A National Assessment of Potential Climate Change Impacts on the Hydrological Yield of Different Hydro-Climatic Zones of South Africa

Report 3
South African and International Verification Studies of the *ACRU* Daily Time-Step Model across a Range of Processes, Applications and Spatial Scales

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This report forms part of a series of three reports. The other reports are -

A National Assessment of Potential Climate Change Impacts on the Hydrological Yield of Different Hydro-Climatic Zones of South Africa. Report 1: Methodology and Results (WRC Report No. 2833/1/22).

A National Assessment of Potential Climate Change Impacts on the Hydrological Yield of Different Hydro-Climatic Zones of South Africa. Report 2: *Perspectives on Adaptation to Climate Change in the South African Water Sector* (WRC Report No. 2833/2/22).

A NATIONAL ASSESSMENT OF POTENTIAL CLIMATE CHANGE IMPACTS ON THE HYDROLOGICAL YIELD OF DIFFERENT HYDRO-CLIMATIC ZONES OF SOUTH AFRICA

Executive Summary to Report 3:

SOUTH AFRICAN & INTERNATIONAL VERIFICATION STUDIES OF THE ACRU DAILY TIME-STEP MODEL ACROSS A RANGE OF PROCESSES, APPLICATIONS & SPATIAL SCALES

In the contract of WRC Project K5/2833 which is titled *A National Assessment of Potential Climate Change Impacts on the Hydrological Yield of Different Hydro-Climatic Zones of South Africa,* it is specified that in the climate change impacts modelling component of the Project, the *ACRU* hydrological model be used. In that regard the following is also stated in the contract, *viz*. ***"****Verification of the ACRU model … will be done using observed historical rainfall at selected locations where suitable observed streamflow records are available and where the upstream catchment does not include large dams or other significant abstractions or inflows".*

This Report 3 addresses the issue of the verification of outputs from the *ACRU* daily time-step process-based agro-hydrological model – an issue that has, over the years, also been requested by many users and potential users of the model. However, this Report 3 goes beyond the typical hydrological model verification studies report in also providing some general background on verification, in addressing problems associated with verifications, giving background on the *ACRU* model *per se*, and showing verifications not only of final streamflow output, but also of internal state variables of the model, as well as also illustrating verifications on the "agro"-component of the *ACRU* agro-hydrological model, while focusing not only on South African verification studies of the model's outputs, but also on international studies.

In Chapter 1 of this Report, under the title ***Setting the Scene***, an explanation is given on what we understand by verification, and what the differences are between verification and validation. Chapter 2 is headed ***Verification is Fraught with Problems: What then are Pre-Conditions for Successful Verification?***, with this question being addressed and then followed by a series of eight case studies as to why verification is fraught with problems, with the Chapter concluding by highlighting the responsibilities of the model developer and the model user in regard to hydrological model verification.

A Synopsis of Statistics Used in Assessing Agro-hydrological Model Verifications is provided in Chapter 3, with this followed in Chapter 4 by ***An Overview of the ACRU Agro-hydrological Modelling System Within a Broader Context of Modelling Water Resources in South Africa, and as a Tool for Verification***, followed by Chapter 5 on some ***Background to Actual Verification Studies with the ACRU Model***.

The theme of Chapter 6 is ***Verification Studies of Internal State Variables within the ACRU Model***, commencing with the verification of soil water content under dryland sugarcane, followed by a verification of soil water content under irigated conditions, of actual evapotranspiration from a lysimeter and of the verification of *Pinus patula* canopy interception values. In Chapter 7 a ***Verification of Biomass Related Yield*** is presented, followed by verifications of the *ACRU* model's dryland maize yield routines, of the model's winter wheat yield simulator, then a verification of the modified *ACRU*-Thompson sugarcane yield model at mill supply level, and of *ACRU*'s timber yield model.

Chapter 8 focusses on ***Verification Studies of Land Use and Land Management Impacts on Runoff*** by first verifying impacts on runoff of changes in catchment land use over time, then verifying impacts of afforestation on streamflows with a Forest Decision Support System, followed by a section on the verification of the impact of a wildfire on streamflow responses and, finally, on the *ACRU* model's flow routing module.

A ***Selection of International Verification Studies of the ACRU Model*** is the theme of Chapter 9, commencing in Australasia with verification studies of streamflows in the operational Manuherikia catchment in Otago, New Zealand, followed by three African verifications, the first being an *ACRU* streamflow verification on a small research catchment in Eritrea, the second on the verification of streamflows from large operational catchments within the Mbuluzi system in Eswatini, and the third being a verification of long-term groundwater level fluctuations in the Romwe catchment in Zimbabwe due to variations in rainfall. Two verifications of the *ACRU* model from the Americas are then presented, the first on an operational catchment with snowmelt in Alberta, Canada and the second of verifications on the Swan River in Canada with results from daily through monthly to annual streamflows, ranked daily streamflows, and exceedance probabilities of "extreme" flood events.

In Chapter 10 the focus is ***On Spatial Scale and Other Issues in Hydrological Verifications with the ACRU Model*** by first seeking approaches and solutions to scale problems in hydrology followed by a series of verification studies on small South African research catchments (but also including one from the USA), then by a verification series on medium-sized in-country operational catchments, thereafter assessing verifications on larger operational catchments by moving across major hydro-climatic regions with *ACRU* model confirmations and by assessing verifications on operational catchments from the WRC's Water Flows Project (WRC project K5/2560) that was completed in 2021. Verification studies on operational catchments that provided more questions than answers were first addressed through a case study of the Sabie system, followed by a sub-chapter on questioning whether "overkill" in hydrological detail in an operational catchment can lead to sub-optimal verification results, using a case study from the Blyde catchment and, finally, assessing the benefits of modelling at Quinary vs Quaternary scales in the Crocodile catchment.

Chapter 11 presents a ***Selection of Verification Studies on Specialised Versions of the ACRU Model*** by first assessing how well snow hydrological modelling with *ACRU-SMiM* performs in the Middle Mountain Range of Germany, then how well a verification of *ACRU-Salinity*, which is a specialised hydro-salinity module of *ACRU*, performs and thereafter a verification is assessed on modelling nutrient and sediment dynamics at the catchment scale with the *ACRU-NPS* version using a calibration-validation approach.

The final Chapter 12 provides a ***Synopsis and a Way Forward***.

Verification studies on the *ACRU* model have been undertaken by many research hydrologists in South Africa and overseas, as well as by many post-graduate students and, in addition to the inputs of the author of this Report, the contributors listed in the various chapters are as follows, in alphabetical sequence:

Angus, G.R., Butterworth, J.A., Byrne, J.M. Caldecott, R.E., Cluer, R., Coburn, C.A. Dent, M.C., Dlamini, D.J.M., Domleo, F.B. Forbes, K.A., Ghile, Y.B., Hayes, L. Haywood, R.W., Henson, W., Herpertz, D. Jewitt, G.P.W., Kienzle, S.W., Kiker, G. Kollongei, J., Lecler, N.L., Leenhardt, D. Lorentz, S.A., Lumsden, T.G., Malevu, N. Moriarty, P., Mugabe, F., Muñoz-Carpenal, R. Pike, A., Rasmussen, J., Royappen, M. Schmidt, E.J., Schmidt, J., Scott, D.F. Shabalala, M., Simmonds, L., Smithers, J.C. Sutcliffe, R., Tarboton, K.C., Teweldebrhan, A.T. Thornton-Dibb, S., Toucher, M., Wangusi, N.

They are all thanked sincerely for their inputs.

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1 SETTING THE SCENE

R.E. Schulze

An important component of the hydrological modelling process is to establish that the model output represents that part of the physical system it is trying to mimic. A model can thus only be applied with confidence by a user, and can only be effective in providing information with which to solve, in our case agro-hydrological problems, once its output has been tested, i.e. verified, against observed data.

Such tests between simulated outputs and observed data are often done by visual comparison of results. However, because such visual comparisons of, for example, comparative time series or scatter plots of simulated vs. observed, can be interpreted highly subjectively, the use of statistical measures is usually resorted to, and the model's *performance*, i.e. its capability to mimic observed values, has to meet certain *appropriate* pre-determined statistical criteria of goodness-of-fit in the reproduction of the observed values. *Appropriate* in this case implies that the model is reproducing adequately those aspects of the output (e.g. runoff volume, or peak discharge or crop yield) which are of relevance in the particular agro-hydrological study being undertaken.

Testing the match between simulated and historically observed values also serves to identify errors and shortcomings, on the one hand, of

- the model's process representations, which can then result in an improved understanding of agro-hydrological processes, eventually leading to model improvements,

and, on the other hand, in identifying

- errors in the observations.

1.1 What do we Understand by Verification, and What are the Differences Between Verification and Validation?

In order to appreciate what is meant by a model's performance, communication of modelling protocol is required among model users and developers. There have been many discussions on the terms of model validation and verification, and these terms are neither used consistently nor uniformly, be it in practice or in the scientific literature. What is one modeller's verification may be another modeller's validation, and this does not promote optimal communication. In fact, the two terms validation and verification are so misleading, that for some decades now there has been a belief that they should be abandoned (e.g. Konikow and Bredenhoeft, 1992). However, for the next decade or so they appear here to stay and hence some definitions therefore follow to try to clarify terminology.

Definitions of Verification and Validation

The Oxford English Dictionary defines *validate* as "well founded and applicable, sound and to the point, against which no objection can be fairly brought". A model that is validated can be accepted as having "official force", according to the English Usage Dictionary. It is "authentic", "true", "admissible" and "applicable" in the Cassels Dictionary's explanation.

Verify, on the other hand, is to "test the accuracy, or establish the truth or correctness, of something by examination or by comparison with known data or some standard" (Oxford English Dictionary). "Known data" in the hydrological sciences are observations. According to the English Usage Dictionary, one verifies facts; in hydrology "facts" again are observations. So again, verification clearly means checking against observations. Verification also implies "confirmation", "certification" or "accreditation", while Cassels explains it as "evidence" and "to demonstrate" the truth, to "settle the question", to "prove". A verification is thus a measure of the performance of the model.

Agro-Hydrological Implications of Verification

Verification, by the above dictionary definitions, thus implies the following:

- demonstrating that the behaviour (i.e. output) of a simulation model is consistent with the behaviour of the physical system it is trying to mimic (i.e. that model output reflects the signals of observed values), and, in doing so,
- determining if the model's output information has sufficient accuracy for the model's intended use, noting that simulation model output does *not* constitute data, but information.
- It is thus a process to determine if the errors between historically observed and simulated values are significant, and thereby, establishing a level of confidence in the model.
- Verification should be objective, i.e. subject to formal and rigorous statistical tests at pre-selected levels of goodness-of-fit, according to the problem at hand and for the hydro-climatic region in which the verification is undertaken. Thus, for example, in arid areas goodness-of-fit is not expected to be as high as in humid regions.
- When verifying model output the assumption is made that the model is valid, including validity in model design, the governing equations and computer coding.
- The "purest" and most severe form of verification of an agro-hydrological model's output consists of so-called *blind testing*. In a blind test, model input variables are identified *a priori* from field evidence and readily available sources of direct or derived information (i.e. observed climate input, land use from fieldwork or remote sensing, soils input from fieldwork or maps…). The model is run with *no prior reference to the observed data* or other model output and its performance then compared to *pre-selected initial criteria* of goodness-of-fit. In a blind test of hydrological outputs, for example,
    - continuous discharges should fall within an acceptable range either side of the observed discharges; similarly,
    - peak discharges, monthly flow totals or overall simulation flow totals should also fall within the pre-selected level of performance.
- Because in verification studies historical observations are used against which to test the model's capability, the term *history matching* is a much more realistic and accurate description of which is actually done (Konikow and Bredenhoeft, 1992).

From the above, the following should therefore be re-iterated and noted:

- Discrepancies between observed and simulated responses of a system such as the hydrological system can be the manifestation of numerical errors in the mathematical representations, or equation-solving algorithms, of the model's processes. These are conceptual errors, i.e. theoretical misconceptions about the basic processes that are incorporated in the model, with these conceptual errors including both neglecting relevant processes as well as representing inappropriate processes.
- Furthermore, simulation results are often less accurate than desired due to uncertainties and inadequacies in the input data provided to the model (be they climatic, regarding soils or in terms of land uses), which thus reflect our inability to describe comprehensively and uniquely attributes of the system in addition to the uncertainties in the modelled processes (Rossouw and Kamish, 2001; Konikow, 2002).

Agro-Hydrological Implications of Validation

Both scientists and decision makers need assurances that the model they apply is valid. Validation is the procedure to ensure that all components of the model give an accurate reflection of the model's conceptualisation. Therefore, for a model to be completely validated, each component of the model requires individual validation.

It is important to note that from a technical or scientific point of view a model is validated when it properly describes the physical processes, whereas from a regulatory point of view it is validated when the model yields adequate predictions with the main goal being to reduce the risk of making inappropriate decisions from the model results. A model is thus a good representation of reality, and hence is valid, if it can be used to predict certain observable phenomena within acceptable accuracy and precision.

Validation therefore includes:

- ensuring that the theories and assumptions, made in the conceptualisation and development of the model, are correct and that the conceptual representation of the system being modelled is reasonable for the intended use of the model, i.e.
  - the level of detail, logic and structure should be appropriate,
  - appropriate statistical methods should be used to determine if any fitted distributions are correct, and
  - all theories used in the model should be applied correctly;
- ensuring that the governing equations and functions used in the model accurately describe the various agro-hydrological processes (e.g. thresholds for runoff to be generated, or switches from no plant stress to mild to severe stress, or when one phenological stage ends and another begins);
- ensuring that the computer programming code is correct (i.e. valid) and correctly solves the individual equations that constitute the mathematical model, as well as the programming being an accurate reflection of the model conceptualisation as a whole (e.g. that all process representations are at a compatible level of sophistication);
- ensuring that the model selected for a particular simulation is a valid one for the application; and
- in models which require parameter calibration
  - ensuring that in the water budgeting procedures moisture is neither incorrectly gained nor lost because a particular function is not operating correctly with certain parameter values,
  - ensuring that parameter values used are "valid" and fall within a physically meaningful range of values and are not unrealistic or unreasonable, and also
  - checking with a second reserve set of observed data, to see that the accuracy and predictive capability have been proven to lie within acceptable limits or errors by tests independent of the calibration data – a step sometimes termed "historical data validation".

Given the complexities of biological and hydrological systems, it is probably not possible to achieve complete scientific validation in agro-hydrological models. Only partial validation is possible, owing to the continual changes in space and time affecting bio-hydrological processes and their interactions, implying that we will probably never completely understand fully the agro-hydrological system. In fact, one goal of model validation should be to determine under which conditions the model is either invalid or, at best, poorly suited.

