there is no direct ground water inflow, ground water may contribute indirectly by feeding channel flow that then enters the wetland. The difference between wetland-surface runoff interactions and wetland-river interactions is that the former represents non-channel surface runoff inflows, while the latter refers to the interactions between the wetland and river channel units, which could be inflows from upstream or outflows to downstream.

Table B2: The main source of water and interactions of the wetland in modelling tools

Description	**ACRU4**	**WRSM-Pitman**	**SPATSIM-Pitman**	**SWAT2012**	**MIKE-SHE**
Inflow sources	River only (Riparian zone: River and ground water*)	River only (Ground water indirect)	River only (Ground water indirect)	River, surface runoff, ground water	River, surface runoff, ground water
Direct interactions					
Wetland – surface runoff	None	None	None	Unidirectional *inflow*	Bidirectional
Wetland – river channel	Bidirectional	Bidirectional	Bidirectional	Unidirectional *outflow*	Bidirectional
Wetland – ground water	Unidirectional *vertical and out to river* (Riparian zone: bidirectional* *(horizontal in and vertical out)*	None	None	Unidirectional *horizontal in only*	Bidirectional *vertical and horizontal, in and out, all possible*

* In addition to its special wetland HRU, ACRU4 has a “riparian zone” HRU that can be used as a wetland with direct subsurface inflows.

APPENDIX C: CASE STUDY MODELLING DETAILS BY CATCHMENT AND MODELLING TOOL

C1: MISTLEY CATCHMENT, UPPER MVOTI RIVER (U40A), KWAZULU-NATAL: FORESTRY AND RIPARIAN ZONE FOCUS

- **Catchment description and modelling goals** are given in the main report, section 5.3.1.
- **Model units and main parameter values** used across the different models are given in tables C1 to C6 below
- **Performance of the models compared to observed streamflow** is described in the main report, section 5.3.3.
- **Model outputs, including water balances**, are compared and discussed in the main report, section 5.3.3. A summary of the streamflow output for each tool for each scenario is given in Table C7 below.

The text sections describe the different model structures, summarise the rationale for structure and parameter decisions, and highlight the main challenges encountered. Approaches common to all tools and the set-up of the pre-existing model, which was used as a reference, are described first, followed by structure and parameter value tables, and then by descriptions of the models built using the other tools.

At the time of writing, the MIKE-SHEc model (MIKE-SHE using complex algorithm options) had not been completed, so only the MIKE-SHEs model (simpler algorithms) is described for this case study.

GENERAL APPROACHES COMMON ACROSS TOOLS

- The pre-existing model of the catchment built in ArcSWAT2012 (Scott-Shaw, 2020) was the reference point for building models using the other tools.
- Calibration adjustments were informed by comparing modelled streamflow to streamflow data from DWS Weir U4H002 for the 1989 to 2016 water years (1 October 1988 to 30 September 2016). Weir data was available from 1985 onwards, but comparison of the rainfall and flow datasets for large events in 1987 and early 1988 suggested that either one of the rainfall station records was in error and/or the weir capacity was exceeded in these events: very high rainfall at one gauge without a commensurate flow peak given the responses to other events in the time-series. It was beyond the project scope to resolve this, so the period was left out of the analysis.
- Models were run with a five-year warm-up period (the 1983 to 1987 water years). Climate time-series were available from 1979 onwards.
- **Spatial distribution of input climate variables and model units:** The spatial distribution of rainfall and atmospheric evaporative demand across the area was represented by subdividing the catchment into spatial units that could be assigned different climate input time-series. The level at which climate data can be assigned, and the practicality of subdivision, varies across modelling tools. For this case study, the following was applicable:

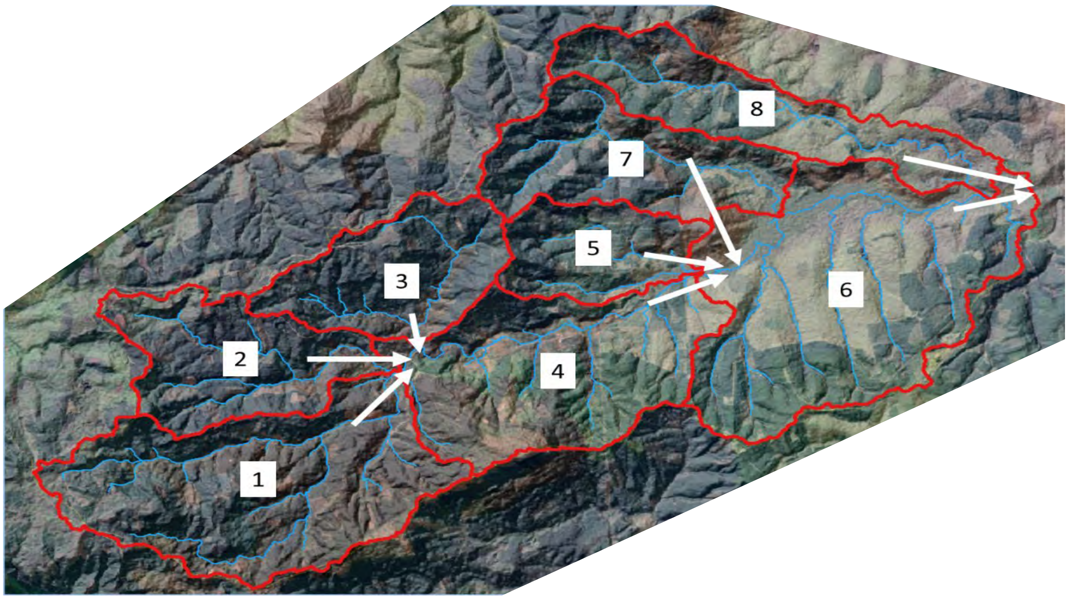


Figure C1: Subcatchment delineation for the Mistley catchment on the Upper Mvoti River as applied in the ACRU, MIKE-SHE, WRSM and SPATSIM models. White arrows indicate routing between subcatchments for all models except SPATSIM in which Subcatchment 8 was routed into Subcatchment 6 (see explanation in text).

  - In the reference **ArcSWAT2012** model, subcatchments were assigned the climate timeseries of the nearest of the three input climate station points. The model had many small subcatchments (73), meaning that this distribution approached what would be achieved using Theissen polygons for the three stations to assign values. Fortunately, the stations were evenly spread across the topography.
  - In **WRSM, SPATSIM, ACRU** and **MIKE-SHEs**, climate inputs were specified by subcatchment using a set of eight subcatchments (Figure C1). This scale was selected so that subcatchments were smaller than the 50 km^2 maximum recommended for ACRU. They were delineated based on the intersections of major tributaries to split areas of obviously different terrain (visual assessment using topography, mapped geology and aerial photography). In Geographic Information Systems (GIS), the shapefile of the small subcatchments used in SWAT was converted to three polygons of the areas that had been assigned to each of the three climate stations in this model. The eight subcatchments were overlain with these station polygons to determine how the station climate data would be applied. Some subcatchments fell entirely within the area assigned to a single station in SWAT. For subcatchments that contained areas that had been assigned to different climate stations in SWAT, area-weighted averaging was applied to the relevant station data to obtain a composite time-series to apply to the subcatchment. This ensured that catchment-scale climate inputs were equivalent to the reference model.

- **Land cover and soil type distribution:** The same land cover and soil type maps were used to derive the inputs for all models. These are described below for the reference SWAT model. Although vegetation cover can influence soil properties, soil properties in the models remained the same in the wetland and buffer area restoration scenario. This assumes that the change in soil properties is secondary in its impact to the change in the input vegetation properties, which may not actually be the case.
- **Riparian zone water access:** In all models, the vegetation in the mapped riparian area along the drainage lines was given greater access to subsurface water to support ET than elsewhere in the landscape. The representation of this varied across the modelling tools.

STARTING REFERENCE MODEL: ARCSWAT2012

A model of the Mistley catchment was built in ArcSWAT2012 as part of a region-wide effort to assess the impact of removing commercial forestry plantations from riparian areas that would otherwise be wetlands (Scott-Shaw, 2020). The model was also constructed to be multi-purpose and allow the smaller-scale exploration of questions about individual properties, and so was built with a high spatial resolution in terms of the number and size of HRUs.

Structure and parameterisation

- **Model units and routing:** By looking at where stream channels were apparent in aerial photography, a 195-ha flow accumulation threshold was selected for stream mapping. This resulted in 73 subcatchments being delineated by the ArcSWAT2012 interface. HRUs within the subcatchments were created in the software by overlaying input maps of land cover (18 types), soil (five types), slope classes (five types) and subcatchments (73). This resulted in 4 974 HRUs in the model.
- HRU surface flow and interflow are automatically routed in parallel to the subcatchment's river channel. Water percolating from the bottom of an HRU soil profile recharges a subcatchment-scale aquifer store, from which outflow is routed to the subcatchment channel.
- **Land cover:** The input land cover map, was derived from combining the 2011 provincial land cover map of KwaZulu-Natal, based on high-resolution (5 m) SPOT 5 satellite imagery (Ezemvelo KZN Wildlife and GeoTerraImage, 2013), and a regional wetland mapping exercise based on satellite imagery, aerial imagery and ground truthing (Lechmere-Oertel, unpublished). Some refining of general cover-type classifications was done based on the water use authorisation and registration management system (WARMS) database (DWS, 2015) and local assessment (Scott-Shaw, unpublished). Areas where wetland has been converted to timber plantation and agriculture were identified. This resulted in 14 land cover types (Table C3), of which plantation areas were further subdivided based on location: in areas that were formerly wetland (drainage lines), in buffer areas around the wetlands, and outside the wetland and buffer zones. This resulted in the 18 classes used to delineate the HRUs. This was done to allow simple conversion of the cover in the former wetland and buffer areas to represent the restoration scenario.
- Initial vegetation-type parameters were taken from the in-built SWAT parameter database, which includes several corresponding types, such as eucalyptus, pines, pasture, sugarcane, rangeland, etc. The full Penman-Monteith equation was applied to calculate ET in this model, as opposed to the option of calculating reference potential ET from climate data and applying a crop coefficient. Key parameters for this method are maximum LAI and root depth, and associated growth curve parameters, maximum stomatal conductance and curve-shape parameters for the relationship with vapor pressure deficit (VPD). These were modified based on local studies (Scott-Shaw 2019). The default growth parameters assume a high latitude, and a northern hemisphere growth pattern with dormancy in the northern hemisphere winter. To avoid this, growth curve parameters were adjusted to minimise this period and the drop in LAI.
- **Soils:** The spatial distribution of soil types and properties were assumed to follow the land-type unit mapping of the Agricultural Research Council (ARC, 2001) with an additional soil type defined for the delineated wetland areas. Property values were assigned based on soil form descriptions and interpretations made in the South African Atlas of Climatology and Agrohydrology (Schulze, 2007). Soils are predominantly well developed, deep sandy clay loams with clay loams and silt loams in lowland and riparian zones.
- SWAT uses the input saturated conductivity to calculate vertical and horizontal flow in soils. However, it uses the empirical SCS-CN method to calculate infiltration (and interception) versus runoff production during rainfall events. Initial CN values were selected based on suggestions in the model documentation for broad vegetation structural types (Arnold et al., 2012), but modified in calibration.

- **Geology and aquifers:** The national Groundwater Resources Assessment II (DWS, 2006l) and the 1:1 million geological map of South Africa of the Council for Geoscience were consulted. However, SWAT uses conceptual linear reservoirs to represent aquifer storage and outflow, so these sources could not be used directly to obtain parameter estimates. The geology of the Mistley catchment is comprised of sandstones, mudstones and shales, predominantly of the Ecca Group, Karoo Supergroup (South African Council for Geoscience, 2019). The distribution of different geologies is reflected in the soil types and topography. However, the aquifers were assigned uniform properties over the catchment given the lack of local information and the assumed more dominant role of the deep soils. The parameter values were assigned based on the model documentation suggested values for slower outflow aquifers (Neitsch et al., 2011) and assessed in calibration.
- Capillary rise or vegetation access to ground water can be represented for any HRU in the model by specifying the maximum proportion of the ET demand that can be met by drawing from the aquifer store (“REVAP” parameter), with values between 0.02 to 0.2 (2–20%) allowed. Areas considered riparian, determined using the valley bottom topographic unit, were assigned the highest value, representing a shallower ground water table at this location. Landscape values were assessed in calibration.
- **River channel network:** SWAT includes one main river channel unit per subcatchment. Channel bed loss was not included in the model for this case study.
- **Small farm dams:** The surface area of small farm dams in the catchment accounted for 1.4 km^2 or 0.4% of the catchment area. The farm dams were not represented as water-storing units because the set-up and parameterisation of dams in SWAT is relatively intensive and would have to be done for each one individually, for which the data was not readily available. They were parameterised as water surfaces, with relatively high AET and adding to surface runoff during storms. This was considered adequate given their relative area in the catchment, the fact that major land covers were not irrigated and they would likely be full most of the time given the climate, and that they were not central to the question being addressed in the modelling effort (i.e. riparian area cover change).
- **Mvoti Vlei wetland:** The large Mvoti Vlei wetland area was represented using SWAT’s wetland subroutine. This module considers wetlands as off-channel surface water bodies that receive flow from HRUs within their subcatchments and drain slowly into the channel when over capacity. This is conceptually incorrect for the Mvoti Vlei, which lies on the main channel itself and would not only receive flow from incremental subcatchments, but also from the entire catchment via the main channel. The module was nevertheless applied as a mechanism to attenuate at least some of the flow from the catchment. Based on field visits to the area (Scott-Shaw, personal communication), it was parameterised so that, at maximum capacity, the full mapped area of the wetland was assumed to hold a metre of water. At its “normal level”, it would have half this depth and the water surface area would be 80% of the full area. It was assumed that 50% of the volume is taken up by dense reeds, reducing the storage volumes used in the model. Other wetland areas along tributaries were differentiated by vegetation and soil properties and capillary rise allowance, but were not considered as water bodies and could not receive landscape flow inputs.

Adjustments to improve calibration

Calibration adjustments were done outside this project for a more regional modelling effort (Scott-Shaw, 2020) using the SWAT-CUP tool (Abbaspour, 2015) to test 300 parameter sets in which 10 parameters were allowed to vary within prescribed ranges. The a-priori model set-up overpredicted streamflow. The parameter set testing identified in several adjustments, which improved performance, was as follows:

- A reduction in the CN values from those suggested in the model documentation, thereby reducing the generation of surface runoff
- An increase in the proportional root water withdrawal permitted from deeper portions of the overall rooting depth
- An increase in the amount of capillary rise permitted to supply ET across the entire catchment

Increasing the permitted capillary rise for the entire catchment would reduce the differentiation of the riparian area in having more ground water access than uplands, so although the maximum performance achieved in the calibration trials included applying the maximum capillary rise rate, 20% of ET demand, everywhere, this was reduced to 15% in the uplands for this exercise.

Scenario representation

The wetland and buffer clearing and restoration scenario was represented by changing the land-cover parameters applied to the wetland and buffer area HRUs, classified as “eucalyptus in wetland” or “eucalyptus in buffer”, for example, in the baseline set-up. Formerly “eucalyptus in wetland” HRUs were assigned wetland parameters as used elsewhere in the landscape, while buffer areas were assigned parameters for indigenous grassland. This was done by altering the vegetation parameter database entry linked to those types (i.e. an entry had been made for “eucalyptus in wetland”, for example), rather than inputting a new cover map, as is likely a more typical approach. The reason to not do this was because adding a new cover map requires redelineating all the HRUs, followed by redoing many manual adjustments of other parameters that had been made in the initial model as that would be erased during in the redelineation process.

Main challenges

- The **CN parameter** is critical as it controls infiltration versus runoff, and while much of the rest of the model uses physical property parameters, determining the value for this parameter appears to typically be a calibration exercise. Values that improved performance in this case were at the low end or below recommended values for similar cover types. This is a common challenge across the different models, although it applies to different particular parameters. A key concern is determining what the differences (absolute or relative) between CN values for different cover types should be. These differences can be maintained in the calibration process. Relationships here were based on the starting point of suggested values from literature tabulated in the model documentation (Arnold et al., 2012)
- Ideally, the calibration exercise in SWAT-CUP should have been set up to enforce higher capillary rise allowances for riparian areas than uplands. SWAT-CUP can be set to adjust all values for a given parameter proportionally, or with a step change, across HRU types to preserve relationships between them. Reducing capillary rise for the uplands after the calibration reduced performance and, as such, the reduction applied was limited. Different values for other parameters may improve performance for such a set-up compared to the ones used. Time did not permit further calibration trials.
- The high number of HRUs included in the set-up significantly slowed the model run time to close to 2 hours for a 33-year run, compared to a few minutes for less discretised models of catchments of a similar size. This also posed limitations to opening the HRU level output. SWAT saves the output for all HRUs for all timesteps in a single text file. For this model, the number of water balance output variables saved had to be reduced to achieve an output file size that could be opened and processed in R statistical software, which can open a text file of up to 10 GB without adding special tools.

Table C1: Numbers and sizes of model units and types included in models of the Mistley catchment using different modelling tools

Modelled units		**Number or average size (km^2) of units**				
		WRSM	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**
Catchment area (km^2): 316.6						
Subcatchments		8	8	8	73	8
	Average subcatchment size	*39.6*	*39.6*	*39.6*	*4.3*	*39.6*
HRUs				63	4947	
	Average HRU size			*5.03*	*0.06*	
Grid cells						87945
	Grid cell size					*0.0036*
Cover types		3	2	8	14	8
Soil types		1	1	(5)	5	5
Topographic zones		2	2	2	2	2
Aquifer types		1	1	1	1	2

Table C2: Soil types explicitly modelled for the Mistley catchment using different modelling tools

Soil type / topographic unit				**Area (km^2)**	***Percentage of catchment (excluding dam)***
Pitman tools	**ACRU**	**SWAT**	**MIKE-SHE**		
All				316.6	
	(area weighted property averaging across types in HRU)	Hutton, upper and midslope, western side, mudstone		98.7	*31%*
		Westleigh, downslope, southwest, sandstone		60.0	*19%*
		Glenrosa, upper elevation, east, shale		19.2	*6%*
		Avalon, mid- and downslope, east, shale		72.6	*23%*
		Oakleaf, valley bottom (riparian zone)		66.1	*21%*
Total			**316.6**		

Table C3: Land cover types explicitly modelled for the Mistley weir catchment using different modelling tools

Cover type				**Area (km²)**			***Percentage of catchment***		
Pitman tools	**ACRU**	**MIKE-SHE**	**SWAT**						
Grassland/pasture/other				107.9			*36.4%*		
	Grassland				53.5			*16.9%*	
			Sourveld			32.8			*10.4%*
			Range-brush			20.7			*6.5%*
	Agriculture				47.3			*14.9%*	
			Pasture			30.5			*9.6%*
			Cropland			6.3			*2.0%*
			Sugarcane			3.0			*0.9%*
			Residential			5.7			*1.8%*
			Residential – low density			1.8			*0.6%*
	Forest		Forest		4.7	4.7		*1.5%*	*1.5%*
Wetland*	Wetland		Wetland	6.1	8.6	8.6		*2.7%*	*2.7%*
Farm dam#	Farm dam		Farm dam	1.4	1.4	1.4		*0.4%*	*0.4%*
Tree plantation				201.2			*63.6%*		
	Eucalyptus		Eucalyptus		123.7	123.4		*39.1%*	*39.0%*
	Wattle		Wattle		52.8	52.8		*16.7%*	*16.7%*
	Pine		Pine		24.7	24.7		*7.8%*	*7.8%*
			Orange orchard			0.3			*0.1%*
Total					**316.6**				

***** *Wetland module included in WRSM only – considered as a water body rather than vegetation cover*

Farm dams represented as water bodies in models build with the Pitman tools (WRSM and SPATSIM) and as cover types in the others

Table C4: Soil and unsaturated zone profile parameter values used in models of the Mistley catchment

Land unit:	**All** (Area average)					**Oakleaf** **(Drainage line)**			**Avalon** **(midslope and low, east, shale)**			**Westleigh** **(midslope and low, southwest, sandstone, shale)**		**Glenrosa** **(upper, southeast, shale)**		**Hutton** **(upper and midslope, northwest, mudstone)**	
Tool:	**WRSM**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SWAT** **ACRU**	**MIKE-SHEs**	**SWAT** **ACRU**	**MIKE-SHEs**	**SWAT** **ACRU**	**MIKE-SHEs**
n layers in profile	*1*	*1*	*2*	*(2)*	*1*	*2*	***4***	*1*	*2*	***3***	*1*	*2*	*1*	*2*	*1*	*2*	*1*
Lateral flow out of profile	*Yes*	*Yes*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
Additional vadose/interflow layer below “soil" profile	*Yes*	*No*	*No**	*Yes***	*Yes*	*No**	*Yes***	*Yes*	*No**	*Yes***	*Yes*	*Yes***	*Yes*	*Yes***	*Yes*	*Yes***	*Yes*
Profile																	
Profile depth (thickness), m	2.00	0.60	2.24	2.24	2.24	2.16	2.16	2.16	2.00	2.00	2.00	3.50	3.50	0.80	0.80	2.00	2.00
Storage at saturation, mm	1000	300	1141	1141	1141	1054	1054	1054	821	821	821	1913	1913	446	446	1100	1100
Storage at field capacity, mm			733	733	733	420	420	420	709	709	709	1322	1322	285	285	690	690
Root zone																	
Average root depth, m	2.00	0.6	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	0.80	0.80	2.00	2.00
Storage at field capacity, mm			622	622	622	393	393	393	709	709	709	767	767	281	281	690	690
Layer 1																	
Layer bottom depth, mbgl			0.50	0.50	2.24	0.23	0.23	2.16	0.30	0.30	2.00	0.30	3.50	0.30	0.80	1.00	2.00
Layer thickness, m			0.50	0.50	2.24	0.23	0.23	2.16	0.30	0.30	2.00	0.30	3.50	0.30	0.80	1.00	2.00
Porosity			0.51	0.51	0.50	0.52	0.52	0.49	0.43	0.43	0.41	0.51	0.55	0.55	0.56	0.55	0.55
Field capacity			0.34	0.34	0.32	0.30	0.30	0.19	0.29	0.29	0.35	0.46	0.38	0.32	0.36	0.32	0.35
Wilting point			0.15	0.15	0.17	0.07	0.07	0.05	0.18	0.18	0.24	0.21	0.22	0.15	0.19	0.15	0.18
AWC			*0.18*	*0.18*	*0.15*	*0.23*	*0.23*	*0.15*	*0.11*	*0.11*	*0.12*	*0.25*	*0.16*	*0.17*	*0.17*	*0.17*	*0.17*
Ksat, mm/hr				35.1	4.9		3.6	2.5		30.0	7.2	110	7.2	17.9	3.6	17.9	3.6
Redistribution factor			0.56			0.45			0.65			0.70		0.50		0.50	

Land unit:	**All** (Area average)					**Oakleaf** **(Drainage line)**				**Avalon** **(midslope and low, east, shale)**			**Westleigh** **(midslope and low, southwest, sandstone, shale)**		**Glenrosa** **(upper, southeast, shale)**		**Hutton** **(upper and midslope, northwest, mudstone)**	
Tool:	**WRSM**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**		**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SWAT** **ACRU**	**MIKE-SHEs**	**SWAT** **ACRU**	**MIKE-SHEs**	**SWAT** **ACRU**	**MIKE-SHEs**
Layer 2 (and below)							**Layer 2**	**Layer 3**	**Layer 4**		**Layer 2**	**Layer 3**						
Layer bottom depth, mbgl			2.25	2.25		2.16	0.51	0.91	2.16	2.00	0.90	2.00	3.50		0.81		2.00	
Layer thickness, m			1.74	1.74		1.93	0.28	0.41	1.25	1.70	0.60	1.10	3.20		0.51		1.00	
Porosity			0.50	0.50		0.48	0.51	0.51	0.47	0.41	0.42	0.40	0.55		0.55		0.55	
Field capacity			0.33	0.33		0.18	0.21	0.20	0.17	0.37	0.34	0.38	0.37		0.37		0.37	
Wilting point			0.19	0.19		0.05	0.06	0.06	0.04	0.25	0.22	0.26	0.22		0.21		0.21	
AWC			*0.14*	*0.14*		*0.13*	*0.15*	*0.14*	*0.13*	*0.12*	*0.12*	*0.12*	*0.15*		*0.16*		*0.16*	
Ksat, mm/hr				40.2			55.0	36.0	36.0		30.0	30.0	100		16.8		16.8	
Redistribution factor			0.61			0.70				0.65			0.70		0.50		0.50	

mbgl = Metres below ground level; **AWC** = Available water holding capacity; **Ksat** = Saturated hydraulic conductivity; **blue text*:*** Conversions, area-weighted and/or depth-weighted averages

*ACRU4: Lateral routing from upland HRU baseflow store (below soil) to riparian HRU soil; **SWAT: Interflow from soil profile only, additional vadose layer only lags recharge to the aquifer store

Table C5: Additional soil and vadose zone layer (below soil profile) parameter values used in models of the Mistley catchment

Land unit:	**All** *(Area-weighted average)*					**Riparian (Oakleaf soil)**			**Upland** *(Area-weighted average)*		
Tool:	**WRSM**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**
Soil profile parameters											
Critical depth: wetness impacts surface runoff generation, m			0.25			0.25			0.25		
Storage in critical depth or top layer$^{\%}$ at saturation, mm			*127*	*256*$^{\%}$	*1 133*$^{\%}$	*130*	*119*$^{\%}$	*1 054*$^{\%}$	*126*	*303*$^{\%}$	*1 164*$^{\%}$
Rain threshold for surface runoff (min infiltration), mm per month	150	0									
Rain threshold for average infiltration rate, mm per month	920	920									
Distribution-average infiltration rate, mm per month	535	460									
Power, percolation rate equation	3	3									
Maximum percolation rate, mm per month	10	14.5									
Power, interflow rate equation	3	3									
Maximum interflow rate, mm per month	10	20									
Additional vadose or interflow layer below "soil" profile	***Yes***	*No*	*No**	***Yes***	***Yes***	*No**	***Yes***	***Yes***	*No**	***Yes***	***Yes***
Lateral interflow out of this layer	***Yes***			*No*	***Yes***		*No*	***Yes***		*No*	***Yes***
Layer bottom depth, mbgl	22.0				4.4			2.0			5.0
Layer thickness, m	20.0				4.4			2.0			5.0
Storage at saturation, mm	80				916			600			1000
Specific yield	0.004				0.22			0.30			0.20
Vertical Ksat, mm per hour											
Power, percolation rate equation	0.2				1			1			1
Delay in recharge, days	30			30			30			30	
Percolation time constant, days	0				4.4			2			5
Horizontal Ksat, mm per hour											
Power, interflow rate equation	n/a				1			1			1
Delay in interflow, days	0			n/a			n/a			n/a	
Interflow time constant, days	0				8.3			2			10

Ksat = Saturated hydraulic conductivity; ^{x}Maximum value allowed by tool; $^{\%}$With different layering and approaches to infiltration calculation the "top" layer water storage capacity has different relevance to surface runoff generation across models. *ACRU4: Lateral routing is included from upland HRU baseflow store, below soil, into riparian HRU soil; [#]MIKE-SHEs: No lateral flow in an unsaturated layer, but saturated zone profile defined in the model overlaps with the unsaturated zone profile, so saturation can be modelled in unsaturated zone depth range. A perched water table can develop in a layer resulting in interflow. Layer shown here is the highly fractured shallow rock material layer, bottom of the unsaturated profile and top of saturated zone profile, above the deeper, less fractured, regional aquifer layer.

Blue text*:* Values not directly input in model – area-weighted averages, unit conversions presented for comparison across models.

Table C6: Aquifer parameter values used in models of the Mistley catchment

Land unit:	**All** (Area-weighted average)						**Riparian**		**Upland** (Area average)	
Tool:	**WRSM**	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**		**ACRU**	**SWAT**	**ACRU**	**SWAT**
Storage parameters					Res 1	Res 2				
Bottom depth, mgbl	40	*	*	*	30	50				
Max thickness, m	40	*	*	*	30	20				
Depth to static water level (no flow), mgbl	20	10	0	0	28	50				
Specific yield, m3/(m*m^2)	0.004	0.004		0.003	0.001	0.001				
Specific storage, /m										
Max storage, mm	160	*	*	*	30	20				
Max storage available for outflow, mm	80	*	*	*	28	20				
Inactive storage (flow threshold), mm	80		0	2,000	2	0				
Flow rate parameters										
Transmissivity, m^2 per day	8.1	8.1								
Horizontal Ksat, mm per hour	8.44									
Vertical Ksat, mm per hour										
Fraction of store flow out per day			0.009				0.009		0.009	
Linear outflow constant, 1/days				0.2	7.7E-05	1.0E-05				
Linear outflow constant, days				5	13,000	100,000				
Power, GW-SW flow rate equation	-0.05			1	1	1				
Maximum regional ground water gradient	0.001	0.011								
Maximum discharge, mm per month	6.5									

Land unit:	**All** (Area-weighted average)						**Riparian**		**Upland** (Area average)	
Tool:	**WRSM**	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**		**ACRU**	**SWAT**	**ACRU**	**SWAT**
Capillary rise / ET from aquifer store										
Maximum fraction of PET met by aquifer				0.17				0.20		0.15
Maximum fraction of outflow diverted for **riparian area ET**	1	1			1	1				
Fraction of upland aquifer outflow routed to **riparian area soil**			1							

Ksat = Saturated hydraulic conductivity; * Tool does not include a limit on the total volume stored in the aquifer (i.e. depth x porosity);

Blue text*:* Values not directly input in model - area-weighted averages, unit conversions presented for comparison across models.