In summary, we validate to sharpen our professional judgement, to provide new insights and to error check. The results of a model evaluation study depend on the availability, usefulness and accuracy of the observed data, on the model's parameterization, the ability of the model to account for dominant processes and our ability to scientifically evaluate the model (Konikow and Bredenhoeft, 1992; Desmond *et al*., 1995).

1.2 What then, is the Overall Objective of a Verification Study?

The overall objective of a verification study is for simulated values to mimic corresponding observed values, either in a time series or for individual discrete events/output, as closely as possible on a 1:1 basis, such that in a time series the

- means of simulated values are conserved when compared with means of observed values; furthermore that
- variances (i.e. deviations about the mean) and skewness (i.e. symmetry of the distribution) are conserved; in order for
- simulated and observed values to show a close association (i.e. high correlation coefficient) with one another; as well as there being
- no systematic under- or over-simulation error, i.e. no bias, between simulated and observed trends; and that there is,
- statistically, no significant difference between the sets of values at a given level of probability.

1.3 What Components of the System do we Verify?

As a general rule one verifies the so-called

- *end-product* of a simulation – in hydrology, for example, the runoff or peak discharge, in agricultural studies the crop's yield.

In process-based deterministic models, in addition to verifying the *end-product* of a simulation, it is equally vital to verify values of the

- *internal state variables* of the model, i.e. those components and processes within the system which are simulated *en route* to "final" estimations (e.g. soil water status, infiltration rates, canopy interception, switches of phenological phases).

Until this check of internal accuracy is done, it is not possible to obtain correct final answers for the right reasons, as one otherwise may just obtain "correct" answers but for the wrong reasons. A good verification of the end-product may ultimately be possible, but it will require the development of algorithms that account for the integration of processes at the scale of individual model elements.

For a verification of runoff, for example, in which we try to improve our basic understanding of the system, additional internal state variable information could include field measurements of actual runoff velocities at points within a catchment, or of subsurface flow responses within a catchment, of distributed measurements of flow depth, conversion rates of rainfall to runoff for areas of similar size to a model element and/or growth and decline of saturated areas during an event. Information on the above would enable more complete testing, development and improvement of a model. If the internal state variables can then be simulated more realistically, the user has more confidence in applying a model outside the range of climates and land uses in which verifications have been performed, and one is more assured of "getting the right answer for the right reason".

2 VERIFICATION IS FRAUGHT WITH PROBLEMS; WHAT THEN ARE PRE-CONDITIONS FOR SUCCESSFUL VERIFICATION?

R.E. Schulze

2.1 Pre-Conditions for Successful Verification

Note at the outset that verification of hydrological models is an experienced specialist's task!

Verify Your Model Across a Range of Hydrological Regimes and Conditions

Typically, model developers/users compare model outputs with measured data for a single or a few sites only where sufficient data are available in order to verify that the model gives reasonable results. Ideally, however, it is necessary/prudent to test the model across a *wide range of conditions* if for no other reason than to determine the limits of the model's application.

- A wide range of conditions implies verification across a *range of hydrological regimes*, including tests in humid areas, sub-humid and arid areas, for both winter and summer rainfall regions, as well as for a variety of land uses and terrain morphologies.
- Models must, equally, be verified for a *range of prevailing conditions within any single hydrological regime*, including checks under extreme and "design-like" conditions, i.e. extreme individual events or particularly wet or dry periods, to ascertain any uncertainties or knowledge gaps in the model description of processes and natural variability.
- Where the model does not perform up to expectations with input data of good quality, the model developers should set out to *check where, within the various sub-systems being modelled, the problems may lie*, so that they can be addressed by way of further research, rather than by "massaging the data until it fits" or "tweaking parameters" until objective functions are met.

Verify against Datasets which, Ideally, are of Long Duration

- Ideally for verification it is necessary to use observed values that are quality controlled, sufficiently detailed and of long duration. As an example, the accepted minimum length of the rainfall data set varies from region to region, as shown for South Africa in **Figure 2.1.1**, with generally the more arid the region the longer the rainfall data set that is required for the user to be confident of having a representative rainfall (Schulze *et al*., 1995).

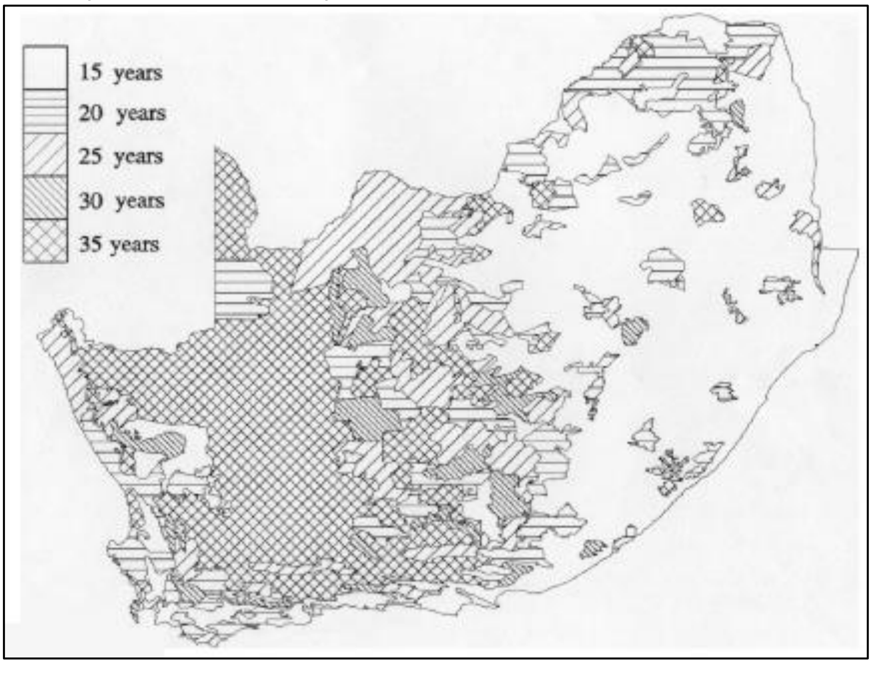

Figure 2.1.1 Minimum record lengths required to ensure that the means of annual rainfall estimates are within 10% of the long term mean 90% of the time (Schulze *et al*., 1995)

Verify against Quality Controlled Datasets – Background

- Perfectly correct datasets are rare because, despite automation to detect errors, quality control remains to a large extent a manual detection exercise.
- Additionally, new methods of collecting data from the field need to be found to keep up with the demands of model verification.
- The impact of uncertainty in input parameters such as rainfall needs to be considered in evaluating model performance. Model evaluation studies should focus on the model structure and algorithms, which are not affected by an uncertainty of inputs.
- Poor field data from instruments in the catchment can lead to poor verification. Many inexperienced modellers, for example, accept the observed streamflow data as being absolute and consisting of error free values, which they are not, and then go on to adjust model parameters/variables to compensate for poor observed data (Schulze, 1995).
- In the case of a model that is calibrated, errors in rainfall or runoff values lead to a false calibration by "forcing" a good model fit, thus obtaining "right" answers for the wrong reasons, and thereby rendering any extrapolations invalid.

Verify against Quality Controlled Datasets – Streamflow Data

- The streamflow data against which the verification is being carried out has to be of high quality, this implying that the gauging structure has been well maintained, kept clear of vegetation and that the rating tables have been updated regularly.

Photo 2.1 A poorly maintained gauging structure full of debris (Photo: R.E. Schulze)

- Furthermore, is the structure capable of recording data accurately over a wide range of flows with no "overtopping" during high flows?
- Check for the stationarity of flow records over the gauging period in regard to land use changes, and if land use has changed significantly over the gauging period apply appropriately changing hydrological land use attributes over time.

Verify against Quality Controlled Datasets – Rainfall Data

- Verifications should include records from as many raingauges with daily data within and adjacent to the catchment as possible.
- Hence, check carefully the siting and density of raingauges being used.
- These raingauges should also have data which are concurrent with that of the streamflow record.
- Since rain generally falls as a discrete event to produce a discrete hydrograph, but historically daily rainfalls have been recorded from 08:00 to 08:00, a rainfall event spanning the 08:00 cut-off would be recorded as two separate events. In a daily time-step hydrological model this greatly diminishes its impact on the hydrological response of the system.
- Rainfall records from many stations show the rainfall recorded at 08:00 against "today's" date instead of the previous day's date. This is termed "rainfall phasing", and appropriate corrections need to be made.

- When conducting a monthly verification study one needs to be aware that if a rain event occurs on the last day or two of the month, the observed runoff will only be reflected in the following month, resulting in poorer statistics of model performance.

Verify against Quality Controlled Land Use and Soils Data

- Detailed and accurate information on soils and land use are also required.
- If the land use inputs only include recent information, the verification may need to be restricted to the time period for which the land use information is considered reasonably representative. This will ensure the stationarity of the streamflow record (Pike and Schulze, 2001).

Ideally, Verify on Research Rather than on Operational Catchments

- Ideally verification studies should be undertaken on small research catchments where there is a dense hydrological network with long term data of high quality and where land use influences are fully accounted for.
- When verification takes place on larger operational (as opposed to smaller research) catchments,
  - the expected performance level should be relaxed because the rainfall network may have been inadequate and the runoff may have been influenced by factors such as upstream dams or river abstractions or return flows; and
  - flow routing should be accounted for.

Check that the Model's Process Representations are Appropriate to the Conditions Prevailing in the Catchment

- Check that the model has been developed/configured to "capture", and hence simulate explicitly, any specialised/unique processes which might prevail in a specific catchment? For example, many commonly used hydrological models do not consider karst/dolomitic conditions, or interflow, or channel transmission losses.

Specify, at the Outset, the Context/Objective of Your Verification

- In any verification one should always qualify up front the conditions under which the model has been tested, e.g. for which years, or what land use was assumed.
- Qualify, furthermore, for what purpose the verification was undertaken, e.g. was it for drought assessment or for flood estimations, or for peak discharge, for land use impacts, or reservoir sizing.

When Verifying, Appreciate Sensitivities of Model Output Errors to Model Input Errors

A model verification should only be performed once the modeller appreciates the model's sensitivity of output to both "external" inputs of climate, soils and vegetation/land use as well as "internal" model inputs of variables or parameter values.

Examples of the sensitivity of changes (or errors) in mean annual runoff in the *ACRU* model to changes (or errors) in mean annual rainfall and maximum (potential) evaporation, shown in **Figure 2.2.1**, illustrate

- both direct sensitivities (e.g. rainfall) and inverse ones (e.g. potential evaporation) sensitivities;
- different degrees of sensitivities, e.g. the rainfall response is greater than that of evaporation;
- the amplification effect, e.g. for a 20% change/error in rainfall, runoff changes by 30-70%, and
- differences in sensitivities evident between different climatic regions (e.g. Elsenburg = winter rain; Outeniqua = all year rain; Mt Edgecombe = summer rainfall-coastal; Cedara = summer rainfall-interior; Roodeplaat = summer rain-far interior; Mara = sub-tropical; Upington = arid)

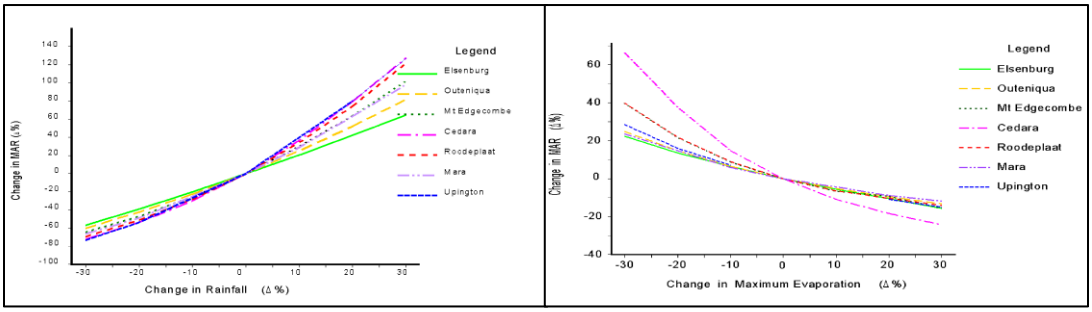

Figure 2.2.1 Examples of sensitivities of runoff to changes/errors in rainfall and potential evaporation in the *ACRU* agro-hydrological model (After Schulze, 1995)

The sensitivity of a model's output to a certain input variable or parameter should be assessed objectively by an objective function. For variable and parameter sensitivity studies with the *ACRU* model the following sensitivity ratings are suggested (Schulze, 1995):

- *extremely sensitive* (E): the percentage change in the output ($\Delta O\%$) is more than twice, i.e. 200%, that of the input parameter being tested ($\Delta I\%$), i.e.
  $$\Delta O\% > 2(\Delta I\%)$$
- *highly sensitive* (H): the output change is more than the input change, but by less than 200%, i.e.
  $$2(\Delta I\%) > \Delta O\% > \Delta I\%$$
- *moderately sensitive* (M): relative output changes less than the relative input change, but by > 50% of the input change, i.e. $\Delta I\% > \Delta O\% > 0.5(\Delta I\%)$
- *slightly sensitive* (S): output changes by between 10% and 50% of the input change, i.e.
  $$0.5(\Delta I\%) > \Delta O\% > 0.1(\Delta I\%)$$
- *insensitive* (I): output changes by less than the 10% of the input change, i.e.
  $$\Delta O\% \;\square\; 0.1(\Delta I\%)$$

Sensitivity ratings of changes to (or errors in) key climate, soils and vegetation variables and parameters on runoff, when using the *ACRU* model, are shown in **Table 2.1.1**, with results indicating that any errors in rainfall are *extremely* sensitive, those in potential evaporation being *highly* sensitive, while errors in both soils vegetation related variables range from *slightly* to *highly* sensitive. The adage of old, that one spends 80% of one's time checking rainfall input, thus certainly hold true in verification studies with the *ACRU* model (and probably most others as well).

Table 2.1.1 Summarised results on sensitivities of runoff to changes/errors in key climate, soils and vegetation input variables and parameters when using the ACRU model

Variable/ Parameter	Sensitivity When Parameter is		Comment
	Reduced	Increased	
RAINFALL	E	E	Most sensitive variable
POTENTIAL	M-H	M-H	High under irrigated conditions
EVAPORATION	H	S	More sensitive when soils are
SOIL THICKNESS	S	S	shallow
SOIL TEXTURE	S	S	
DRAINAGE RATES	H	S	
CRITICAL SOIL DEPTH	M	S	High when *SMDDEP* < 0.15 m
INDEX OF	S	S	
INFILTRABILITY	H	H	Baseflow very sensitive
STRESS SONT INDEX	S	S	Similar in impact to Potential
CROP COEFFICIENT	S	S	Evaporation
ROOTS IN TOPSOIL			Baseflow very sensitive
INTERCEPTION			

E = extremely sensitive; H = highly sensitive; M = moderately sensitive; S = slightly; I = insensitive

2.2 Case Study 1 on Hydrological Model Verification being Fraught with Problems: Non-Stationarity of Observed Data Associated with Overtopping

As a case study on problems encountered in the course of a verification study, those encountered in a Sabie Catchment verification (Pike and Schulze, 2001) are presented below.

Overtopping of Some of the Gauging Structures

This may occur when flows exceed a certain threshold. An example of this problem is illustrated in **Figure 2.3.1** where the daily streamflows are shown for gauging station X3H007.

The non-stationarity of the record in X3H007 associated with the problem of the gauging station overtopping renders these records unsuitable for verification purposes. Here the observed streamflows initially do not exceed 0.6 mm equivalent. This is then rectified and later the threshold becomes a 1.0 mm equivalent flow and even later still the gauging structure is again enlarged to yield observed flows shown in the last years in **Figure 2.3.1**. All pre-1986 values would have rendered this weir useless for verifications. Sometimes, at other gauging weirs the overtopping was either flagged as "overtopped" or recorded as zero flows. Not having checked visually for overtopping would have done an injustice to the hydrological model being verified.

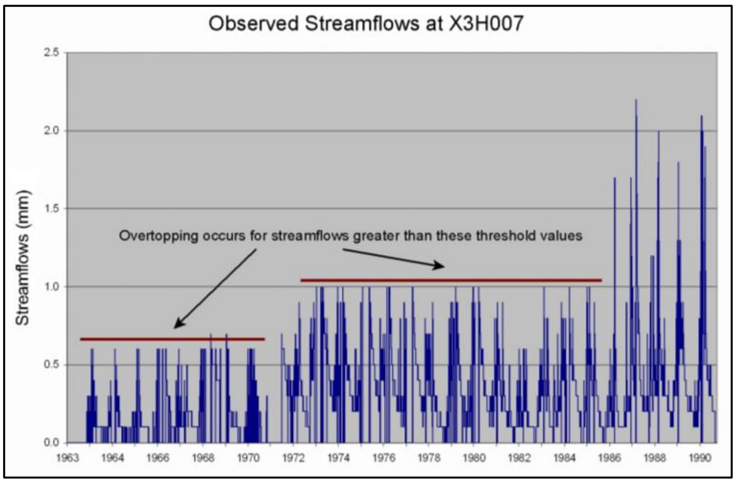

Figure 2.3.1 Plot of available observed daily streamflow data at gauging station X3H007 for the period 13 November 1963-15 September 1991, showing the non-stationarity of the record up to 1986 because of overtopping of the structure (Pike and Schulze, 2001)

Checking Data by Regression Analysis and Double Mass Plots on Operational Catchments

- Data need to be thoroughly checked before undertaking a verification study. A simple regression plot of daily rainfall and observed streamflows will reveal many problems which can occur when the structure is overtopped
- The streamflow record should be checked for systematic errors which may indicate that the rating table is incorrect or outdated. These data need to be flagged as being unreliable eliminated before a meaningful verification can take place;
- Double mass plots can indicate non-stationarity in the streamflow record. This usually occurs when present land use information is used for the duration of a long-term verification study (so-called "hindcasting") without due consideration being given to major changes in land use and/or management practices within a catchment.

Discarding Data

Sometimes data have to be discarded from a verification study. This problem could be the result of one or more of the following factors:

- either the rainfall or streamflow records include serious observational errors which have not been flagged as unreliable data, or
- an inaccuracy has occurred in process of converting the stage data to runoff data via a rating table, or thirdly
- these “rogue” data points are records of flows which were generated by rainfall events which were not recorded at the raingauges selected for this study (Pike and Schulze, 2001).

2.3 Case Study 2 on Hydrological Model Verification being Fraught with Problems: Sources of Error and Uncertainty

In a study by Kiker (2013) the following key observations were made on hydrological verification:

- Discrepancies between observed and simulated responses of a hydrological system can be the manifestation of several sources of errors.
- According to Konikow (2002), in applying hydrological models to field problems, there are three sources of errors:
    - One source consists of ***conceptual errors***, i.e. theoretical misconceptions about the basic processes that are incorporated in the model. Conceptual errors include both neglecting relevant processes as well as representing inappropriate processes.
    - A second source of error involves ***numerical errors*** arising in the equation-solving algorithm.
    - A third source of error arises from ***uncertainties and inadequacies in the input of data*** that reflect our inability to describe comprehensively and uniquely attributes of the system.

In most model applications conceptualisation problems and uncertainties concerning data are the most common sources of error.

In regard to ***effects of uncertainty*** in hydrological measurement, Kiker (2013) makes the following observations from a verification study in the Crocodile Catchment in the Mpumalanga Province of South Africa:

- Uncertainty in measurements can be caused by either random or systematic errors in the data.
- ***Random errors*** can include outliers in the data which can either be representative of the actual hydrological conditions in the catchment often caused by sudden and extreme weather such as storm events, water theft causing sudden reductions in discharge or indicate data collection errors.
- While it is unethical and inaccurate to correct these points to improve correlation data based on the expected trend in the data, it is valuable to understand and explain the model bias as well as identify outliers. This diagnosis pinpoints possible errors in the data which can then be verified as either valid deviations or actual errors in the observed data.
- ***Systematic errors*** that occur during data collection are caused by flow alteration at monitoring points by gauging structures that creates a discrepancy in data quality.
- The South African Directorate of Hydrological Services (SADHS) in the Department of Water and Sanitation (DWS and subsequent Departmental re-namings) has a policy of building gauging structures to pre-calibrate the discharge at flow stations. The gauging structure creates an artificial control in the river channel that creates a determinable relationship between stage and discharge. The most commonly used gauging structures in South Africa are Crump weirs. However, a study by SADHS found that the observed flow at the Crump weirs over-estimated actual discharge by 4.3% (Wessels and Rooseboom, 2009).

Various studies have demonstrated that considering uncertainty simply by using stage-discharge relationships, as proposed by Wessels and Rooseboom (2009), is insufficient in accounting for measurement errors. Measured data can range from ideal, average to poor quality data and, simply, ideal data have less error, and data of poor quality are assumed to have significantly more error, with the use of poor data spuriously resulting in poor model performance which, to the inexperienced model user, then ***reflects on the model rather than on the data***. Further work, therefore, needs to be done to fully find an accurate correction factor for poor observed hydrological data, in Kiker’s (2013) case in the Crocodile Catchment.

2.4 Case Study 3 on Hydrological Model Verification being Fraught with Problems: Using Indicators of Hydrological Alteration Software to Identify Non-Homogeneities in Flows

In an attempted *ACRU* model verification of runoff in the Thukela catchment in KwaZulu-Natal, an initial selection was Quaternary catchment V14C monitored by weir V1H009. However, during the initial phases of the study it became evident that there had been a change in the catchment that had altered the streamflow (Toucher *et al*., 2021). Using the Indicators of Hydrological Alteration software, it appeared that the impact year was 1981. To illustrate this, graphs of the one day, 7-day and 90-day maximum flows with the 25th, 50th and 75th percentile lines are shown in **Figure 2.4.1**.

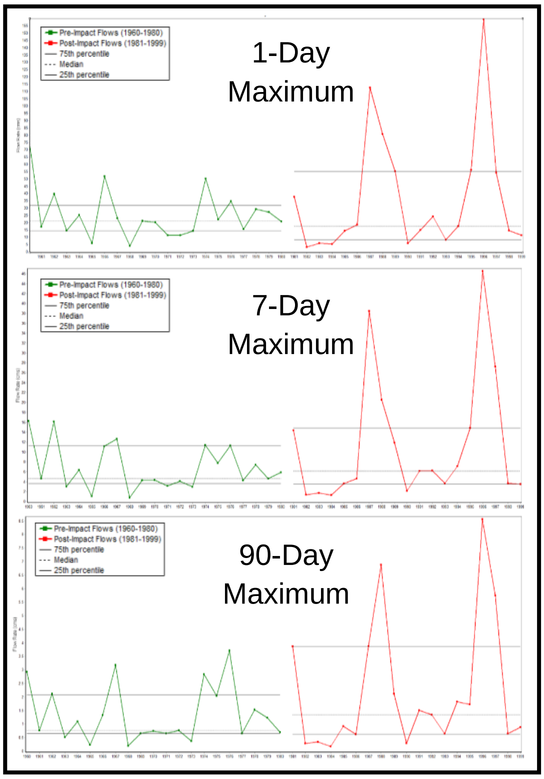

Figure 2.4.1 Example of the changes in streamflows in Thukela catchment V14C at weir V1H009 post-1981 using the 1-day, 7-day and 90-day maximum flow rates from the Indicators of hydrological Alteration software to illustrate non-homogeneities in the flow record (Toucher *et al*., 2021)

Between the periods 1961-1980 and 1981-1999, there are clear differences in these percentiles indicating the non-homogeneity in the flow record between these periods. However, no documentation on the impact could be traced. Based on the above, the choice was taken to rather undertake a verification study elsewhere.

2.5 Case Study 4 on Hydrological Model Verification being Fraught with Problems: The Dated Rating Table and Missing Rainfall Data Problem

The Rating Table Dilemma

In a verification for a Water Research Commission study, more details of which are given in **Chapter 10.5**, it was observed for the gauging weir T3H004, which monitored at the outlet of Quaternary catchment T32C in the Mzimvubu catchment and has an area of 1 029 km^2, as well as for gauging wier that so-called 'over-topping' was taking place, and no daily average flows exceeded 38 m^3.s^{-1}. However, when the weir's Ratings Table was consulted, the most recent Ratings Table was one from 1951 and that no allowance was made for flows in excess of 1.07 m deep. Despite best efforts to extend the ratings curve there, this was not possible and it remained problematic to have any confidence in the verification. For verifications to be valid, it is thus important that rating tables be up-to-date.

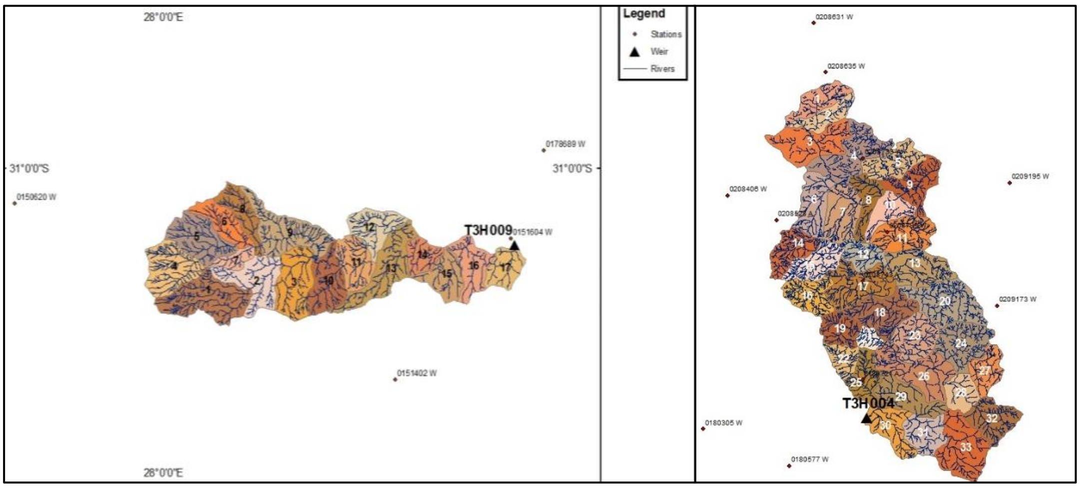

Figure 2.5.1 Catchment sub-delineations, rainfall stations and the weir locations of verification catchments T35 upstream of weir T3H009 (left) and T32A-T32C upstream of weir T3H004 (right) within the Mzimvubu system

Missing / Lack of Rainfall Data

One of the biggest problems faced in verifying streamflows by hydrological modelling in these, and in many other gauged operational catchments in South Africa, is that of finding acceptably suitable rainfall data as input to a model for both operational and for verification purposes, given especially that rainfall is arguably the most sensitive hydrological input variable in runoff simulations. For example, given the 1 029 km^2 area of catchment T32C upstream of the streamflow gauging structure T3H004, which from north to south extends over a distance of > 50 km (**Figure 2.5.1** right), as well as the 307 km^2 area of catchment T35 upstream of gauge T3H009, these catchments for which verifications were required for a Water Research Commission project, did ***not have a single rainfall station within their bounds***, although there were numerous rainfall measuring stations outside their bounds (**Figure 2.5.1**). Additionally, many of those rainfall stations for these two catchments had either highly unreliable data or large percentages of patched data, implying that the driving rainfall stations for the simulations were limited to very few external stations, some of which were at a distance to the catchment (see **Figure 2.5.1**). Given that historically much of the Mzimvubu catchment is made up of the former Transkei homeland, it is not surprising that there is such a sparse network of monitoring systems in place, yet it is a region where major water resources development is currently taking place, and historical hydrological data are desperately required.

2.6 Case Study 5 on Hydrological Model Verification being Fraught with Problems: The "Washday Effect" and the "Thirsty Train Effect"

These two true sources of error, while anecdotal in nature, were actually experienced by the author.

The "Washday Effect"

In the early 1980s the results from the outlet streamflow gauging weir at the Ntabamhlope Research Catchments in the Midlands of KwaZulu-Natal the digitised result invariably displayed a rapidly rising hydrograph over a period of about half an hour at around 09:00 on Mondays, followed by a sudden drop in the water level to around its original level an hour later. Field investigation showed that local women placed a plank across the V-notch to raise water levels to enable them to do the Monday laundry. When done, they would remove the plank and the surge of water allowed them to rise their washing very effectively! Following that discovery that sudden fake hydrograph was omitted from the digitisation procedures.

The "Thirsty Train Effect"

The railway line between Greytown and Kranskop in the Midlands of KwaZulu-Natal runs adjacent to the streamflow gauging weir on the Hlimbitwa River. Again, in the early 1980s, the hydrograph would, around a certain time and on a daily basis, decline very rapidly within minutes and the rise again gradually to near its original level. Field observation showed that the steam train would halt near the weir and withdraw water out of the weir via a suction pump until it had enough water again! Once discovered, this "thirsty train effect" was accounted for in streamflow analyses.

2.7 In Summary: Responsibilities of the Model Developer and the Model User in Regard to Hydrological Model Verification

Responsibilities of the Model Developer in Regard to Model Verification

The model developer, as the creator or conceptualiser of a model, provides the tool of the trade for practising engineers and hydrologists and, as such, has to render the model effective, robust, relatively easy to use and easy to verify against observed data. The developer thus has to satisfy

- the user and decision maker, by rendering the model a credible and useable product in which the decision maker can have confidence in the model results/outputs,
- and satisfy his/her scientific credibility (and curiosity) by a willingness to add new routines and/or to make refinements to routines in order to improve verification results for the "right reasons", and thereby to add to the hydrological knowledge base, rather than by simply calibrating/changing values of parameters and variables to (artificially) "force a good fit" which may be invalid at other locations.