Table C7: Modelled streamflow for the Mistley catchment for two different scenarios using five different modelling tools

Statistic	**Modelled streamflow, October 1988 to September 2016, for different land cover scenarios: Full forestry, and wetland and buffer restoration**									
	WRSM		**SPATSIM**		**ACRU**		**SWAT**		**MIKE-SHEs**	
	WB	**FF**	**WB**	**FF**	**WB**	**FF**	**WB**	**FF**	**WB**	**FF**
Annual stream yield (mm^3)										
Mean	23.9	19.5	22.9	18.4	25.9	18.6	22.4	21.6	25.4	18.9
Standard deviation	18.3	15.4	15.0	13.7	23.0	20.4	12.8	12.0	24.6	19.1
CV	0.77	0.79	0.66	0.74	0.89	1.10	0.57	0.56	0.97	1.01
Minimum	2.3	1.7	4.7	2.3	1.7	0.9	7.3	7.2	1.0	1.0
Maximum	69.5	60.6	66.6	58.3	81.5	67.1	53.0	52.0	85.9	67.9
Monthly streamflow (mm^3)										
Mean	2.0	1.6	1.9	1.5	2.2	1.5	1.9	1.8	2.1	1.6
Standard devieation	2.6	2.2	2.3	2.1	3.2	2.8	2.2	2.1	3.6	2.7
CV	1.31	1.33	1.19	1.36	1.48	1.79	1.18	1.18	1.68	1.72
Minimum	0.00	0.00	0.08	0.02	0.08	0.03	0.00	0.00	0.02	0.01
5th percentile	0.06	0.00	0.22	0.06	0.13	0.08	0.04	0.04	0.05	0.05
50th percentile	1.2	1.0	1.2	0.9	1.1	0.6	1.1	1.0	0.6	0.5
95th percentile	7.0	5.6	5.7	5.2	8.9	6.4	6.2	5.6	9.2	6.5
Maximum	18.1	16.6	17.6	16.0	21.7	19.2	13.2	13.0	21.5	17.7
Daily streamflow (cm)										
Mean					0.82	0.59	0.71	0.68	0.81	0.60
Standard deviation					1.45	1.28	1.05	1.02	1.65	1.22
CV					1.77	2.17	1.48	1.49	2.05	2.04
Minimum					0.03	0.01	0.00	0.00	0.00	0.00
5th percentile					0.05	0.03	0.00	0.00	0.02	0.01
50th percentile					0.37	0.18	0.36	0.35	0.21	0.17
95th percentile					3.1	2.4	2.6	2.5	3.9	2.8
Maximum					27.9	23.9	26.9	26.8	22.0	16.7

ACRU4

Structure and parameterisation

- **Model units and routing:** The catchment was represented with the eight subcatchments described in Figure C1, each comprised of differing numbers of hydrological response units, representing areas of different land covers and either upland or riparian topographic positions. Because of the manual HRU set-up and adjustment in ACRU4, compared to automated and batched processes in ArcSWAT2012, an effort was made to reduce the number of HRUs by simplifying the land cover and soils representation as described below, resulting in 63 HRUs in the model.
- Surface and shallow subsurface flows ("quick" and "delayed stormflow", see section 2.4) from all HRUs are routed in parallel to river channel elements in their subcatchments. Aquifer ("baseflow store") outflow from upland HRUs were routed to the soils of the riparian HRU soils. Aquifer ("baseflow store") outflow from riparian HRUs were routed to channels. Routing between subcatchments is manually input and followed the pattern shown in Figure C1 above.
- **Land cover:** Because each HRU in the model is created, parameterised, linked and adjusted manually and individually in ACRU4, the number of land cover types explicitly represented was reduced from the 14 used in the SWAT model down to eight (Table C3). Cover types making up minor areas and those likely to have relatively similar parameter values were grouped together.
- Root depths from the SWAT model were applied, with area-weighted averaging for combined classes where relevant. Unlike SWAT, ACRU calculates canopy interception and uses a "crop coefficient" to calculate AET. Parameter values for these were based on values in the in-built "compoveg" database in ACRU4, as this included appropriate vegetation types. For plantations, "medium" age plantation classes in this database were selected to represent the mix of stages in the landscape.
- The plantation area mapped within the riparian zone that would be wetland if cleared of forestry was determined for each subcatchment. This area was represented with the special riparian HRU, which received upland "baseflow" water, while the remainder of the plantation area was represented with a separate uplandor "regular" HRU. Both were assigned the same vegetation parameters.
- **Soils:** To maintain a manageable number, HRUs were defined by land cover, upland vs. riparian zones, and subcatchments only, and not land cover-soil type combinations as done in SWAT. To preserve the spatial distribution of soil properties used in SWAT, soil properties for each ACRU HRU were calculated as area-weighted averages of the properties of the soil types overlapping with the particular vegetation and position type in a subcatchment. Given the number of units, a code was written to do this in R statistics software.
- ACRU4 uses different soil parameters to SWAT, and requires a two-layer soil profile. SWAT requires inputs of soil bulk density and texture inputs by layer, which the software then uses to internally calculate porosity, field capacity and wilting point soil moisture. These water retention values are needed as direct input in ACRU4, so their values were calculated from the SWAT input parameters using the same equations as SWAT applies internally (Neitsch et al., 2011). Thickness-weighted averaging of these values across the layers used in SWAT was used to get property values for two layers as needed in ACRU.
- The ACRU4 interface suggests that the soil profile should not exceed 2 m, with a suggested maximum of 0.5 m for the upper layer and 1.5 m for the lower layer. In SWAT, the soil profile could reach 3.5 m, and these same depths were input in ACRU. Despite the warning messages, the model ran successfully with these values. Unlike SWAT, the soil depth used in ACRU4 is cut to the input rooting depth for the vegetation, regardless of the depth specified in the soil profile. In this case study, these values were similar for the dominant vegetation types, so this was not a major departure.
- ACRU does not use soil conductivity as an input parameter. It uses a modified version of the SCS-CN method to calculate infiltration in a rain event and a "soil response fraction" parameter in calculating the rate of percolation between the two horizon layers and out of the lower layer.

  - The "critical stormflow depth", the depth of soil over which soil moisture is used to determine runoff versus infiltration, was initially input as 30 cm based on model documentation recommendations for wetter climates and deeper soils.
  - Values for the soil response fraction were selected based on the texture and conductivity values used in SWAT following guidance in the model documentation (Schulze, 1995).
- **Runoff lag:** Surface and shallow subsurface runoff calculated for a storm event is routed to the stream with a lag determined by the "stormflow response fraction" parameter, the fraction runoff reaching the stream each day. The initial input value used was 30%, the default value suggested for mid-range slopes and soil depths.
- **Geology and aquifer:** Aquifer ("baseflow") storage and outflow are calculated for each HRU individually using a conceptual outflow rate coefficient. Uniform aquifer properties were assigned in SWAT, so the same "baseflow" coefficient was assigned to all HRUs, using the default value (0.009) as a starting value for calibration (see below).
- Vegetation access to ground water or capillary rise was represented using special riparian zone HRUs in the model, which receive the "baseflow" outputs of upland HRUs as described.
- **River channel network:** River channel units were defined in each subcatchment associated with each riparian HRU. Channel transmission loss was not explicitly included as it cannot be calculated in the tool. Riparian HRUs are linked to a channel module and channel flow in excess of an input threshold is applied to the HRU surface, intended to represent overbank flooding. In this case, this mechanism could also be interpreted as representing riparian vegetation access of water in the hyporheic zone surrounding the channel and transmission losses.
- **Small farm dams:** As with SWAT, the small farm dams were represented as land cover rather than a water body in ACRU, given their relatively small size and likely importance to the modelling question. To include small farm dams in ACRU4, the dams in a subcatchment could be lumped to reduce the set-up intensity. However, the subcatchment area above and below dams, hence above and below the lumped model dam, would need to be estimated and HRUs set up for both parts, potentially almost doubling the HRU count.
- **Mvoti Vlei wetland:** The large Mvoti Vlei wetland area was represented with a riparian zone HRU, so that the area received the "baseflow" inputs of the upland areas of Subcatchment 6. Because the main channel feeds directly into the vlei and the vlei itself is almost unchanneled, the channel capacity threshold for the river associated with the riparian HRU was set at its minimum (0.02 cm), so that all incoming channel flow would be made to flow across the wetland. This was a more realistic set-up for this type of wetland (unchanneled valley bottom) than was possible in ArcSWAT.

Adjustments to improve calibration

Parameter value adjustments were manually set up and tested. Parameter values drawn directly from the SWAT model of the catchment (soil properties, root depth) were not adjusted.

The initial model set-up produced average flows that were much lower (by almost 30%) than the observed mean, with low flows (5th percentile and below) being too high, mid- to high-range flows being too low, except for the highest peaks. To improve fit, the following adjustments were trialed:

- **Canopy interception and crop coefficients:** Several different vegetation types listed in the in-built parameter database ("compoveg") were considered potentially appropriate for the types found in the catchment (e.g. different types of grassland and rangeland, different densities or preparation types of eucalyptus, etc. are available). To increase average flows by decreasing ET and improve fit, out of the relevant vegetation types, those with the lowest crop coefficients were selected. This improved performance. However, modelled flow remained more than 25% below the mean. Crop coefficients for all cover types were reduced to 85% of their database value, which brought the mean to within 21% of the observed flow. These values were found to provide good performance in the MIKE-SHE model (see below), so were not adjusted further to maintain consistency across the tools.

- **Critical soil depth for runoff production:** Decreasing the soil depth used in the runoff generation calculation from 30 cm to 25 cm was considered potentially reasonable given the intense storms the area can receive, and would increase the model's "stormflow" generation. Although it was assumed that the catchment does not often have large surface flow contributions, the "stormflow" amount also contributes to "interflow". The change increased medium and high flows. It brought the average within 16% of the average, and increased the NSE of log transformed daily flow, but also increased the highest peaks that were already too high, and so slightly decreased the untransformed NSE.
- **Decreasing soil drainage rates (response fraction):** Several trials of reducing the soil response fraction values were done (with and without the critical soil depth adjustment). This change holds more water in the soil, which can allow build-up of soil saturation in wet periods, creating more overland flow. Holding more water in the soil can also increase AET over time. Initial response fraction values were 0.5–0.6 for different types, given the generally loamy soils as parameterised in SWAT. Values were reduced to 0.35 and 0.25 only for the lower horizon, and then for both horizons. These changes increased higher flows and peaks, and improved the mean (within 14 to 18% of observed across the trials), but did not improve the median and lower flows much. Adjustments that improved the mean more also increased the already too high peaks more, reducing the NSE and R^2.

The soil parameter trials showed that other adjustment types are likely necessary to improve performance further: change improved one part of the hydrograph, while decreasing performance elsewhere. Given 63 HRUs that each required manual adjustment for every trial, there was not time for further testing. The trial in which the critical soil depth was decreased to 0.25 cm balanced an improvement in mean with the best R^2 and NSE of log-transformed flows of the trials completed, although untransformed NSE was in the middle, and was selected for use in scenario modelling. The deep soils and rooting depths used, compared to what the ACRU4 software suggests as a maximum, and the water retention values appeared to allow too much storage for ET over time. However, the same depths and water-holding capacities were deemed representative of the site and were applied in the SWAT model with better outcomes. This is likely because SWAT includes lateral outflow from soils (interflow), as well as percolation to ground water.

Scenario representation

To model the wetland and buffer area clearing and restoration scenario, the vegetation parameters in the riparian zone HRUs that had been values for eucalyptus plantation were changed to those used for wetlands. All other parameters and the overall structure of the model remained the same.

Main challenges

- **Finding commensurate values for parameters compared to the reference dataset, particularly more conceptual ones:** The full Penman-Monteith equation was used to calculate AET in SWAT, which requires quite different parameters to the crop factor values used in ACRU4. As a result, crop factors from ACRU's in-built database were selected, representing "typical use" of the tool, although not necessarily equivalence with the SWAT model. It appears that these were not equivalent, though, as they resulted in too much ET in the model. Similarly, it was not straightforward to select the more conceptual parameters like the critical soil response depth, initial abstraction, runoff response fraction or soil response fractions to be equivalent to what was used in the SWAT model, i.e. the CN, even more conceptual, and soil hydraulic conductivity, more physical.
- **Soil depth, root depth and interflow representation:** In an effort to maintain equivalence with the catchment properties available and the inputs in the SWAT model, the soil and root depths used were deeper than recommended for ACRU. Because ACRU does not represent interflow directly from the soil profile, so that saturation excess overland flow or percolation from the soil profile are needed for the lateral flow of soil-stored water to occur in ACRU, cutting off the modelled soil depth somewhat artificially, assuming the depths used were realistic for the site's soils, may actually be a more realistic representation of processes for this case.

- **Model interface:** A high number of steps are required to establish structure and connectivity, make and test calibration adjustments, export water balance components and process at a catchment scale. Very few actions can be "batched".

MIKE-SHE, SIMPLER OPTIONS

Structure and parameterisation

- **Model units and routing:** Calculations of interception, infiltration, ET, and soil storage and percolation are done at the grid cell scale. A grid cell size of 60 m was applied, a multiple of the input cover and topography grid resolutions, coarsened given the catchment size. Surface flow routing, interflow, and aquifer recharge and outflow are calculated for separately input zones within each subcatchment. The eight subcatchments described in Figure C1 were used, with upland and riparian zones in each used for routing, so that surface and interflow generated in uplands are routed through the riparian area before reaching the channel network. The subcatchments were also used as the zones for climate inputs to maintain consistency across the other models.
- **Land cover**: The input land cover map was simplified to the same eight classes used in the ACRU4 model (Table C3). Unlike ACRU, but similar to SWAT, areas of different cover types are internally extracted from map input, and the parameters for a vegetation type can be specified at the vegetation type-level, rather than separately setting up each model unit of a type. However, MIKE-SHE does not have an inbuilt parameter database, unlike SWAT and ACRU, and all values are input manually, which increases set-up effort when many types are used.
- Root depth values from SWAT were used with area weighting when classes had been lumped. Unlike SWAT, but similar to ACRU, MIKE-SHEs calculates canopy interception and uses a "crop coefficient" to calculate AET. Parameter values for these were kept consistent with values used in ACRU4 (as described above), which required an adjustment for the evaporative demand-type (reference PET vs A-pan). MIKE-SHEs algorithms use LAI, but only to calculate canopy interception. The LAI values from SWAT were used, but the canopy interception coefficient (mm per unit leaf area) was selected so that the canopy interception would match that of ACRU.
- **Soils:** The soil-type map used in SWAT could be input and used directly in MIKE-SHE.
- MIKE-SHEs algorithms (the "two-layer" method (DHI, 2017)) require soil porosity, field capacity and wilting point, like ACRU, and conductivity, like SWAT. The profile is modelled with uniform properties over the depth, although storage and movement calculations are done for two layers: the root zone and the vadose zone between the rooting depth and the "saturated zone" (aquifer). The water retention values were calculated for each SWAT soil layer using SWAT's own pedotransfer functions, as described for ACRU above, and layer thickness-weighted averaging to get profile average values.
- Layer thickness-weighted averaging of SWAT's soil conductivity inputs was used to get starting values. Understanding this simplification may not be realistic given the impacts that contrasts in conductivities between layers would have. MIKE-SHEs uses the conductivity values to calculate infiltration into the soil, while SWAT used the SCS-CN to calculate this. SWAT uses soil conductivity to calculate vertical percolation and lateral interflow.
- MIKE-SHEs represents interflow with a separate **"interflow reservoir"** fed by percolation out of the soil profile, rather than modelling lateral flow directly out of the soil storage. It is governed by linear reservoir equations with separate rate constants for vertical percolation and lateral interflow. For the Mistley catchment model, two interflow reservoirs in sequence were used in each subcatchment: upland flowing into riparian flowing into the river, with percolation to ground water possible en route. Parameterising these was largely a calibration exercise, but it was assumed flows out of the riparian zone reservoir would be much faster.
- **Geology and aquifers:** As with the other models, only one type of "baseflow reservoir" set of parameter values was used in the model to represent aquifer storage and outflow at the subcatchment scale. Thickness and specific yield values were drawn from the Groundwater Resource Assessment II, but determining the linear reservoir parameters was largely a calibration exercise.

- Vegetation access to ground water or capillary rise is only considered for cells overlying the lowest interflow zone. These can access a portion of the aquifer (“baseflow reservoir”) outflow to meet an ET deficit, representing a shallower ground water table in this part of the landscape. It was assumed that there was potential for all the calculated aquifer output to be accessed for ET in this zone.
- **River channel network:** Given the lack of local channel data, a full hydraulic model was not applied, although possible in the tool, and channels were simple routing elements by subcatchment with no transmission losses.
- **Small farm dams:** As described and justified for the SWAT and ACRU models, the small farm dams were represented only using the land cover parameters, rather than setting them up as water storage bodies. In MIKE-SHE, including reservoirs as water bodies requires that they be on the model channel network and have detailed bathymetry.
- **Mvoti Vlei wetland:** Because the detailed hydraulic modelling was not included, the Mvoti Vlei area could not receive overflow from the main channel in the simulation. It was differentiated through the soils and vegetation parameters. Being the most downslope overland flow zone within its incremental subcatchment, it received overland flow from surrounding hillslopes, as was the case in the SWAT model. Unlike SWAT it was not represented as a water body, but was assigned high detention storage of overland flow. As in other models, the area was allowed access to ground water to meet ET deficits.

Adjustments to improve calibration

As with the ACRU model, the initial model set-up, which used the same vegetation parameters and similar soil parameters to ACRU, had low average streamflow compared to the observed flow. To reduce ET and increase average streamflow, the crop coefficients were reduced to 0.85 of their initial values, which brought the average flow within 15% of the observed flow. Without a physical basis for justification, further adjustment of these values was avoided.

The AutoCal tool in MIKE-SHE was used to explore parameter value ranges for the interflow and aquifer (“baseflow”) linear reservoir parameters, as well as the soil hydraulic conductivity values, using a set of 300 runs to be roughly equivalent to the level of effort applied for the SWAT model. Although soil conductivity values were input in the SWAT model, their use to calculate infiltration in MIKE-SHEs and not in SWAT means the parameter has a notably different meaning. Relationships between different soil types were preserved and value options were constrained by literature values by texture types reported in García-Gutiérrez et al. (2018). Reducing soil conductivity notably improved performance. The exercise improved the overall fit (brought daily flow NSE into positive values). However, overall flow remained too low. This may have been linked to differing soil storage and outflow representation in SWAT.

Scenario representation

To model the wetland and buffer area clearing and restoration scenario, an altered land cover map was simply input. Parameterisations of each vegetation type remained constant, but the area and spatial distribution of each type changed.

Main challenges

- **Finding commensurate values for parameters compared to the reference dataset:** As described for ACRU, SWAT required quite different vegetation parameters to the crop factor values used in MIKE-SHEs. As a result, crop factors from ACRU’s in-built database were selected, representing “typical use” of the tool, although not necessarily equivalence to the SWAT model. It appears that these were not equivalent, though, as they resulted in too much ET in the model, although this may also have been linked to differences in soils’ representation. Soil hydraulic conductivity (K_{sat}) was used in different ways in SWAT and MIKE-SHEs, so these values were altered in calibration.

SPATSIM-PITMAN

Several important parameters in the Pitman model are conceptual, so that values could not be directly calculated from the available estimates of local vegetation, soil and geology property values, although the parameter values are linked to these (Kapangaziwiri, 2007). Initial values were selected based on documented experience with the tool in similar settings, followed by a calibration procedure.

Structure and parameterisation

- **Model units and routing**: The catchment was represented with the same eight subcatchments as in the other models. As most parameters were held constant across subcatchments, the primary purpose was to include spatial climate variability.

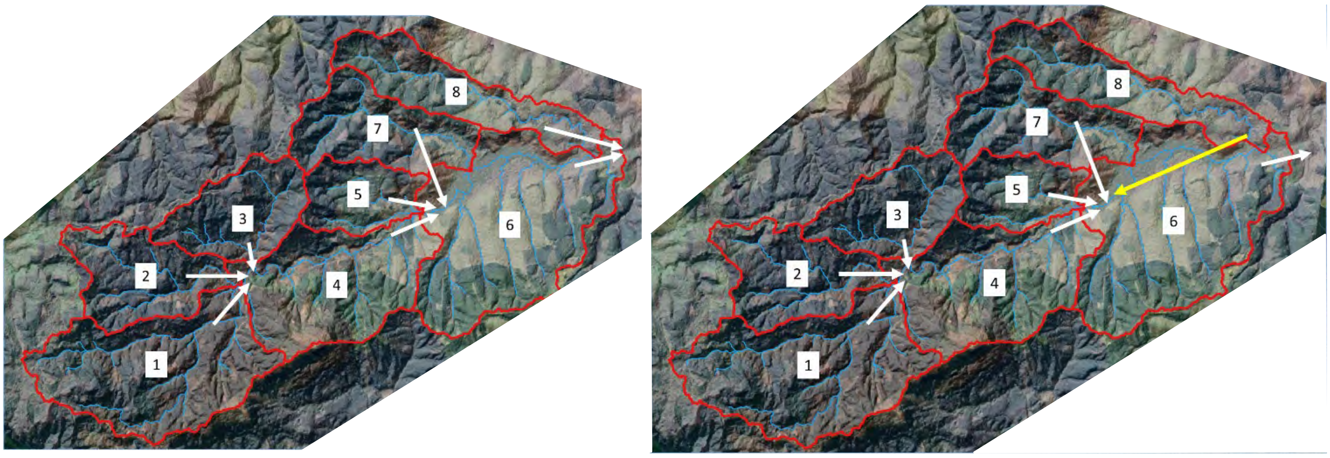


Figure C2: Subcatchment routing in for the Mistley catchment as implemented in different models: (a) routing for models built with ACRU4, MIKE-SHEs and WRSM; (b) routing for the model built in SPATSIM, Subcatchment 8 routed through Subcatchment 6 rather than directly to the catchment's outlet.

- Because the SPATSIM model's channel network is tied to subcatchments, rather than being nodular or separately specified, the routing differed to other models, as shown in Figure C2. In SPATSIM, the tributary Subcatchment 8 had to be routed into the upstream end of the main channel in Subcatchment 6. In other tools, Subcatchment 8 and Subcatchment 6 could be routed to the catchment outlet, a more accurate representation of the drainage network. Routing Subcatchment 8 through Subcatchment 6 results in more flow in the channel of Subcatchment 6. If channel transmission loss was substantial, this could cause differences in the catchment-scale output. This was considered unlikely to be important in this case. However, it may have contributed to the poor model fits achieved when adding the Mvoti wetland using the wetland module (see below).
- **Land cover:** Two land cover types were explicitly represented: lumped indigenous and agricultural cover types (grassland, rangeland, croplands, etc.), represented through the subcatchment ET parameters (canopy interception, ET decline coefficient) and commercial forestry plantations represented by specifying fractions of the subcatchment area that is treed and the ratio of its ET rate vs. the other vegetation. There is no way to directly specify where in the catchment the forestry is located, such as in the riparian zone. However, this was taken into consideration in the ET ratio.
- Parameters for the non-forestry vegetation were assumed to be the same across all the subcatchments. Differences in the distributions of types across the subcatchments could potentially have been considered in the parameterisation. However, this variation and its potential impacts on the model outcomes were considered small in this case. Determining appropriate differences in values across subcatchments, including a calibration process, would not have been straightforward.
- **Soils:** Soils were represented with a single, lumped soil storage unit per subcatchment with the parameters held constant across subcatchments to facilitate calibration.

- **Geology and aquifer:** Ground water recharge, storage and flow are represented at the subcatchment scale, and parameter values were assumed to be constant over the eight subcatchments. Delays in recharge from percolation through material not represented in the "soil" moisture store are implicitly represented in the aquifer parameterisation.
- Capillary rise or vegetation access to ground water is only considered for a user-specified riparian zone area in the subcatchment, assumed to have a shallow ground water table. Any ET demand deficit for this area, after drawing from the soil, can be met by the aquifer store. This area is not assigned a distinct vegetation type of its own: it has the same ET parameters, including the proportion of alien vegetation, as the rest of the subcatchment.
- **River channel network:** Each subcatchment automatically has a channel that collects and routes flows from upstream catchments. When modelled ground water levels are low, channel transmission losses will be calculated.
- **Small farm dams:** Small farm dams are simpler to include as water bodies in SPATSIM (and WRSM) models than for the other tools used, and SPATSIM does not have an alternative means of representing them (i.e. open water as a "land cover"). They are represented as a lumped reservoir fed by a user-specified proportion of the subcatchment area. The mapped surface area of dams in each subcatchment was used with the suggested generic area-volume parameters in ACRU documentation (Schulze, 1995) to estimate volume (surface area m^2) = 7.2 * (volume $m^3)^{0.8}$. Total volume was estimated at 2.3 mm^3. Proportions of each subcatchment contributing its dams was estimated by delineating subcatchments for a few larger dams and additional visual analysis.
- **Mvoti Vlei wetland:** The SPATSIM wetland module represents wetlands as water bodies located on or next to the channel. The wetland module was set up for Subcatchment 6, using the areas and volumes estimated for SWAT (see above). Its inclusion notably decreased performance, as discussed below, perhaps because it also accessed flow from Subcatchment 8, and it was removed from the final model version applied.

Adjustments to improve calibration

Potential parameter adjustments were tested both using the uncertainty module of SPATSIM, as well as by manual adjustment trials. In the uncertainty module, 1 000 parameter sets were tested, varying the soil infiltration rate distribution parameters (Zmin, Zmax, Zave), maximum soil storage (ST), maximum interflow rate (FT) and maximum ground water recharge parameters.

- In the initial model set-up, regional parameters were applied from previous national studies. When the wetland module was added with the values described above, it almost halved the predicted outflow. Because of this large impact, two parameter testing optimisation exercises were done, with and without the wetland module included. Even with the optimisation effort, the model structure with the wetland module included still had roughly half the mean outflow and half the NSE value (0.27 vs. 0.56). The area and volume, and outflow parameterisation of the wetland module was based on rough estimation. These results suggest that it needs further evaluation against the representation of wetlands in SPATSIM-Pitman. The impact of adding the water body-like wetland module in SWAT was much smaller, likely because of the more limited flow directed to it. The wetland module in SPATSIM also intercepted additional flow compared to the actual vlei because of the subcatchment routing. The model SPATSIM structure without the wetland module would have implicitly accounted for the wetland's processes and effects on flow through the values of the catchment-scale parameters. A decision was made to use the version without the wetland module given limited time to explore and improve it. In other models, wetlands were represented through vegetation and soil properties, as well as some greater access to subsurface water sources and routed surface flows in some cases. In SPATSIM, the proportion of the subcatchment specified as riparian would partially account for wetland processes without the additional module.
- Notable value adjustments found to improve performance were a reduction in the minimum infiltration (Zmin), or the threshold of monthly rainfall, which can produce surface runoff, an increase in soil storage capacity (ST) and a reduction in the maximum interflow rate (FT) versus starting values.

These served to increase surface runoff, which had been almost negligible in the initial set-up, but also to increase ET withdrawal in dry periods, given the storage and slower interflow.

Scenario representation

The wetland and buffer area clearing scenario was represented by decreasing the proportion of each subcatchment afforested in the model based on the cover mapping. There was no way to explicitly represent the fact that this afforested area had been in the riparian zone, particularly, except for through a change in the parameter controlling how much more ET the afforested portion of the catchment is assumed to have versus the other vegetation. When a portion of the plantation area is riparian, the difference in ET was assumed to be higher.

Main challenges

- The representation of plantation coverage in a subcatchment is not spatially explicit, which poses a challenge for reliably representing a change in riparian vegetation cover specifically.
- The wetland module parameterisation for the Mvoti Vlei area, based on available information, appeared to inappropriately represent processes. There was insufficient time for further exploration.

WRSM-PITMAN

Several important parameters in the Pitman model are conceptual, so that values could not be directly calculated from the available estimates of local vegetation, soil, and geology property values, although the parameter values are linked to these (Kapangaziwiri, 2007). With the exception of the ground water module, which differs across the tools, parameter values from the calibrated SPATSIM-Pitman model (see SPATSIM below) were used as starting values for calibration. SPATSIM includes automated batch testing of parameter sets drawn from user-input distributions. Values from the model of the U40A quaternary catchment calibrated for the WR2012 study (Bailey and Pitman, 2015) were also consulted for reference. However, this model was calibrated with different climate input.

Structure and parameterisation

- **Model units and routing**: The catchment was split up into the same eight subcatchments used in the other models, each represented with “runoff modules” having linked, afforestation and alien vegetation “child modules” to represent the upland and riparian plantation areas (described below). These were linked by channel modules to accumulate flow contributions at the point of the Mistley weir. Reservoir modules representing small farm dams were linked in this network, receiving specified fractions of runoff outflow.
- **Land cover:** Three land cover types were explicitly represented: lumped indigenous and agricultural cover types (grassland, rangeland, croplands, etc.), represented through the runoff module ET parameters (canopy interception, ET decline coefficient); upland commercial forestry plantations, represented using afforestation modules linked to each runoff module; and riparian commercial forestry plantations, represented using alien vegetation modules linked to each runoff module.
- In the afforestation modules, the percentages of pine, wattle and eucalyptus mapped in the upland plantation area of each subcatchment were input. The riparian plantation areas were represented with alien vegetation modules instead because these allow the specification of proportion riparian (100% in this case), although this just serves to increase the overall runoff reduction applied rather than targeting ground water access.

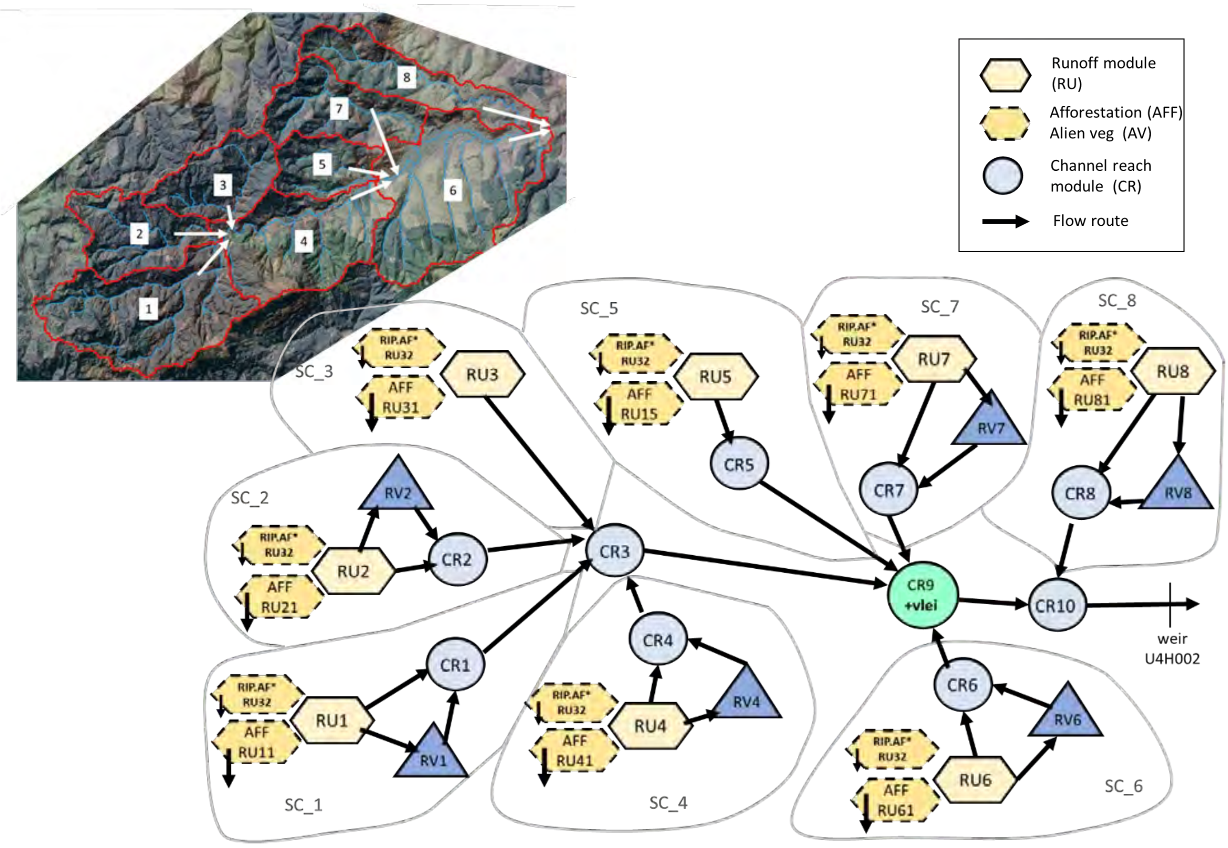


Figure C3: Model structure routing diagram for the Mistley catchment model built with WRSM-Pitman

- Parameters for the non-forestry vegetation were assumed to be the same across all the subcatchments. Differences in the distributions of types across the subcatchments could potentially have been considered in the parameterisation. However, this variation and its potential impacts on the model outcomes were considered small in this case. Determining appropriate differences in values across subcatchments, including a calibration process, would not have been straightforward.
- **Soils:** Soils were represented with a single, lumped soil storage unit per subcatchment with the parameters held constant across subcatchments to facilitate calibration. Initial values were taken from the SPATSIM model calibration.
- **Geology and aquifer:** Ground water recharge, storage and flow are represented at the subcatchment scale, and parameter values were assumed to be constant over the eight subcatchments. A separate vadose zone ("unsaturated zone") model unit between the soil and aquifer storages serves to lag recharge.
- Initial values of aquifer depth and thickness were drawn from GRA II. Storativity, transmissivity and the depth to static water level (outflow threshold) from SPATSIM were used to derive the related WRSM inputs (i.e. aquifer storage when at the static water level). The maximum ground water outflow rate was set using the maximum June (lowest flow month) flow in the weir record, 6.5 mm.
- Capillary rise or vegetation access to ground water is only considered for a user-specified riparian zone area in the subcatchment, assumed to have a shallow ground water table. This area was assumed to be the valley bottom topographic unit. Any ET demand deficit for this area, after drawing from the soil, can be met by the aquifer store. It is not assumed to be a different vegetation type to the rest of the runoff module. However, the algorithm for this zone uses separately specified A-pan coefficients, while the broader runoff module uses S-pan.
- **River channel network:** Channel reach modules were simply used to aggregate flows, and no lags were introduced, given the small catchment and monthly timestep. No channel transmission losses were included for the channel modules. Within the runoff modules, a two-way exchange between an implicit subcatchment channel and the aquifer is calculated based on comparative levels.