To achieve and ensure a statistically acceptable and hydrologically valid verification (assuming that the observed rainfall and the observed runoff are accurate), the model developer thus

- needs to have a *high level of conceptualisation* of the hydrological system and the processes making it up, implying therefore that he/she needs to select a model structure and combinations of sub-structures which are appropriate to *the model's objectives/purpose*;
- has to ensure, when linking model components, that each routine and/or process representation be at a *comparable level of complexity* and conceptualisation, because in hydrological modelling the "weakest link in the chain" concept holds, i.e. the model is only as good as its weakest process representations, and not as good as its best routines;

and, thus, has to

- take care to *avoid mixing and matching* of routines from different models at different levels of complexity or conceptualisation, otherwise a fundamental rule of model development is violated and the verification result may be invalid;
- guard against over-parameterization, which again may yield good verification outcomes at one location, but not necessarily elsewhere;
- in the model's documentation, state clearly the initial and boundary conditions;
- identify clearly under what conditions the model or module is valid and not valid, hence identify its uses and non-uses;
- state all assumptions and limitations, because failing that is not only poor modelling ethic, but may also eventually ruin user confidence in applying the model because verifications may be poor;
- indicate which parameters/variables the model is sensitive to;
- test the model's final output (e.g. runoff) as well as its internal state variables (such as soil moisture content) to its limits across a wide range of hydro-climatic conditions to see where/when it "crashes"; and has to
- provide guidelines on verification procedures and sequences.

Responsibilities of the Model User in Regard to Verification

Probably the major responsibility of the model user in regard to undertaking a verification study is to *understand the model*. That includes

- working within the model's goals and objectives,

and understanding

- its structure,
- its assumptions and limitations, especially in regard to scales of space and time,
- its potential, and
- its input requirements.

What the user should *avoid* in a verification study is taking a *black box view* of the model, e.g. by attempting shortcuts, or not studying the manual carefully, or not understanding the theory behind the various concepts, options or pathways in the model.

Users tend to want to verify a model's output against observations too quickly,

- without carefully *checking model input* parameters and especially input data (NB: GIGO, i.e. *garbage in, garbage out*) and
- without going through the various steps to ensure the end answers are hydrologically valid, and thus
- without always applying "*hydrologic logic*" to model output, i.e. checking that the output is intuitively correct, and
- without *interpreting the results* carefully before disseminating results to the client. This ensures that upon subsequent checking or re-running the model all assumptions are known.

The user has to feed back problems, poor (and good!) verification results or interpretations to the developer, not only as a validation of accredited usage, but also to suggest improvements.

Finally, it remains the responsibility of the user to obtain latest versions and/or updates of the model when undertaking a verification study.

3 A SYNOPSIS OF STATISTICS USED IN ASSESSING AGRO-HYDROLOGICAL MODEL VERIFICATIONS

3.1 General Aim of a Good Hydrological Simulation

The general aim of a good hydrological simulation is

- a one to one correspondence between simulated and observed values, with
- a high correlation, a
- minimum symmetric error and the
- conservation of means, deviations and other statistics (Smithers and Schulze,1995),

The wide range of goodness-of-fit statistics comparing observed and simulated values can be categorised into conservation statistics and regression statistics.

3.2 Conservation Statistics

Conservation statistics include comparisons of means, standard deviations and the skewness coefficient between observed and simulated values. The *general aim* with regard to the *conservation statistics* is to minimise:

- the percentage difference between means of observed and simulated values, between
- the percentage difference in standard deviation, i.e. in minimising the difference in dispersion of the observed and simulated data about their mean values, and between
- the percentage difference in skewness coefficient, i.e. the symmetry of observed vs simulated values.

3.3 Regression Statistics

Similarly, *regression statistics* for comparison of observed and simulated values include the correlation coefficient, coefficient of determination, slope as well as y-intercept for the scatter plot of observed versus simulated values. The aim with regard to *regression statistics* is to:

- maintain a slope as close as possible to 1.0 since a slope value greater than one indicates over-simulation whereas a slope value less than 1.0 indicates under-simulation,
- minimise the base constant (y-intercept) to zero,
- maximise the correlation coefficient to unity, and
- maximise the coefficient of determination to unity.

More details on some key statistics used (albeit not all) in verification studies are described below.

3.4 Difference of Mean Annual Flow

A key variable is simulation of the Mean Annual Flow (*MAF*), shown in the equation below, using the Smithers and Schulze (1995) classification, according to whom a difference of less than 5% is characterized as “Excellent”, and one over 15% is classed as “Unsatisfactory” (**Table 3.1**). The equivalent *PBIAS* value (see below) is classified using the Moriasi *et al.* (2007) equation, where values under 10% are classified as “Excellent”, and values over 25% are classed as “Unsatisfactory”.

$$MAF_{Diff} = \left(\left(\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} O_i * 100 \right) - 100 \right)$$

where MAF_{Diff} is the difference of summed streamflow during the observation period, expressed as a percentage, and P_i is the simulated daily streamflow, with O_i the observed daily streamflow.

The Percent Bias (*PBIAS*) is calculated using the same input variables as the equation for Mean Annual Flow Differences:

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (O_i - P_i) * 100}{\sum_{i=1}^{n} (O_i)} \right]$$

3.5 Difference in Standard Deviation

The difference in standard deviation is important for hydrological simulations as this objective function provides a measure to evaluate how well the model mimics the range and frequencies of often highly variable streamflow volumes (equation below). Following recommendations by Smithers and Schulze (1995), values less than 5% are characterized as “Excellent”, and the aim is to keep the difference below 15%. In order to categorize four evaluation classes, differences below 15% are considered to be “Good”, values under 25 are considered “Satisfactory”, and differences over 25% are considered “Unsatisfactory”.

$$STDEV_{Diff} = \big((STDEV_{Sim} - STDEV_{Obs}) * 100\big) - 100$$

where $STDEV_{Diff}$ is the difference between simulated ($STDEV_{Sim}$) and observed ($STDEV_{Obs}$) standard deviations, expressed as a percentage.

3.6 Coefficient of Determination, r2

As mentioned above already, the Coefficient of Determination (r^2) describes the degree of collinearity between simulated and measured data, thus describing the proportion of the variance in measured data explained by the model. The r^2 (equation below) ranges from 0 to 1, with higher values indicating less error variance. As a rule, r^2 values greater than 0.5 are considered acceptable. However, here the evaluation criteria by Smiters and Schulze (1995) are applied, which are more stringent. Although the r^2 has been commonly used for model verification, it is considered to be oversensitive to high extreme values (floods) and insensitive to accurate simulation of low flows.

$$r^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]$$

where O_i is the i^{th} observation of daily streamflow, P_i is the i^{th} simulated value of daily streamflow, $\bar{O}$ is the mean of observed data, $\bar{P}$ is the mean of simulated data, and n is the total number of observations.

3.7 RMSE-Observations Standard Deviation Ratio (RSR)

The *RMSE* statistic has already been described above. The *RMSE*-observations standard deviation ratio (*RSR*) is recommended as a model evaluation statistic and normalizes the *RMSE* by using the observed standard deviation (see equation below). A value of zero indicates a perfect model simulation. The smaller the *RSR* is, the better is the simulation. *RSR* is rated here following Moriasi *et al*. (2007) to be “Excellent” when values are less than or equal 0.5, and “Unsatisfactory” when values are greater than 0.7.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}}\right]$$

where $RMSE$ is the root-mean-square-error, $STDEV_{obs}$ is the standard deviation of observed streamflows, O_i is the i^{th} observation of daily streamflow, P_i is the i^{th} simulated value of simulated daily streamflow, $\bar{O}$ is the mean of observed data, $\bar{P}$ is the mean of simulated data, and *n* is the total number of observations.

3.8 Nash-Sutcliffe Coefficient of Efficiency (NSE)

The Nash-Sutcliffe efficiency coefficient (*NSE*) is a normalized statistic that describes the relative magnitude of the residual variance, referred to as “noise”, and compares it to the measured data variance, referred to as “information”. The *NSE* indicates how well the plot of observed versus simulated data fits the 1:1 line. *NSE* is computed by the equation below:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right]$$

where O_i is the ith observation of daily streamflow, P_i is the ith simulated value of daily streamflow, $\bar{O}$ is the mean of observed data, and *n* is the total number of observations. *NSE* values range from $-\infty$ and 1.0, with *NSE* = 1 being the optimal value. According to Moriasi *et al*. (2007), *NSE* values greater than or equal to 0.0 are generally viewed as acceptable levels of performance, whereas values below 0.0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. However, following the guidelines suggested by Moriasi *et al*. (2007), *NSE* values must be greater than or equal to 0.5 to be considered satisfactory. It has been proposed that the *NSE* is the best objective function for reflecting the overall fit of a hydrograph.

3.9 Slope of the Regression Line

The slope of the regression line (*b*) indicates the relative relationship between simulated and measured values (see equation below). A slope of 1 for simulated against observed streamflows indicates that the model reproduces the magnitudes of measured data perfectly. A slope greater than 1 indicates over-simulation of daily streamflows, and a slope less than 1 reveals under-simulation of daily streamflows. The slope is highly sensitive to very high values (flood events). The slope is commonly examined under the assumption that measured and simulated values are linearly related.

$$b = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

where b is the slope of the regression line, expressed as a ratio, where O_i is the ith observation of daily streamflow, P_i is the jth simulated value of daily streamflow, $\bar{O}$ is the mean of observed data, $\bar{P}$ is the mean of simulated data, and *n* is the total number of observations. Slope values are rated according to Smithers and Schulze (1995), and classed as “Excellent” when the slope is greater than or equal to 0.9, and “Unsatisfactory” when it is less than 0.6.

3.10 Summary of Key Verification Statistics and Thresholds Defining their Respective Evaluation Classes

In summary, key verification statistics and thresholds defining their respective evaluation classes are shown in **Table 3.1**.

Table 3.1 Verification statistics and thresholds defining their evaluation classes

Verfication Statistic	Excellent	Good	Satisfactory	Unsatisfactory
% Difference of Mean Annual Flows	≤ 5	≤ 10	≤ 15	> 15
Difference in Standard Deviation	≤ 5	≤ 15	≤ 25	> 25
r^2 of Daily Flows	≥ 0.80	≥ 0.70	≥ 0.60	< 0.60
r^2 of Monthly Flows	≥ 0.85	≥ 0.75	≥ 0.65	< 0.65
Slope of the Regression Line	≥ 0.90	≥ 0.80	≥ 0.60	< 0.60
Percent Bias	≤ 10%	≤ 15	≤ 25	> 25
RSR	≤ 0.50	≤ 0.60	≤ 0.70	> 0.70
NSE	≥ 0.75	≥ 0.65	≥ 0.50	< 0.50

3.11 References

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4 THE *ACRU* AGRO-HYDROLOGICAL MODELLING SYSTEM WITHIN A BROADER CONTEXT OF MODELLING WATER RESOURCES IN SOUTH AFRICA, AND AS A TOOL FOR VERIFICATION

4.1 What Makes Up the Hydrological System that We Need to Model?

From a South African water resources context, now and into the future, modelling the impacts of changing land uses in a topographically, socio-economically and climatically diverse and complex landscape upon which will be superimposed changing and challenging future climatic conditions, it becomes evident that hydrological modelling involves two "streams" of action, but which need to be merged. This is illustrated in **Figure 4.1.1** in a context of climate change. On the one hand,

- our hydrological landscape, especially if climate change is also a consideration, demands an innovative approach to modelling *hydrological processes*, because perturbations in the drivers of these processes, e.g. changes in precipitation characteristics (*ΔP*), changes in temperature (*ΔT*) and higher atmospheric concentrations of CO_2 (ΔCO_2) and the feedbacks of the latter on transpiration, will result in changes in evaporative demand, changes in the partitioning of rainfall into the different runoff components (e.g. stormflow, baseflow) and, hence, changes in water quality (e.g. sediment yield).
- In essence these response changes occur on the *landscape component* of the catchment on which both natural land cover and soils properties may already have been altered by human actions.
- Key climate related drivers in regard to the landscape component include direct changes in responses of runoff processes to the altered climatic drivers, but also indirect changes, for example, to the hydrological baseline against which impacts are assessed, or to altered water quantity and quality responses resulting from spatial changes in land use patterns associated current and projected new climates (Schulze, 2005).

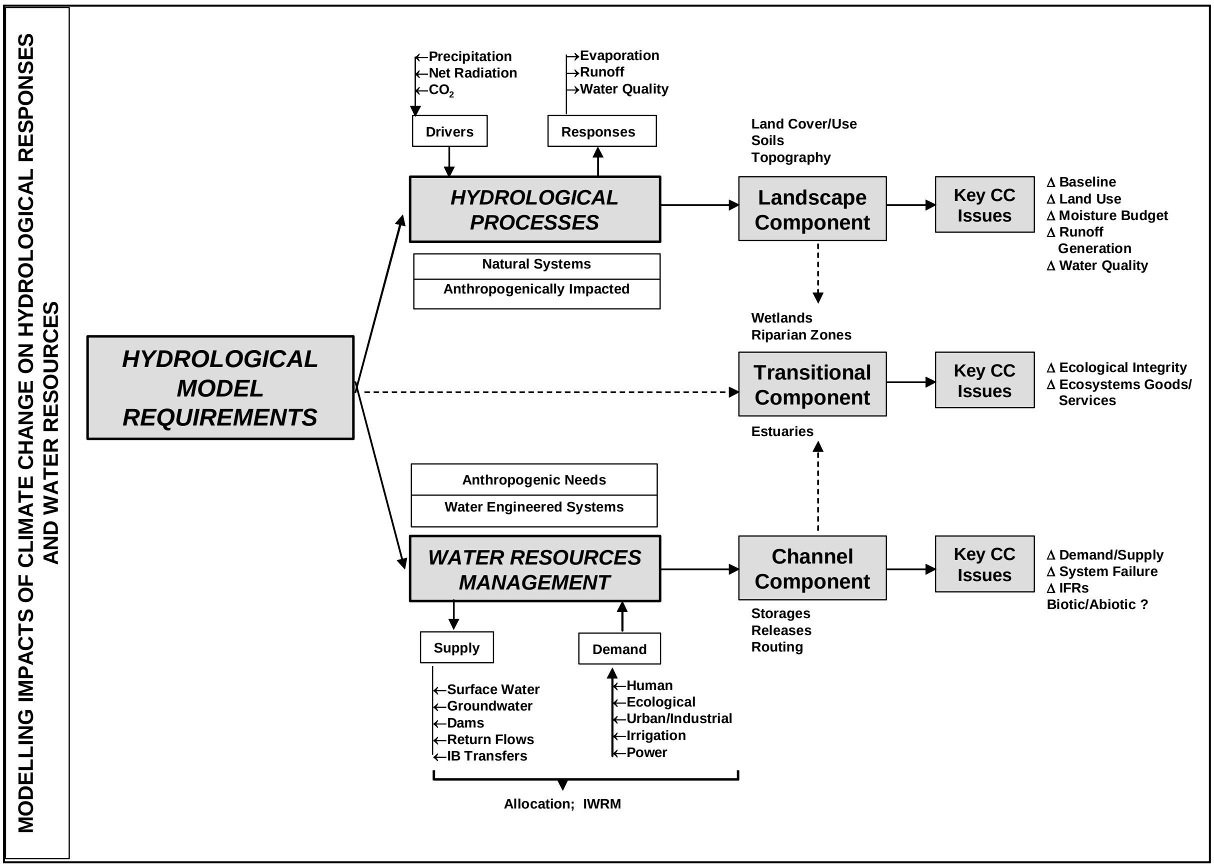

Figure 4.1.1 Hydrological model requirements under conditions of climate change (Schulze, 2005)

On the other hand, as illustrated in **Figure 4.1.1**,

- *water resources practitioners and managers* have to grapple, now and with future demands in future climates, with balancing the supply of water (be it from rivers, groundwater, impoundments, return flows or water transfers) with the demand for water (e.g. from basic human and ecological needs to requirements for the urban / industry sectors, power and irrigation) and to allocate available water, now and under projected future socio-economic and climatic conditions, in a sustainable manner through holistic planning which includes Integrated Water Resources Management (IWRM) and adopting a nexus approach.
- In most instances allocation of water involves manipulations of the *channel component* of the catchment through "controls" of storage (e.g. dams), releases (e.g. for urban, irrigation or environmental demands) and routing of water (e.g. for flood control or through inter-basin transfers).
- Key change related challenges in this instance generally revolve around engineering issues of changes in supply / demand, limits to the design of hydraulic structures in regard to system failure, as well as around environmental consequences of changes in natural flow regimes including in-stream flow requirements and other abiotic / biotic effects downstream (Schulze, 2005).

Wedged, in a manner of speaking, between the landscape and channel components are the

- *intermediate / transitional components* of the hydrological system, such as the wetlands, riparian zones and estuaries.
- These sensitive and often fragile ecosystems are frequently in delicate equilibria with the natural environment, and they may "flip" as a consequence of upstream landscape and channel manipulations. Under conditions of global warming these ecosystems may become even more fragile and / or sensitive.
- Key challenges in regard to wetlands, riparian zones and estuaries will need to be assessments of changes in their functioning and to the goods and services these ecosystems provide (Schulze, 2005).

For pro-active management all the above challenges have to be met explicitly or implicitly by appropriate hydrological modelling. Some model requirements are, therefore, listed and discussed below.

Requirements for Modelling Hydrological Processes 1: The Need to Be Able to Model Explicitly the Dynamics of Different Streamflow Generation Mechanisms

Streamflow is made up of various components which are generated by different mechanisms and are generated from different (and dynamic) source areas within a catchment, both of which may alter with land use and/or climate change. The different streamflow components display different properties and hydrological functions (Schulze, 2005), with

- *overland flows*, which may be generated either from connected (adjunct) impervious areas, or from saturated zones of variable areas, or when rainfall intensities exceed infiltrability, and with these flows having short residence times of minutes to hours, being event-based, removing / transporting sediments and other surface material (e.g. fertilizers, pesticides, industrial pollutants) and being critical in peak discharge estimations as well as in water quality determinations; whereas
- *subsurface stormflows* having slower response times and displaying different water chemistries; and
- *baseflows*, which are sustained by recharge through the soil profile or from preferential zones within a catchment, having long memories, displaying slow decay, a different water chemistry again and having a different criticality in that they maintain different biological functions to those of stormflows.

The proportions of these components of streamflow will vary, *inter alia*, with changed attributes of rainfall patterns and antecedent catchment wetnesses associated with land use and climate (Schulze, 2005), as well as with altered land uses and altered climates which are anticipated in future. Because of their variable residence times / lags, as well as their different origins within a catchment and their associated properties in regard to water quantity and quality, these streamflow components need to be *modelled explicitly* as *distinct individual components* (and not by empirical hydrograph separation) if certain key questions in their responses to climate change, and IWRM in general, are to be answered adequately.

Requirements for Modelling Hydrological Processes 2: The Need to Distinguish Clearly Between Landscape Based and Channel Based Processes

Within morphologically similar landscapes, hydrological processes which occur down hillslopes tend to be *repetitive*, with the hillslope elements of the catchment being the generators of streamflow in its different forms. Catchment (as distinct from channel) processes under conditions of present and future land uses and climates therefore to be modelled separately by *water budgeting* procedures, which are complex and may not always be fully understood (Schulze, 2005).

Channel processes, on the other hand,

- tend to be *additive* with catchment size,
- are *attenuated* by channel characteristics of slope, shape and roughness as well as by transmission losses to floodplains, banks and alluvial beds and by open water evaporation,
- may be *manipulated* (e.g. by abstractions, diversions and impoundments, **Figure 4.1.1**) and
- need to be modelled *hydraulically*, with often complex equations describing relatively well understood relationships.

If catchment and channel processes, as well as those of transitional hydrological features (the riparian zones, wetlands and estuaries) are not separated explicitly in models used for water resources and climate change impact studies, and IWRM in general, scaling problems emerge in parameterisations between smaller and larger catchments (Schulze, 2005).

Requirements for Modelling Hydrological Processes 3: The Ability to Model Hillslope Processes

Be it impacts of fertilizer or pesticide movement, the different generation mechanisms of streamflow or sediment production, or water demand by land uses in riparian vs. upslope areas, these are all influenced by hillslope hydrological processes and pathways with the respective thresholds, rates, accumulations and feedbacks of the different elements making up the landscape, *viz*. the crest, the scarp, the midslope, the footslope and the riparian zone. The hillslope elements and their accumulative downslope interactions ideally need to be represented in a conceptually sound manner in order to answer prognostically the many questions which catchment managers will be posing in the near future, and which are likely to be exacerbated by climate change (Schulze, 2005).

Requirements for Modelling Hydrological Processes 4: The Ability to Model the Different Processes Which May Dominate in Different Climatic Regimes

Southern Africa displays a wide climatic range with mean annual precipitations from < 80 mm to > 3 000 mm (Lynch, 2004) and with some precipitation falling with low intensity, often over a period of several days, occasionally as snow, and some associated with short, high intensity convective storms. The precipitation is, furthermore, highly variable both within a year and from one year to the next. This precipitation falls on landscapes varying from steep montane areas to undulating hills to flat plains. All this implies a highly variable spatio-temporal conversion of precipitation to streamflow, as well as a regionally and seasonally variable partitioning of the streamflow into overland flows, subsurface stormflows, baseflows or even snowmelt and, in the case of the groundwater table, this may or may not be “connected” to the channel, depending again on season and location.

For example, groundwater recharge may be through the soil matrix in more humid areas or by channel transmission losses in more arid zones, while evaporation losses may be dominated by riparian zone processes, or by transpiration, or by soil water evaporation, depending on climatic regimes and vegetation coverage, or evaporation rates may be influenced strongly by slope and aspect. By way of another example, mountain catchments’ hydrology may be dominated by poorly understood

precipitation:altitude gradients which vary with rain vs. snow, with rainfall intensities, numbers of rainfall days and event magnitudes, since all of these change with elevation and with season.
Climate change will alter the spatial patterns of hydroclimatic regimes. Directly, or by surrogate means, the various processes which under present climatic conditions may be present or absent, or may dominate in specific hydroclimatic regimes, will have to be encapsulated in model process representations for effective modelling of water resources and climate change impacts on water resources.

Requirements for Modelling Hydrological Processes 5: The Ability to Model Different Intensities of Land Management Practices

Identical broad land cover categories can produce significantly different hydrological responses, depending on the level or intensity of management practices. Thus, for example, grassland in overgrazed vs. well managed conditions can change sediment yield by a factor of four or more (e.g. Schulze and Horan, 2007), or annual crops grown on fields with vs. without contour banks, or under conventional vs. conservation tillage practices, can yield significantly different magnitudes not only of sediment yields, but also of total runoff, in addition to changes occurring in the partitioning of that runoff into stormflows vs. baseflows (Lumsden *et al*., 2003).

In an era when, in southern Africa, streamflow reduction activities, best management practices, payments for ecosystems goods and services, the polluter pays principle and a nexus approach are integral components of water management, and where land uses are likely to shift spatially in future with the result that adaptive management practices are likely to be applied, models have to be able to simulate differences in land use management practices realistically under present and, particularly, future climatic conditions.

Arising out of the Above Requirements: The Need for a Daily Time Step, Conceptual-Physical, Process-Based and Non-Linear Dynamic Response Model

In order to model potential impacts of global change on hydrological processes and responses (the top component in **Figure 4.1.1**), in line with the model requirements discussed above, such a model needs the following attributes:

- be *conceptual* in that it conceives of a one or multi-dimensional system in which important processes and couplings are idealised, and
- be *physical* to the degree that the physical processes are represented explicitly through observable variables.
- The model should, at minimum, be of the functional deterministic category (i.e. threshold based, with initial and boundary conditions) in its process representation (Schulze, 1998).
- Hydrological processes should account for present and future climate exchanges of water vapour, CO_2 and energy (e.g. precipitation attributes, streamflow generation responses, evaporation and transpiration together with its CO_2 driven feedbacks for modelling plant-soil interactions of future climates),
- modified by characteristics of the
  - *soil* (surface infiltrability, subsurface transmissivity of soil water and water holding capacity),
  - *land cover and land use / management* (e.g. with above-ground attributes related to intra-seasonal biomass; surface attributes of soil protection by litter / mulch or of tillage practices; below-ground attributes relating to root distribution), and
  - *topographic features* of the landscape (altitude, slope, aspect, toposequence and topographic position).
- The model should reproduce non-linear and scale-related catchment responses explicitly, where these may be associated with
  - *spatial heterogeneity* in surface processes (e.g. topography, soils, rainfall, evaporation, land use),
  - *non-linearities* responding to episodic events (e.g. rainfall), cyclicity (e.g. seasons, evaporation), hillslope processes (e.g. on and below surface), immediate responses (e.g. surface runoff from

connected impervious areas; saturated overland flow), rapid responses (e.g. stormflow), ephemerality (e.g. discontinuous flows during the year), continuous responses (e.g. groundwater movement) and delayed responses (e.g. baseflow),

- *thresholds which are required* for surface and subsurface streamflow processes to commence, and
- *dominant processes which change with scale or human interference*, including emerging properties (e.g. advection) and representations of disturbance regimes (e.g. drainage of fields, changes in streamflow regimes resulting from dam construction / abstractions / return flows), gradual changes in land use intensification over time (e.g. agriculture and urbanisation), or in extensification (e.g. overgrazing impacts), or abrupt changes resulting from fires or flooding.

- As such the model should essentially be devoid of parameter adjustment, since parameterisation "hides" the reason for changes in hydrological responses while a conceptual-physical model "provides" the reason and should, in theory, not require external calibration procedures to produce robustly acceptable results under current and projected future climates.
- Furthermore, for most operational modelling, simulations should take place at daily time steps since
  - the day is the shortest *universal natural time step,* and
  - climate variables from GCMs are nowadays output at daily values. Furthermore,
  - diurnality encapsulates (albeit not perfectly) many hydrologically related processes which are important in climate change studies (e.g. evaporation, transpiration and many discrete rainfall events), while
  - many operational decisions are currently, and in future climates will also be, made according to daily conditions (e.g. irrigation, reservoir releases) and
  - daily climate data for baseline hydrological conditions are readily available.
- Model output for impact studies of land use and/or projected climate change within a framework of IWRM will have to address management conflicts for a range of spatial scales from upslope vs. downslope impacts, upstream vs. downstream impacts, as well as those within vs. between Water Management Areas (Schulze, 2008a).

The major advantage of such daily time step, conceptual-physical, non-linear response models is that, because of their high level of process representation and physically based boundary conditions, they may be used with confidence in extrapolations involving "what-if" scenarios of hitherto unmeasured land management strategies, extreme events or climate variability which may be associated with global change and which are essential ingredients of IWRM.

The *ACRU* model aspires to encapsulate the attributes outlined, and some details of the model are given below.

4.2 The ACRU Modelling System

Model Attributes

The *ACRU* agro-hydrological modelling system (Schulze, 1995; Schulze and Smithers, 2004 and updates), which has been, and is currently being, used extensively in water resources and climate change studies in southern Africa is centred around the following objectives and attributes (**Figures 4.2** and 4.3):

- It is a *daily time step, conceptual-physical* model,
- with variables (rather than optimised parameters values) estimated from physically-based characteristics of the catchment, and
- with the model revolving around daily *multi-layer soil water budgeting*.
- As such, the model has been developed essentially into a versatile simulation model of the hydrological and related system (**Figure 4.3.1**), structured to be highly sensitive to climate drivers and to land cover, land use and management changes on the soil water and runoff regimes, and with its water budget being responsive to supplementary watering by irrigation, to changes in tillage

practices, to enhanced atmospheric CO_2 concentrations associated with climate change, or to the onset and degree of plant stress, which may change with global warming.

- *ACRU* is a *multi-purpose* model which integrates the various water budgeting and runoff production components of the terrestrial hydrological system (**Figure 4.2.1**). It can be applied as a versatile model for design hydrology (including flow routing through channels and dams), crop yield estimation, reservoir yield simulation, ecological requirements, wetlands hydrological responses, riparian zone processes, irrigation water demand and supply, water resources assessment, planning optimum water resource utilisation / allocation, conflict management in water resources and land use impacts – in each case with associated risk analyses – and all of which can respond differently with climate change.