- **Small farm dams:** Small farm dams are simpler to include as water bodies in WRSM (and SPATSIM) models than for the other tools used. WRSM does not have an alternative means of representing them (i.e. open water as a "land cover"). They were represented as lumped reservoirs for each subcatchment, fed by a user-specified proportion of the runoff leaving linked runoff modules. These were parameterised as described for SPATSIM above.
- **Mvoti Vlei wetland:** Like SPATSIM, the WRSM wetland module represents wetlands as water bodies located on or next to the channel, although the wetland is associated with a channel module rather than located inside a "run-off module". A wetland module was added to the channel module receiving flows from all subcatchments except Subcatchment 8. The areas and volumes were estimated for SWAT (see above).

Adjustments to improve calibration

Parameter adjustment trials had to be done manually. As mentioned above, many initial parameter values were found in the SPATSIM calibration process, which used an automated batch-run facility (see SPATSIM). However, the model using the initial parameters used had poor performance, overpredicting mean flow by 74%. Improvements were made by increasing water entering and being stored in the soil to allow more ET withdrawal over time:

- Increasing the minimum infiltration (Zmin) from 0 to 150 mm, which is in the range suggested for wet, highly vegetated areas.
- Increasing the soil moisture storage capacity (ST) from 300 to 1 000 mm, which is in line with the soil profile storage at saturation for the other tools. Values of up to 1 500 mm were tested.
- Increasing the soil moisture storage required for interflow to be initiated from 0 to 100 mm.
- Decreasing the maximum monthly interflow rate from 20 to 10 mm.
- Doubling the vadose zone storage capacity from 40 mm, initially estimated from the GRA II, listed "normal" depth to ground water and the weathered material specific yield, to 80 mm. Specific yield is often higher for shallower material, supporting the increase.

These changes were the result of testing value adjustments in larger and smaller increments (generally half and twice the changes selected), alone and in combination. This was a relatively laborious process, but fortunately the model runs very quickly. The final model had a mean within 12% of the observed flow and an NSE of 0.23. Further improvements are likely possible. To compare with SPATSIM, a trial without the wetland module was done and was found to increase mean flow by 5%, but deceased other fit statistics, so was not used further.

Scenario representation

The wetland and buffer area clearing scenario was represented by removing the riparian alien vegetation modules from the model. These operate as subsets of the subcatchment area specified for the runoff modules to which they are linked, so no areas need to be updated.

Main challenges

- Conceptual parameters and no automated batch run facility to assist the calibration process were applied. WR2012-calibrated values and previous studies for an area are helpful, but are relevant to the scale of the models built.
  - Workaround: SPATSIM was used for this here. However, the model structures differ, so values are not expected to be identical.
- Representation of "riparian" alien vegetation using the "proportion riparian" input in the WRSM alien vegetation module does not mean that proportionally more water can be drawn from the aquifer to meet the ET demand.

C2: UPPER BERG RIVER CATCHMENT (PORTION OF G10A) WESTERN CAPE: STEEP ROCKY CATCHMENT, INVASIVE ALIEN

- **Catchment description and modelling goals** are given in the main report, section 5.4.1.
- **Model units and main parameter values** used across the different models are given in tables C8 to C14 below.
- **Performance of the models compared to observed streamflow** is described in the main report, section 5.4.3.
- **Model outputs, including water balances**, are compared and discussed in the main report, section 5.4.3. A summary of the streamflow output for each tool for each scenario is given in Table C15.

The text sections describe the different model structures, summarise the rationale for structure and parameter decisions, and highlight the main challenges encountered. Approaches common to all tools and the set-up of the pre-existing model, which was used as a reference, are described first, followed by structure and parameter value tables, and by descriptions of the models built using the other tools. At the time of writing, the MIKE-SHEs model (MIKE-SHE using simpler algorithm options) had not been calibrated. The structure is described, but results are not presented.

GENERAL APPROACHES COMMON ACROSS TOOLS

- The pre-existing model of the catchment built in MIKE-SHE, using the tool's complex algorithm options (Rebelo and Holden, in prep), was the reference point for building models using the other tools.
- Calibration was done by comparing model streamflow output for the 41.05 km^2 catchment area of DWS Weir G1H076 to the weir flow data for March 2008 to August 2018 to inform adjustments.
- For scenario comparisons, parameters calibrated for the weir subcatchment were extended to the 73.25 km^2 area feeding the Berg River Dam. Models were run using climate data for 2004 to 2018, and outputs were compared for the 2007 to 2018 water years to allow a three-year model warm-up period.
- **Spatial rainfall distribution:** The rainfall distribution across this mountainous area was represented by subdividing the catchment into spatial units that could be assigned different rainfall input time-series. The level at which climate data can be assigned and the practicality of subdivision varies across modelling tools (discussed in the main report, section 5.5.2). For this case study:
  - In the **MIKE-SHE** models, each grid cell received different rainfall inputs.
  - In the other models, rainfall input was assigned by subcatchment. Three subcatchments were delineated for use across all tools (Figure C4). They also informed the location of the weir used for model performance assessment and by the rainfall distribution. Rainfall series for subcatchments were spatial averages from surfaces used in MIKE-SHE.
- **Highly fractured rock layer:** See detailed discussion in section 5.4.2. The catchment is conceived as having a highly fractured rock layer below the relatively thin soils and above the water table of the regional bedrock aquifer(s). Fracture density and hydraulic conductivity in TMG rock are known to decrease with depth (Xu et al., 2009). More fractured layers and tallus nearer the surface support interflow. Such a layer was considered in all models, although represented in different ways:
  - In the **WRSM and SPATSIM-Pitman** models, this layer was implicitly considered in the "soil" storage unit, which produces interflow, and in WRSM's vadose zone/percolation store.
  - In the **ACRU** and **SWAT** models, a layer with properties representing this highly fractured rock was included as the lower layer in the "soil" profile.
  - In the **complex MIKE-SHE** model, a layer with estimated fractured rock properties was included in both the unsaturated zone material profile, as the bottom layer, and the saturated zone material profile, as the top layer. These profiles purposefully overlap to allow modelled water tables to rise up into the depth range covered by the unsaturated zone.
  - In the **simpler MIKE-SHE** model, it was included specifically as an "interflow reservoir", hence was not included in the soil profile.

- **Riparian zone water access:** Vegetation in areas delineated as valley bottom topographic units was assumed to have greater access to subsurface water for ET than in the uplands. This is supported by the presence of riparian wetlands and forest in these areas. This was represented in all the models in different ways. The same map of riparian versus upland area was used to delineate relevant units or area parameters as needed:
  - In the **complex MIKE-SHE** model, topography is explicitly included in routing surface and subsurface flows, such that modelled water tables are shallower and soils wetter at low points in the topography. Depending on material parameters, this may reach the root zone.
  - In the **WRSM, SPATSIM** and **MIKE-SHEs** models, the valley bottom area within subcatchments were given access to subcatchment aquifer storage to meet ET demands not met by soil storage.
  - In the **ACRU4** model, aquifer outflow from upland HRUs was routed to the lower soil layer of riparian HRUs. Associated river channel overflow can add water to the surface.
  - In the **SWAT** model, valley bottom HRUs were given greater access to subcatchment aquifer storage to meet ET demand than upland HRUs. This is input as a maximum proportion of the ET demand that can be met by the aquifer, with a maximum of 20%.
- **Modelling flow into a large dam – the reservoir edge as the catchment "outlet":** The intention was to model flow into the Berg River Dam, without the need to model flow through the reservoir itself. The catchment area was still delineated to the dam wall outlet. Delineating the catchment area to an upstream "inflow" point on the main river to exclude the reservoir surface area would exclude flanking hillslopes that contribute flow along the sides of the reservoir. To only model inflow from the contributing catchment feeding into the dam, the reservoir itself (5.1 km^2 water surface area, 7% of the catchment area to the dam wall) needed to be excluded. This needed to be done in different ways in the different tools:
  - In the **WRSM, SPATSIM** and **ACRU4** models, unit areas are directly entered by the user, so the surface area of the dam could simply be excluded from the modelled catchment area.
  - In **ArcSWAT2012** and **MIKE-SHE**, the modelled catchment area and sub-units are delineated in a GIS interface based on topography from the input DEM. The dam water surface area is necessarily part of the model catchment area as a result. The dam area was therefore parameterised to effectively exclude it from contributing to the modelled water balance:
    - In MIKE-SHE, it was set up to receive no rain and to be impervious, so that surface runoff reach flows directly to the channel network.
    - In SWAT, rainfall is assigned by subcatchment, but runoff is not routed between HRUs, so the dam HRU was parameterised so that all rainfall infiltrated and percolated to a deep aquifer unit that was disconnected from the streamflow.
  - An alternative to these approaches, which was not tried here, would have been to include the dam using the tools reservoir modules. However:
    - In SWAT2012, the reservoir module does not appear to handle large surface areas or remove the reservoir surface area entered in the reservoir module from the contributing land area, as delineated from the DEM.
    - In MIKE-SHE, to account for the open water surface area in the model, and exclude this from the contributing catchment land surface, detailed bathymetry of the dam would need to be input.
- **Soil property variation:** Soil properties were assumed to vary with topographic position. Although vegetation cover can influence soil properties, this impact was considered to be secondary in this setting, given the sandy soils and steep terrain. As such, soil properties assigned to topographically defined units were held constant across the models of different land cover scenarios, even when the land cover in an area was changed.

STARTING REFERENCE MODEL: MIKE-SHE COMPLEX, FULLY DISTRIBUTED OPTIONS

The more complex MIKE-SHE model of the Upper Berg catchment was built for the Socio-economic Benefits of Ecological Infrastructure (SEBEI) project to explore the impacts of clearing invasive alien vegetation on water resources. A more detailed account of the model development can be found in reports accessed from the project website: http://www.acdi.uct.ac.za/socio-economic-benefits-ecological-infrastructure-sebei.

Structure and parameterisation

- **Model units and routing:** A 60 m cell size was used for the model's computational grid. The resolution was selected to be a multiple of the cell size of the input topography data (12 m ALOS-PALSAR DEM) to balance the resolutions of other input data and account for the computational burden. Flows are routed between grid cells based on calculated surface and subsurface water heights.
- **Land cover:** Land cover was mapped using remote sensing for the SEBEI project (Holden et al., 2021). Vegetation parameters for the 18 cover types identified were drawn from literature and the "compoveg" database of vegetation parameters that accompanies the ACRU modelling tool (Clark et al., 2012; Schulze, 1995).
- **Soils:** Soil properties were sampled at the site across a variety of topographic positions as part of the SEBEI project. Properties were averaged across mapped topographic units for input into the model for the upper layers of the unsaturated zone profile.
- **Geology and aquifers:** Properties of the underlying geology and aquifers reported in literature on the TMG region (Xu et al., 2009) were used to select initial parameters for the saturated zone profile.
- **River channel network:** Field sampling of channel dimensions was used to inform the channel cross-sections applied in the hydraulic model. The channel network exchanges surface and subsurface flows back and forth with neighbouring grid cells based on explicitly calculated surface and ground water table heights.

Adjustments to improve calibration

Multiple structural options and parameter value adjustments were manually set up and sequentially tested, evaluating performance against the observed flow data and the impacts on processes contributing to the water balance.

Key trials and findings in the process were as follows:

- Given the level of information about the subsurface properties, several configurations of the saturated zone were attempted with different levels of complexity. The best performance was achieved with two layers, a highly conductive upper layer and a much less conductive lower layer, representing the tallus and the deeper fractured bedrock aquifer, respectively.
- Despite obtaining estimates for soil properties by topographic zone, it was found that this made little difference to the outcomes compared to applying a single soil property set over the whole catchment. The soil property variability was less important than topographic and climate gradients over this steep catchment.

Scenario representation

The land cover scenarios were modelled by inputting different land cover maps. Parameterisations of each vegetation type remained constant, but the area and spatial distribution of each type changed. Although vegetation cover can influence soil properties, this impact was considered to be secondary in this setting, given the sandy soils and steep terrain. Soil properties were not altered between scenarios.

Main challenges

- **Subsurface layer parameterisation (soil, vadose zone, aquifer material properties):** Property values taken directly from field sampling and literature as model input parameters did not provide reasonable model results. Literature and field values informed spatial and depth or layering patterns of input parameter values. However, magnitudes needed to be adjusted.

Table C8: Numbers and sizes of model units and types included in models of the Upper Berg River catchment using different modelling tools

Modelled units		**Number or average size (km^2) of units**					
		WRSM	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**
Catchment area (km^2): 73.25							
Subcatchments		3	3	3	3	3	N/A
	Average subcat size	24.42	24.42	24.42	24.42	24.42	
HRUs				21	107		
	Average HRU size			3.49	0.68		
Grid cells						20,348	20,348
	Grid cell size					0.0036	0.0036
Cover types		3-4	3-4	6	10	18	18
Soil types		1	1	2	5	5	1
Topographic zones		2	2	2	5	5	5
Aquifer types		1	1	2	1	2	2

Table C9: Soil types explicitly modelled for the Upper Berg River catchment using different modelling tools

Soil type / topographic unit				**Area (km^2)**	***Percentage of catchment (excluding dam)***
Pitman tools	**ACRU**	**SWAT**	**MIKE-SHE**		
All				73.25	
	Riparian	Riparian		6.20	*8%*
	Upland			67.05	*92%*
		Lowslope		26.41	*36%*
		Upslope		35.22	*48%*
		Cliff		2.32	*3%*
		Peak		3.10	*4%*
Total				**73.25**	

Table C10: Land cover types explicitly modelled for the Upper Berg River catchment using different modelling tools

Cover type				Area (km^2)	*Percentage of catchment (excluding dam)*
Pitman tools	**ACRU**	**SWAT**	**MIKE-SHE**		
Impervious	Impervious (disjunct)			2.87	*3.9%*
		Rock	Rock	2.24	*3.1%*
		Bare ground	Bare ground	0.63	*0.9%*
		Burnt area	Burnt area	0.002	
		Urban	Urban	0.03	*0.04%*
Fynbos				63.46	
	Fynbos low density	Fynbos low density	Fynbos low density	33.78	*46.1%*
	Fynbos high density	Fynbos high density	Fynbos high density	28.31	*38.7%*
	Indigenous forest	Indigenous forest	Indigenous forest	0.51	*0.7%*
	Wetland/riparian fynbos	Wetland	Wetland	0.87	*1.2%*
Alien trees	Alien trees (pines)			6.89	*9.4%*
		Alien trees (pines), mature		6.75	*9.2%*
			Alien trees: pine > 15 years	0.09	*0.1%*
			Alien trees: pine 7–15 years	6.61	*9.0%*
			Alien trees: black wattle > 6 years	0.01	*0.02%*
			Alien trees: other > 6 years	0.04	*0.1%*
		Alien trees (pines), young		0.14	*0.2%*
			Alien trees: pine 4–6 years	0.02	*0.03%*
			Alien trees: pine 2–4 years	0.04	*0.05%*
			Alien trees: black wattle 3–6 years	0.003	
			Alien trees: black wattle 2–3 years	0.0005	
			Alien trees: other 4–6 years	0.08	*0.1%*
			Alien trees: other 2–4 years	0.001	
Total				**73.25**	

Table C11: Vegetation parameter values used in models of the Upper Berg catchment

Process:	**Canopy interception (CI)**						**Evapotranspiration (crop) coefficient, K_c**								**Root depth**			
Modelling tool:	**Pitman tools**	**ACRU**	**MIKE-SHE**				**WRSM**			**ACRU**		**SWAT**		**MIKE-SHE**	**Pitman tools**	**ACRU**	**SWAT**	**MIKE-SHE**
Input parameter:	**Max CI**	**Max CI**	*Max CI per timestep= CI coeff x LAI*		CI coeff	LAI	S-pan coeff	A-pan coeff	***ref PET coeff***	A-pan coeff	***Ref PET coeff***	LAI max	***Ref PET coeff***	**Ref PET coeff**	**Root depth = soil depth**	**Root depth = soil depth ***	**Root depth, max****	**Root depth**
Unit:	**mm/ day**	**mm/ day**	***mm/ day***	***mm/ 2 hr***	mm/ ts	m/m									**m**	**m**	**m**	**m**
Fynbos / all indigenous	1.5	*(1.1)*	*(1.1)*				0.90	0.64	*0.77*	*(0.54)*	*(0.65)*		*(0.66)*	*(0.65)*	*(1.2)*	*(1.30)*	*(2.13)*	*(2.36)*
Fynbos low density		1.0	*0.8*	*0.07*	0.04	1.70				0.48	*0.58*	1.75	*0.58*	0.58		1.30	1.40	1.40
Fynbos high density		1.1	*1.3*	*0.11*	0.04	2.79				0.60	*0.72*	2.20	*0.73*	0.72		1.30	3.00^{x}	3.50
Indigenous forest		3.2	*3.3*	*0.28*	0.07	3.93				0.85	*1.02*	3.93	*1.00*^{x}	1.02		1.30	0.92	0.92
Wetland/riparian fynbos*		1.1								0.59	*0.71*					1.30	3.00^{x}	3.50
Wetland		*(0.6)*	*0.5*	*0.04*	0.02	2.18						2.85	*0.95*	0.95				
Alien trees (pines)	*2.1*^{S}	3.0	*(3.2)*							0.85	*1.02*		*(1.00)*	*(1.01)*		1.30	*(2.95)*	*(2.80)*
Alien trees, mature												5.00	*1.00*^{x}				3.00^{x}	
Pine >15 years			*3.0*	*0.25*	0.05	5.00								1.01				3.47
Pine 7–15 years			*3.2*	*0.27*	0.06	4.50								1.01				2.74
Wattle > 6 years			*2.4*	*0.20*	0.05	4.00								1.08				6.33
Other > 6 years			*2.6*	*0.22*	0.05	4.30								1.01				6.68
												2.85	*0.95*				1.00	

Process:	**Canopy interception (CI)**						**Evapotranspiration (crop) coefficient, K_c**								**Root depth**			
Modelling tool:	**Pitman tools**	**ACRU**	**MIKE-SHE**				**WRSM**			**ACRU**		**SWAT**		**MIKE-SHE**	**Pitman tools**	**ACRU**	**SWAT**	**MIKE-SHE**
Input parameter:	**Max CI**	**Max CI**	*Max CI per timestep= CI coeff x LAI*		CI coeff	LAI	S-pan coeff	A-pan coeff	***ref PET coeff***	A-pan coeff	***Ref PET coeff***	LAI max	***Ref PET coeff***	**Ref PET coeff**	**Root depth = soil depth**	**Root depth = soil depth ***	**Root depth, max****	**Root depth**
Unit:	**mm/ day**	**mm/ day**	***mm/ day***	***mm/ 2 hr***	mm/ ts	m/m									**m**	**m**	**m**	**m**
Alien trees, young																		
Pine 4–6 years			*3.6*	*0.30*	0.12	2.50								1.01				0.65
Pine 2–4 years			*3.4*	*0.29*	0.19	1.50								1.01				0.20
Wattle 3–6 years			*1.7*	*0.14*	0.04	3.50								1.08				4.80
Wattle 2–3 years			*1.2*	*0.10*	0.04	2.50								0.48				3.60
Other 4–6 years			*2.4*	*0.20*	0.06	3.33								1.01				6.48
Other 2–4 years			*2.4*	*0.20*	0.07	2.88								0.86				5.65

coeff = Coefficient; **ts** = Timestep; **ref PET** = Potential evapotranspiration for standard reference vegetation (FAO-56); *Maximum value allowed by tool; ^{S}SPATSIM only: Calculates afforested area CI and ET with an upscaling factor, WRSM uses a different method; *****ACRU: Soil/root depth varied with topographic zone; **SWAT: Access to ground water below soil is set with a separate parameter by topographic zone; **Black text**: Values entered in model; **Blue text*:*** Values calculated from model inputs for comparison across tools, i.e. area-weighted averages for broader cover classes (shown in brackets), applying value conversions or model algorithms, e.g. in MIKE-SHE, Maximum CI = CI coefficient x LAI; in SWAT, ET coefficient = LAI/3 if LAI <3 or 1 if LAI ≥3); Grey shaded columns: Comparable values/units

Table C12: Soil and unsaturated zone profile parameter values used in models of the Upper Berg catchment

Land unit:	**All** (Area average)						**Riparian**			**Upland** (Area average)			**Lowslope**		**Upslope**		**Cliff**		**Peak**	
Tool:	**WRSM**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**
n layers in profile	*1*	*1*	*2*	*2*	*1*	*(27)#*	*2*	*2*	*1*	*2*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	*1*
Lateral flow out of profile	*Yes*	*Yes*	*No**	*Yes*	*No*	*Yes#*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*yes*	*No*
Additional vadose or interflow layer below "soil" profile	*Yes*	*No*	*No**	*Yes***	*Yes*	*N/A#*	*No**	*Yes***	*Yes*	*No**	*Yes***	*Yes*	*Yes***	*Yes*	*Yes***	*Yes*	*Yes***	*Yes*	*Yes***	*Yes*
Profile																				
Profile depth (thickness), m	1.25	1.15	1.25	3.50^{x}	3.74	10	1.30	3.50^{x}	0.90	1.25	3.50^{x}	4.00	3.50^{x}	4.00	3.50^{x}	4.00	3.50^{x}	4.00	3.50^{x}	4.00
Storage at saturation, mm	500	450	528	1 378	2 199	3 800	541	1 393	484	527	1 376	2 357	1 384	2 244	1 376	2 460	1 339	2 240	1 348	2 240
Storage at field capacity, mm			230	598	1 007	1 650	216	580	154	232	600	1 086	590	825	610	1 338	578	720	579	720
Root zone																				
Max root depth, m	1.25	1.15	1.25	3.00^{x}	3.50	3.50	1.30	3.00^{x}	0.90	1.25	3.00^{x}	3.50	3.00^{x}	3.50	3.00^{x}	3.50	3.00^{x}	3.50	3.00^{x}	3.50
Storage at field capacity, mm			230	516	883	578	216	497	154	232	517	950	507	722	528	1171	496	630	497	630
Layer 1																				
Layer bottom depth, mbgl			0.25	0.24	3.74	10	0.30	0.40	0.90	0.25	0.23	4.00	0.30	4.00	0.19	4.00	0.05	4.00	0.10	4.00
Layer thickness, m			0.25	0.24	3.74	10	0.30	0.40	0.90	0.25	0.23	4.00	0.30	4.00	0.19	4.00	0.05	4.00	0.10	4.00
Porosity			0.58	0.58	0.58	0.38	0.54	0.54	0.54	0.59	0.59	0.59	0.56	0.56	0.62	0.62	0.56	0.56	0.56	0.56
Field capacity			0.26	0.26	0.26	0.17	0.17	0.17	0.17	0.27	0.27	0.27	0.21	0.21	0.33	0.33	0.18	0.18	0.18	0.18
Wilting point			0.08	0.09	0.09	0.03	0.07	0.07	0.07	0.09	0.09	0.09	0.07	0.07	0.10	0.10	0.12	0.12	0.12	0.12
AWC			*0.17*	*0.18*	*0.18*	*0.14*	*0.10*	*0.10*	*0.10*	*0.18*	*0.18*	*0.18*	*0.14*	*0.14*	*0.24*	*0.24*	*0.06*	*0.06*	*0.06*	*0.06*
Ksat, mm/hr				65.7	318	7.0		200	1307		53.3	227	100	540	24.8	24.8	10.7	10.7	10.7	10.7
Redistribution factor			0.05				0.05			0.05										
Layer 2																				
Layer bottom depth, mbgl			1.25	3.50^{x}			1.30	3.50^{x}		1.25	3.50^{x}		3.50^{x}		3.50^{x}		3.50^{x}		3.50^{x}	
Layer thickness, m			1.00	3.26			1.00	3.10		1.00	3.27		3.20		3.31		3.45		3.40	
Porosity			0.38	0.38			0.38	0.38		0.38	0.38		0.38		0.38		0.38		0.38	
Field capacity			0.17	0.17			0.17	0.17		0.17	0.17		0.17		0.17		0.17		0.17	
Wilting point			0.03	0.03			0.03	0.03		0.03	0.03		0.03		0.03		0.03		0.03	
AWC			*0.14*	*0.14*			*0.14*	*0.14*		*0.14*	*0.14*		*0.14*		*0.14*		*0.14*		*0.14*	
Ksat, mm/hr				7.0				7.0			7.0		7.0		7.0		7.0		7.0	
Redistribution factor			0.03				0.03			0.03										

mbgl = Metres below ground level; **AWC** = Available water holding capacity; **Ksat** = Saturated hydraulic conductivity; **Blue text:** Conversions, area-weighted and/or depth-weighted averages *ACRU4: Lateral routing included from upland HRU baseflow store, below soil, into riparian HRU soil; **SWAT: Interflow from soil profile only, additional vadose layer only lags recharge to the aquifer store; #MIKE-SHEs: Single property layer subdivided into computational layers. Saturated zone profile overlaps unsaturated; no lateral flow if unsaturated.

Table C13: Additional soil and vadose zone layer (below soil profile) parameter values used in models of the Upper Berg catchment

Land unit:	**All** *(Area weighted average)*						**Riparian**			**Upland**		
Tool:	**WRSM**	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**
Soil profile parameters												
Critical depth: wetness impacts surface runoff generation, m			0.25				0.30			0.25		
Storage in critical depth or top layer$^{\%}$ at saturation, mm			*148*	*142$^{\%}$*	*2167$^{\%}$*	*76$^{\%}$*	*161*	*215$^{\%}$*	*484$^{\%}$*	*147*	*133$^{\%}$*	*2357$^{\%}$*
Rain threshold for surface runoff (min infiltration), mm/month	50	0										
Rain threshold for average infiltration rate, mm/month	500	450										
Distribution-average infiltration rate, mm/month	225	275										
Power, percolation rate equation	3	3										
Max percolation rate, mm/month	33	33										
Power, interflow rate equation	2	2										
Max interflow rate, mm/month	40	47										
Additional vadose or interflow layer below "soil" profile	***Yes***	*No*	*No**	***Yes***	***Yes***	*N/A#*	*No**	***Yes***	***Yes***	*No**	***Yes***	***Yes***
Lateral interflow out of this layer	***Yes***			*No*	***Yes***	***Yes#***		*No*	***Yes***		*No*	***Yes***
Layer bottom depth, mbgl	41.25				8.48	*10.00*			2.90			9.00
Layer thickness, m	40.00				4.75	*10.00*			2.00			5.00
Storage at saturation, mm	200^{x}				966	*2 000*			600			1 000
Specific yield	0.005				0.21	*0.20*			0.30			0.20
Vertical Ksat, mm/hour						*144*						
Power, percolation rate equation	0.2				1				1			1
Delay in recharge, days	30			180				180			180	
Percolation time constant, days	0				4.7				2			5
Horizontal Ksat, mm/ouhr						*14.4*						
Power, interflow rate equation	n/a				1				1			1
Delay in interflow, days	0			N/A				N/A			N/A	
Interflow time constant, days	0				9.3				2			10

Ksat = Saturated hydraulic conductivity; ^{x}Maximum value allowed by tool; $^{\%}$With different layering and approaches to infiltration calculation the "top" layer water storage capacity has different relevance to surface runoff generation across models *ACRU4: Lateral routing is included from upland HRU baseflow store, below soil, into riparian HRU soil; #MIKE-SHEs: No lateral flow in an unsaturated layer, but saturated zone profile defined in the model overlaps with the unsaturated zone profile so saturation can be modelled in unsaturated zone depth range. A perched water table can develop in a layer resulting in interflow. Layer shown here is the highly fractured shallow rock material layer, bottom of the unsaturated profile and top of saturated zone profile, above the deeper, less fractured, regional aquifer layer.

Blue text*:* Values not directly input in model – area-weighted averages, unit conversions presented for comparison across models

Table C14: Aquifer parameter values used in models of the Upper Berg catchment

Land unit:	**All** (Area-weighted average)						**Riparian**		**Upland** (Area average)		**Lowslope**	**Upslope**	**Cliff**	**Peak**
Tool:	**WRSM**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**ACRU**	**SWAT**	**ACRU**	**SWAT**	**SWAT**	**SWAT**	**SWAT**	**SWAT**
Storage parameters														
Bottom depth, mgbl	400[#]	*	*	*	170	404[#]								
Max thickness, m	400[#]	*	*	*	170	404[#]								
Depth to static water level (no flow), mgbl	75	75	0	0	170	404[#]								
Specific yield, m^3/(m*m^2)	0.001	0.001		0.003	0.3	1.00E-8								
Specific storage, /m						1.77E-6								
Max storage, mm	400	*	*	*	51 000	0.004								
Max storage available for outflow, mm	75	*	*	*	51 000	0.004								
Inactive storage (flow threshold), mm	325		0	0	0	0.000								
Flow rate parameters														
Transmissivity, m^2/day	26.7	26.7												
Horizontal Ksat, mm/hour	2.78					0.0007								
Vertical Ksat, mm/hour						0.07								
Fraction of store flow out /day			0.05				0.05		0.05					
Linear outflow constant, 1/days				0.005	0.003									
Linear outflow constant, days				*200*	*365*									
Power, GW-SW flow rate equation	-0.05			1	1									
Max regional GW gradient	0.001	0.012												
Max discharge, mm/mon	12													

Land unit:	**All** (Area-weighted average)						**Riparian**		**Upland** (Area average)		**Lowslope**	**Upslope**	**Cliff**	**Peak**
Tool:	**WRSM**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**ACRU**	**SWAT**	**ACRU**	**SWAT**	**SWAT**	**SWAT**	**SWAT**	**SWAT**
Capillary rise / ET from aquifer store														
Max fraction of PET met by aquifer				0.08				*0.15*		0.07	0.10	0.05	0.02	0.02
Max fraction of outflow diverted for **riparian area ET**	1	1			1									
Fraction of upland aquifer outflow routed to **riparian area soil**			1											

Ksat = Saturated hydraulic conductivity; # Spatially averaged depth across model domain or subcatchments; * Tool does not include a limit on the total volume stored in the aquifer (i.e. depth x porosity); **Blue text:** Values not directly input in model – area-weighted averages, unit conversions presented for comparison across models

Table C15: Modelled streamflow for the Upper Berg catchment for three different scenarios using five different modelling tools

Statistic	**Modelled streamflow, October 2006 to September 2018, for different land cover scenarios: Sc1 IAP cleared (no pines); Sc2 current cover (upland pines); Sc3 riparian pines**														
	WRSM			**SPATSIM**			**ACRU**			**SWAT**			**MIKE-SHE**		
	Sc1-NP	**Sc2-UP**	**Sc3-RP**	**Sc1-NP**	**Sc2-UP**	**Sc3-RP**	**Sc1-NP**	**Sc2-UP**	**Sc3-RP**	**Sc1-NP**	**Sc2-UP**	**Sc3-RP**	**Sc1-NP**	**Sc2-UP**	**Sc3-RP**
Annual stream yield (mm^3)															
Mean	131	123	121	131	129	129	143	142	141	126	127	126	137	135	134
Std. dev.	46	44	43	44	44	44	46	46	46	42	42	42	47	47	47
CV	0.35	0.36	0.36	0.34	0.34	0.34	0.32	0.32	0.33	0.34	0.33	0.34	0.35	0.35	0.35
Minimum	66	61	60	67	66	65	76	75	74	65	66	65	69	68	67
Maximum	219	206	204	214	212	212	231	229	229	210	210	209	231	229	228
Monthly streamflow (mm^3)															
Mean	10.9	10.2	10.1	10.9	10.8	10.7	11.9	11.8	11.8	10.5	10.6	10.5	11.4	11.3	11.2
Std. dev.	12.9	12.0	11.9	12.2	12.1	12.1	13.7	13.6	13.7	11.6	11.7	11.7	13.1	13.1	13.2
CV	1.18	1.17	1.18	1.12	1.13	1.13	1.15	1.16	1.16	1.10	1.11	1.11	1.15	1.16	1.18
Minimum	0.24	0.24	0.24	0.17	0.16	0.16	0.26	0.25	0.09	0.45	0.43	0.44	0.68	0.65	0.52
5th percentile	0.43	0.48	0.48	0.32	0.31	0.30	0.62	0.61	0.47	0.83	0.73	0.66	0.97	0.93	0.77
50th percentile	5.1	4.8	4.7	5.8	5.7	5.6	6.6	6.4	6.4	6.1	6.2	6.2	6.1	5.9	5.8
95th percentile	38.7	36.2	35.8	36.1	35.9	35.8	36.7	36.5	36.6	32.5	32.4	32.3	36.4	36.3	36.4
Maximum	65.7	61.7	61.6	60.0	59.8	59.7	69.5	69.4	69.4	59.8	60.5	60.4	71.6	71.5	71.5
Daily streamflow (cm)															
Mean							4.52	4.49	4.47	4.01	4.01	3.99	4.33	4.28	4.25
Std. dev.							9.80	9.79	9.79	8.92	8.60	8.79	9.51	9.46	9.50
CV							2.17	2.18	2.19	2.22	2.15	2.20	2.20	2.21	2.24
Minimum							0.08	0.08	0.03	0.04	0.04	0.03	0.23	0.19	0.15
5th percentile							0.19	0.18	0.11	0.13	0.14	0.13	0.30	0.29	0.24
50th percentile							1.54	1.46	1.48	1.21	1.24	1.22	1.18	1.15	1.11
95th percentile							21.9	21.9	21.9	16.8	16.7	16.5	20.6	20.5	20.5
Maximum							139.4	139.4	139.3	156.9	153.5	156.4	144.5	144.2	144.5

MIKE-SHE, SIMPLER OPTIONS

A MIKE-SHE model, using the tool's simpler algorithm options, has been built. However, calibration has not been completed.

Structure and parameterisation

- **Model units and routing:** The same grid cell size as the complex MIKE-SHE model was used, as well as the three subcatchments mentioned above. In this model, calculations of interception, infiltration, ET and soil storage and percolation are done at the grid-cell scale. Surface flow routing, interflow and aquifer recharge and outflow are calculated separately for input zones within each subcatchment.
- **Land cover and soils:** Cover and soil-type classifications and parameter values remained the same as were applied in the complex model, except that the fractured rock layer, included in the unsaturated zone material profile in the complex model, was instead considered as an "interflow reservoir", a separate unit below the soil layer.
- Surface or overland flow, generated at the grid-cell scale, was lumped and routed across five ordered topographic zones within subcatchments (peaks, cliffs, upper slopes, lower slopes, valley bottoms) with potential for infiltration on the path. Slope gradients and lengths for each zone type were derived from the DEM.
- **Geology and aquifers:** Interflow is modelled using "interflow reservoirs" below the model's soil profile. Two types of interflow reservoir were included: the uplands and the riparian areas. Interflow reservoirs are considered by subcatchment and receive percolation from overlying grid cells. Within a subcatchment, lateral interflow leaving the upland interflow reservoir was routed to the riparian interflow reservoir. Lateral interflow leaving the riparian interflow reservoir was routed to the river channel.
  - Division of the conceptualised fractured rock interflow layer into two different reservoir units was primarily done to define a 'riparian' zone with more water access in the model. The interflow reservoir delineation is also used in the algorithm that represents capillary rise in MIKE-SHE's linear reservoir subsurface flow calculations. The area overlying the lowest mapped interflow reservoir type in a subcatchment is the only part of the subcatchment that will receive water from the baseflow reservoir to meet ET demand, representing a shallower water table and capillary rise into the root zone in low-lying riparian areas.
  - The riparian interflow reservoir was assumed to be more conductive, having more valley-fill tallus, and a shorter flow path, and so was assigned faster horizontal and vertical storage-outflow rate constants than the uplands reservoir. These are relatively conceptual parameters and require calibration, but are informed by the timings of peaks and recessions.
- One type of "baseflow reservoir", hence one set of parameter values, was used in the model to represent the deep bedrock aquifer. This is automatically subdivided into independent subcatchment-scale aquifer reservoirs in the model. These receive recharge from overlying interflow reservoirs and discharge to the channel network. There was not sufficient information to justify splitting this reservoir spatially or into two vertical layers with differing parameters, although this is possible in the tool.
- Capillary rise or vegetation access to ground water is only considered for cells overlying the lowest interflow zone. These can access a portion of the aquifer outflow to meet an ET deficit, representing a shallower ground water table in this part of the landscape. It was assumed that there was potential for all the calculated aquifer output to be accessed for ET in this zone.
- **River channel network:** The same channel hydraulic model is used as the complex MIKE-SHE model. However it uses surface, interflow and ground water inputs from the lowest overland flow zone, interflow reservoir and baseflow reservoir in the subcatchment. Channel transmission losses to the aquifer were not included.

Adjustments to improve calibration

This is still underway.

Scenario representation

The land cover scenarios were modelled by inputting different land cover maps. Parameterisations of each vegetation type remained constant, but the area and spatial distribution of each type changed.

Main challenges

- Determining appropriate unit divisions and parameter values for conceptual linear reservoirs representing subsurface flow.

WRSM-PITMAN

Several important parameters in the Pitman model are conceptual, so that values could not be directly calculated from the available estimates of local vegetation, soil and geology property values, although the parameter values are linked to these (Kapangaziwiri, 2007). With the exception of the ground water module, which differs across the tools, parameter values from the calibrated SPATSIM-Pitman model (see SPATSIM below) were used as starting values for calibration. SPATSIM includes the automated batch testing of parameter sets drawn from user-input distributions. Values from the model of the G10A quaternary catchment calibrated for the WR2012 study (Bailey and Pitman, 2015) were also consulted for reference. However, this model was calibrated for a different spatial extent (larger catchment) with different climate inputs.

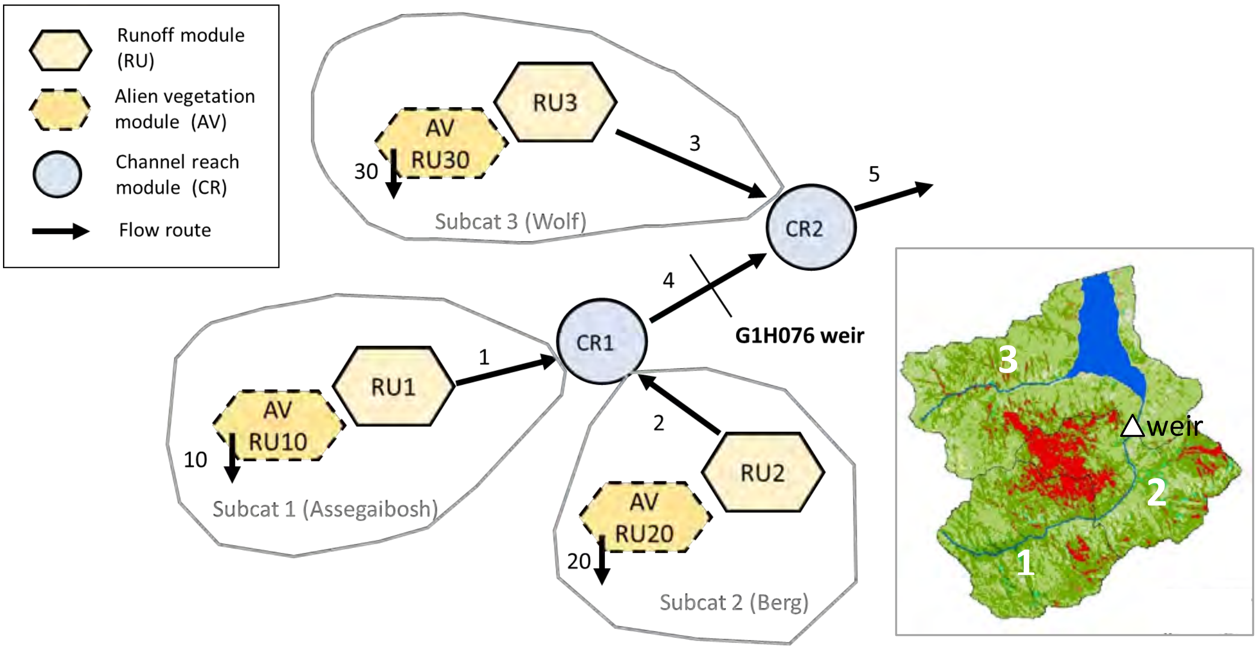


Figure C4: Model structure routing diagram for the Upper Berg catchment model built with WRSM-Pitman

Structure and parameterisation

- **Model units and routing:** The catchment was divided into three subcatchments, each represented with "runoff modules" having linked, alien vegetation "child modules". These were linked by channel modules to accumulate flow contributions at the point of the observation weir and as inflow into the Berg River Dam (Figure C4).
- **Land cover:** Three land cover types were explicitly represented: lumped indigenous vegetation (fynbos, wetlands and forest), represented through the runoff module's general ET parameters (canopy interception, evaporation pan factors, ET decline coefficient), exposed rock and bare ground, represented by specifying a fraction of the runoff module area considered impervious, and alien vegetation (mostly pines), represented using the alien vegetation module (set as dominated by mature trees, 0% riparian).

- Alien vegetation coverage, impervious area and riparian area were mapped and input for each subcatchment, but the general runoff module ET parameters were held constant across the three subcatchments. Initial values for these were taken from the SPATSIM calibration and found to be the same as the WR2012 G10A model.
    - Differences in the distribution of high- and low-density fynbos, forest and wetland across the three subcatchments could potentially have been considered in the parameterisation. However, this variation and its potential impacts on the model outcomes were considered small in this case. Determining appropriate differences in values across subcatchments, including a calibration process, would not have been straightforward.
- **Soils:** Soil types and the fractured rock layer were represented with the single, lumped soil storage unit per runoff module (subcatchment). Because the distribution of topographic units, and hence assumed soil types, was not highly variable across the three subcatchments, the same parameter set for this soil layer was used in all three subcatchments.
- **Geology and aquifer:** Ground water is represented with a lumped aquifer storage unit by subcatchment and most property values were assumed to be constant over the three subcatchments. A separate model unit between the soil storage and aquifer serves to lag ground water recharge, representing unsaturated rock below the zone, contributing significantly to interflow.
    - The total aquifer thickness input was spatially averaged from the gridded values used in MIKE-SHE by subcatchment.
    - The aquifer storativity and transmissivity found in SPATSIM were input directly, while the depth to the static water level used in SPATSIM was used to derive the related WRSM inputs (i.e. the aquifer storage when at the static water level).
    - The regional ground water gradient used in SPATSIM (0.012) was too high for the WRSM model and resulted in errors, so the default value of 0.001 was applied.
    - The roughly 900 mm storage capacity of the intermediate fractured rock layer in MIKE-SHE was assumed to represent the maximum storage of the additional vadose zone layer, which lags percolating water in recharging the aquifer in the mode. However, the maximum value allowed in the tool is 200 mm, so this was used.
    - The maximum ground water outflow rate used (12 mm) was estimated from the highest monthly runoff observed for the month of the year with the lowest average; February in this case.
- Capillary rise or vegetation access to ground water is only considered for a user-specified riparian zone area in the subcatchment, assumed to have a shallow ground water table. This area was assumed to be the valley bottom topographic unit. Any ET demand deficit for this area, after drawing from the soil, can be met by the aquifer store. It is not assumed to be a different vegetation type to the rest of the runoff module. However, the algorithm for this zone uses separately specified A-pan coefficients, while the broader runoff module uses S-pan.
- **River channel network:** Channel reach modules were simply used to aggregate flows and no lags were introduced, given the small catchment and monthly timestep. No channel transmission losses were included for the channel modules. Within runoff modules, two-way exchange between an implicit subcatchment channel and the aquifer is calculated based on comparative levels.

Adjustments to improve calibration

Parameter adjustment trials had to be done manually. However, as mentioned above, many initial parameter values were found in the SPATSIM calibration process, which used an automated batch-run facility (see SPATSIM below). The model using the initial parameter values had reasonable performance (monthly NSE 0.87, 15% overprediction of mean), but overpredicted several monthly peaks and underpredicted low flows.

- A small increase in performance was obtained with minor increases in the infiltration rate parameters and decrease in the interflow rate parameter (NSE unchanged, 12% overprediction of mean). Larger parameter changes resulted in performance trade-offs and were not accepted.

- A trial run was done using parameter values from WR2012 for the larger G10A quaternary catchment. The infiltration parameters were similar, but the maximum interflow, maximum recharge rate, aquifer storage and maximum aquifer outflow parameters were lower than the set from the SPATSIM calibration. As a result, the outflow was too high (a 23% overestimate of the mean) and more surface flow with less interflow, recharge and aquifer outflow was predicted, although the monthly NSE was acceptable (0.82).

Scenario representation

- The alien-clearing scenario was represented by removing the alien vegetation modules. These can be effectively removed without the effort of altering the model set-up, using the in-built option of running a “naturalised” version of each runoff module.
- The riparian pines scenario was represented by changing the proportion of the alien vegetation specified as being “riparian” in each alien vegetation module from 0 to 100%.
    - “Riparian” alien vegetation in the alien vegetation module is different to the “riparian” vegetation, which is separately set up in the runoff module. The latter refers to an area that can access aquifer outflow to meet ET demands. In the alien vegetation module, the “proportion riparian” input is a factor determining the shape of the empirical runoff reduction curve that is applied to the runoff module. A greater “proportion riparian” will result in greater estimated runoff reductions, without necessarily drawing a greater fraction of this water from ground water for this. In this way, it differs from the representation of this scenario achieved in the other modelling tools.

Main challenges

- There were conceptual parameters and no automated batch run facility to assist the calibration process. WR2012-calibrated values and previous studies for an area are helpful, but are relevant to the scale of the models built.
    - Workaround: SPATSIM was used for this here. However, the model structures differ, so values are not expected to be identical.
- Representation of “riparian” alien vegetation using the “proportion riparian” input in the WRSM alien vegetation module does not mean that proportionally more water can be drawn from the aquifer to meet the ET demand.

SPATSIM-PITMAN

Several important parameters in the Pitman model are conceptual, so that values could not be directly calculated from the available estimates of local vegetation, soil and geology property values, although the parameter values are linked to these (Kapangaziwiri, 2007). Initial values were selected based on documented experience with the tool in similar settings, followed by a calibration procedure.

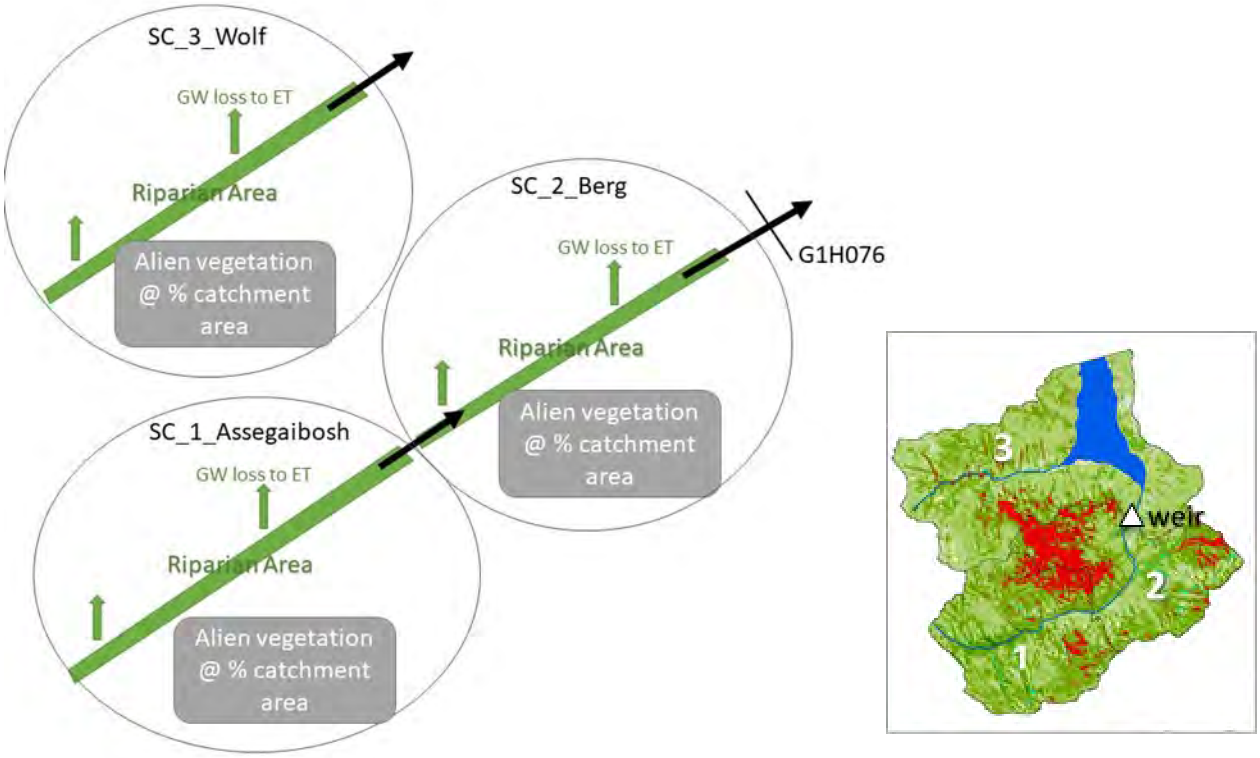


Figure C5: Model structure routing diagram for the Upper Berg catchment model built with SPATSIM-Pitman

Structure and parameterisation

- **Model units and routing**: The catchment was represented with three subcatchments, similar to other tools. Because the SPATSIM model channel network is tied to subcatchments, rather than being nodular or separately specified, the model output from Subcatchment 2 and Subcatchment 3 (Figure C5) had to be generated separately and summed outside the model interface to obtain the total for the case study catchment.
  - Subcatchment 1 (Assegaibosh) is the upstream subdivision of the catchment area feeding the weir on the Berg tributary. Subcatchment 2 is the incremental downstream portion. Subcatchment 3 is primarily the catchment of the Wolf tributary, which flows directly into the Berg River Dam, separately to the Berg tributary. SPATSIM considers the volume of water in the channel when calculating surface water-ground water interactions in a subcatchment. Outflow from Subcatchment 1 was routed through Subcatchment 2, as occurs in reality, but artificially routing streamflow from Subcatchment 3 through Subcatchment 2 for the sake of producing a single output from the model would introduce process inaccuracies from having too much water in the channel of Subcatchment 2.
  - An alternative would be to add a fourth subcatchment to collect flows from both Subcatchment 2 and 3, and parameterise this to have no ET, but this was considered an unnecessary complication because calibration was being done on the outflow of Subcatchment 2. If automated parameter set testing was to be done on the full catchment outflow in the model software, this latter strategy would have been worth doing.
- **Land cover:** Three land cover types were explicitly represented: lumped indigenous vegetation (fynbos, wetlands and forest), represented through the subcatchment ET parameters (canopy interception, ET decline coefficient), exposed rock and bare ground, represented by specifying a fraction of the subcatchment considered impervious, and alien vegetation, represented by specifying a fraction of the subcatchment area that is treed, and the ratio of its ET rate vs. the other vegetation.

- Alien vegetation coverage, impervious area and riparian area were mapped and input for each subcatchment, but the general ET parameters were held constant across the three subcatchments.
  - Differences in the distribution of high- and low-density fynbos, forest and wetland across the three subcatchments could potentially have been considered in the parameterisation. However, this variation and its potential impacts on the model outcomes were considered small in this case. Determining appropriate differences in values across subcatchments, including a calibration process, would not have been straightforward.
- **Soils:** Soil types and the fractured rock layer were represented with the single, lumped, soil storage unit per subcatchment. Because the distribution of topographic units, and hence assumed soil types, was not highly variable across the three subcatchments, the same parameter set for this soil layer was used in all three subcatchments.
- **Geology and aquifer:** Ground water recharge, storage and flow are represented at the subcatchment scale, and parameter values were assumed to be constant over the three subcatchments. Delays in recharge from percolation through material not represented in the "soil" moisture store are implicitly represented in the aquifer parameterisation.
- Capillary rise or vegetation access to ground water is only considered for a user-specified riparian zone area in the subcatchment, assumed to have a shallow ground water table. Any ET demand deficit for this area, after drawing from the soil, can be met by the aquifer store. This area is not assigned a distinct vegetation type of its own: it has the same ET parameters, including the proportion of alien vegetation, as the rest of the subcatchment.
- **River channel network:** Each subcatchment automatically has a channel that collects and routes flows from upstream catchments. When modelled ground water levels are low, channel transmission losses can be calculated.

Adjustments to improve calibration

Potential parameter adjustments were tested using the uncertainty module of SPATSIM, as well as by manual adjustment trials. In the uncertainty module, 1 000 parameter sets were generated from user-input value ranges and tested for performance against the observed flow.

Scenario representation

- The alien-clearing scenario was represented by changing the subcatchment's "treed" proportion to 0%.
- The riparian pines' scenario was represented by increasing the ratio of alien vegetation vs. indigenous vegetation ET from 1.4 to 1.6. The tool does not offer a way to explicitly specify that the "treed" cover is in the riparian zone, but it has been observed that riparian vegetation will have increased AET compared to upland vegetation of the same species (Le Maitre et al., 2016). When modelled this way, the additional ET demand will not be specifically met by additional ground water withdrawals – the percentage of alien vegetation cover is effectively the same inside as outside the riparian zone.

Main challenges

- The representation of alien vegetation coverage in a subcatchment is not spatially explicit and the specified riparian zone is implicitly assumed to have the same cover distribution as the rest of the subcatchment, so specifically riparian alien vegetation cannot be directly represented.

ACRU4

Structure and parameterisation

- **Model units and routing:** The catchment was represented with three subcatchments, each comprised of differing numbers of HRUs, representing areas of different land cover, soil and topographic positions. The current cover scenario set-up had 21 HRUs (Figure C6).
- Surface and shallow subsurface flows from HRUs were routed in parallel to river channel elements in their subcatchments, which were, in turn, routed to subcatchment “nodes”. Aquifer outflows from upland HRUs were routed to riparian HRU soils. Aquifer outflows from riparian HRUs were routed to channels (Figure C6).
- The model’s catchment node, the ultimate outlet of the modelled area, allowed flow from Subcatchment 2 and 3 to be brought together in the outlet output without routing one “through” the other. This is the same for the WRSM model, but could not be done internally in SPATSIM.
- **Land cover:** Because each HRU in the model is created, parameterised, linked and adjusted manually and individually in ACRU4 software, the number of land cover types, as well as soil and topographic unit types explicitly represented was reduced from the number mapped and input in the original MIKE-SHE model to keep the number of HRUs to a manageable number. A total of six individually parameterised land cover types was included: high-density fynbos, low-density fynbos, invasive pines, indigenous forest, wetlands or riparian fynbos and impervious cover (exposed rock, bare ground).
- Land cover parameters used in ACRU are similar to those used in MIKE-SHE, with some unit conversions and adjustment for the means of inputting the atmospheric ET demand. Values could largely be input by selecting the relevant vegetation types included in the tool’s in-built “compoveg” database as this had been used in the original MIKE-SHE model (with unit conversions applied where necessary), while others had to be manually entered. The lumped wetland or riparian fynbos cover type was parameterised by area-weighting the parameters of the wetlands and fynbos.
  - ***Root depth*** in ACRU is linked to HRU soil depth. This led to different root depths specified in ACRU than in MIKE-SHE and SWAT, in which these are separately input.

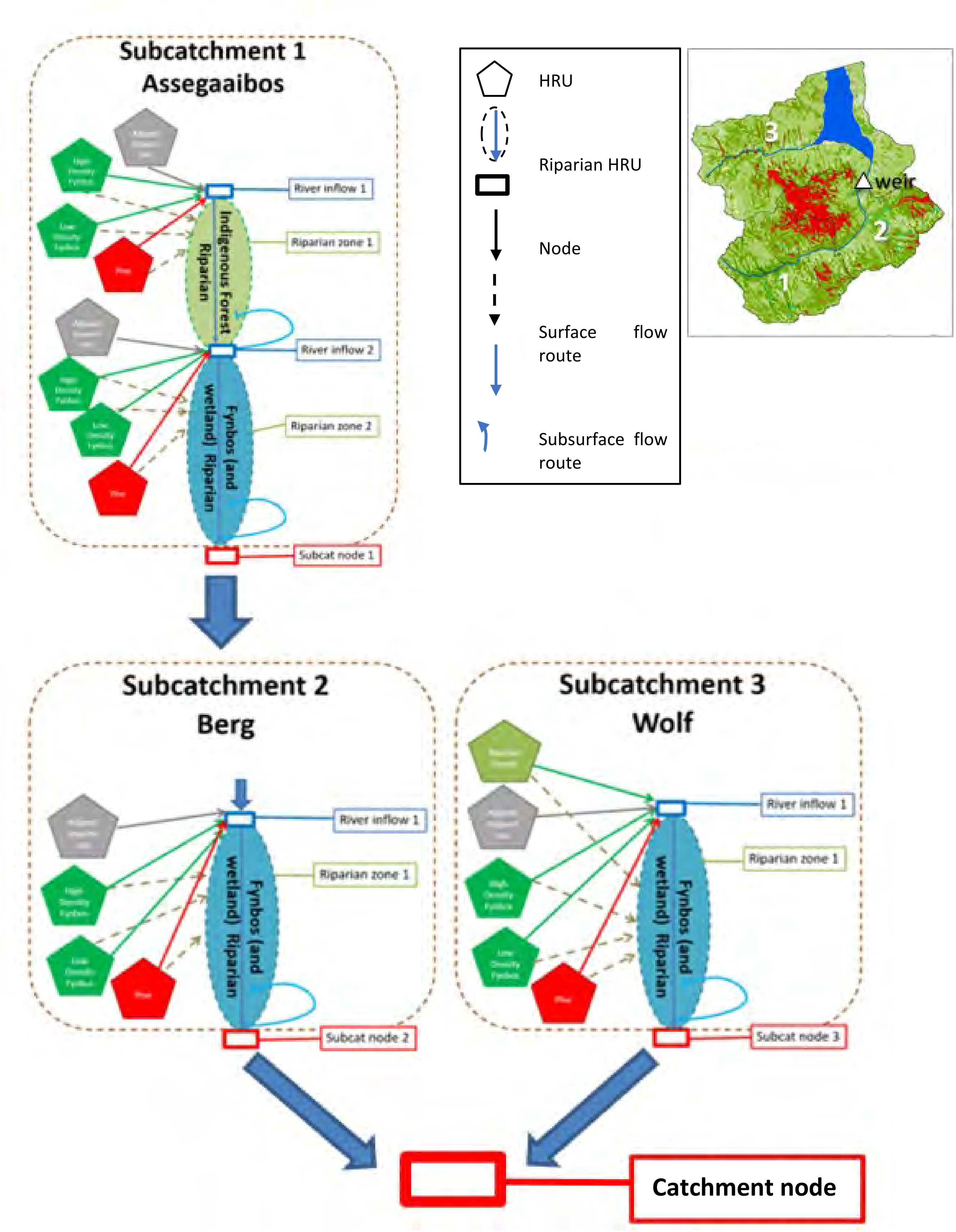


Figure C6: Model structure routing diagram for the Upper Berg catchment model built with ACRU4

- **Soils:** The five soil types associated with topographic units, as sampled and described in the SEBEI project, were simplified into two types in ACRU: upland and riparian (valley bottom). This was done to keep the number of cover type-soil type combinations, hence HRUs, manageable.
- Soil parameters required were mostly similar to those needed in MIKE-SHE and could be obtained directly from the available soil property estimates. Parameters for the upland soil were estimated by taking the area-weighted average of the peak, cliff, upslope and lowslope soil properties.
- The final model included a "soil" profile in which the top layer (ACRU's A-horizon) was parameterised as the sampled soils described above, while the lower layer (ACRU's B-horizon) was assigned parameter values to represent a highly fractured rock layer. Parameter values for this layer were consistent with those used in MIKE-SHE, except for depth, and were held constant over all HRUs.
    - An initial model set-up was tried with a soil profile only covering the estimated depth of the transition to tallus or highly fractured rock (30–40 cm in lower-lying areas). In this case, the same properties were applied to the two required horizon layers with each assigned half the total depth. The shallow profile curtailed landscape water storage, root depth and ET, producing high flow volumes (discussed further below).
- ACRU does not use soil conductivity as a parameter value, instead it uses a modified version of the SCS-CN method to calculate infiltration in a rain event and a "soil response fraction" parameter in calculating the rate of percolation between the two horizon layers and out of the lower layer.
    - The "critical stormflow depth", the depth of soil over which soil moisture is used to determine runoff versus infiltration, was assumed to be the same depth as the shallow upper soil layer in the profile.
    - Values for the soil response fraction were initially selected using guidance in the model documentation, suggesting high values for high-conductivity, coarse soils (Schulze, 1995). These were later modified as a workaround to approximate the conceptualised interflow generation process with saturation-excess overland flow generation.
- **Runoff lag:** Surface and shallow subsurface runoff, calculated for a storm event, is routed to the stream with a lag determined by the "stormflow response fraction" parameter, the fraction runoff reaching the stream each day. This represents a combination of several landscape properties and processes: slope, roughness, flow path length, potential soil properties linked to interflow, etc. Based on ACRU modelling done for other catchments in the TMG region (Le Maitre et al., 2014; Warburton et al., 2012), this value was set to 0.6 for upland HRUs, meaning that 60% "stormflow" runoff exits the catchment on the same day. A value of 0.3, the model default, was used for the riparian HRUs based on their lower slope and thicker vegetation. Warburton et al. (2012) applied a value of 0.6 when modelling the Upper Breede, given the steepness of the catchment. In a study in the Garden Route, also in TMG terrain, Le Maitre et al. (2014) found that a response fraction of 0.6 produced the best result in calibration trials.
- **Geology and aquifer:** Aquifer storage and outflow are calculated for each HRU individually using a conceptual outflow rate coefficient. Part of the vadose zone between the soils and the bedrock aquifer was represented with the highly fractured rock layer included in the soil profile as described. Remaining unsaturated fractured rock below this, which would delay percolating water from reaching an aquifer, is implicitly represented in the ground water outflow rate parameter. In the other models, the bedrock aquifer was conceptualised with uniform properties across the catchment, with the exception of thickness in some cases. Similarly, the same "baseflow" outflow coefficient was assigned to all HRUs, using the default value (0.009) as a starting value for calibration (see below).
- Vegetation access to ground water or capillary rise was represented using special riparian zone HRUs in the model. "Baseflow store" (aquifer) outflows of linked upland HRUs are routed into the lower soil layer of riparian HRUs in the same subcatchment (Figure 5.25). As in other tools, the areas considered riparian were determined using the valley bottom topographic unit. Vegetation parameters for riparian-zone HRUs were kept the same as the parameters for the same vegetation type located in the uplands when applicable (i.e. pines were located in both positions, while wetlands were only located in the riparian zone).