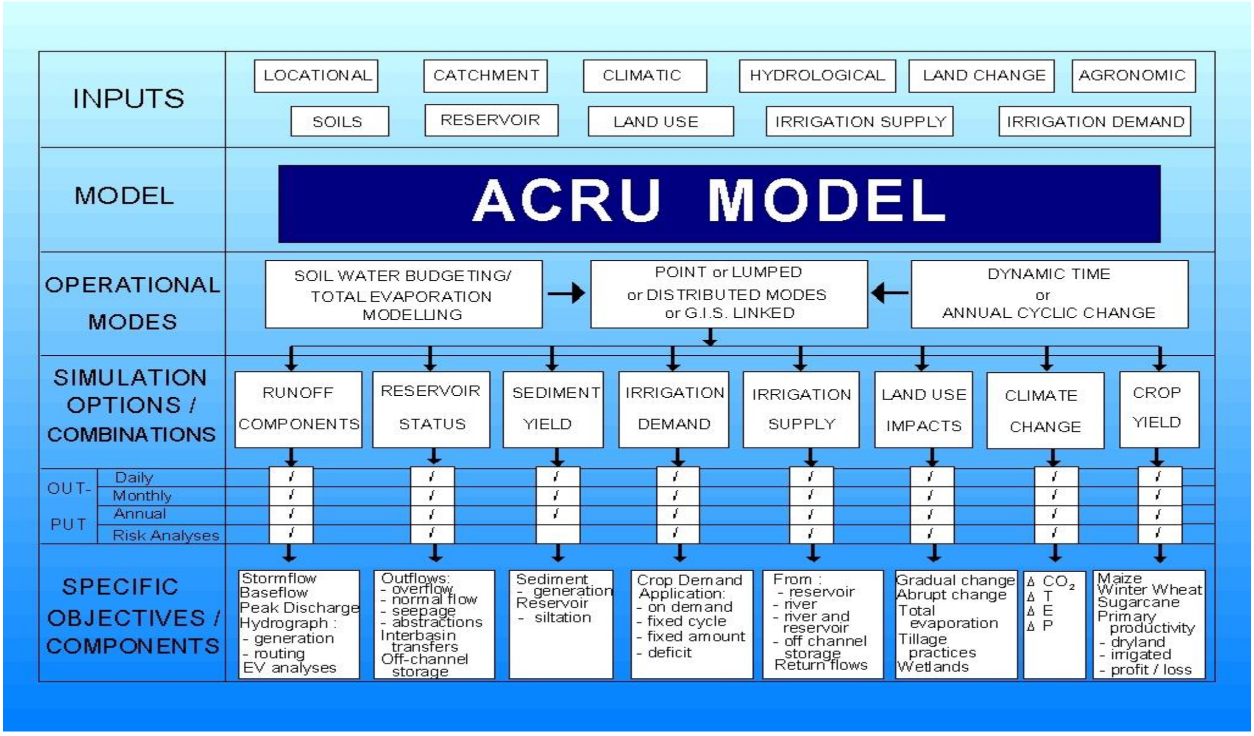

Figure 4.2.1 General structure and multi-purposeness of the *ACRU* model (After Schulze, 1995)

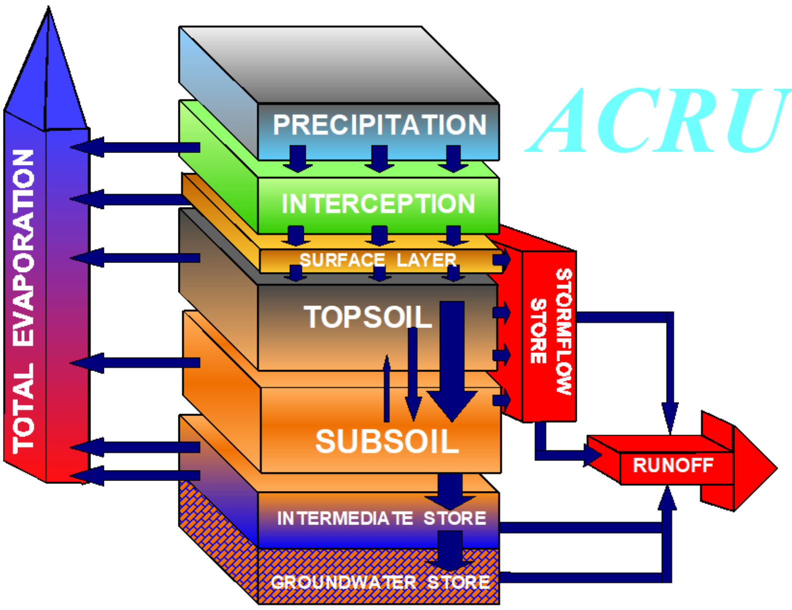

Figure 4.3.1 Schematic of major processes represented in the *ACRU* model (After Schulze, 1995)

- *ACRU* can operate at multiple scales as a *point* model or as a *lumped* small catchments model, on large catchments or at national scale as a *distributed* cell-type model with flows taking place from “exterior” through “interior” cells according to a predetermined scheme, with the facility to generate individually requested outputs at each sub-catchment’s exit.
- The model includes a *dynamic input option* to facilitate modelling of hydrological responses to climate or land use or management changes in a time series, be they long term / gradual changes (e.g. urbanisation or climate trends), or abrupt changes (e.g. construction of a dam), or changes of an intra-annual nature (e.g. crops with non-annual cycles).
- The *ACRU* model has been linked to the Southern African National Quaternary and Quinary Catchments Databases (Schulze and Horan, 2010) for applications at a range of scales in the RSA, Lesotho and Eswatini for climate change impacts and other studies.

General Structure of the ACRU Model

Multi-layer soil water budgeting by partitioning and redistribution of soil water is depicted in a highly simplified schematic in **Figure 4.3.1**. That rainfall and/or irrigation application that not abstracted as interception or converted to stormflow (either rapid response or delayed), first enters through the surface layer and "resides" in the topsoil horizon. When that is "filled" to beyond its drained upper limit (field capacity) the "excess" water percolates into the subsoil horizon as saturated drainage at a rate dependent on respective horizon soil textural characteristics, wetness and other drainage related properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed its drained upper limit, saturated vertical drainage/recharge into the intermediate and eventually groundwater stores occur, from which baseflow may be generated at an exponential decay rate dependent on geological / aquifer characteristics and the groundwater store.

Unsaturated soil water redistribution, both upwards and downwards, also occurs, but at a rate considerably slower than the water movement under saturated conditions, and is dependent, *inter alia*, on the relative wetnesses of adjacent soil horizons in the root zone. Evaporation takes place from water previously intercepted by the crop’s or vegetation’s canopy, as well as simultaneously from the various soil horizons, in which case it is either split into separate components of soil water evaporation (from the topsoil horizon only) and plant transpiration (from all horizons in the root zone), or combined, as total evaporation.

Evaporative demand on the plant is estimated, *inter alia*, according to atmospheric demand (through a reference potential evaporation) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density within the respective horizons, except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

It is vital in agro-hydrological modelling to determine at which point in the depletion of the plant available water reservoir plant stress actually sets in, since stress implies a soil water extraction below optimum, the necessity to irrigate, a reduction in crop yield and a lower runoff potential. In modelling terms, this problem may be expressed as the critical soil water content at which total evaporation, E, is reduced to below the vegetation's maximum evaporation, E_m (formerly termed "potential evapotranspiration"). E equals E_m until a certain fraction of maximum (profile) available soil water to the plant, *PAW*, is exhausted (**Figure 4.4.1**, left). The critical soil water fraction at which stress commences varies according to atmospheric demand (the hotter, the sooner stress commences) and the critical leaf water potential of the respective vegetation, the latter being an index of the resilience of the vegetation to stress situations. Plant stress, and a reduction in evaporative losses, however, also occurs when the soil is too wet, i.e. soil water content exceeds *PAW*. Furthermore, plant stress, when the soil dries out, can be either mild or severe, as illustrated in **Figure 4.4.1** (right). The various levels of stress are defined as follows:

- *Excess soil water stress* occurs when actual soil water content θ exceeds that at the drained upper limit θ_{DUL}, i.e. $\theta > \theta_{DUL}$
  and total evaporation, *E*, drops to below its maximum, E_m
- *No soil water stress* occurs when the plant can transpire at its maximum rate (i.e. $E = E_m$) with the soil water content then below that of the *DUL*, but exceeding the soil water content at a specified fraction of *PAW* at which plant stress commences, *viz*. θ_{fs}, which in the case where it has been set at 0.4 *PAW*, $\theta_{DUL} > \theta > \theta_{fs}$
  or $\theta_{DUL} > \theta > 0.4(\theta_{DUL} - \theta_{PWP}) + \theta_{PWP}$
  where θ_{PWP} = *soil water content at the permanent wilting point*
- *Mild soil water stress* is experienced when soil water content is below the stress fraction, θ_{fs}, but the plant is still transpiring at more than 20% of its maximum evaporation, i.e.
  $\theta_{fs} > \theta > 0.2\ E/E_m$
  $\theta_{fs} > \theta > 0.6\ (\theta_{fs} - \theta_{PWP}) + \theta_{PWP}$
- *Severe soil water stress* is defined as the soil water content at which total evaporation has been reduced to below 20% of maximum evaporation, i.e.
  $\theta < 0.2\ E/E_m$
  which in this case equates to $\theta < 0.6\ (\theta_{fs} - \theta_{PWP}) + \theta_{PWP}$

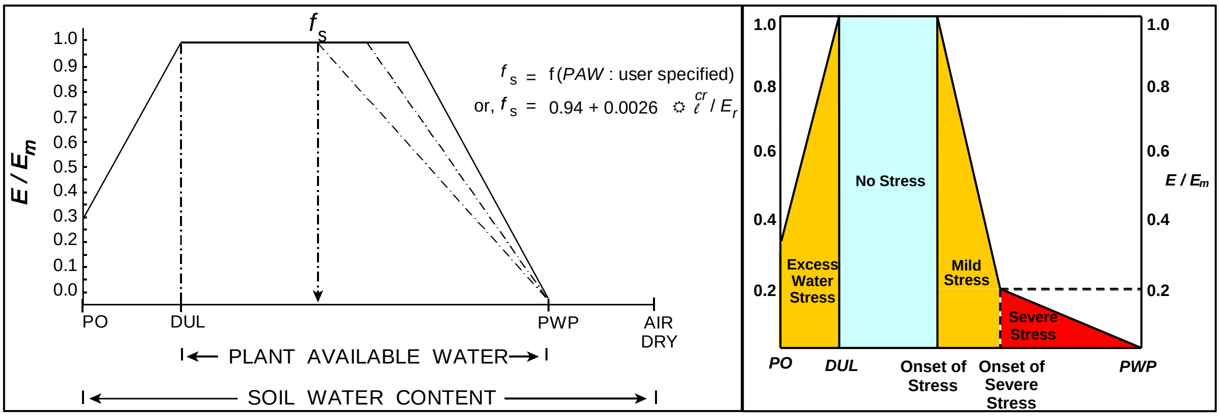

Figure 4.4.1 Interrelationships used in *ACRU* between soil water content and the ratio of $E : E_{tm}$ which expresses the level of plant water stress (right) and (left) different levels of stress experienced by plants (Schulze, 1995; 2008)

Generation of Stormflows with the ACRU Model

Stormflow, *Q*, is defined as the water which is generated from a specific rainfall event, either at or near the surface in a catchment or sub-catchment, and which contributes to flows of streams within that catchment/sub-catchment (**Figure 4.5.1**). It is largely from stormflow events that, for example, reservoirs are filled and design runoffs for selected return periods are computed. Furthermore, the soil detachment process in the production of sediment yield from a catchment is highly correlated with the volume of stormflow from an event. Important statistics on stormflows include annual means, inter-annual variabilities, magnitudes in wet and dry years and the number of stormflow events per annum exceeding critical thresholds.

Stormflow can be generated from both the impervious parts of the catchment connected directly to a stream (e.g. paved surfaces, roofs, permanently saturated areas directly adjacent to a stream; *ACRU* variable name ADJIMP in **Figure 4.5.1**) and from the pervious portions of a catchment. The amount of the stormflow which is generated from the pervious areas (expressed either as a depth equivalent in mm, or as a volume in m^3) in essence depends on the magnitude of the rainfall event (*P* in **Figure 4.5.1**) and how wet the catchment is just prior to the rainfall event.

Stormflow, Q_s, is computed in the *ACRU* model (Schulze, 1995 and updates) in mm equivalents as

$$Q_s = (P_n - I_a)^2 / (P + I_a + S) \quad \text{for } P_n > I_a$$

with P_n = net rainfall (mm), i.e. gross (measured) rainfall minus canopy interception losses,
I_a = initial abstractions (mm) before stormflow commences, consisting mainly of that infiltration which occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage, and
S = the soil's potential maximum retention (mm), which is equated to the soil water deficit and is an expression of the wetness or dryness of the soil.

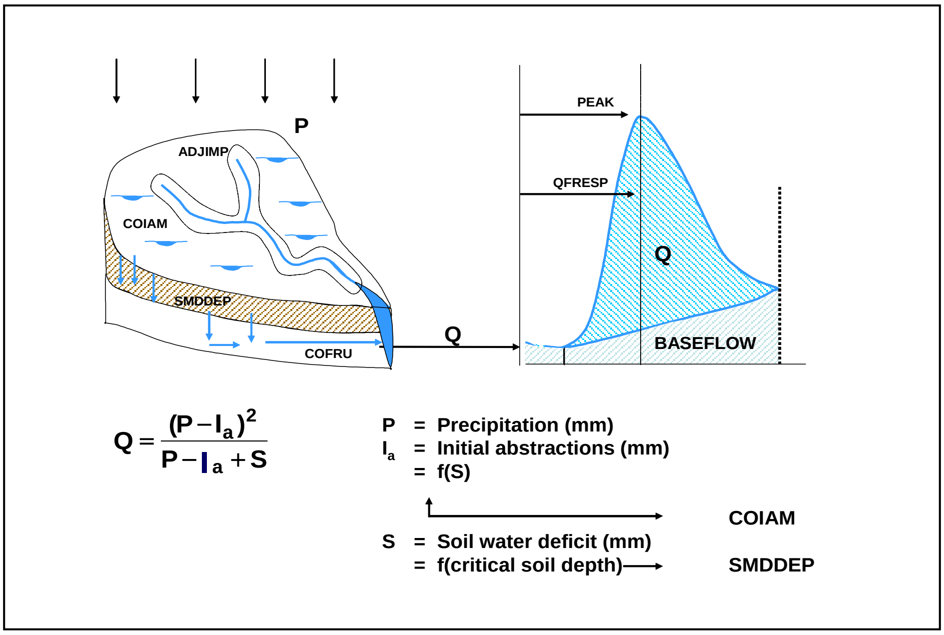

Figure 4.5.1 Schematic of runoff generating mechanisms in the *ACRU* model

In *ACRU*, the soil water deficit S is calculated by the daily multi-layer soil water budget, and for computations of stormflow a critical soil depth, D_{sc} (*SMDDEP*, in m, in **Figure 4.5.1**) is defined from which S is determined. The depth of D_{sc} accounts for the different dominant runoff producing mechanisms which may vary in different climates, as well as with catchment land uses, tillage practices, litter / mulch cover and soil conditions. This depth is therefore generally shallow in more arid areas characterised by eutrophic (i.e. poorly leached and drained) soils and high intensity storms which would produce predominantly surface runoff, but is generally deeper in high rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and "push-through" runoff generating mechanisms predominate. For all hydrological simulations in this report, D_{sc} was defined as the thickness of the topsoil.