- **River channel network:** River channel units were defined in each subcatchment associated with each riparian HRU. Channel transmission loss was not explicitly included as it cannot be calculated in the tool. Riparian HRUs are linked to a channel module, and channel flow in excess of an input threshold is applied to the HRU's surface, intended to represent overbank flooding. In this case, this mechanism was also assumed to represent the vegetation access of water in the hyporheic zone surrounding the channel.

Adjustments to improve calibration

Parameter value adjustments were manually set up and tested.

- Vegetation and soil parameters with direct correspondence to property information and values used in the MIKE-SHE model were not adjusted.
- Adjustments were trialled for the more conceptual parameters with less direct quantitative derivation from measurable properties: the stormflow response fraction, the critical soil response depth, the soil response fraction and the baseflow response fraction.
- Soil profile parameters were adjusted to include fractured rock material in the profile, while maintaining the surface soil parameters informed by field sampling.

The initial model set-up, with the shallow soil profile, hence root zone, and default soil and aquifer drainage parameters, overpredicted mean daily flow by close to 30% and had recessions that were too slow between winter peak events, but showed too much flow recession from winter to summer, so that summer low flows were too low.

- To reduce modelled mean outflow, while maintaining consistent property parameters, the modelled soil profile was deepened by including a fractured rock layer. This increased the root zone, in line with values used in other tools, and reduced overprediction of the mean to 14%. However, it slowed modelled flow recessions, worsening the model fit during winter storms and the winter-to-summer seasonal recession.
- Increasing the aquifer drainage parameter (the baseflow response fraction) from the 0.009 default increased recession steepness, but the impact was relatively small. High values (i.e. 0.1) resulted in a baseflow deficit in late summer. A value of 0.05 was used.
- The stormflow response fraction was already relatively high (0.6). Increasing it to 0.8 made a minimal difference (<0.1% change in mean, no NSE improvement), so it was left at 0.6, in keeping with literature for the region.
- A large decrease in the soil response factor, from the initial 0.7 down to 0.05, was trialled in an attempt to approximate interflow processes with modelled saturation-overland flow generation. This improved predictions of peaks, recessions between winter events and the shape of the seasonal recession, although this remained slow compared to the observed flow.

Scenario representation

To model the alternative land cover scenarios, the land cover distribution within each subcatchment was recalculated and the HRUs used in the "current cover" model for calibration were manually altered in accordance. Parameter values for the various land cover and soil types remained the same, but HRU areas were changed.

- For the alien clearing scenario, the pine HRUs were deleted and the areas of fynbos HRUs were increased.
- For the riparian invasion scenario, riparian zone HRUs were given the pine vegetation parameters, while upland pine HRUs were deleted and upland fynbos HRU areas were increased. The upland to riparian HRU connections and connections to river channel elements were manually reconfigured.

Main challenges

- **Interflow representation:** The modelling tool representation of interflow, controlled by the same thresholds as surface flow, appeared different to the conceptualisation of the process in the catchment.
- **Soil profile and root zone depth tied:** The soil profile depth and rooting depth are tied in the model, which was constraining in terms of representing any vadose zone storage below the root zone.
- **Model interface:** There is a high number of steps to establish structure and connectivity, make and test adjustments, and export water balance components and process them at a catchment scale. Very few actions can be "batched".

SWAT

Structure and parameterisation

- **Model units and routing:** The catchment was represented with three subcatchments, each comprised of differing numbers of HRUs, representing areas of different land cover, soil and topographic positions. The current cover scenario set-up had 107 HRUs, created automatically by ArcSWAT2012 from overlaying maps of cover, soil and subcatchments.
- HRU surface flow and interflow are automatically routed in parallel to the subcatchment's river channel. Water percolating from the bottom of an HRU's soil profile recharges a subcatchment-scale aquifer store from which outflow is routed to the subcatchment's channel.
- SWAT, similar to SPATSIM, models one river channel element per subcatchment, and the catchment's outlet is a channel element, rather than a routing "node" like ACRU. Channel outflow from Subcatchment 2 was therefore routed into the channel passing through Subcatchment 3 (see map in Figure 5.1), which was the outlet. This connection was established internally in the software from the spatial arrangement of drainage lines and the input subcatchment delineation points.

    - The only way to avoid this would be to subdivide Subcatchment 3 into two parts so that both Subcatchment 2 and 3 would flow into a new Subcatchment 4 (not done here).
    - Routing Subcatchment 2's flows through the channel of Subcatchment 3 was assumed to have minimal impact on process calculations in this case. Unlike SPATSIM, in SWAT, the amount of water in the channel is not used to calculate ground water flow into the channel. The representation of channel transmission losses is also optional, and was not considered important in this case study.
- **Land cover:** Land cover types considered were reduced to 10 from the 18 considered in MIKE-SHE, only lumping alien vegetation age subdivisions that had minimal coverage (Table C10). Because the ArcSWAT2012 tool delineates HRUs and determines area, topographic properties and routing internally using geospatial map inputs, and because land cover and soil properties are input by type, the labour and risks of user error associated with having many HRUs is far less than in ACRU.
- Land cover types were parameterised to match the properties assigned in MIKE-SHE as much as possible:
    - **ET (crop) coefficient (K_c):** To match the reference PET input of the original MIKE-SHE model, the user-input reference PET entry method in SWAT was used, which had implications for the vegetation PET calculation and parameters needed. With this method, SWAT calculates the ET coefficient (K_c) for the vegetation type internally as a function of LAI, so input LAI values were selected to produce K_c values matching those input in MIKE-SHE. The LAI values are not used for other hydrological processes in the model. The algorithm for calculating K_c in SWAT limits K_c to a maximum value of 1, so the invasive pines had a lower K_c in SWAT than in MIKE-SHE or ACRU.
        - SWAT calculates the HRUs' LAI daily based on inputs of maximum LAI for the vegetation, dormancy LAI and growth parameters. The maximum dormancy LAI input is 0.98.

        However, growth curve and management parameters were set to ensure that the model considered vegetation to be mature throughout the simulation.
    - **Root depth:** Maximum root depth was input to match the MIKE-SHE root depth.
        - Root depth is also calculated daily based on vegetation growth curves, so these parameters need to be set to maintain mature vegetation cover across the simulation.
- In addition to hydrological flows, SWAT also models plant growth, nutrient cycling and sediment movement. These are not optional routines. This means that many more land cover properties are needed compared to other tools. However, ArcSWAT2012 comes with an extensive database of parameterised vegetation types. The additional parameters needed were taken from types in the database assumed to have similar structures to the vegetation types in this case study (i.e. forest, shrubland, etc.).
- **Soils:** The five soil types associated with mapped topographic units, as sampled and described in the SEBEI project, were used directly in the SWAT model. SWAT estimates interflow by calculating lateral flow from the soil profile. For this reason, the highly fractured rock layer was included in the model's "soil" profile, given the properties assigned to this layer in MIKE-SHE. Like the final version of ACRU, the SWAT model soil profile included two layers: the shallow sandy top layer and the underlying fractured rock. The fractured rock layer extended to the maximum depth possible (3.5 m total for the profile).
    - SWAT uses wilting point, field capacity and saturation soil moisture in its soil water movement calculations. However, these water-retention properties are not directly input by the user. The tool uses in-built pedotransfer equations to calculate these values based on user-input bulk density, available water-holding capacity and percentage clay content. Values for these inputs were back-calculated using the water-retention properties explicitly input in the other tools.
- SWAT uses the input saturated conductivity to calculate vertical and horizontal flow in soils. However, it uses the empirical SCS-CN method to calculate infiltration (and interception) vs. runoff production during rainfall events. Initial CN values were selected based on suggestions in the model documentation for broad vegetation structural types (Arnold et al., 2012).
- **Geology and aquifers:** Ground water recharge, storage and flow are represented at the subcatchment scale, and parameter values were assumed to be constant over the three subcatchments.
- Like WRSM, SWAT represents the passage through additional vadose zone material below the modelled soil profile by lagging percolating water in recharging the aquifer. Outflow from the aquifer to the channel is calculated using a conceptual linear reservoir rate constant. Initial values were set at the model defaults and adjusted in calibration.
- Capillary rise or vegetation access to ground water can be represented for any HRU in the model by specifying the maximum proportion of the ET demand that can be met by drawing from the aquifer store, with values between 0.02 and 0.2 (2–20%) allowed. Areas considered riparian, determined using the valley bottom topographic unit, were assigned the highest value, representing a shallower ground water table at this location.
- **River channel network:** SWAT includes one main river channel unit per subcatchment. Channel bed loss was not included in the model for this case study.

Adjustments to improve calibration

Parameter value adjustments were manually set up and tested.

- Vegetation and soil parameters with direct correspondence to property information and values used in MIKE-SHE were not adjusted, with the exception of saturated hydraulic conductivity values.
- Adjustments were trialled for the more conceptual parameters, with less direct quantitative derivation from measurable properties: the curve number, the recharge lag and the aquifer outflow recession constant.

The initial model parameterisation overpredicted mean average flow, underpredicted the highest flow peaks, but had slower recessions than observed, and overpredicted peaks for small events. Only a small fraction of the overall flow (about 5%) was considered to come from surface flow, while interflow dominated.

- To increase flow peaks, curve number values were increased. However, too large of an increase resulted in worsening baseflows.
- Very high saturated conductivity values for valley bottom and low slope areas were reduced to values still in the range of the literature for loamy sands to reduce the rate at which water was leaving the soil and so increase ET.
- Increasing both the delay in recharge value and slowing the aquifer outflow improved the fit of low flows.

Scenario representation

The land cover scenarios were modelled by inputting different land cover maps. Parameterisations of each vegetation type remained constant, but the area and spatial distribution of each type changed.

Main challenges

- The limit on capillary rise or ET from ground water, in combination with the lack of the landscape routing of surface and subsurface flows between HRUs (as opposed to parallel routing to the stream) hindered the representation of additional water access in riparian areas. The high hydraulic conductivity and low water-holding capacity of the sandy riparian soils made SWAT predict water deficits in the riparian zones, despite the ground water access.
- Soil-saturated conductivity is assumed to be the same vertically as horizontally, reducing control over the balance between lateral and vertical flow through the soil profile.

Lateral flow can further be controlled by altering the slope length for the HRU. However, the calculation of this value is input from the topography in the model, and deciding upon the value to which to change it would be a trial-and-error exercise.

C3: UPPER KROMME RIVER CATCHMENT (K90A,B) EASTERN CAPE: MOUNTAIN RANGE RAINFALL GRADIENTS, MOUNTAIN VALLEY CONNECTIVITY, VALLEY BOTTOM WETLANDS, INVASIVE ALIEN VEGETATION

- **Catchment description and modelling goals** are given in the main report, section 5.6.1.
- **Model units and main parameter values** used across the different models are given in tables C16 to C22 below.
- **Performance of the models compared to observed streamflow** is described in the main report, section 5.6.5.
- **Model outputs, including water balances**, are compared and discussed in the main report, section 5.6.5. A summary of the streamflow output for each tool for each scenario is given in Table C23.

The text sections describe the different model structures, summarise the rationale for structure and parameter decisions, and highlight the main challenges encountered. Approaches common to all tools and the set-up of the pre-existing model, which was used as a reference, are described first, followed by structure and parameter value tables, and by descriptions of the models built using the other tools.

Note: A model was built using the complex options in MIKE-SHE, but the calibration and analyses were not completed in time for inclusion. Some inputs of this model are presented in parameter tables below for reference.

GENERAL APPROACHES COMMON ACROSS TOOLS

- The pre-existing model of the catchment built in MIKE-SHE, using the tool's simpler algorithm options (Cornelius et al., 2019) was the reference point for building models using the other tools.
- Calibration was done by comparing model streamflow output for the 357 km^2 catchment area feeding the Kromrivier Dam (Churchill Dam) to the estimated inflow to the dam provided by DWS for 1 January 1960 to 10 September 2017. Models were run from 1 January 1957 to have a three-year warm up. This estimated stream inflow is the residual of a water balance for the dam calculated based on measured dam water levels used to estimate volume and volume change, and surface area based on dam bathymetry (stage-area, stage-volume curves), overflow spill based on water height and wall dimensions, rainfall and pan evaporation measured at the dam wall scaled to the dam surface area, and gauge measurements of the controlled releases to supply systems.
- For baseline water balance comparisons and scenario modelling, the models were run from 1957 to 2018 with comparisons done for 1960 to 2018, allowing a three-year warm-up.
- **Spatial rainfall distribution:** The rainfall distribution across this mountainous area was represented by subdividing the catchment into spatial units that could be assigned different rainfall input time-series. The level at which climate data can be assigned and the practicality of subdivision varies across modelling tools. This is discussed in detail for the Upper Kromme River catchment in the main report, section 5.5.2. MIKE-SHE allows climate inputs by grid cell or zones, which can be independently delineated, compared to the other tools for which climate inputs need to be done by subcatchment, requiring various amounts of effort to set up. Different subcatchment delineations were used in different tools (shown in Figure 5.26), and described in their respective sections below), but for all models, the climate zones and inputs that were used in the original MIKE-SHEs model were used as the underlying spatial distribution. The climate inputs for these zones were derived from a set of driver stations (from SAWS, ARC, DWS and SAEON), and the monthly spatial rainfall distribution surfaces derived by Lynch (2003), as described in Cornelius et al. (2019). For the other tools, the subcatchment delineation was overlayed on the mapped climate zones used in MIKE-SHE to determine the area of each zone in a given subcatchment. The area-weighted average of the inputs for the contributing MIKE-SHE climate zones was used as the subcatchment input. As a result, all models had the same catchment-averaged rainfall.

- The same vegetation, soil, and topographic unit maps, derived and described in Cornelius et al. (2019), were used to inform all model set-ups. Soil types were assigned by topographic unit.
- **Riparian zone water access:** Vegetation in areas delineated as valley bottom topographic units, kloof floors (mountain tributary drainage lines) and the main floodplain was assumed to have greater access to subsurface water for ET that in the uplands. This was represented in all the models, but in different ways:
  - In the **simple MIKE-SHE, SPATSIM and SWAT2012** models, these areas were given access to their subcatchment's aquifer storage to meet ET demands not met by soil storage. In SWAT2012, the maximum proportion of the ET demand that can be met by the aquifer is capped by the tool at 20%.
  - In the **ACRU4** model, aquifer outflow from upland HRUs was routed to the lower soil layer of riparian HRUs, and associated river channel overflow can add water to the HRU's surface.
- **Modelling flow into a large dam – the reservoir edge as the catchment "outlet":** The intention was to model flow into the Kromme River Dam, without the need to model flow through the reservoir itself. The catchment area was still delineated to the dam wall outlet. Delineating the catchment area to an upstream "inflow" point on the main river to exclude the reservoir surface area would also exclude flanking hillslopes that contribute flow along the sides of the reservoir. To only model inflow from the contributing catchment feeding into the dam, the reservoir itself (2 km^2 water surface area, 0.6% of the catchment area to the dam wall) needed to be excluded. This needed to be done in different ways in the different tools:
  - In **SPATSIM and ACRU4**, unit areas are directly entered by the user, so the surface area of the dam could simply be excluded from the modelled catchment area.
  - In **ArcSWAT2012** and **MIKE-SHE**, the modelled catchment area and sub-units are delineated in a GIS interface based on topography from the input DEM. The dam water surface area is necessarily part of the model catchment area as a result. The dam area was therefore parameterised to effectively exclude it from contributing to the modelled water balance:
    - In MIKE-SHE, it was set up to receive no rain and be impervious, so that surface runoff reaching it flows directly to the channel network.
    - In SWAT, rainfall is assigned by subcatchment, but runoff is not routed between HRUs, so the dam's HRU was parameterised so that all rainfall infiltrated and percolated to a deep aquifer unit that was disconnected from the streamflow.
- **Soil property variation:** Although vegetation cover can influence soil properties, this impact was considered to be secondary in this setting, given the sandy soils and steep terrain. As such, soil properties assigned to topographically defined units were held constant across the models of different land cover scenarios, even when the land cover in an area was changed.

STARTING REFERENCE MODEL: MIKE-SHE SIMPLER, MORE LUMPED OPTIONS

The MIKE-SHE model of the Upper Kromme River catchment was built for the WRC K5-2527 project, "Participatory hydrological modelling for collective exploration of water resource protection, restoration and water use management options in the western Algoa water management area", to explore the impacts of clearing invasive alien vegetation or discontinuing current clearing activities, as well as other catchment management scenarios, on water resources. A more detailed account of the model development can be found in the project report (Cornelius et al., 2019)

Structure and parameterisation

- **Model units and routing:** A 50-m cell size was used for the model's computational grid. The catchment was delineated into 11 subcatchments as shown in Figure 5.26. In this model, calculations of interception, infiltration, ET, and soil storage and percolation are done at the grid-cell scale. Surface flow routing, interflow and aquifer recharge and outflow are calculated for separately input zones within each subcatchment.

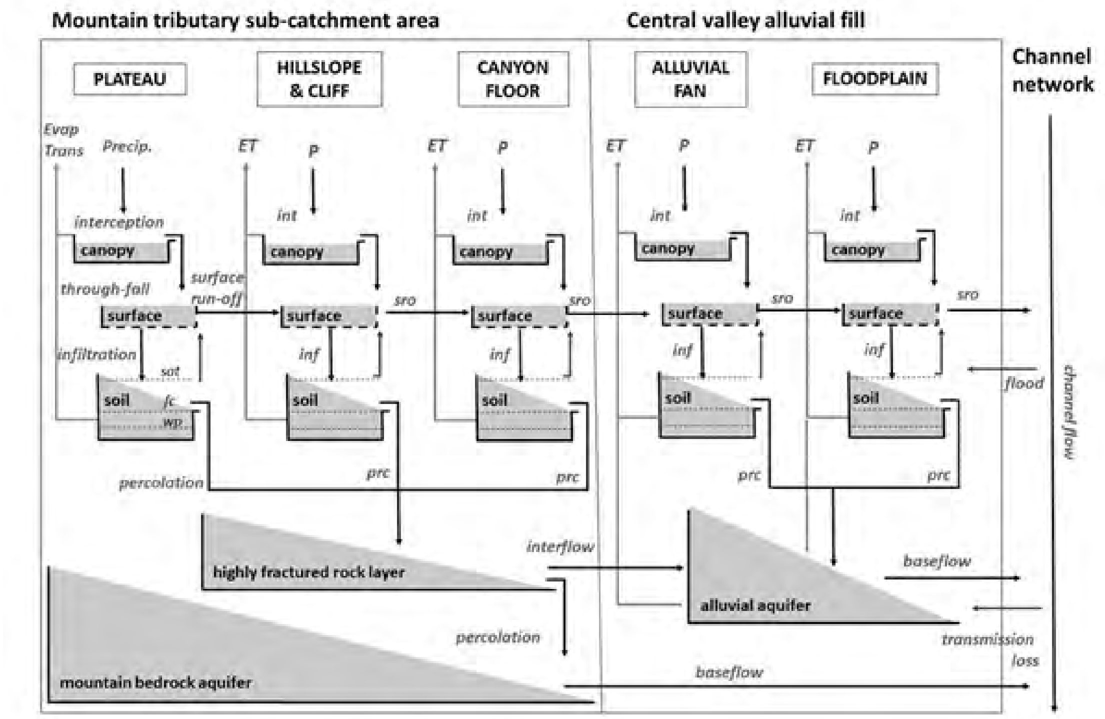


Figure C7: Schematic diagram of the model of the Upper Kromme River catchment built in MIKE-SHE (Cornelius et al., 2019)

- **Land cover:** Cornelius et al. (2019) developed a "current" (2014/15) land cover map through a composite of several source maps: the national land cover dataset (DEA, 2019), regional vegetation-type mapping (Euston-Brown, 2006; Vlok et al., 2008), wetland and alien vegetation cover mapping (Rebelo, 2012), and irrigation and agricultural field mapping (Bromley et al., 2015; De Jager et al., 2010) done for other studies. Vegetation parameters for the resulting 11 cover types were drawn from literature and the "compoveg" database of vegetation parameters that accompanies the ACRU modelling tool (Clark et al., 2012; Schulze, 1995).
- **Soils:** Cornelius et al. (2019) delineated the catchment into topographic units (plateau, cliff, hillslope, toeslope, kloof floor, alluvial fan and floodplain) using the SU-DEM topography dataset (Van Niekerk, 2016). It was assumed that these units had relatively distinct soil types. The palmiet wetlands in the floodplain were also assigned their own soil properties. Wetland, non-wetland floodplain and alluvial fan soil properties were informed by field sampling done in various studies and piezometer installations (Cornelius et al., 2019; Tanner et al., 2019). Upland properties were informed by the ARC land type (ARC, 2001) and autosoils databases (Schulze, 1995; 2007) and field observation.
- Surface or overland flow, generated at the grid-cell scale, was lumped and routed across seven ordered topographic zones (listed above) within subcatchments with potential for infiltration on the path. Slope gradients and lengths for each zone type were derived from the DEM.
- **Geology and aquifers:** Interflow was modelled using "interflow reservoirs" below the model's soil profile. Two types of interflow reservoir were included: the mountain fractured rock and tallus, and the central valley alluvial fill (fans and floodplain). Interflow reservoirs are considered by subcatchment and receive percolation from overlying grid cells. Within a subcatchment, lateral interflow leaving the mountain interflow reservoir was routed to the floodplain fill interflow reservoir. Lateral interflow leaving the floodplain interflow reservoir was routed to the river channel.
  - The area overlying the lowest mapped interflow reservoir type in a subcatchment, in this case the floodplain fill, is the only part of the subcatchment that will receive water from the baseflow reservoir to meet ET demand, representing a shallower water table and capillary rise into the root zone in low-lying areas.

  - The floodplain alluvial fill “interflow reservoir” was used to primarily direct incoming mountain interflow vertically to join the alluvial aquifer unit, allowing water to be accessible to vegetation (MIKE-SHEs interflow reservoirs cannot feed ET, but its “baseflow” aquifer reservoirs can). Assumed to be more conductive and with a shorter flow path than the mountain tallus, it was assigned faster storage-outflow rate constants than the mountain reservoir. These are relatively conceptual parameters and require calibration, but are informed by the timings of peaks and recessions.
- As with the interflow reservoirs, two types of “baseflow reservoir” were used in the model to represent the deep mountain bedrock aquifer (TMG) and the floodplain alluvial fill aquifers. These are automatically subdivided into independent subcatchment-scale aquifer reservoirs in the model. These receive recharge from overlying interflow reservoirs, discharge to the channel network, and can feed ET in soils of areas overlying the lowest-lying interflow zone in the subcatchment. Properties of aquifer layers reported in literature on the TMG region (Xu et al., 2009) were used to select initial parameters for the mountain bedrock unit.
- **River channel network:** Field sampling of channel dimensions was used to inform the channel cross-sections applied in the hydraulic model. Palmiet wetlands were assigned very wide and rough channel cross-sections.

Adjustments to improve calibration

Multiple structural options and parameter value adjustments were manually set up and sequentially tested, evaluating performance against the observed flow data. Key trials and findings in the process were as follows:

- The initial model set-up produced too little water. The ET crop coefficients adopted from the ACRU “compoveg” database were reduced, which improved performance. (Values had been rescaled to apply to reference PET rather than A-pan atmospheric demand).
- Similarly, the soil infiltration rate based on the input saturated hydraulic conductivity was reduced from initial values to increase flow and improve the fit to peak flows.
- To achieve the relatively consistent, but low baseflow values observed in dry periods, the recession constant for the mountain bedrock baseflow reservoir had to be set very high.
- On a daily scale, modelled flow peaks were often a day earlier than the peak in the observational data. This may have been linked to the river routing. However, it may also have been an artefact of the estimated dam inflow data, so additional effort was not put into rectifying this.

Scenario representation

The land cover scenarios were modelled by inputting different land cover maps. Parameterisations of each vegetation type remained constant, but the area and spatial distribution of each type changed. Although vegetation cover can influence soil properties, this impact was considered to be secondary in this setting, given the sandy soils and steep terrain. Soil properties were not altered between scenarios.

Table C16: Numbers and sizes of model units and types included in models of the Upper Kromme River catchment using different modelling tools

Modelled units		**Number or average size (km^2) of units**				
		SPATSIM	**ACRU4**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**
Catchment area (km^2): 357						
Subcatchments		33	12	55	11	N/A
	Average subcatchment size	10.8	29.8	6.5	32.5	
HRUs			46	861		
	Average HRU size		7.76	0.41		
Grid cells					142 801	35 701
	Grid-cell size				0.0025	0.01
Cover types		4	9	12	11	11
Soil types		2	6	8	8	8
Topographic zones		2	6	8	8	8
Aquifer types		2	2	2	2	3

Table C17: Soil types explicitly modelled for the Upper Kromme River catchment using different modelling tools

Soil type / topographic unit				**Area (km^2)**			***Percentage of catchment (excluding dam)***	
SPATSIM	**ACRU4**	**SWAT**	**MIKE-SHE**					
Upland				343			*96%*	
	Mountain*				298			*83%*
		Plateau				112		
		Cliff				45.5		
	Hillslope*	Hillslope			8.0	125		*2%*
	Toeslope*	Toeslope			29.2	46.3		*8%*
	Kloof floor	Kloof floor			7.1	14.4		*2%*
Floodplain				14.1			*4%*	
		Alluvial fan				3.3		
	Floodplain	Floodplain			12.4	9.3		*3%*
	Palmiet	Palmiet			1.5	1.5		*0.4%*
Total				**357**				

* ACRU4 fynbos HRUs were given a "mountain" soil type: area-weighted average of properties across upland topographic units.

Table C18: Land cover types explicitly modelled for the Upper Kromme River catchment using different modelling tools

Cover type				**Area (km^2)**			***Percentage of catchment (excluding dam)***		
SPATSIM	**ACRU4**	**SWAT**	**MIKE-SHE**						
Fynbos, woodland and seep wetland				304.2			*85%*		
	Fynbos				293.4			*82%*	
		Fynbos	Fynbos			249.9			*70%*
		Fynbos – cliff, low-density	Fynbos – cliff, low-density			43.5			*12%*
	Riparian woodland	Riparian woodland	Riparian woodland			6.2			*1.7%*
Wetland*	Wetland, palmiet**	Wetland, palmiet**	Wetland, palmiet**	1.5		1.5	*0.4%*		*0.4%*
	Wetland, seep**	Wetland, seep**	Wetland, seep**			4.7			*1.3%*
Irrigated agriculture				19.7			*5.5%*		
	Pasture	Pasture	Pasture			18.3			*5.1%*
	Apple orchard	Apple orchard	Apple orchard			1.4			*0.4%*
Farm dam$^{\#}$	Farm dam$^{\#}$	Farm dam	Farm dam	0.5		0.5	*0.1%*		*0.1%*
Invasive trees				30.6			*8.6%*		
	Wattle	Wattle	Wattle			27.4			*7.7%*
	Pine	Pine	Pine			3.3			*0.9%*
Impervious$^{@}$	Impervious$^{@}$			0.8			*0.2%*		
		High density residential	High density residential$^{@}$			0.8			*0.2%*
		Low density residential				1.4			*0.4%*
Total				**357**					

***** SPATSIM wetland module used for palmiet wetlands, more similar to a water body than a "cover type"; upland seeps implicitly included in the general subcatchment vegetation

** Wetland types (palmiet vs upland seep) differentiated by soil and position

$^{\#}$ Farm dams represented as a water body not a cover type

$^{@}$ Impervious portion of mapped residential areas estimated and included, remaining area included in the "field" cover class.

Table C19: Vegetation parameter values used in models of the Upper Berg River catchment

Process	**Canopy interception (CI)**					**Evapotranspiration (crop) coefficient, K_c**					**Root depth**			
Modelling tool:	**SPAT-SIM**	**ACRU**	**MIKE-SHE**			**ACRU**		**SWAT**		**MIKE-SHE**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHE**
Input parameter:	**Max CI**	**Max CI**	*Max CI per ts = coeffxLAI*	24 hr CI coeff$^{@}$	LAI	A-pan coeff	***Ref PET coeff***	LAI max	***Ref PET coeff***	**Ref PET coeff**	**Root depth = soil depth**	**Root depth = soil depth***	**Root depth*, max****	**Root depth***
Unit:	**mm/ day**	**mm/ day**	***mm/ day***	mm/ ts	m/m						**m**	**m**	**M**	**m**
Fynbos, woodland, seep	1.5	(0.7)	*(0.8)*				*(0.44)*		*(0.48)*	(0.47)	0.60	1.1	1.9	1.9
Fynbos		0.7	*0.9*	0.6	1.5	0.35	*0.42*	1.5	*0.50*	0.50		1.1	2.0	2.0
Fynbos – cliff, low- density			*0.2*	0.6	0.4			0.9	*0.30*	0.25			1.0	1.0
Riparian woodland		3.2	*1.8*	0.6	3.0	0.85	*1.02*	2.4	*0.80*	0.80		1.0	2.0	2.0
Wetland, seep		0.6	*0.6*	0.3	1.8	0.60	*0.72*	1.8	*0.60*	0.60		1.0	2.0	2.0
Wetland, palmiet		0.6	*0.6*	0.3	1.8	0.60	*0.72*	1.8	*0.60*	0.60		3.0	3.0	3.0
Irrigated agriculture		(1.3)	*(1.3)*				*(0.83)*		*(0.80)*	0.61		(1.0)	(1.1)	(1.1)
Pasture		1.3	*1.3*	0.5	2.5	0.68	*0.82*	2.4	*0.80*	0.60		1.0	1.0	1.0
Apple orchard		1.5	*1.5*	0.6	2.5	0.80	*0.96*	2.4	*0.80*	0.80		1.5	2.0	2.0
Invasive trees	2.1^{s}	(1.8)	*(2.5)*				*(1.07)*		*(1.00)*	(1.09)	0.60	(1.4)	(2.2)	(2.4)
Wattle		1.7	*2.5*	0.5	5.0	0.90	*1.08*	6.0	*1.00*	1.10		1.4	2.2	2.4
Pine		2.9	*2.5*	0.5	5.0	0.85	*1.02*	5.0	*1.00*	1.00		1.0	2.0	2.0

coeff = Coefficient; **ts** = Timestep; **ref PET** = Potential evapotranspiration for standard reference vegetation (FAO-56); ^{x}Maximum value allowed by tool; ^{S}SPATSIM: calculates afforested area CI and ET with an upscaling factor, WRSM uses a different method; *****Soil/root depth varied with topographic zone – values given here are area-weighted averages for type; **SWAT: access to ground water below soil is set with a separate parameter by topographic zone; $^{@}$MIKE-SHE: Fifferent timesteps in lumped (24 hour) and distributed (~2 hour) required different coefficients for same daily CI. **black text**: Values entered in model; **Blue text*:*** Values calculated from model inputs for comparison across tools, i.e. area-weighted averages for broader cover classes (shown in brackets), applying value conversions or model algorithms, e.g. in MIKE-SHE, Max CI = CI coefficient x LAI; in SWAT, ET coefficient = LAI/3 if LAI <3 or 1 if LAI ≥3); Grey shaded columns: comparable values/units

Table C20: Soil and unsaturated zone profile parameter values used in models of the Upper Kromme River catchment, area-weighted averages for broad zones

Land unit:	**All** (Area-weighted average)				**Floodplain, alluvial fan, palmiet wetland** (Area-weighted average)				**Upland** (Area-weighted average)			
Tool:	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**
n layers in profile	*1*	*2*	*2*	*1*	*1*	*2*	*2*	*1*	*1*	*2*	*2*	*1*
Lateral flow out of profile	*Yes*	*No**	*Yes*	*No*	*Yes*	*No**	*Yes*	*No*	*Yes*	*No**	*Yes*	*No*
Additional vadose or interflow layer below "soil" profile	*No*	*No**	*Yes*[**]	*Yes*[#]	*No*	*No**	*Yes*[**]	*Yes*[#]	*No*	*No**	*Yes*[**]	*Yes*[#]
Profile												
Profile depth (thickness), m	0.55	1.29	1.93	2.12	0.58	3.50	3.50	5.00	0.55	1.21	1.87	2.00
Storage at saturation, mm	202	513	756	788	250	1 498	1 496	2 138	200	476	726	733
Storage at field capacity, mm		235	350	366		796	779	1 118		213	319	319
Root zone												
Average root depth, m	0.55	1.29	1.82	1.84	0.58	3.50	2.39	2.84	0.55	1.21	1.07	1.80
Storage at field capacity, mm		235	328	331		796	537	636		213	194	335
Layer 1												
Layer bottom depth, mbgl		0.31	0.31	2.12		0.50	0.50	5.00		0.30	0.30	2.00
Layer thickness, m		0.31	0.31	2.12		0.50	0.50	5.00		0.30	0.30	2.00
Porosity		0.39	0.37	0.37		0.46	0.45	0.43		0.39	0.37	0.37
Field capacity		0.18	0.17	0.17		0.23	0.23	0.22		0.17	0.17	0.17
Wilting point		0.05	0.05	0.05		0.08	0.08	0.06		0.05	0.05	0.05
AWC		0.12	0.12	0.12		0.15	0.15	0.17		0.12	0.12	0.12
Ksat, mm/hour			23.5	15.2			24	175			23.5	8.7
Redistribution factor		0.54				0.49				0.55		

Land unit:	**All** (Area-weighted average)				**Floodplain, alluvial fan, palmiet wetland** (Area-weighted average)				**Upland** (Area-weighted average)			
Tool:	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**
Layer 2												
Layer bottom depth, mbgl		1.29	1.93			3.50	3.50			1.21	1.87	
Layer thickness, m		0.98	1.62			3.00	3.00			0.91	0.83	
Porosity		0.39	0.37			0.42	0.42			0.39	0.37	
Field capacity		0.18	0.17			0.23	0.22			0.17	0.17	
Wilting point		0.05	0.05			0.06	0.06			0.05	0.05	
AWC		0.12	0.12			0.17	0.17			0.12	0.12	
Ksat, mm/hr			25.9				27				25.8	
Redistribution factor		0.54				0.49				0.55		

mbgl = Metres below ground level; **AWC** = Available water holding capacity; **Ksat** = Saturated hydraulic conductivity; **Blue text:** Conversions, area-weighted and/or depth-weighted averages *ACRU4: Lateral routing included as upland HRU baseflow store into riparian HRU soil; **SWAT:Iinterflow from soil profile, additional vadose layer lags recharge to the aquifer;

#MIKE-SHEs: Single property layer subdivided into computational layers. Saturated zone profile overlaps unsaturated; no lateral flow if unsaturated.