A major determinant of initial abstractions is soil water content. In order to eliminate estimations of both I_a and S in the equation above, I_a is expressed as a coefficient, c, of S, where c is an index of infiltrability into the soil and varies with rainfall intensity (in the thunderstorm season: smaller c), tillage practice and surface cover / litter / mulch (Schulze, 1995). For all simulations of baseline hydrological responses in this document, the c of I_a was input as that value assigned on a month-by-month basis (*ACRU* variable COIAM in **Figure 4.5.1**) by Schulze (2004) for the 70 baseline land cover types found in South Africa, as defined by Acocks (1988). For simulations with other land uses (including fire and degradation / rehabilitation regimes) the monthly values of the c of I_a were taken from Schulze (2008b), in which all assumptions are explained.

Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurs, and the fraction that does depends on the size of the catchment, the catchment's slope and other factors (Schulze, 1995). This necessitates a stormflow response coefficient, F_{sr}, to be input, which controls the "lag" of stormflows and is effectively an index of interflow (*ACRU* variable name *QFRESP* in **Figure 4.5.1**). In all simulations on all sub-catchments in this document, F_{sr} was set at 0.3, a value which has been found experimentally to be typical in South Africa for use at the spatial scale of Quaternary and Quinary Catchments (e.g. Kienzle *et al*., 1997; Warburton *et al*., 2010) when the *ACRU* model's flow routing option is not used, as in this case.

Generation of Baseflows with the ACRU Model

Baseflows consist of contributions to runoff from the intermediate / groundwater store which had been previously recharged. These contributions are made up of slow and delayed flows to the catchment's streams. In the *ACRU* model it is assumed that the groundwater store is always "connected" to the stream system. Unlike many other models which compute baseflow indirectly from total runoff hydrographs with an empirically derived "separation curve", *ACRU* computes baseflow explicitly from recharged soil water stored in the intermediate / groundwater zone (Schulze, 1995).

The stored water is derived from rainfall of previous events which has been redistributed through the various soil horizons and has drained into the intermediate / groundwater store when the deepest soil horizon's water content exceeds its drained upper limit (field capacity). The *rate of drainage* of this "excess" water out of the deepest soil horizon *into the groundwater store* depends on that horizon's soil texture class, which in this Report has been input to vary from catchment to catchment according to soil attributes.

The rate of release of water from the groundwater store into the stream is determined by a release coefficient, F_{bff}, which is dependent *inter alia* on the geology, area and slope of the catchment. F_{bff} operates as a "decay" function which is input for a catchment as a single value (*COFRU* in **Figure 4.5.1**), but based on experiences with *ACRU* in many catchment studies, F_{bff} is not a constant decay function, but is enhanced or decreased internally in *ACRU*, dependent on the magnitude of the previous day's groundwater store, S_{gwp}, such that empirically

$$F_{bff} = F_{bfi}\ [[[(S_{gwp})^2 - S_{gwp}] / 1000 + 1.3] / 11]$$

where

F_{bff} = final baseflow release coefficient

F_{bfi} = input baseflow release coefficient and

S_{gwp} = magnitude of previous day's intermediate / groundwater store (mm).

For all simulations in this document an experimentally determined typical value of F_{bff} of 0.009 (Kienzle *et al*., 1997) has been applied in all Quinary Catchments in the study area.

Peak Discharge

The peak discharge is the highest flow rate of a hydrograph (cf. **Figure 4.5.1**). In the *ACRU* model an estimate of the peak discharge associated with each day's stormflow volume generated for the selected simulation period can be made by assuming a single triangular unit hydrograph. For these simulations the SCS peak discharge equation (USDA, 1972), modified significantly by Schulze and Schmidt (1995) is used. In its modified version

$$q_p = 0.2083 Q_s A / 1.83\ L$$

where

q_p = peak discharge ($m^3.s^{-1}$),

Q_s = stormflow depth (mm) from an individual catchment,

A = catchment area (km^2),

L = catchment lag (response) time (h)

= $\dfrac{A^{0.35} MAP^{1.1}}{41.67 y^{0.3}\, \bar{I}30^{0.87}}$ and

1.83 = a multiplier which was computed assuming high intensity rainfall to be associated with annual maximum one day storms over relatively small catchments, with the lag equation having been developed by Schmidt and Schulze (1984) using several hundred hydrographs from over 20 research catchments at seven hydro-climatically divergent regions in the USA and South Africa, and in which

- A = catchment area (km^2),
- MAP = mean annual precipitation (MAP in mm),
- Y = mean catchment slope (%), determined in the case of this Report from a 200 m digital elevation model, and
- $\bar{I}_{30}$ = magnitude of the 2-year return period 30-minute rainfall intensity ($mm.h^{-1}$).

As is evident from the above equations, Schmidt and Schulze (1984) found that climatic attributes played a major role in determining a catchment's runoff response, or lag, time. For example, they found that a rainfall event's intensity, best represented by the most intense 30-minute period of that event, significantly affects catchment lag time (Schmidt and Schulze, 1984), as did the mean annual precipitation, which was used as a surrogate variable to describe the retardation of stormflow as affected by a catchment's vegetative cover. Therefore, by using the lag equation above (i.e. L =), the potential effects of climate change on catchment lag, and hence peak discharge, can be estimated.

Generation of Sediment Yields with the ACRU Model

Complex deterministic models are available to estimate erosion processes and sediment transport. However, these models are limited in their application owing to their reliance on calibration. The Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), is an equation which has received recognition as an empirical method useful for planning and design purposes. This method is the foundation for other empirical equations which is then applied at a catchment scale to estimate sediment yield, such as the daily stormflow event based Modified Universal Soil Loss Equation, MUSLE (Williams, 1975), which has been widely verified world-wide and in South Africa (Kienzle *et al.*, 1997).

Sediment yield at any Quinary outlet (or that of any other spatial unit) may be estimated using the *ACRU* model, with the MUSLE imbedded and expressed as

$$Y_{sd} = \alpha_{sy} (Q_v \, x \, q_p)^{\beta_{sy}} K \, x \, LS \, x \, C \, x \, P$$

where Y_{sd} = sediment yield (t) from an individual stormflow event,

- Q_v = stormflow volume for the event (m^3),
- q_p = peak discharge for the event (m^3/s),
- K = soil erodibility factor (t h/N/ha),
- LS = slope length and gradient factor (-),
- C = cover and management factor (-), and
- P = support practice factor (-).

The MUSLE coefficients, α_{sy} and β_{sy} are location specific (Simons and Sentürk, 1992) and are determined for specific climatic zones. However, default values set at 8.934 for α_{sy} and 0.56 for β_{sy} were used in sediment yield simulations for this research.

Information needed for each Quinary Catchment when estimating sediment yield thus includes

- the stormflow volume for each event (using the equations given earlier in this Chapter, but with the mm equivalent Q being converted to a volume Q_v in m^3 by multiplying out for area);
- the peak discharge (m^3) for each event (using the equations given earlier in this section);
- the 30-minute rainfall intensity (mm/h) for the 2-year return period, I_{30}, used in the peak discharge equation and computed for historical data as outlined in Schulze (2012) and for climate change studies in South Africa by techniques developed by Knoesen (2011);
- the soil erodibility factor, K, determined from the ISCW's soil land types and mapped in detail for South Africa by Schulze and Horan (2008);

- the slope length factor, calculated from each Quinary Catchment's average slope gradient determined from, for example, a 200 m resolution Digital Elevation Model and an equation developed by Schulze (1979) which relates slope gradient to the slope length factor;
- the cover and management factor, *C*, as determined by Schulze (2004);
- the support practice factor, *P*, not applicable for these simulations under baseline land cover conditions and thus set to 1; and
- a factor proportioning the amount of the sediment generated from a stormflow event and which reaches the outlet to the respective Quinary Catchment on the day of the event, in order to account for sediment eroded at one location and which may be stored temporarily only to be subsequently remobilised several times before reaching the catchment outlet, and generally defaulted to 0.45 in South African studies.

Previous Verification Studies on the ACRU Model's Output

The *ACRU* model is arguably the most comprehensively verified (as against calibrated) model in southern Africa (Schulze, 2008a; this document), and in addition to verifications of end-product outputs such as streamflow (cf. **Photo 4.1**), its components of baseflow and stormflow or sediment yield, internal state variables such as soil water content have been verified against observed data.

Photo 4.1 Illustration of a streamflow gauging structure on the Mvoti river in KwaZulu-Natal, data from which have been used in streamflow verification studies (Photo: R.E. Schulze)

Some of the more comprehensive verification studies from South Africa are reported in Schulze (1995). Since 1995, Kienzle *et al*. (1997), Pike and Schulze (2001), Royappen *et al*. (2002), Dzukamanja *et al*. (2005) and Warburton *et al*. (2010) have undertaken detailed further verification studies using South African catchment data, an example of which is given in **Figure 4.6**, while other verification studies have been undertaken on observed catchment data from the USA (Schulze, 1984; Schmidt *et al*., 1986), Germany (Herpertz, 1994; 2001), Eswatini (Dlamini, 2001), Eritrea (Ghile, 2004) and Zimbabwe (Butterworth *et al*., 1999). More specifically in a context of impacts of land use, verifications have been undertaken by Schulze and George (1987), Haywood and Schulze (1990), Lumsden *et al*. (1998), Jewitt and Schulze (1999), Kienzle *et al*. (1997), Schmidt *et al*. (1998), Lumsden *et al*. (2003) and Warburton *et al*. (2010).

Model Links to Databases

As has already been alluded to, the *ACRU* model has been linked to historical daily climate databases for the 5 838 Quinary Catchments covering South Africa (Schulze *et al*., 2010), as well as to daily climate output for present and future scenarios from Global Climate Models (GCMs), downscaled to Quinaries (e.g. Schulze, 2011; 2012; 2016; Schulze and Davis, 2018), to accomplish analyses of climate change impacts on water resources in South Africa.

For application in climate change studies, rainfall and potential evaporation input in the *ACRU* model are perturbed in accordance with changes from regionally downscaled GCMs. A further option available in *ACRU*, but not used in this study, is modelling the enhanced CO_2 feedback on losses, in which a distinction is made between C3 and C4 pathways in crops

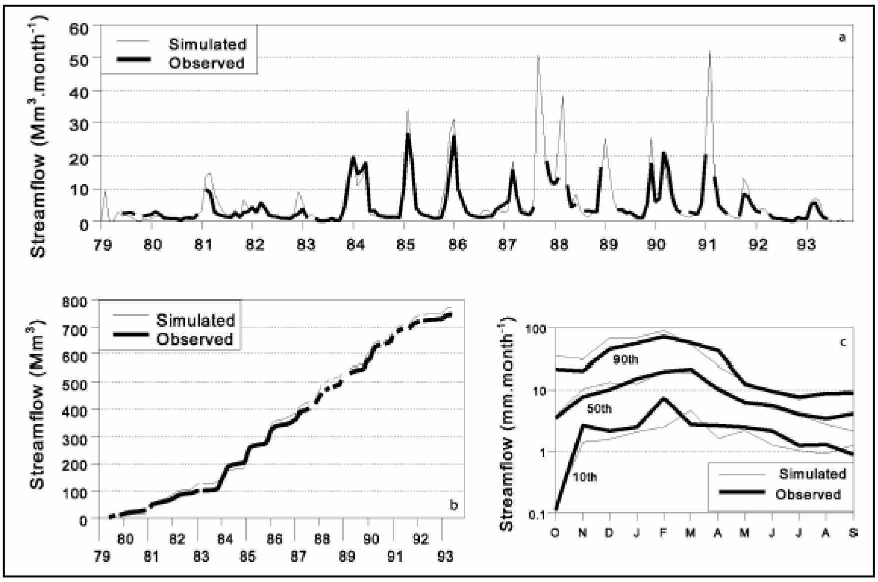

Figure 4.6 An example of a verification of streamflow with the *ACRU* model taken from the Lions River Quaternary Catchment in the Mgeni system (After Kienzle *et al*., 1997)

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5 BACKGROUND TO ACTUAL VERIFICATION STUDIES ON THE *ACRU* MODEL

5.1 More Detail on Previous Reviews on Verification Studies of the ACRU Agro-Hydrological Model

The first formal review of verification studies on the *ACRU* model was in 1995 in Chapter 22 of the so-called *ACRU* Theory titled "Hydrology and Agrohydrology: A Text to Accompany the *ACRU* 3.00 Agrohydrological Modelling System" (Schulze, 1995; pp 552) and consisted of 10 verification studies with 17 figures and 11 tables on both internal state variables in the model and direct model outputs, *viz*.

- The Von Hoyningen-Huene Canopy Interception Equation: A Verification on a Non-Agricultural Land Use (R.E. Schulze);
- Simulation of Soil Water Content by *ACRU* (M.C. Dent and R.E. Schulze);
- Simulation in Lumped Mode of Monthly Totals of Daily Streamflow from a Small Catchment at Cathedral Peak, KwaZulu-Natal (R.E. Schulze and W.J. George)
- Verifications of Design Runoff Depth and Peak Discharge Estimation by *ACRU* (E.J. Schmidt, R.E. Schulze and S.J. Dunsmore)
- Simulation in Distributed Mode of Monthly Totals of Daily Streamflow from a Larger Catchment of the Mgeni System (S.W. Kienzle and R.E. Schulze)
- An Application of the Dynamic Input Option for Hydrological Modelling with Changing Land Use over Time (K.C. Tarboton and R.E. Schulze)
- Verification of Hydrograph Routing in *ACRU* (J.C. Smithers and R.E. Caldecott)
- Simulation of Water Yield from Forested Catchments (J.P.W. Jewitt and R.E. Schulze)
- The *Eucalyptus grandis* Timber Yield Model (R.E. Schulze and D. Leenhardt); and
- Verifications of *ACRU*'s Maize and Winter Wheat Yield Models (R.E. Schulze and F.B. Domleo).

The second review, undertaken in 2008, consisted of an in-house listing of references on verification studies with the *ACRU* model (Schulze, 2008) and included the following:

- interception (1 entry),
- reference potential evaporation (2 entries),
- the soil water budget in *ACRU* (4),
- streamflow generation in *ACRU* (7),
- snowmelt hydrology (2),
- streamflow on international catchments (9) and
- streamflow on South African catchments (22),
- design hydrology (5),
- land use impacts of
  - afforestation (4 entries), of
  - sugarcane (5), of
  - tillage practices (1), of
  - fire (3), and of
  - general land uses (3 entries),
- wetlands processes and impacts (2 entries),
- groundwater table/baseflows (2),
- water quality (3),
- crop yields (4), and
- tree growth attributes (1 entry).