Table C21: Soil and unsaturated zone profile parameter values used in models of the Upper Kromme River catchment for alluvial fill areas (4% of catchment)

Land unit:	**Floodplain, alluvial fan, palmiet wetland** (Area-weighted average)				**Floodplain**			**Palmiet wetland**			**Alluvial fan**	
Tool:	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**
n layers in profile	*1*	*2*	*2*	*1*	*2*	*2*	*1*	*2*	*2*	*1*	*2*	*1*
Lateral flow out of profile	*Yes*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*Yes*	*No*
Additional vadose or interflow layer below "soil" profile	*No*	*No**	*Yes***	*Yes#*	*No**	*Yes***	*Yes#*	*No**	*Yes***	*Yes#*	*Yes***	*Yes#*
Profile												
Profile depth (thickness), m	0.58	3.50	3.50	5.00	3.50	3.50	5.00	3.50	3.50	5.00	3.50	5.00
Storage at saturation, mm	250	1 498	1 496	2 138	1 480	1 480	2 000	1 650	1 650	3 000	1 475	2 150
Storage at field capacity, mm		796	779	1 118	770	770	1 100	1 015	1 015	1 500	700	1 000
Root zone												
Average root depth, m	0.58	3.50	2.39	2.84	3.50	2.32	2.82	3.50	3.00	3.00	2.32	2.82
Storage at field capacity, mm		796	537	636	770	510	620	1 015	875	900	464	564
Layer 1												
Layer bottom depth, mbgl		0.50	0.50	5.00	0.50	0.50	5.00	0.50	0.50	5.00	0.50	5.00
Layer thickness, m		0.50	0.50	5.00	0.50	0.50	5.00	0.50	0.50	5.00	0.50	5.00
Porosity		0.46	0.45	0.43	0.44	0.44	0.40	0.60	0.60	0.60	0.43	0.43
Field capacity		0.23	0.23	0.22	0.22	0.22	0.22	0.35	0.35	0.30	0.20	0.20
Wilting point		0.08	0.08	0.06	0.08	0.08	0.05	0.10	0.10	0.10	0.08	0.05
AWC		0.15	0.15	0.17	*0.14*	*0.14*	*0.17*	*0.25*	*0.25*	*0.20*	*0.12*	*0.15*
Ksat, mm/hr			24	175		24	*144*		20	*360*	24	180
Redistribution factor		0.49			0.50			0.40				

Land unit:	**Floodplain, alluvial fan, palmiet wetland** (Area-weighted average)				**Floodplain**			**Palmiet wetland**			**Alluvial fan**	
Tool:	**SPATSIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**
Layer 2												
Layer bottom depth, mbgl		3.50	3.50		3.50	3.50		3.50	3.50		3.50	
Layer thickness, m		3.00	3.00		3.00	3.00		3.00	3.00		3.00	
Porosity		0.42	0.42		0.42	0.42		0.45	0.45		0.42	
Field capacity		0.23	0.22		0.22	0.22		0.28	0.28		0.20	
Wilting point		0.06	0.06		0.05	0.05		0.10	0.10		0.05	
AWC		0.17	0.17		*0.17*	*0.17*		*0.18*	*0.18*		*0.15*	
Ksat, mm/hr			27			27			20		30	
Redistribution factor		0.49			0.50			0.40				

mbgl = Metres below ground level; **AWC** = Available water holding capacity; **Ksat** = Saturated hydraulic conductivity; **Blue text:** Conversions, area-weighted and/or depth-weighted averages *ACRU4: Lateral routing included as upland HRU baseflow store into riparian HRU soil; **SWAT: Interflow from soil profile, additional vadose layer lags recharge to the aquifer;

[#]MIKE-SHEs: Single property layer subdivided into computational layers. Saturated zone profile overlaps unsaturated; no lateral flow if unsaturated.

Table C22: Soil and unsaturated zone profile parameter values used in models of the Upper Kromme River catchment for upland topographic units (96% of area)

Land unit:	**Upland** (Area-weighted average)				**Kloof floor**			**Toeslope**			**Hillslope**			**Cliff**		**Plateau**		**Mountain**$^{@}$
Tool:	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**	**ACRU**
n layers in profile	*1*	*2*	*2*	*1*	*2*	*2*	*1*	*2*	*2*	*1*	*2*	*2*	*1*	*2*	*1*	*2*	*1*	*2*
Lateral flow out of profile	*Yes*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*No**	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*No**
Additional vadose or interflow layer below "soil" profile	*No*	*No**	*Yes***	*Yes*$^{\#}$	*No**	*Yes***	*Yes*$^{\#}$	*No**	*Yes***	*Yes*$^{\#}$	*No**	*Yes***	*Yes*$^{\#}$	*Yes***	*Yes*$^{\#}$	*Yes***	*Yes*$^{\#}$	*No**
Profile																		
Profile depth (thickness), m	0.55	1.21	1.87	2.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	2.00	2.00	1.00	2.00	2.00	2.00	1.14
Storage at saturation, mm	200	476	726	733	400	800	800	880	880	880	420	840	840	50	100	840	800	440
Storage at field capacity, mm		1 086	319	825	150	300	300	400	400	400	200	400	400	20	40	400	360	197
Root zone																		
Max root depth, m	0.55	1.21	1.07	1.80	1.00	2.00	2.00	2.00	1.50	1.50	1.00	2.00	2.00	1.00	2.00	2.00	2.00	1.14
Storage at field capacity, mm		213	194	335	150	300	300	400	300	300	200	400	400	20	20	400	360	197
Layer 1																		
Layer bottom depth, mbgl		0.30	0.30	2.00	0.30	0.30	2.00	0.30	0.30	2.00	0.30	0.30	2.00	0.30	2.00	0.30	2.00	0.30
Layer thickness, m		0.30	0.30	2.00	0.30	0.30	2.00	0.30	0.30	2.00	0.30	0.30	2.00	0.30	2.00	0.30	2.00	0.30
Porosity		0.39	0.37	0.37	0.40	0.40	0.40	0.44	0.44	0.44	0.42	0.42	0.42	0.05	0.05	0.40	0.40	0.39
Field capacity		0.17	0.17	0.17	0.15	0.15	0.15	0.20	0.20	0.20	0.20	0.20	0.20	0.02	0.02	0.18	0.18	0.17
Wilting point		0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.05	0.06	0.06	0.06	0.01	0.01	0.05	0.05	0.05
AWC		0.12	0.12	0.12	*0.10*	*0.10*	*0.10*	*0.14*	*0.14*	*0.15*	*0.14*	*0.14*	*0.14*	*0.02*	*0.02*	*0.13*	*0.13*	*0.12*
Ksat, mm/hr			23.5	8.7		80	3.6		10	36		20	0.36	50	0.18	15	11	
Redistribution factor		0.55			0.60			0.45			0.50							0.55

Land unit:	**Upland** (Area-weighted average)				**Kloof floor**			**Toeslope**			**Hillslope**			**Cliff**		**Plateau**		**Mountain**@
Tool:	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**	**SWAT**	**MIKE-SHEs**	**ACRU**
Layer 2																		
Layer bottom depth, mbgl		1.21	1.87		1.00	2.00		2.00	2.00		1.00	2.00		1.00		2.00		1.14
Layer thickness, m		0.91	0.83		0.70	1.70		1.70	1.70		0.70	1.70		0.70		1.70		0.84
Porosity		0.39	0.37		0.40	0.40		0.44	0.44		0.42	0.42		0.05		0.40		0.39
Field capacity		0.17	0.17		0.15	0.15		0.20	0.20		0.20	0.20		0.02		0.18		0.17
Wilting point		0.05	0.05		0.05	0.05		0.05	0.05		0.07	0.07		0.01		0.05		0.05
AWC		0.12	0.12		*0.10*	*0.10*		*0.15*	*0.15*		*0.13*	*0.13*		*0.02*		*0.13*		*0.12*
Ksat, mm/hr			25.8			80			15			20		50		20		
Redistribution factor		0.55			0.60			0.45			0.50			0.05				0.55

mbgl = Metres below ground level; **AWC** = Available water holding capacity; **Ksat** = Saturated hydraulic conductivity; **Blue text*:*** Conversions, area-weighted and/or depth-weighted averages *ACRU4: Lateral routing included as upland HRU baseflow store into riparian HRU soil; **SWAT: Interflow from soil profile, additional vadose layer lags recharge to the aquifer;

#MIKE-SHEs: Single property layer subdivided into computational layers. Saturated zone profile overlaps unsaturated; no lateral flow if unsaturated. @ACRU: Used one “mountain” soil type for fynbos

Table C23: Additional soil and vadose zone layer (below soil profile) parameter values used in models of the Upper Kromme River catchment

Land unit:	**All** (Area-weighted average)				**Floodplain, alluvial fan, palmiet wetland** (Area-weighted average)				**Upland** (Area-weighted average)			
Tool:	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**
Soil profile parameters												
Critical depth: wetness impacts surface runoff generation, m		0.2				0.5				0.2		
Storage in critical depth or top layer[%] at saturation, mm	*202*[%]	84	113[%]	788[%]	*250*[%]	228	227[%]	2 138[%]	*200*[%]	78	108[%]	733[%]
Rain threshold for surface runoff (min infiltration), mm/month	4.0				100				0			
Rain threshold for average infiltration rate, mm/month	407				600				400			
Distribution-average infiltration rate, mm/month	206				350				200			
Power, percolation rate equation	2.0				2				2			
Max percolation rate, mm/month	33.7				2				35			
Power, interflow rate equation	2.0				2				2			
Max interflow rate, mm/month	9.7				2				10			
Additional vadose or interflow layer below “soil” profile	*No*	*No**	***Yes***	***Yes***	*No*	*No**	***Yes***	***Yes***	*No*	*No**	***Yes***	***Yes***
Lateral interflow out of this layer			*No*	***Yes***			*No*	***Yes***			*No*	***Yes***
Layer bottom depth, mbgl				4.1				5.5				4.0
Layer thickness, m				1.9				0.5				2.0
Storage at saturation, mm				198				150				200
Specific yield				0.1				0.3				0.1
Vertical Ksat, mm/hour												
Power, percolation rate equation												
Delay in recharge, days			24				1				25	
Percolation time constant, days				240				2				250
Horizontal Ksat, mm/hour												
Power, interflow rate equation												
Delay in interflow, days												
Interflow time constant, days				10				1				10

Ksat = Saturated hydraulic conductivity; [x] Maximum value allowed by tool; [%] With different layering & approaches to infiltration calculation the ’top’ layer water storage capacity has different relevance to surface runoff generation across models; *ACRU4: Lateral routing is included from upland HRU baseflow store, below soil, into riparian HRU soil; **Blue text:** Values not directly input in model – area-weighted averages, unit conversions presented for comparison across models

Table C24: Aquifer parameter values used in models of the Upper Kromme River catchment

Land unit:	**All** (Area-weighted average)					**Floodplain** (Area-weighted average)					**Upland** (Area-weighted average)				
Tool:	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc[#]**
Storage parameters															
Bottom depth, mgbl	*	*	*	384	2399	*			8	10	*			400	2500
Max thickness, m	*	*	*	384	2399	*			8	10	*			400	2500
Depth to static water level (no flow), mgbl	74				288	50			8	10	75			400	300
Specific yield, m3/(m*m2)	0.007		0.012	0.012	0.009	0.001		0.3	0.3	0.2	0.007		5E-04	5E-04	0.001
Specific storage, /m					4E-05					1E-04					3E-05
Max storage, mm	*	*	*	287	2778	*	*	*	2 400	2 000	*	*	*	200	2814
Max storage available for outflow, mm	*	*	*	287	403	*	*	*	2 400	2 000	*	*	*	200	338
Inactive storage (flow threshold), mm				0	2 375				0	0				0	2 476
Flow rate parameters															
Transmissivity, m^2/d															
Horizontal Ksat, mm/hour					138					3499					0.004
Vertical Ksat, mm/hr					1					13					0.333
Fraction of store flow out /day		0.009					0.010					0.009			
Linear outflow constant, 1/days				1.4E-04				0.95	0				0.35	9E-06	
Linear outflow constant, days				11 0331				1.1	300				2.9	1E+05	
Power, GW-SW flow rate equation	3					3					3				
Max regional GW gradient	0.011					0.011					0.011				
Max discharge, mm/month															

Land unit:	**All** (Area-weighted average)					**Floodplain** (Area-weighted average)					**Upland** (Area-weighted average)				
Tool:	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**	**SPAT-SIM**	**ACRU**	**SWAT**	**MIKE-SHEs**	**MIKE-SHEc**$^{\#}$
Capillary rise / ET from aquifer store															
Max fraction of PET met by aquifer	0.03					*0.2*					0.02				
Max fraction of outflow diverted for **riparian area ET**				1					1					1	
Fraction of upland aquifer outflow routed to **riparian area soil**		1													

Ksat = Saturated hydraulic conductivity; * Tool does not include a limit on the total volume stored in the aquifer; $^{\#}$ Volume averaged properties across layers / formations included: tallus, Peninsula and Nardouw quartzites, Bokkeveld and Cedarberg shale aquicludes, **Blue text*:*** Values not directly input in model – area-weighted averages, unit conversions presented for comparison across models

Table C25: Modelled streamflow for the Upper Kromme River catchment for two different scenarios using four different modelling tools

Statistic	**Modelled streamflow, October 1960 to September 2018, for different land cover scenarios: Sc1 current cover; Sc2 IAP expansion**							
	SPATSIM		**ACRU**		**SWAT**		**MIKE-SHEs**	
	Sc1-CC	**Sc2-IAPx**	**Sc1-CC**	**Sc2-IAPx**	**Sc1-CC**	**Sc2-IAPx**	**Sc1-CC**	**Sc2-IAPx**
Annual stream yield (mm^3)								
Mean	54	23	53	29	45.7	36.2	45	31
Standard deviation	25	22	40	28	28	17	37	29
CV	0.46	0.97	0.76	0.97	0.61	0.47	0.83	0.94
Minimum	20	1	6	1	10	11	3	2
Maximum	129	79	158	108	125	84	141	105
Monthly streamflow (mm^3)								
Mean	4.5	1.9	4.4	2.4	3.8	3.0	3.8	2.5
Standard deviation	4.2	4.7	8.1	6.4	5.2	3.6	7.5	6.4
CV	0.92	2.50	1.83	2.66	1.38	1.19	2.00	2.53
Minimum	1.22	0.00	0.03	0.02	0.04	0.05	0.01	0.01
5th percentile	1.55	0.00	0.16	0.04	0.44	0.39	0.05	0.04
50th percentile	3.0	0.4	1.7	0.4	2.2	2.0	1.1	0.5
95th percentile	12.8	9.4	17.8	11.4	12.1	8.9	16.3	12.0
Maximum	33.8	47.9	75.1	65.0	49.4	29.7	70.3	61.4
Daily streamflow (cm)								
Mean			1.68	0.92	1.45	1.15	1.43	0.97
Standard deviation			7.63	6.50	4.04	3.20	6.97	6.37
CV			4.54	7.06	2.79	2.79	4.87	6.58
Minimum			0.01	0.01	0.00	0.00	0.00	0.00
5th percentile			0.04	0.01	0.07	0.06	0.01	0.00
50th percentile			0.51	0.11	0.73	0.61	0.15	0.06
95th percentile			4.6	2.2	4.2	3.4	5.0	2.8
Maximum			350.7	331.7	223.5	152.7	331.7	311.9

SPATSIM-PITMAN

Several important parameters in the Pitman model are conceptual, so that values could not be directly calculated from the available estimates of local vegetation, soil, and geology property values, although the parameter values are linked to these (Kapangaziwiri, 2007). Initial values were selected based on documented experience with the tool in similar settings, followed by a calibration procedure.

Structure and parameterisation

- **Model units and routing:** The catchment was represented by 33 subcatchments (Figure 5.26). These were based on the 11 MIKE-SHEs subcatchments, which divide the catchment along the west to east main valley. Each of these west-east subcatchments was subdivided into three additional subcatchments: the northern mountains (Suuranys, drier), the floodplain and the southern mountains (Tsitsikamma, wetter). For each set of three subcatchments, the outflow from the two mountain subcatchments was routed to the floodplain subcatchment. This was then routed to the next floodplain subcatchment downstream. This delineation allowed the north-south and east-west rainfall gradients to be directly represented.
- **Land cover:** Four land cover types were explicitly represented: lumped indigenous vegetation (fynbos, riparian forest) represented through the subcatchment ET parameters (canopy interception, ET decline coefficient), built-up area (Kareedouw town) represented by specifying a fraction of the subcatchment considered impervious, alien vegetation represented by specifying a fraction of the subcatchment area that is treed and the ratio of its ET rate vs the other vegetation, and irrigated areas represented by specifying the fraction of the subcatchment and the irrigation demand. Two additional “cover types” were included: farm dams and wetlands, which are both treated are water bodies rather than land units.
- **Soils:** Soils and highly fractured upper rock layers (interflow layers) were represented with the single, lumped soil storage unit per subcatchment. Mountain subcatchments were parameterised differently to floodplain subcatchments, with the floodplains having faster infiltration and a bit more soil storage.
- **Geology and aquifer:** Ground water recharge, storage and flow are represented at the subcatchment scale, and different parameters were assigned to mountain and floodplain subcatchments, while floodplains have a shallower water table.
- Capillary rise or vegetation access to ground water is only considered for a user-specified riparian zone area in the subcatchment, assumed to have a shallow ground water table. Any ET demand deficit for this area, after drawing from the soil, can be met by the aquifer store. This area is not assigned a distinct vegetation type of its own: it has the same ET parameters, including the proportion of alien vegetation, as the rest of the subcatchment. This riparian zone was the kloof floor topographic zone in the mountain subcatchments, and covered most of the floodplain subcatchments.
- **River channel network:** Each subcatchment automatically has a channel that collects and routes flows from upstream catchments. When modelled ground water levels are low, channel transmission losses can be calculated.

Adjustments to improve calibration

Potential parameter adjustments were tested using both the uncertainty module of SPATSIM, as well as by manual adjustment trials. In the uncertainty module, 1 000 parameter sets were generated from user input value ranges and tested for performance against the observed flow.

Scenario representation

- The alien vegetation expansion scenario was represented by increasing the IAP cover proportions in each subcatchment in accordance with the scenario map. This also entailed removing the wetland units that were converted to IAP stands in the scenario, effectively drying up and losing their water-storing function.

Main challenges

- The Kromme River's main valley floodplain is known to receive subsurface flow input from the mountain areas, which feeds the floodplain vegetation. This could be represented using SPATSIM's riparian zone in a subcatchment, which has ground water access. However, the floodplain and the mountain areas were in different subcatchments to allow representation of the spatial rainfall gradients. SPATSIM models subsurface flow between subcatchments, but it is difficult to parameterise for this appropriately. The alternative is to represent this as aquifer contributions to the channel flow within a subcatchment that can feed downstream areas through channel transmission loss and/or can feed model wetland units that are located on the channel network, which was done here.

ACRU4

Structure and parameterisation

- **Model units and routing:** The catchment was represented by 12 subcatchments. These were delineated following a similar strategy to the 33 subcatchments used in SPATSIM, longitudinal divisions along the catchment's length (west to east) and separation of the north and south mountains and the central floodplain, for the purpose of representing climate gradients. However, in this case, four rather than 11 longitudinal divisions were used to reduce the number of modelling units to set up and connect. Each subcatchment, in turn, comprised differing numbers of HRUs, representing areas of different land cover, soil, and topographic positions (Figure C8). The current cover scenario set-up had 46 HRUs
- Surface and shallow subsurface flows from HRUs were routed in parallel to river channel elements in their subcatchments, which were, in turn, routed to subcatchment "nodes". Aquifer outflows from upland HRUs were routed to riparian HRU soils. Aquifer outflows from riparian HRUs were routed to channels (Figure C8). In mountain subcatchments, riparian HRUs were used to represent kloof floor drainage lines, which could have indigenous fynbos seep wetlands, riparian forest or wattle invasions. In the floodplain subcatchments, riparian HRUs were used for palmiet wetland or wattle invasion areas. Because they were in a different model subcatchments to the mountains, the floodplain riparian HRUs could not receive subsurface routed flows, but could gain access to water coming from mountain subcatchments using channel overflow as a workaround.
- **Land cover and soil:** Because each HRU in the model is created, parameterised, linked and adjusted manually and individually in ACRU4 software, the number of land cover type, soil and topographic unit type combinations explicitly represented was reduced from the number in the original MIKE-SHE model to keep the number of HRUs manageable. For example, mountain fynbos was considered using one type of HRU, without differentiating rocky cliff areas or otherwise assigning different soils to different topographic units. Wattle HRUs in the mountain subcatchments had kloof floor soil, and those in the floodplain subcatchments had floodplain soil parameters.
- Land cover parameters were input by selecting relevant vegetation types included in the tool's in-built "compoveg" database as this had been used in the original MIKE-SHE model.
  - ***Root depth*** in ACRU is linked to HRU soil depth. This led to different root depths specified in ACRU rather than in MIKE-SHE and SWAT, in which these are separately input.
- The soil parameters required were mostly similar to those needed in MIKE-SHE and could be obtained directly from the available soil property estimates. MIKE-SHEs uses uniform soil properties in its two-layer profile (above and below the root zone), so the ACRU4 A and B soil horizons were given uniform properties. Initial soil profile depths were reduced compared to the MIKE-SHE set-up based on values from Autosoils and the ACRU quinaries database.

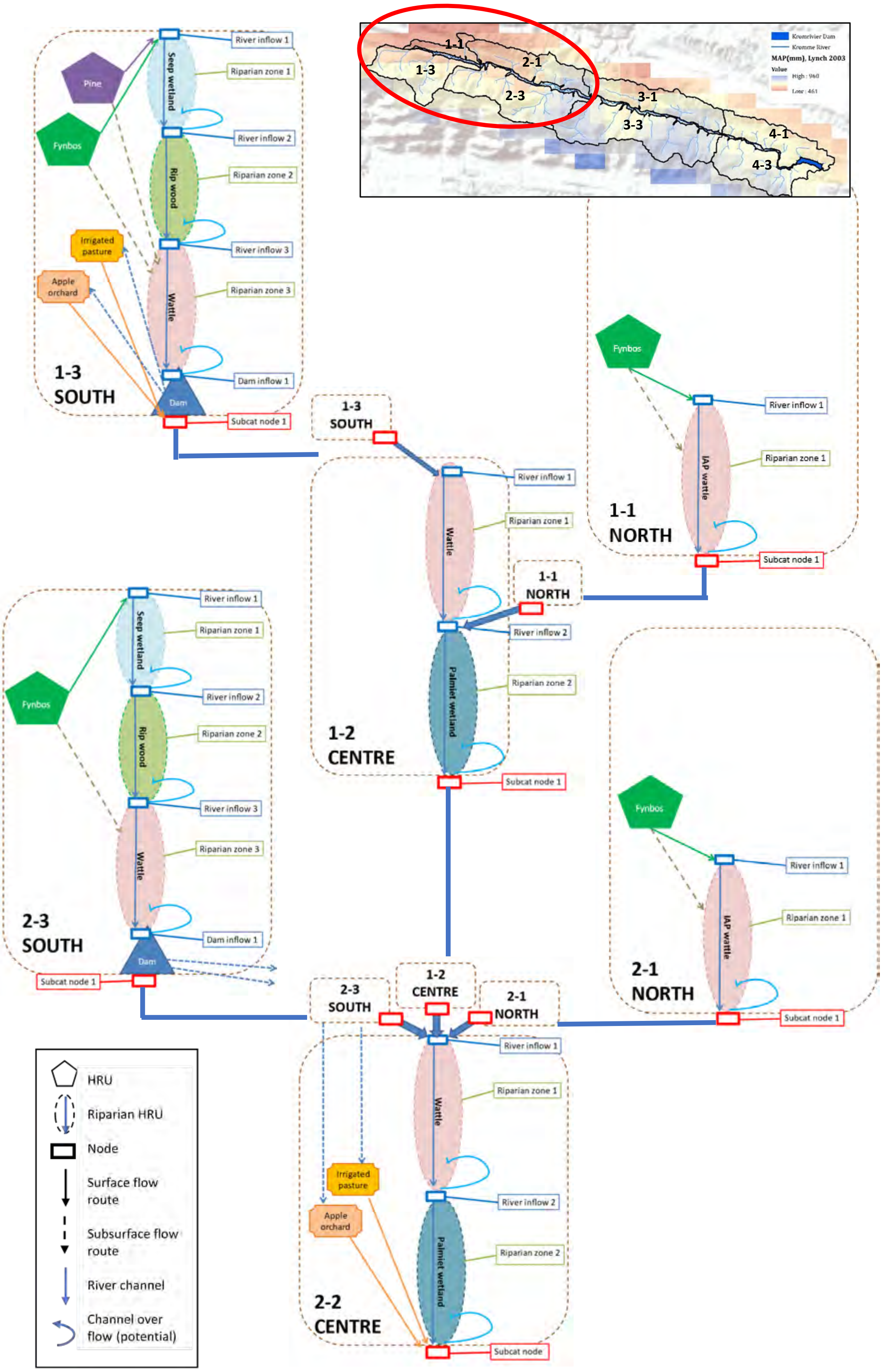


Figure C8: Schematic diagram of the model of the Upper Kromme River catchment built in ACRU4, showing only the upper six subcatchments

- **Runoff lag:** Surface and shallow subsurface runoff calculated for a storm event is routed to the stream with a lag determined by the "stormflow response fraction" parameter, the fraction runoff reaching the stream each day. This represents a combination of several landscape properties and processes: slope, roughness, flow path length, potential soil properties linked to interflow, etc. Based on ACRU modelling done for other catchments in the TMG region (Le Maitre et al., 2014; Warburton et al., 2012), this value was set to 0.5 for upland HRUs, meaning that 50% of "stormflow" runoff exits the catchment on the same day. A value of 0.3, the model default, was used for the floodplain HRUs based on their lower slopes, thicker vegetation and conductive sediment.
- **Geology and aquifer:** Aquifer storage and outflow are calculated for each HRU individually using a conceptual outflow rate coefficient. A slightly higher value than the default was used for the floodplain area (0.01 vs default of 0.009).
- **River channel network:** River channel units were defined in each subcatchment associated with each riparian HRU. Channel transmission loss is not calculated in the tool. However, the channel flow in excess of an input threshold is applied to the associated riparian HRU's surface, intended to represent overbank flooding. In this case, this mechanism was also assumed to represent the vegetation access of water fed by upland areas via surface and/or subsurface flow to the lowlands. For palmiet wetlands, which are unchannelled in the valley bottom, fed by the main river channel, the threshold for overflow was set to 0 cm.

Adjustments to improve calibration

Parameter value adjustments were manually set up and tested. The initial model set-up produced too little streamflow (only about half of the observed flow), so the following adjustments were made:

- Vegetation types in the compoveg database relevant to the cover types are mapped, but with lower ET coefficients selected. In particular, for the fynbos HRUs, the "Kouga grassy fynbos – degraded" type (mean K_c of 0.35), instead of the intact type (mean K_c of 0.5) was used. This was deemed appropriate because the rocky cliff areas, which have low vegetation density, had been lumped into the "fynbos" area to reduce the number of HRUs.
- To increase the flood peaks, the critical soil depth for runoff generation was reduced from the default thickness of the topsoil layer, 30 cm, to 20 cm, and the quickflow response coefficient (proportion of storm runoff leaving the catchment on the same day) was increased from the default 0.3 to 0.5 (50%).
- To increase baseflows, the baseflow response coefficient for riparian HRUs was increased from 0.009 to 0.01.

These changes greatly improved performance and fit, and actually resulted in slightly too much average runoff despite the highest daily peaks being underpredicted. The soil depths used in the ACRU4 set-up were quite shallower than those used in the MIKE-SHE and SWAT2012 models, initially done as a test, but kept because the initial model was predicting too little runoff. However, in the adjusted model, which overpredicted flow, increasing soil depth may have resulted in an appropriate reduction in runoff. This would store more water in the profile to feed ET instead of runoff. This was not tested due to time constraints and the adequate performance of the model compared to the other models in the case study.

Scenario representation

To model the alternative land cover scenarios, the land cover distribution within each subcatchment was recalculated and the HRUs used in the "current cover" model used for calibration were manually altered in accordance. Parameter values for the various land cover and soil types remained the same, but HRU areas were changed. Several riparian HRUs, which had been indigenous cover types, were completely deleted, which required rearranging the routing in the model.

Main challenges

- **Channel transmission loss** is not modelled, subsurface flow connections across subcatchments are not included, and climate is input by subcatchment. This led to trade-offs and workarounds to include the climate gradient and give the valley alluvial fill vegetation access to water coming from the mountain areas in separate subcatchments.
- **Conceptual parameters:** Several critical parameters (quickflow response fraction, critical soil response depth, baseflow response fraction) are relatively conceptual in that their values cannot be directly determined from physical data from the catchment, although different value ranges are suggested for different conditions. This means that a calibration exercise is needed to determine which value in the feasible range is best for a given catchment. This is a time-consuming activity when the model set-up is complex (many HRUs to manually adjust each time).
- **Model interface:** A high number of steps is needed to establish structure and connectivity, make and test adjustments, export water balance components and process them at a catchment scale. Very few actions can be "batched".

SWAT2012

Structure and parameterisation

- **Model units and routing:** The catchment was represented by 55 subcatchments (Figure C8), each comprising differing numbers of HRUs, representing areas of different land cover, soil and topographic positions. The current cover scenario set-up had 861 HRUs, created automatically by ArcSWAT2012 from overlaying maps of cover, soil and subcatchments. As with the other tools, the subcatchments were delineated to allow the north vs south and east vs west rainfall gradient to be explicitly included. Unlike ACRU4 or SPATSIM, or even the simple options for MIKE-SHE, where the user inputs the subcatchments manually, when using ArcSWAT2012, the typical approach is to delineate subcatchments from the input DEM within the tool itself. This meant that, in order to represent the drier northern Suuranys mountain areas separately from the wetter southern Tsitsikamma mountain areas, because of the catchment's trellis drainage pattern out of these parallel mountain ranges, subcatchments for each major mountain tributary leaving these mountains had to be delineated (Figure C8).
    - While it was time consuming to select the 55 drainage end points to delineate these subcatchments, the alternative would have been the careful preparation of a more conceptual subcatchment GIS shapefile, like those used for ACRU4 or SPATSIM (Figure C8), in which several parallel mountain tributaries have been lumped. This user-input subcatchment shapefile would need to have an attribute table with all the meta-data SWAT2012 requires, such as connections and slopes, which the tool will create itself when the subcatchments are delineated from the DEM in the tool. This preparation would have taken at least as much time, if not more, depending on the number of subcatchments included.
- HRU surface flow and interflow are automatically routed in parallel to the subcatchment's river channel. Water percolating from the bottom of an HRU soil profile recharges a subcatchment-scale aquifer store, from which outflow is routed to the subcatchment channel.
- **Land cover and soil:** Because the SWAT2012 HRUs are automatically generated and parameterised based on cover and soil type, the same cover type and soil type (based on topographic units) and soil type maps were input as were used in the original MIKE-SHEs model.
- Starting parameter values for cover types and soils were also taken from the original MIKE-SHEs model.
    - **ET (crop) coefficient (K_c):** When using alternative methods other than the full Penman-Montieth method to calculate AET, SWAT2012 calculates reference vegetation PET and modifies this using an ET coefficient (K_c), internally derived based on vegetation LAI. As such, input LAI values were selected to produce K_c values matching those input in MIKE-SHE. The LAI values are not used for other hydrological processes in the model.

The algorithm for calculating K_c in SWAT2012 limits K_c to a maximum value of 1, so the invasive wattle had a lower K_c in the SWAT2012 model than in MIKE-SHE or ACRU4.

  - SWAT calculates HRU LAI daily based on inputs of maximum LAI for the vegetation, dormancy LAI and growth parameters. The maximum dormancy LAI input is 0.98. However, for non-agricultural cover types, the growth curve and management parameters were set to ensure that the model considered vegetation to be mature throughout the simulation.
- **Root depth:** Maximum root depth was input to match the MIKE-SHE root depth. Root depth is also calculated daily based on vegetation growth curves, so these growth curve parameters need to be set to maintain mature vegetation cover across the simulation for the non-agricultural types.
- The MIKE-SHEs model uses uniform soil properties over the full depth of its unsaturated zone profile. The same was done for SWAT2012. However, two layers were created to establish a differential wetness profile, as in the ACRU4 model, as this may influence runoff. An initial trial was performed using the shallower soil depths from the Autosoils database, as was used in ACRU4. However, this produced far too much runoff, compared to using the depths included in MIKE-SHEs.
  - SWAT2012 uses wilting point, field capacity and saturation soil moisture in its soil water movement calculations. However, these water retention properties are not directly input by the user. The tool uses in-built pedotransfer equations to calculate these values based on user input bulk density, available water holding capacity and percentage clay content. Values for these inputs were back-calculated using the water retention properties explicitly input in the other tools.
- SWAT2012 uses the input saturated conductivity (K_{sat}) to calculate vertical and horizontal flow in soils. However, it uses the empirical SCS-CN method to calculate infiltration (and interception) versus runoff production during rainfall events. Initial CN values were selected based on suggestions in the model documentation for broad vegetation structural types (Arnold et al., 2012). MIKE-SHEs uses K_{sat} to calculate infiltration, so the values used in that model were influenced by the parameter impact on surface runoff generation and peak flows, while in SWAT2012, K_{sat} has a larger influence on interflow and storage in soil for ET, validating the selection of different values compared to the MIKE-SHEs model.

- **Geology and aquifers:** Ground water recharge, storage and flow are represented at the subcatchment scale. As in the MIKE-SHEs model, mountain area aquifer parameters were selected to represent the TMG bedrock, while valley floor area aquifer parameters represented the alluvial aquifer, with faster recharge and faster drainage.
- Capillary rise or vegetation access to ground water can be represented for any HRU in the model by specifying the maximum proportion of the ET demand that can be met by drawing from the aquifer store, with values between 0.02 to 0.2 (2–20%) allowed. Areas considered riparian (kloof floor and main valley floodplain HRUs) were assigned the highest value, representing a shallower ground water table.
- **River channel network:** SWAT2012 automatically includes one main river channel unit per subcatchment.
  - **Channel transmission loss** was explicitly included for channels in the central floodplain subcatchments, with a channel bed conductivity of 25 mm/hour selected based on suggested values for sandy loam in the tool's input/output documentation (Arnold et al., 2012). This was included to allow central valley floodplain areas to access water from channel flows fed by the mountain subcatchments. This is a partial workaround to represent the subsurface flows from the mountain areas to the central valley areas, which cannot be explicitly included when these areas are different subcatchments.
    - **Palmiet wetlands**, which are unchanneled on the main river line, were set up with wide, rough channel cross-sections as done in the MIKE-SHEs model. They were given low rates of drainage for their "bank storage", which is the storage fed by channel transmission loss in SWAT2012, allowing this water to feed ET.

Adjustments to improve calibration

The initial model set-up produced far more runoff than observed. As mentioned above, using the soil depths from the MIKE-SHEs set-up, rather than the Autosoils values, improved this, bringing runoff down significantly. SWAT-CUP was then applied using 1 000 runs to look at proportional changes to the CN parameters, soil conductivity and ground water drainage parameters, as these were considered to be significant parameters not directly linked to the values selected in the other models. The process showed that the model was the most highly sensitive to CN values, while a wide range of soil and ground water parameter adjustments produced equal performance outputs. The suggested optimised CN values were actually below the minimum value the SWAT2012 interface will allow to be entered (35). Additional parameter value adjustments were also manually set up and tested. The following adjustments were accepted as improving performance:

- Reducing curve numbers to reduce surface flow so more water is available for ET.
- Reducing soil conductivity so that more water is held in the soil and available for ET. Once this was reduced, curve numbers above the minimum were successful and needed to improve the fit to the peak flows.
- Increasing mountain aquifer drainage speed (decreasing recession constant parameter, one/days) compared to the model default (the alluvial aquifer was already set up to be fast draining).

Scenario representation

The land cover scenarios were modelled by inputting different land cover maps and removing the channel parameterisation (wide, flat, rough transmission loss with slow bank release) applied to the reaches that comprised palmiet wetlands in the current cover model (see above). Parameterisations of each vegetation type remained constant, but the area and spatial distribution of each type changed.

Main challenges

- No subsurface connection across subcatchments and climate inputs were given by subcatchment. Because the climate inputs are specified by subcatchment and because of the shape of the Kromme River catchment and its rainfall gradients, the central valley floodplain of the Kromme River was delineated in separate subcatchments to the mountain areas as such channel transmission loss was used to give the floodplain areas access to water from the mountains. However, it was not clear if the amount achieved was realistic. It was difficult to determine how much ET from the channel bank storage was actually modelled because this was not directly output.
- SWAT-CUP is a separate software program and runs the SWAT2012 algorithms without using the ArcSWAT2012 user interface. As such, it can apply parameter values that the ArcSWAT2012 interface will not accept.

C4: MIDDLE LETABA RIVER CATCHMENT (B82A-D) LIMPOPO: IRRIGATION FROM FARM DAMS AND GROUND WATER, CHANNEL TRANSMISSION LOSS

- **Catchment description and modelling goals** are given in the main report, section 5.6.1.
- **Model units and main parameter values** used across the different models are given in tables C26 to C32.
- **Performance of the models compared to observed streamflow** is described in the main report, section 5.6.5.
- **Model outputs, including water balances**, are compared and discussed in the main report, section 5.6.5. A summary of the streamflow output for each tool for each scenario is given in Table C33.

The text sections describe the different model structures, summarise the rationale for structure and parameter decisions, and highlight the main challenges encountered. Approaches common across tools and the set-up of the pre-existing model, which was used as a reference, are described first, followed by structure and parameter value tables, and then by descriptions of the models built with and/or proposed for the other tools. In addition to the reference model in WRSM-Pitman, only the SWAT2012 models of the baseline and alternative scenarios were completed. The team discussed potential model structures using the other tools, but which were not completed due to complexities of representation and insufficient time to test approaches and complete calibration:

- SPATSIM-Pitman does not include irrigation directly from ground water. A similar approach as used in WRSM-Pitman could have been applied: ground water withdrawal in equal amounts to irrigation applied from an external source.
- ACRU4 is not able to include ground water withdrawal. However, an ACRU4 model with only surface water irrigation could be compared to and potentially calibrated against the surface water irrigation only scenario models in the other tools.
- The complexity of methods for including small farm dams that can be used as irrigation sources in the MIKE-SHE models meant there was insufficient time to complete the set-up.

GENERAL APPROACHES COMMON ACROSS TOOLS

- The pre-existing model of the catchment built in WRSM-Pitman (Haasbroek et al., 2015) was the reference for building models using the other tools.
- Calibration was done by comparing model streamflow output for the 1 805 km^2 catchment area of the Middle Letaba Dam to the estimated inflow into the dam for October 1992 to September 2008 to inform adjustments.
- For scenario comparisons, models were run for 1979 to 2011 based on available daily climate data, and outputs were compared for the 1983 to 2011 water years to allow a five-year model warm-up.
- The 1 805 km^2 catchment area used includes the area covered by the Middle Letaba Dam itself. The reasons for not attempting to exclude the surface area taken up by the dam in this case is that the maximum dam surface area is 19.2 km^2 (Haasbroek et al., 2015), which is only 1% of the total catchment area. Because the area is relatively dry and the bathymetry of the dam is relatively wide and shallow, the dam's surface area is generally much less than this and closer 5 km^2 on average. In addition, this was the approach taken in the WRSM-Pitman model.

Spatial rainfall distribution

The pre-existing WRSM model used the four quaternary catchments, B82A–D, as a base. As such, the rainfall and evaporative demand values were assigned for this scale. The topographic gradient from the escarpment to the lowland results in a rainfall gradient across the catchment: estimated mean annual precipitation (MAP) of 1 300 mm in the escarpment, down to 440 mm in the lowland (Lynch, 2003).

Because each quaternary included both escarpment and valley or lowland areas, its spatially averaged MAP values only varied by about 100 mm, with the highest being 712 mm and the lowest being 615 mm. This quite highly averaged distribution was also applied to the models built in the other tools, both to keep the number of modelled units manageable in the more manually set-up tools, and to have valley floor areas hydrologically connected to uplands in tools where climate is input by subcatchment. Daily climate data obtained for stations was rescaled to match the annual averages in the dataset used in the initial WRSM model.

Topographic zones and soils

The quaternary scale of the WRSM model meant that variations in soils across topography and geology were largely averaged out. To explicitly include this in models with finer spatial discretisation, despite limited data, four topographic units were delineated: uplands, midlands, lowlands and riparian areas. Uplands, midlands, and lowlands were delineated using a 30 m DEM obtained from ALOS (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm) and calculating a topographic position index (Dilts, 2010; Jenness, 2006) using a 100 km analysis window. These units aligned well to ARC land unit borders, which are delineated similarly. The riparian terrain unit from the ALOS terrain product was overlaid on the midlands and lowlands. This was based on a visual analysis of aerial photography: the lower riparian areas appeared much greener than their surroundings. This riparian zone covered roughly 7% of the catchment, in line with the 9% riparian/ground water access area in WRSM. Starting values for soil properties were assigned based on values in the AutoSoils and ARC land type databases, as well as local literature (Dippenaar et al., 2010; Holland, 2011; Riddell et al., 2017; Walker et al., 2018)

Riparian zone water access

Vegetation in the delineated riparian topographic unit was assumed to have greater access to subsurface water for ET than other areas. In similar conditions, in a neighbouring catchment, Walker et al. (2018) found that bed loss into the sandy riparian alluvial deposit can support a shallow (<1 m), potentially perched water table. The riparian zone was represented in all the models, although they use different approaches:

- **WRSM, SPATSIM, simpler MIKE-SHE:** Specified riparian sub-areas within subcatchments' (WRSM "runoff modules") access subcatchment aquifer storage to meet ET demand not met by soil storage.
- **SWAT:** Riparian HRUs were given greater access to subcatchment aquifer storage to meet ET demand than upland HRUs.
- **ACRU4:** Aquifer or "baseflow" outflow from upland HRUs was routed to the lower soil layer of riparian HRUs. Associated river channel overflow adds water to the surface.
- **Complex MIKE-SHE:** Topography is explicitly included in the routing surface and subsurface flows, so that modelled water tables can be shallower and soils wetter at low points in the topography.

Channel transmission loss

The sandy channels in the lower topography in this region are known to have significant channel transmission losses (Riddell et al., 2017; Walker et al., 2018). An effort was made to represent this in all the models, although they use different approaches:

- **WRSM:** Channel transmission loss rates (mm^3/month) specified for channel modules' lower channel reaches. This water leaves the model, so can be assumed to feed ET or recharge an aquifer that does not supply channels elsewhere in the area modelled.
- **SPATSIM (and WRSM within runoff modules) and complex MIKE-SHE:** Exchange between ground water and the channel is determined by the estimated gradients between them.
- **Simpler MIKE-SHE:** Channel bed conductivity is specified, and water is added to the lowest subcatchment aquifer ("baseflow reservoir").

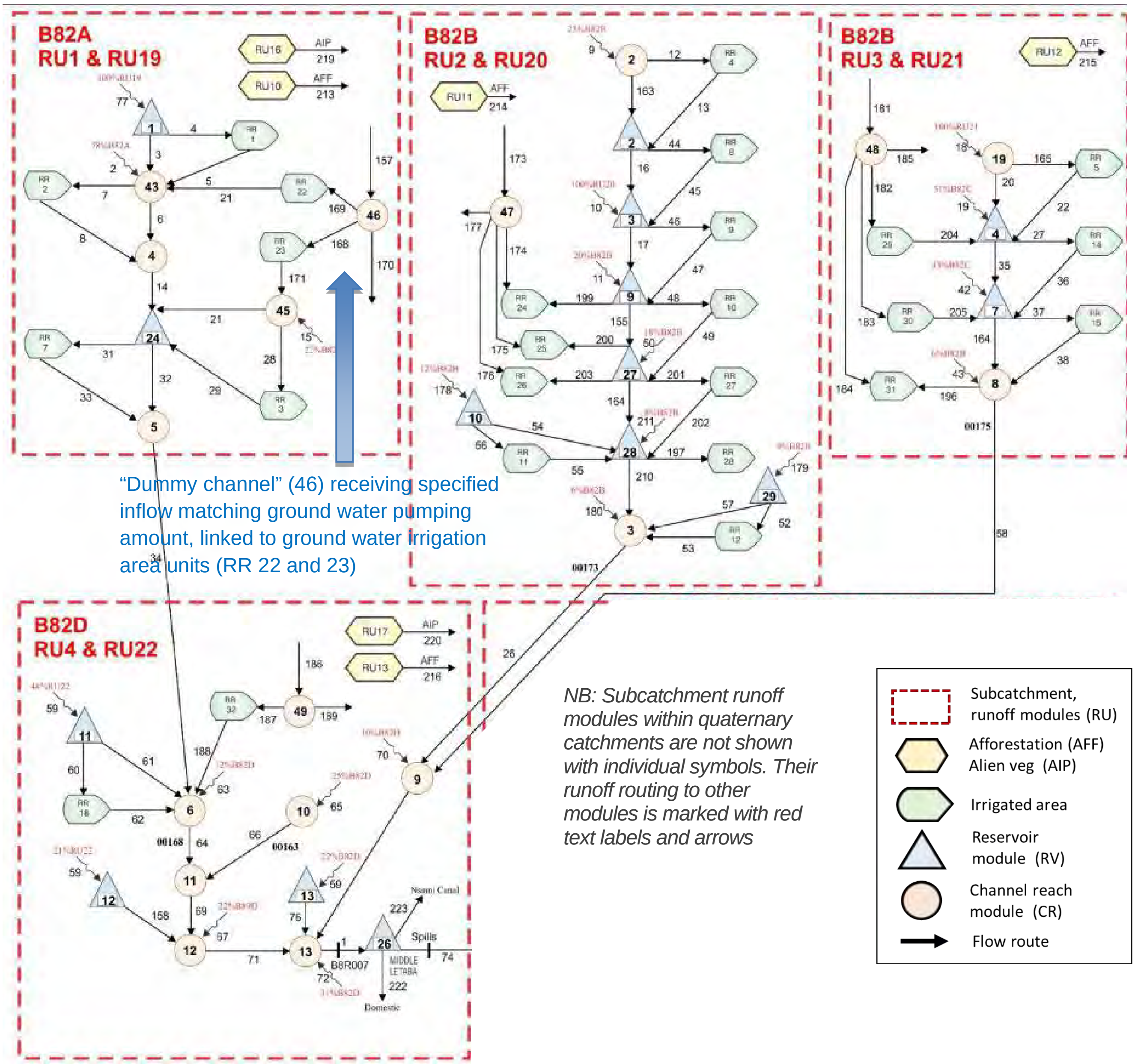
- **SWAT:** Channel bed conductivity is specified. Bed loss water is added to a bank storage with a re-release rate into the channel. In theory, this water is available for ET to riparian HRUs, but it is not clear how these are specified. A proportion can be routed to the deep aquifer (no further interaction), which would effectively mimic ET loss.
- **ACRU4:** Channel transmission loss cannot be explicitly represented. However, channels associated with riparian HRUs can overflow onto the HRU surface. Channel capacities in lowlands were set to 0 so that all channel flow was spread onto the riparian HRU surface (a relatively small area), effectively acting as the channel bed.

Land cover

The WRSM model from Haasbroek et al. (2015) had variable areas of irrigated crops (and farm dam sizes), forestry plantation and invasive alien vegetation over time over a model run from 1920 to 2011. This is not a common option or simply operationalised in the other tools, so an adapted version was made with fixed values. Values from 1998 to 1999 were used, close to the middle of the 1992 to 2008 calibration period. Haasbroek et al. (2015) provided the irrigated field and forestry plantation shapefiles used. While 23 crop types were mapped, the WRSM model used one composite crop type with irrigation demand externally calculated in SAPWAT. Irrigated areas were classed into three generalised crop types for use in other tools that require more detailed vegetation parameters. These were tomatoes and summer vegetables, pumpkin and autumn vegetables, and fruit and nut orchards (mango, avocado, macadamia). These were used in combination with the NLC dataset (DEA, 2019) to make a land cover map that could be used in the other tools. The NLC had 48 land cover types, which were generalised to 8 to 10 types for use in other tools (see Table C26).

Lumped representation of small farm dams

The NLC dataset indicates that there may be more than 150 small water storages in the catchment. In the WRSM model, these were lumped into 14 larger dams, which were explicitly represented. A lumped representation of these storages was also used in the other tools, with further lumping into eight dams in ACRU4 because each would need its own set of contributing HRUs, manually set up.



“Dummy channel” (46) receiving specified inflow matching ground water pumping amount, linked to ground water irrigation area units (RR 22 and 23)

NB: Subcatchment runoff modules within quaternary catchments are not shown with individual symbols. Their runoff routing to other modules is marked with red text labels and arrows

Figure C9: WRSM model structure for the Middle Letaba catchment (Haasbroek et al., 2015)

STARTING REFERENCE MODEL: WRSM-PITMAN, SAMI GROUND WATER

A model of the catchment area feeding the Middle Letaba Dam was built in WRSM-Pitman by Haasbroek et al. (2015) as part of the DWS Reconciliation Strategy for the Luvuvhu and Letaba Water Supply System. Further details about the set-up can be found in the project reports: http://www.dwa.gov.za/Projects/Luvuvhu/documents.aspx. There was explicit inclusion of irrigation from ground water, despite the WRSM-Pitman tool not catering for this directly.

Structure and parameterisation

- **Model units and routing:** The catchment of the Middle Letaba Dam was subdivided into four quaternary catchments (B82A, B, C and D), with each one delineated further into an upper and main/lower portion. The resulting eight subcatchments were represented with “runoff modules”.
- The model included 14 reservoir modules representing farm dams. Reservoir modules can be fed by channel modules, irrigation area return flow and user-input proportions of the outflow from one or more runoff modules. Runoff from the upper and lower subcatchments was routed to different reservoirs, representing dams located along tributary streams in the highlands and dams along the main river in the valley floor. The smaller “upland” runoff modules had linked commercial forestry and alien vegetation “child modules” to represent the additional ET from treed areas. The larger “lowland” runoff modules had linked irrigation modules, each set up to draw irrigation water from a different source: a river channel, reservoir or ground water “dummy channel” module (Figure C9).
- **Land cover:** Four broad land cover types were explicitly represented. Lumped indigenous woodland, subsistence agriculture and medium-density residential areas were represented as one through the runoff modules’ general ET parameters (canopy interception, evaporation pan factors, ET decline coefficient). Lumped irrigated agriculture was represented with irrigation modules. Commercial timber plantation (mostly eucalyptus) was represented with afforestation modules. Alien vegetation infestation was represented using the alien vegetation modules.
- No impervious cover was explicitly considered, although 6% of the catchment was mapped as medium-density residential and 1% as bare, rock or paved in the NLC dataset (DEA, 2019). Impervious cover would therefore be represented implicitly in other parameter values (i.e. infiltration rate parameters).
- Irrigated areas, tree plantations and IAP areas were mapped and input for each subcatchment, but the general “runoff module” ET parameters were the same across the eight subcatchments. The NLC dataset showed composition differences across the quaternaries for this area that were represented by the runoff module ET parameters (i.e. the non-treed, non-irrigated portion). The proportion of medium-density residential area ranged from 1 to 12% of this portion, and subsistence agriculture ranged from 8 to 16%. Using the same parameters across the subcatchments assumes that it is of low importance to represent these spatial composition differences explicitly when trying to model processes at the scales of interest.
- Individual crop types were not represented separately. However, the demand by each crop type was calculated outside of the model using SAPWAT. An area-weighted average water demand across crops was used. All irrigation modules in a subcatchment had the same “composite crop” water demands, but values differed across the quaternaries. This represents the spatial distributions of different crops and differing climate factors used in SAPWAT by quaternary.
- **Soils:** Soil types and the fractured rock layer were represented with the single, lumped soil storage unit per “runoff module” (subcatchment). Soil parameters were relatively similar across subcatchments, with all having a minimum infiltration (ZMIN) of 50 mm/month, a threshold for surface runoff and a maximum profile storage (ST) of 750 mm, except B82 D, which had 700 mm (Table C30). The “upland” subcatchments had higher maximum interflow rates (8 mm/month), while the lowest main subcatchment had the lowest maximum rate (2 mm/month). This represents material, slope and slope length.

- **Geology and aquifer:** Ground water is represented with a lumped aquifer storage unit by subcatchment. Parameters were relatively similar across subcatchments, with all having the same transmissivity (10 m^2/day) and maximum outflow rate (5 mm/month). However, B82C and B82B were assigned slightly more storage in their vadose "percolation store", storativity and thickness in their aquifers, and faster recharge than the others. These two have more granite in their escarpments, while the rest of the area is predominantly gneiss. Quaternaries also differed in how much ground water storage is needed for aquifer outflow, with B82D requiring the most, 130 mm, and B82A the least, 80 mm.
- For "lower" subcatchments or runoff modules, 10% of the area was considered riparian (access to ground water for ET), while for "upper" ones, this was 5%.
- **River channel network and channel transmission loss:** Channel reach modules were used to aggregate flows and no lags were introduced. Within runoff modules, two-way exchange between an implicit subcatchment channel and the aquifer is calculated based on comparative levels. In addition, channel transmission loss rates were also specified on the lowest channel modules in the three upper subcatchments (B82A–C) and the main connecting channels through the downstream B82D. Rates varied from 0.02 mm^3/month for the upper channels to 0.15 mm^3/month in the most downstream channels.
- **Irrigation:** Each irrigation module can only be supplied by one source, in this case either a reservoir module, a normal channel module, or an "external source" channel module set up to represent ground water (Figure C9). A ground water withdrawal series was specified for each of the lower/main runoff modules in a quaternary. These amounts were then input as an external water source series added to a channel module. Based on trials estimating the surface water shortage for the irrigation demand, it was estimated that one third of the irrigation comes from ground water (Haasbroek et al., 2015). To represent this, one third of the irrigated area was assigned to these ground water "external source" modules. The ground water withdrawals were based on the estimated demand and capped at the harvest potential estimated for the aquifer (from GRA II). Water entering the "external source" ground water channel module that is not drawn by the irrigation module flows out of the model rather than joining the channel network.

Adjustments to improve calibration

No calibration was attempted beyond what was done by Haasbroek et al. (2015). The only change made to the model was to hold the irrigation, tree plantation, invasive alien and dam areas constant over time at 1998 to 1999 levels, as described above.

Scenario representation

- **Surface water irrigation only, no irrigation from ground water:** The ground water abstractions from the runoff modules were removed, the "external source" channels were removed and the irrigated area in the modules fed by ground water were removed, with their area subdivided across the other irrigation modules in the subcatchment so that the total irrigated area in each subcatchment remains the same.
- **No irrigation:** Set the irrigation demand to zero in the irrigation modules.

Main challenges

- **Irrigation from ground water workaround:** A challenge in the ground water withdrawal plus external water source approach to representing irrigation from ground water in WRSM is that the amount potentially pumped and the amount supplied are predetermined and separate. If the amount drawn from the aquifer in the model is more than is actually needed for the irrigated area, the excess leaves the model. Excess extraction could artificially decrease aquifer outflow to the channel in the model. Similarly, if storage in the aquifer drops in the model, the amount actually withdrawn may be less than the amount specified in the set-up. This would mean that the predetermined amount of water separately made available for irrigation via the "external source" input would be more than what was actually pumped. To avoid these issues, the demand of the irrigation area can be determined using a model run, and the "external source" input can be adjusted if it is found that there are times with a shortfall in modelled aquifer storage. However, this iterative process of establishing a workable ground water withdrawal/external water source set would need to be done each time a relevant parameter or other aspect of the model is changed (e.g. a longer model run, different rainfall input, adjust crop parameters, adjust ground water parameters to improve calibration, etc.).

Table C26: Numbers and sizes of model units and types included in models of the Middle Letaba catchment

Modelled units	**Number *or average size (km^2)* of units**		
	WRSM	**ACRU**	**SWAT**
Catchment area (km^2): 1805			
Subcatchments	8	4	17
Average subcatchment size	*226*	*451*	*106*
HRUs		32	320
Average HRU size		*0.25*	*0.06*
Cover types	3	8	10
Soil types	3	3	4
Topographic zones	3-4*	3	4
Aquifer types	4	1	1

* WRSM model had three sets of soil parameters following topographic position: upper runoff modules in quaternaries, lower/main runoff modules in the upper three quaternaries (B82A–C), and lower/main runoff module, lower quaternary (B82D). Each module had a riparian zone, another representation of topography.

Table C27: Soil types explicitly modelled for the Middle Letaba catchment using different modelling tools

Soil type / topographic unit			**Area (km^2)**			***Percentage of catchment***		
WRSM	**ACRU**	**SWAT**						
Upland*	Upland[#]	Upland	138	368	490	*8%*	*20%*	*27%*
Midland*		Midland	1067		518	*59%*		*29%*
Lowland*	Mid/lowland[#]	Lowland	600	1318	674	*33%*	*73%*	*37%*
	Riparian	Riparian		119	119		*7%*	*7%*
Total			**1805**					

* WRSM: "Upland", "midland", "lowland" refer to different delineations vs other tools. In WRSM, soil parameters are input by runoff module (subcatchment), each of which includes multiple topographic zones. "Upland" refers to more upland runoff module vs other modules, etc.

[#] ACRU: The DEM-based topographic unit delineation was the starting point. However, to make HRUs, vegetation-soil combinations, as well as above and below farm dam areas, were generalised, resulting in a different split into three parameterised soil types vs SWAT, which used the DEM-based units unaltered.

Table C28: Land cover types explicitly modelled for the Middle Letaba catchment using different modelling tools

Cover type			**Area (km^2)**			***Percentage of catchment***		
WRSM	**ACRU**	**SWAT**						
Non-irrigated, non-forested cover			1 607.8			*89.1%*		
	Woodland (arid lowveld)	Woodland (arid lowveld)		1 306.0	1 293.3		*72.4%*	*71.7%*
	Subsistence farming	Subsistence farming		200.6	190.4		*11.1%*	*10.6%*
	Residential	Residential		101.2	101.2		*5.6%*	*5.6%*
		Bare/rock/paved			11.3			*0.6%*
Irrigated crops*	Irrigated crops*		146.4	146.4		*8.1%*	*8.1%*	
		Irrigated crop 1, tomato and summer vegetables			121.0			*6.7%*
		Irrigated crop 2, pumpkin and autumn vegetables			12.9			*0.7%*
		Irrigated crop 3, fruit and nut trees			12.2			*0.7%*
Commercial forestry	Commercial forestry	Commercial forestry	29.2	29.2	28.5	*1.6%*	*1.6%*	*1.6%*
Invasive alien vegetation	Invasive alien vegetation	Invasive alien vegetation	21.6	21.6	21.4	*1.2%*	*1.2%*	*1.2%*
		Dam – open water			9.2			*0.5%*
(Dam[#])	(Dam[#])	(Dam[#])	(3.4)	(3.4)	(3.4)	*(0.2%)*	*(0.2%)*	*(0.2%)*
Total			**1805**					

*Parameterised as area-weighted average of multiple crop types

[#] Farm dams as a water body, not as cover types. Maximum surface areas listed. Excludes the Middle Letaba Dam

Table C29: Vegetation parameter values used in models of the Middle Letaba catchment (ACRU4 not yet calibrated, shown for reference)

Process:	**Canopy interception (CI)**		**Evapotranspiration (crop) coefficient, K_c**								**Root depth**			
Modelling tool:	**WRSM**	**ACRU**	**WRSM**			**ACRU**		**SWAT**			**WRSM**	**ACRU**	**SWAT**	
Input parameter:	**Max CI**	**Max CI**	S-pan coeff	A-pan coeff	***ref PET coeff***	A-pan coeff	***ref PET coeff***	LAI max	*LAI ave$^{\#}$*	***ref PET coeff***	**Root depth = soil depth**	**Root depth = soil depth***	**Root depth, max****	**Root depth, ave$^{\#}$****
Unit:	**mm/ day**	**mm/ day**									**m**	**m**	**m**	**m**
Non-irrigated, non-forest	1.5	(1.8)	0.93	0.74	*0.89*	(0.54)	*(0.65)*			(0.74)	1.70	(0.79)		(2.80)
Woodland (arid lowveld)		2.0				0.56	*0.67*	2.25	*2.25*	0.75		0.78	3.00^x	*3.00*
Subsistence farming		0.6				0.40	*0.48*	2.70	*2.70*	0.90		0.82	2.00	*2.00*
Residential		2.2				0.65	*0.78*	2.13	*1.10*	0.37		0.82	2.00	*2.00*
Bare/rock/paved										0.10				
Irrigated crops		1.3	*0.82*	*0.65*	*0.78*	0.68	*0.82*			(0.32)	1.70	0.82		(0.56)
Irrigated crop 1 (tomato)								3.00	*0.76*	0.25			1.50	*0.38*
Irrigated crop 2 (pumpkin)								3.00	*0.98*	0.33			1.50	*0.49*
Irrigated crop 3 (mango)								3.00	*2.84*	0.95			2.50	*2.37*
Commercial forestry		2.6				1.00	*1.20*	5.00	*5.00*	1.00	1.70	0.53	3.00^x	*3.00*
Invasive alien vegetation		3.6				1.00	*1.20*	6.00	*6.00*	1.00	1.70	0.53	3.00^x	*3.00*

coeff = Coefficient; **ts** = Timestep; **ref PET** = Potential evapotranspiration for standard reference vegetation (FAO-56);

$^{\#}$ SWAT models crop growth internally given planting and harvest dates and growth cover, max LAI and root depth are user inputs, average annual values were obtained from model output to compare to other tools

^{x} Maximum value allowed by tool

*****ACRU: Soil/root depth varied with topographic zone

**SWAT: Access to ground water below soil is set with a separate parameter by topographic zone

Black text: Values entered in model

Blue text*:* Values calculated from model inputs for comparison across tools, i.e. area-weighted averages for broader cover classes (shown in brackets), applying value conversions or model algorithms, e.g. in SWAT, ET coeff = LAI/3 if LAI < 3 or 1 if LAI ≥3

Grey shaded columns: Comparable values/units

Table C30: Soil and unsaturated zone profile parameter values used in models of the Middle Letaba catchment (ACRU4 not yet calibrated, shown for reference)

Land unit:	**All** (Area-weighted average)			**Riparian**		**Lowlands**			**Midlands**		**Uplands**		
Tool:	**WRSM**	**ACRU**	**SWAT**	**ACRU**	**SWAT**	**WRSM**	**ACRU**	**SWAT**	**WRSM**	**SWAT**	**WRSM**	**ACRU**	**SWAT**
n layers in profile	1	2	2	2	2	2	2	2	2	2	2	2	2
Lateral flow out of profile	Yes	No*	Yes	No*	Yes	Yes	No*	Yes	Yes	Yes	Yes	No*	Yes
Additional vadose/interflow layer below "soil" profile	Yes	No	Yes*	No	Yes*	Yes	No	Yes*	Yes	Yes*	Yes	No	Yes*
Profile													
Profile depth (thickness), m	2.94	0.79	3.50	1.20	3.50	2.51	0.82	3.50	3.25	3.50	3.25	0.53	3.50
Storage at saturation, mm	733	344	745	522	1247	700	359	850	750	688	750	234	538
Storage at field capacity, mm		177	455	285	490		185	577		413		116	324
Root zone													
Max root depth, m	2.94	0.79	2.62	1.20	2.62	2.51	0.82	2.62	3.25	2.62	3.25	0.53	2.62
Storage at field capacity, mm		177	341	285	367		185	432		309		116	242
Layer 1													
Layer bottom depth, mbgl		0.30	1.21	0.30	3.00		0.30	1.50		1.00		0.30	0.60
Layer thickness, m		0.30	1.21	0.30	3.00		0.30	1.50		1.00		0.30	0.60
Porosity		0.45	0.44	0.45	0.40		0.45	0.44		0.45		0.45	0.44
Field capacity		0.20	0.25	0.20	0.14		0.20	0.26		0.24		0.21	0.26
Wilting point		0.11	0.13	0.11	0.05		0.11	0.14		0.12		0.13	0.14
AWC		*0.09*	*0.12*	*0.09*	*0.09*		*0.09*	*0.12*		*0.12*		*0.08*	*0.12*
Ksat, mm/hour			37.9		150			30		30			30
Redistribution factor		0.40		0.49			0.41					0.33	

Land unit:	**All** (Area-weighted average)			**Riparian**		**Lowlands**			**Midlands**		**Uplands**		
Tool:	**WRSM**	**ACRU**	**SWAT**	**ACRU**	**SWAT**	**WRSM**	**ACRU**	**SWAT**	**WRSM**	**SWAT**	**WRSM**	**ACRU**	**SWAT**
Layer 2													
Layer bottom depth, mbgl		0.79	3.50	1.20	3.50^x		0.82	3.50^x		3.50^x		0.53	3.50^x
Layer thickness, m		0.49	2.29	0.90	0.50		0.52	2.00		2.50		0.23	2.90
Porosity		0.43	0.09	0.43	0.094		0.43	0.094		0.094		0.43	0.09
Field capacity		0.24	0.04	0.25	0.042		0.24	0.042		0.042		0.23	0.04
Wilting point		0.15	0.00	0.17	0.002		0.15	0.002		0.002		0.14	0.00
AWC		*0.09*	0.04	*0.08*	*0.040*		*0.09*	*0.040*		*0.040*		*0.09*	*0.04*
Ksat, mm/hour			10		10			10		10			10
Redistribution factor		0.40		0.49			0.41					0.33	

Table C31: Additional soil and vadose zone layer (below soil profile) parameter values used in models of the Middle Letaba catchment (ACRU4 not yet calibrated, shown for reference)

Land unit:	**All** (Area-weighted average)			**Riparian**		**Lowlands**			**Midlands**		**Uplands**		
Tool:	**WRSM**	**ACRU**	**SWAT**	**ACRU**	**SWAT**	**WRSM**	**ACRU**	**SWAT**	**WRSM**	**SWAT**	**WRSM**	**ACRU**	**SWAT**
Soil profile parameters													
Critical depth: wetness impacts surface runoff, m		*0.30*		*0.30*			*0.30*					*0.30*	
Storage in critical depth or top layer$^{\%}$ at saturation, mm		*135*	*534*$^{\%}$	*135*	*1200*$^{\%}$		*135*	*661*$^{\%}$		*452*		*135*	*264*$^{\%}$
Rain threshold for surface runoff (minimum infiltration), mm/month	50					50			50		50		
Rain threshold for average infiltration rate, mm/month	1 000					1 000			1 000		1 000		
Distribution-average infiltration rate, mm/month	525					525			525		525		
Power, percolation rate equation	2					2			2		2		
Maximum percolation rate, mm/month	8					7			8		8		
Power, interflow rate equation	2					2			2		2		
Maximum interflow rate, mm/month	4					2			4		8		
Additional vadose/interflow layer below "soil"	**Yes**	No*	**Yes**	No*	**Yes**	**Yes**	No*	**Yes**	**Yes**	**Yes**	**Yes**	No*	**Yes**
Lateral interflow out of this layer	**Yes**					**Yes**			**Yes**		**Yes**		
Layer bottom depth, mbgl	14.3					14.4			14.3		14.6		
Layer thickness, m	11.3					11.9			11.0		11.3		
Storage at saturation, mm	52					51			53		51		
Specific yield	0.0046					0.0043			0.0048		0.0045		
Vertical Ksat, mm/hour													
Power, percolation rate equation	0.2					0.2			0.2		0.2		
Delay in recharge, days	282		5		5	360		5	240	5	270		5
Percolation time constant, days													
Horizontal Ksat, mm/hour													
Power, interflow rate equation	N/A					N/A			N/A		N/A		
Delay in interflow, days	6.5		N/A		N/A	7.5		N/A	6	N/A	6		N/A

Ksat = Saturated hydraulic conductivity

$^{\%}$ With different layering and approaches to infiltration calculation the "top" layer water storage capacity has different relevance to surface runoff generation across models

*ACRU4: Lateral routing is included from non-riparian HRU *baseflow store*, below soil, into riparian HRU soil

Table C32: Aquifer parameter values used in models of the Middle Letaba catchment (ACRU4 not yet calibrated, shown for reference)

Land unit:	**All** (Area-weighted average)			**B82D**	**B82C**	**B82B**	**B82A**
Tool:	**WRSM**	**ACRU**	**SWAT**	**WRSM**	**WRSM**	**WRSM**	**WRSM**
Storage parameters							
Bottom depth, mgbl	32	*	*	33	34	32	31
Max thickness, m	32	*	*	33	34	32	31
Depth to static water level (no flow), mgbl	11			9.7	8.0	12.9	13.2
Specific yield, $m^3/(m*m^2)$	0.0046		0.003	0.0043	0.0050	0.0047	0.0045
Specific storage, /m							
Max storage, mm	148	*	*	142	170	150	140
Max storage available for outflow, mm	50	*	*	42	40	60	60
Inactive storage (flow threshold), mm	98	0	100	100	130	90	80
Flow rate parameters							
Transmissivity, m^2/day	10			10	10	10	10
Horizontal Ksat, mm/hour	13			12.63	12.25	13.02	13.44
Vertical Ksat, mm/hour							
Fraction of store flow out /day		0.009					
Linear outflow constant, 1/days			0.3				
Linear outflow constant, days			3.3				
Power, GW-SW flow rate equation	-0.05		1	-0.05	-0.05	-0.05	-0.05
Max regional GW gradient	0.001			0.001	0.001	0.001	0.001
Max discharge, mm/month	5			5	5	5	5
Capillary rise / ET from aquifer store							
Max fraction of PET met by aquifer			0.10				
Max fraction of outflow diverted for **riparian area ET**	1			1	1	1	1
Fraction of upland aquifer outflow routed to **riparian area soil**		1					

Table C33: Modelled streamflow for the Middle Letaba catchment for three different scenarios using two modelling tools

Statistic	**Modelled streamflow, October 1982 to September 2011: SW and GW irrigation (Sc1), SW irrigation only (Sc2), no irrigation**					
	WRSM			**SWAT**		
	Sc1 SW and GW	**Sc2 SW**	**Sc3 NIrr**	**Sc1 SW and GW**	**Sc2 SW**	**Sc3 NIrr**
Annual stream yield (mm³)						
Mean	61.4	61.4	116.6	65.9	64.7	75.3
Standard deviation	174	174	182	181	183	183
CV	2.84	2.83	1.56	2.75	2.82	2.43
Minimum	1.3	2.6	31.7	3.5	3.0	7.2
Maximum	950	950	1032	984	990	999
Monthly streamflow (mm³)						
Mean	5.1	5.1	9.7	5.5	5.4	6.3
Standard deviation	34.1	34.3	34.3	34.7	35.1	34.8
CV	6.65	6.70	3.53	6.32	6.50	5.55
Minimum	0.00	0.00	1.44	0.001	0.001	0.001
5th percentile	0.00	0.12	2.32	0.03	0.02	0.05
50th percentile	0.8	0.9	5.4	0.6	0.5	1.1
95th percentile	12.8	12.4	19.0	12.2	12.0	15.2
Maximum	543	547	549	528	537	534
Daily streamflow (cm)						
Mean				2.09	2.05	2.39
Standard deviation				32.97	33.15	33.16
CV				15.80	16.16	13.90
Minimum				0.000	0.000	0.000
5th percentile				0.004	0.004	0.004
50th percentile				0.11	0.08	0.24
95th percentile				2.6	2.7	3.3
Maximum				2 045	2 058	2 056

ACRU4

ACRU4 does not include a representation of ground water withdrawal. A “workaround” approach to approximating irrigation from ground water in ACRU4 was considered, but was stretching too far from what could be deemed “normal” use. A model of the Middle Letaba catchment with only surface water irrigation was designed, intended for comparison to the surface water irrigation scenario modelled in other tools and to a no-irrigation scenario. This was to be roughly calibrated against the outputs of other models for the surface water irrigation-only scenario, as well as the observed case. However, the time available precluded finalising the calibration and analyses. The initial structure and parameter values are presented here to document the decision-making process and difference in approach to other tools.

Structure and parameterisation

- **Model units and routing:** The catchment was represented with the four quaternary catchments as subcatchments to allow climate input at this scale. The subcatchments each contained different numbers of HRUs with 32 HRUs in total. These HRUs were delineated based on the areas of different major land cover types in each quaternary and the contributing catchment areas of the lumped farm dams as defined in the WRSM model. To keep the number of HRUs workable, the number of farm dams explicitly represented was reduced from the 14 in WRSM to eight in ACRU4, two per subcatchment.
- Surface and shallow subsurface flows from HRUs were routed in parallel to dams or river channel elements in their subcatchments, which were, in turn, routed to subcatchment “nodes”. In the upper portions of the subcatchments, above the upper dam, aquifer outflow (or “baseflow” output) from contributing HRUs was also routed directly to channels or dams. In the lower portion, below the first dam, aquifer outflows from non-riparian HRUs were routed to riparian HRU soils (Figure C10). Aquifer outflows from riparian HRUs were routed to channels.
- **Land cover:** Because each HRU in the model is created, parameterised, linked and adjusted manually and individually in ACRU4 software, the number of land cover types, as well as soil and topographic unit types explicitly represented, was reduced from the number mapped. Six individually parameterised land cover types were included: indigenous woodland (arid lowveld), subsistence farming, medium-density residential, irrigated crops, commercial forestry (mostly eucalyptus) and invasive alien vegetation. In cases where only a very small area of a cover type was present in a subcatchment, instead of including one more, very small HRU, this area was added to the HRU of that type in another subcatchment, with an equal adjustment to another cover class to keep the subcatchment sizes and total areas of each cover class in the catchment as a whole unchanged.
- Initial land cover parameters were assigned by selecting relevant vegetation types included in the tool’s in-built “compoveg: database.
  - ***Root depth*** in ACRU4 is linked to the HRU’s soil depth rather than being input by vegetation type (although the density of roots with depth is specified by vegetation type).

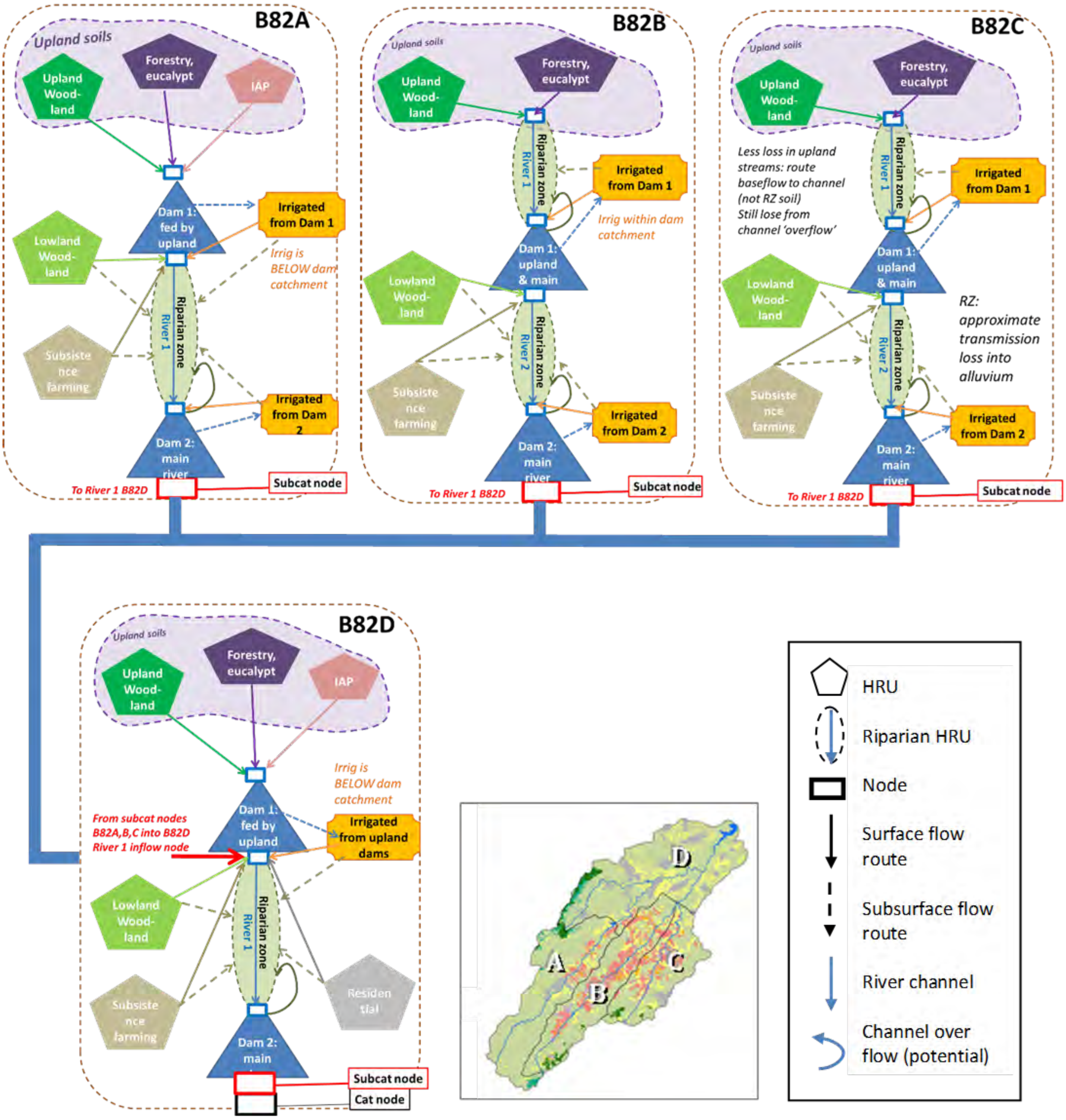


Figure C10: Schematic diagram of proposed set-up for modelling the Middle Letaba catchment in ACRU4

- **Soils:** Three soil types were explicitly included, linked to topographic position: upland, midland/lowland and riparian. This was reduced from the four topographic units delineated (see general section above) to limit the number of vegetation type-soil type-upstream or downstream of dam combinations, and hence HRUs.
- Initial soil parameters required were obtained from the Autosoils database and GIS layer, using area-weighted averaging across types mapped in the topographic units. The critical soil depth for stormflow generation was left as the depth of the topsoil layer to start, but would be a potential value to adjust in calibration, as the steeper soils in the uplands may justify a smaller value.
- **Runoff lag:** Surface and shallow subsurface runoff calculated for a storm event is routed to the stream with a lag determined by the "stormflow response fraction" parameter, the fraction runoff reaching the stream each day. This is linked to several landscape properties: slope, roughness, flow path length, potentially soil profile properties linked to interflow, etc. The model default, 0.3, was assigned as a starting value, but would need to be assessed in calibration.
- **Geology and aquifer:** Aquifer storage and outflow are calculated for each HRU individually using an outflow rate coefficient. There is no direct correspondence between this parameter and the WRSM ground water parameters to inform value selection or if/how values should vary across the four subcatchments or HRU types. As such, the same "baseflow" outflow coefficient was assigned to all HRUs, using the default value (0.009) as a starting value for calibration.
- Riparian vegetation access to ground water, and channel transmission loss water (see point below) was represented using special riparian zone HRUs. "Baseflow store" (aquifer) outflows of linked non-riparian HRUs are routed into the lower soil layer of riparian HRUs in the same subcatchment (Figure C10).
- **River channel network and transmission loss:** River channel units were defined in each subcatchment associated with each riparian HRU. ACRU4 does not have an algorithm for channel transmission loss. Channel flow in excess of an input threshold can be applied to the linked riparian HRU surface, intended to represent overbank flooding. This mechanism was used to approximate channel transmission loss by setting the channel capacity to 0. As such, all flow would go over the riparian area surface where it could potentially infiltrate and be lost to ET, while some may leave as surface flow and baseflow output. Because the riparian areas were relatively small compared to the contributing landscape, it was assumed that large flows would quickly saturate the riparian zone. The stormflow response fraction and baseflow response fraction for riparian zones would likely need to be made larger than the rest of the catchment given proximity to the channel.
- **Farm dams and irrigated areas:** The storage capacities and area-volume ratios of the dams included in WRSM were used to set up the dams in the ACRU4 model. Similarly, the contributing catchment areas and the sizes of the irrigation areas fed by them were maintained, the same as in WRSM, just lumped so that there were only two dams and two irrigated HRUs per subcatchment. Irrigation demand can be input using several approaches in ACRU4, which differ to WRSM. The initial set-up was to assume automated irrigation based on soil water deficit, given that the area is dominated by highly commercial farms, with crop factors estimated by area-weighting across the crop types.

Adjustments to improve calibration

Comparisons would need to be primarily against the surface water irrigation-only scenario model output from the models built in WRSM and SWAT. This has not yet been completed.

Scenario representation

A no-irrigation scenario would be established by converting the irrigated HRUs into normal HRUs with the same vegetation and soil parameters and landscape positions (i.e. routing to channels or dams).

Main challenges

- **No ground water withdrawal representation:** Precluded using the tool to look at the impacts of irrigation from ground water.
- **No channel transmission loss algorithm:** In this case, a workaround was used, using the algorithm for channel overbank flooding, which may work well enough to mean that this is not a significant challenge. However, in other cases, this workaround may be more problematic. The channel capacity threshold set to zero or very low to approximate transmission loss, because this can occur with any amount of flow, rather than needing a threshold of flow to be exceeded. This means actual overbank flooding, which would need a higher channel flow threshold, cannot be represented simultaneously.
- **Model interface:** A high number of steps is required to establish structure and connectivity, make and test adjustments, export water balance components, and process at a catchment scale. Very few actions can be “batched”.
    - In this case, this was the motivation to reduce the number of HRUs included, which resulted in **further lumping of farm dams and irrigation areas**. A relatively high number of separated areas had been included in the WRSM model to explicitly estimate when deficits might occur in different areas, given the specific water storage to which they have access. Some of this may be lost when storages are more lumped.

SWAT2012

Structure and parameterisation

- **Model units and routing:** The catchment was represented with 17 subcatchments, delineated to explicitly include the 14 farm dams represented in the original WRSM model and to separate the four quaternary catchments for climate input. SWAT2012 “reservoir” units are necessarily located at the outlets of subcatchments. (Other water body types can be added internal to subcatchments, but these are off the main river and cannot be used for irrigation).

– It was clear in the WRSM set-up (Figure C10) that nine of the dams were on the main river. Finding the represented main river dams using the land cover and aerial photography data was straightforward and the topographically delineated catchments had reasonably similar sizes to that included in WRSM. The case was similar for two dams on tributaries. For the remaining three dams located off the main rivers, subcatchment delineation points had to be found that would result in a subcatchment of a similar size to that used in WRSM. This was done using a “flow accumulation” surface created from the DEM using ArcMap Spatial Analyst. These model dams in WRSM are lumped representations of many smaller dams on many smaller streams, rather than one dam with a single contributing subcatchment. As such, the exact location of these conceptual lumped reservoirs and their subcatchments was relatively arbitrary, except for being in the same quaternary catchment. These three were small and only one fed an irrigated area.

- HRUs were automatically delineated in ArcSWAT2012 from overlaying maps of cover, soil and subcatchments, which resulted in 320 HRUs in the catchment.
- HRU surface flow and interflow are automatically routed in parallel to the subcatchment’s river channel. Water percolating from the bottom of an HRU soil profile recharges a subcatchment-scale aquifer store, from which outflow is routed to the subcatchment channel.
- SWAT models one river channel element per subcatchment and the flow routing between them is automatically determined during the subcatchment delineation process from the DEM done within the ArcSWAT2012 interface.
- **Land cover:** Ten land cover types were included, simplified from the NLC and irrigated fields datasets described above (Table C29). Because SWAT explicitly models the growth from planting to harvest of crops, rather than using predetermined crop factor values, the crops were generalised into the three basic types that could be appropriately parameterised (1 tomatoes and summer vegetables, 2 pumpkin and autumn vegetables, 3 fruit and nut trees).

- Land cover types were parameterised using both SWAT's internal vegetation type database and values in ACRU4's Compoveg database (both include tomatoes, cabbages or brassicas used to inform the autumn vegetables, and Compoveg includes values for mangos and avocados):
  - **ET (crop) coefficient (K_c):** To match the reference PET input of the WRSM model, the user-input reference PET entry method in SWAT was used, which had implications for the vegetation PET calculation and parameters needed. With this method, SWAT calculates the ET coefficient (K_c) for the vegetation type internally as a function of LAI, so input LAI values were selected to try to produce K_c values matching those in Compoveg. The LAI values are not used for other hydrological processes in SWAT2012 in this case. The algorithm for calculating K_c in SWAT limits K_c to a maximum value of 1, so the plantations and alien vegetation had a lower K_c in SWAT than in ACRU. However, these covered a relatively small area. The growth curve parameters in the SWAT2012 database for relevant crops were used (heat unit accumulation to reach maximum LAI and rooting depth), while other vegetation types were set to have more temporally constant LAI and root depth close to the input (maximum) values.
  - **Root depth:** Root depths are not separately input in WRSM or ACRU4, but instead are assumed to access the entire soil profile as input. Depths informed by the SWAT2012 database were used. (The maximum allowed is 3 m.)
- **Soils:** The four soil types associated with mapped topographic units were parameterised using the Autosoils database and local literature, which provided estimates of depth and saturated hydraulic conductivity (K_{sat}) (Dippenaar et al., 2010; Holland, 2011; Riddell et al., 2017; Walker et al., 2018). The riparian areas were parameterised to represent the sand deposits that were several meter deep, as described by Walker et al. (2018). For the other zones, initially, depths from the Autosoils database were used, but the profiles were deepened to allow more storage and hence ET. SWAT allows a profile of up to 3.5 m to be input, so below an upper layer informed by Autosoils, a lower layer was added with properties more similar to the weathered rock aquifer. The resulting catchment-averaged potential profile storage (745 mm) was similar to the soil storage in the WRSM model (733 mm) (Table C30).
- SWAT uses the input saturated conductivity to calculate vertical and horizontal flow in soils. However, it uses the empirical SCS-CN method to calculate infiltration (and interception) versus runoff production during rainfall events. Initial CN values were selected based on suggestions in the model documentation for broad vegetation structural types (Arnold et al., 2012).
- **Geology and aquifers:** Ground water recharge, storage and flow are represented at the subcatchment scale, and parameter values were assumed to be constant over the four subcatchments because most of the values used in WRSM were relatively similar to each other. SWAT2012 uses a conceptual recession constant to estimate aquifer outflow to the channel, which does not have a direct correspondence to the WRSM parameters. However, the threshold of storage for outflow parameter was set to 100 mm to match WRSM ("static water level storage").
- Vegetation access to ground water can be represented for any HRU in the model by specifying the maximum proportion of the ET demand (from 2 to 20%) that can be met by drawing from the aquifer store. Riparian areas were assigned the highest value, and uplands the lowest.
- **River channel network and channel transmission losses:** SWAT includes one main river channel unit per subcatchment. A bed conductivity value was specified to allow channel transmission loss. In SWAT2012, this water can be added to a bank storage that is re-released into the channel. A proportion can be routed to a deep aquifer, essentially removing it from the model. This could also represent loss to evaporation. In theory, the bank storage water can feed evaporation for bordering HRUs (Neitsch et al., 2011). However, it is not clear if this feature is operational as there is no specific output that confirms it, and tests did not indicate increasing ET with increased bank storage. As such, parameters were specified, which resulted in similar amounts of channel transmission loss water being removed from the model, as in the WRSM model. These were 50 mm/hour bed conductivity, consistent with documentation suggestions for sandy bed, and 5% of the water going to the deep aquifer.

- **Farm dams:** The storage capacities and area-volume ratios of the dams included in WRSM were used to set up the dams in SWAT2012. SWAT reservoir units require an input of a principal spillway for controlled release and an emergency spillway for overtopping. It was assumed that the dams did not have any controlled release in this case. Although not covered in the documentation, the SWAT2012 interface has size limits for the reservoirs that can be modelled: 1 to 3 000 ha maximum area and 0.15 to 30 mm^3. This would have precluded including the full Middle Letaba Dam, which is too large. It also meant that four of the dams that were slightly too small in terms of storage had to be set up to release water at a lower spillway.
- **Irrigation from surface and ground water:** It was assumed that crop HRUs were fed from the dam (or channels for a few) in their subcatchment as a similar assumption seems to have been made in WRSM. SWAT2012 is not explicitly designed to allow irrigation from multiple sources. However, both “manual” and “automated” irrigation instructions can be assigned to an HRU, and each of these can be given a separate source. Irrigation amounts for the represented crop types were generalised from the monthly SAPWAT demand estimates that were used to inform the WRSM set-up (Haasbroek et al., 2015). These were input as manual amounts drawn from the surface water sources, applied every third day during the crop’s growing season. An automated irrigation operation was also set up for the same time period to irrigate when there was a soil moisture deficit. In both cases, the amount of water applied would be curtailed if there was insufficient water in the source. In this way, ground water would be drawn when the surface water irrigation was inadequate, which would presumably occur when surface water sources were low.

Adjustments to improve calibration

Parameter value adjustments were manually set up and tested. Other than soil storage and the threshold ground water storage for outflow, not many property parameters were directly numerically related to the values in the WRSM model set-up. Parameters were kept within the value ranges suggested for related soil and vegetation types in the databases referenced (Compoveg, SWAT database, AutoSoils), with parameter adjustments focusing on the more conceptual parameters: the curve number, the recharge lag and the aquifer outflow recession constant.

The initial parameterisation greatly overestimated mean flow, and high and low flows, predicting almost twice as much flow. To improve fit, the following was done:

- The initial ground water storage was dropped, which had been left at the default, and was not equalising by the end of the warm-up period.
- Curve number values were reduced, maintaining the relationship across cover types. After a certain point, additional decreases actually resulted in increased outflow because of interflow from infiltrated water.
- The soil conductivity values were decreased to reduce interflow and percolation, allowing more ET. There were order of magnitude ranges in the values found in the literature.
- The upper soil layer (which has a higher water-holding capacity) and root depths were deepened, compared to that in AutoSoils, to be deep enough for the vegetation rooting depths suggested in the SWAT2012 database. These were relatively high (often close to 2 m, even for annual crops), compared to the soil depths typically used in ACRU.

The resulting model had sufficient performance in mean streamflow and runoff sources of a similar proportional to WRSM, on average. However, the irrigation amounts that were predicted were much lower than WRSM. This was because of restricted supply rather than the irrigation instructions, because amounts similar to WRSM were achieved when the model as a whole was producing too much flow.

Scenario representation

- **Surface water irrigation only, no irrigation from ground water:** The ground water irrigation instruction was simply removed from the crop HRU's "management" parameters. The surface water irrigation was set to be automatic, triggered by soil moisture deficit.
- **No irrigation:** Remove all irrigation operations in the set-up.

Main challenges

- **Selecting appropriate CN values:** Values suggested in the model's documentation for corresponding vegetation types generally produce too much stormflow (seen across case studies).
- **Channel transmission loss:** Although the documentation suggests that bank storage water can also feed ET in the model, the model outputs make it appear that this algorithm is not active or some other setting that is not clearly documented is needed (i.e. which HRUs are adjacent to the river).
- **Irrigation from multiple sources:** This relied on using both automated and manual irrigation management set-ups. Manual irrigation instructions need to be specified by individual days of the year, with a set of values to enter for each day, rather than specifying a frequency or other rule. This is quite labour-intensive to set up and adjust.
- **Reservoirs:** There were size and location restrictions.
- **Crop growth modelling:** Database parameters for the same or similar crops were applied. However, the resulting pattern of LAI, and hence effective crop coefficients, were much lower than those in Compoveg (Table C29). This may have been partly responsible for the lower ET from the irrigated area, compared that estimated in WRSM. It is not necessarily known which irrigation output is more accurate. The crop growth parameters used in SWAT differ from the parameterisation generally used in the other tools, and it is less clear how to adjust them if one needs to produce a better match.