These entries, on numerous occasions, were double entries as they may have appeared in a thesis as well as in a subsequent publication. The verification studies included those reported in

- 5 PhD theses up to that point in time and
- 21 MSc or MSc Engineering dissertations, with
- 21 verification studies having been published in refereed journals,
- 19 in other refereed publications or conference proceedings, and

- 17 in Water Research Commission reports,

again, with some studies mentioned in more than one category.

5.2 Specialist Versions of the Model

The most commonly used version of the *ACRU* model is the so-called "standard" version, the details of which are contained in the *ACRU* theory and user manuals (Schulze, 1995; Smithers and Schulze, 1995). However, over the years specialist versions of the model have been developed to serve specialist needs. These include versions known as

- *ACRU*-Salinity
- *ACRU*-NPS
- *ACRU*-Snow
- TOP-*ACRU*
- *ACRU*-Grasslands
- *ACRU*-Groundwater
- *ACRU-E. coli*
- *ACRU*-Timber.

Verification results of some, but not all of these, are included in this Document.

6 VERIFICATION STUDIES OF INTERNAL STATE VARIABLES WITHIN THE *ACRU* MODEL

6.1 Verification of Soil Water Content Under Dryland Conditions: The Case of Sugarcane (Original Researchers: R.W. Haywood and R.E. Schulze)

Background

The Farm Planning Department of the South African Sugar Association Experiment Station undertook a range of sugarcane-related monitoring at the La Mercy Experiment Farm and research catchments, situated 28 km north of Durban, from 1977 until the mid-1990s at which point the King Shaka International Airport was constructed there. Observed soil moisture data from a plot of sugarcane for the period 31 August 1989 to 12 July 1990 were obtained from Inman-Bamber (1990). The sugarcane plot on the Experiment Farm is 2 km north of Catchment 102 (**Figure 6.1.1**). Information from Inman-Bamber (1990) which was used to determine soils and crop input values for the *ACRU* (and CREAMS) agro-hydrological model, consisted, *inter alia*, of measurements of soil water retention contents, soil textures and bulk densities of the soil profile as well as crop coefficients for sugarcane over time.

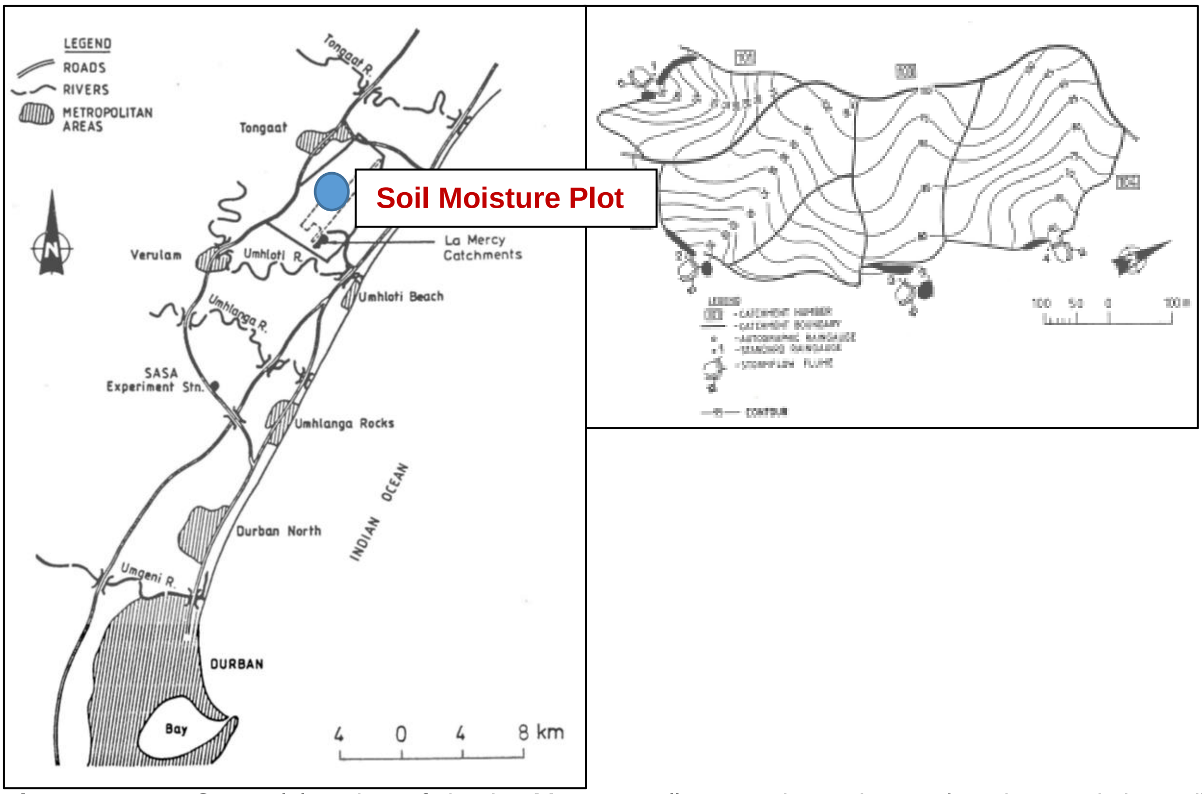

Figure 6.1.1 General location of the La Mercy small research catchments' project and the soil moisture plot, as well as more details of the catchment layout (After Haywood, 1991)

The sugarcane plot was harvested on 1 August 1989 and the period of this verification study concerned a ratoon crop. Daily rainfall data were obtained from an autographic raingauge 300 m from the site. Daily A-pan evaporation was obtained by calculating average values, weighted by inverse distance from the plot, measured at the SASA climatological sites at Mount Edgecombe Experiment Station and Tongaat (locations shown in **Figure 6.1.1**).

Method

The soil moisture of the top 100 mm of the soil profile was measured by gravimetric samples. Below this depth, soil moisture was measured by neutron probe at intervals of 150 mm down the soil profile to a depth of 1 300 mm (Inman-Bamber, 1990). In this verification the soil water content was initially modelled for the entire soil profile as a single horizon. However, since *ACRU* soils input and model output is for the topsoil and subsoil horizons separately, the soil water contents of these two horizons, as simulated by *ACRU*, were also verified separately against measured information. The soil horizons, determined by examining the measured texture and bulk densities of the profile, were 0-600 mm for the topsoil and 600-1050 mm for the subsoil. The soil moisture of the profile of the sugarcane plot was observed at weekly intervals. The simulated soil water status was noted for the days on which soil moisture observations were made.

Results and Discussion

Time series plots of *ACRU* (and CREAMS) simulated soil water contents vs. those observed for the entire soil profile as a single horizon are presented in **Figure 6.1.2**.

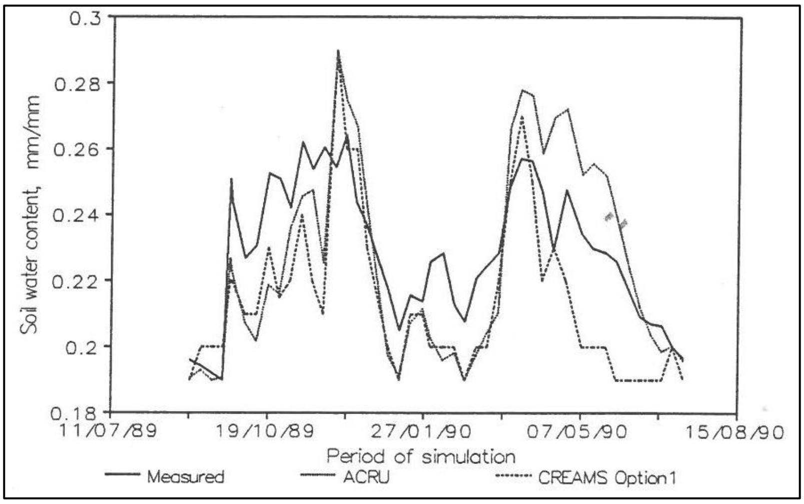

Figure 6.1.2 *ACRU* (and CREAMS) simulated versus measured soil moisture content for the entire soil profile on a plot of sugarcane at the La Mercy Experiment Farm (After Haywood, 1991)

The results presented in **Figure 6.1.2** show that the performance of the *ACRU* model was generally acceptable on a seasonal basis, but with sometimes marked differences in shorter term responses evident, in some cases with the model's responses more rapid than those observed while at other times the modelled responses of soil water content were slower than those observed.

In seeking possible reasons for these inconsistencies, the results of *ACRU*'s simulations of the soil water content of the topsoil and subsoil horizons were assessed separately, and are presented in **Figure 6.1.3** (left for the topsoil and right for the subsoil). The soil water status of the topsoil horizon has been simulated reasonably well by *ACRU*, but the rate of reduction of soil water content is too rapid (**Figure 6.1.3** left). However, *ACRU* did not simulate the soil water content of the subsoil horizon well (**Figure 6.1.3** right), with results under wet soil conditions being too high.

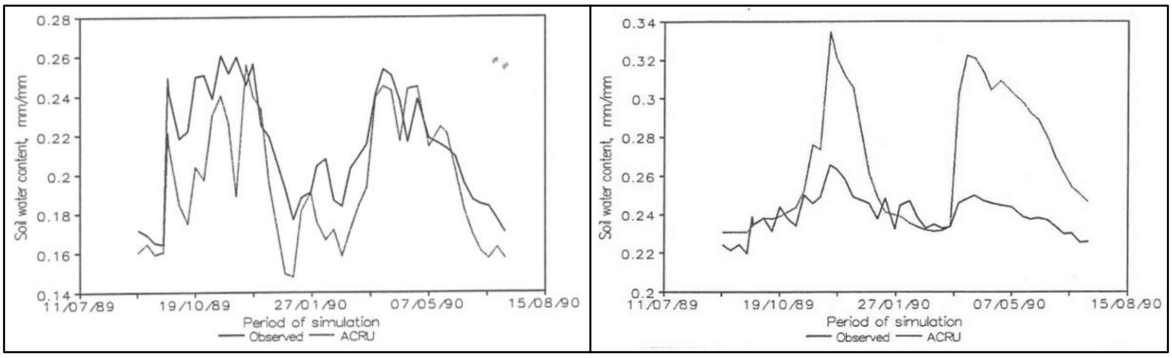

Figure 6.1.3 *ACRU* simulated versus measured soil moisture content of the topsoil horizon (left) and the subsoil (right) on a plot of sugarcane at the La Mercy Experiment Farm (After Haywood, 1991)

Possible Sources of Error in the Verification

The results presented above were for a so-called "blind" verification with the neutron probe measurements accepted as being correct and the *ACRU* input variables, taken from available information, being realistic. When verifications are broadly acceptable, but not in their finer detail, one invariably seeks possible sources of error and improvement. Possible sources of error in the simulation of *ACRU*'s topsoil horizon were hypothesised by Haywood (1991) to have included the following:

- the thickness of the topsoil as input into *ACRU* could have been too shallow,
- the vegetative crop coefficient and leaf area index values could have been too high, resulting in simulated soil water content often being too low,
- the fraction of plant available water at which total evaporation was assumed to drop below the maximum evaporation could have been too low,
- the proportion of roots in the topsoil could have been too high, resulting in higher evaporative losses and consequently simulated soil water content being too low,
- the saturated drainage rate from the topsoil to the subsoil horizons could have been too high, resulting in more rapid losses in *ACRU* when the soil was wet,
- incorrect soil water retention parameter values may have been used,
- the neutron probe calibration curve could have been unrepresentative of the soil occurring in the plot, and
- soil water uptake by the roots may not have been modelled realistically.

The soil water retention values measured by Inman-Bamber (1990) were checked and were considered correct. In order to try and improve the verifications, a number of sensitivity runs were performed to determine, for example, the effects of increasing the thickness of the topsoil horizon and the fraction of plant available water at which total evaporation was assumed to drop below the maximum evaporation, and reducing the crop coefficient, LAI, fraction of roots in the topsoil and the saturated drainage rate from the top- to the subsoil. For each sensitivity run, there were slight improvements in the model performances, but the rate of reduction in soil water content remained similar to that the original run (Haywood, 1991). Since no major improvements were obtained in the model performance after these variables and parameters, mentioned above, had been varied as hypothesised, further reasons for the poor model performance were attributed to a possibly unrepresentative probe calibration curve and soil water uptake by the roots not being modelled realistically.

Conclusions

Soil water status, and especially that of the topsoil, is a major determinant not only of evaporative losses, but also of runoff generation. Simulations of soil water by *ACRU* on a plot of sugarcane gave generally satisfactory results for the topsoil, which engenders confidence in the model's factoring in antecedent soil water conditions when simulating runoff and when simulating total evaporation (often referred to as "actual evapotranspiration").

However, the subsoil's water content was not simulated satisfactorily, with *ACRU* under-simulating this. In the discussion above, a major source of possible error was attributed to saturated drainage rates in *ACRU* having been set too high. With saturated drainage rates from the top- to the subsoil reduced, this would have enhanced not only the topsoil's verification, but also that of the subsoil. At the time that this verification study was undertaken in 1990, suggestions were for further research into water uptake by the roots and for the verification of the soil water status on the plot of sugarcane to be repeated after the probe has been calibrated for this site.

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Haywood, R.W. 1991. *Model Evaluation for Simulating Runoff from Sugarcane Fields*. MScEng Dissertation, University of Natal (now KwaZulu-Natal), Pietermaritzburg, RSA.

6.2 Verification of Soil Water Content under Irrigated Conditions (Original Researchers: M.C. Dent, R.E. Schulze and G.R. Angus, 1988)

Background

Accurate estimates of soil water content by the *ACRU* model are important for many applications such as runoff responses to rainfall, crop yield estimates and irrigation requirement, since the soil water budget lies at the "heart" of the model. This section describes a verification of *ACRU's* output of soil water content under irrigated conditions.

The Verification Experiment

Observed soil water data on plots planted to wheat and soybeans were obtained respectively for Roodeplaat in Gauteng and Cedara in KwaZulu-Natal. Details on the sites, their soil properties, irrigation regimes and soil moisture observation techniques are described in detail by Dent *et al*. (1988), as are the goodness-of-fit statistics of the verifications. Results are shown in **Figure 6.2.1**.

Results of the Verification

The *ACRU* model simulations of soil water content at Roodeplaat were particularly encouraging since they spanned the entire growing season (5 months), during which period the observed soil moisture in the top 0.9 m of soil experienced a range of 100 mm, the nine irrigation applications ranged from 6 mm to 152 mm and the five rainfall events ranged from 9 mm to 80 mm.

The above comparison of observed and *ACRU* simulated soil water content at two locations with different climates, irrigation strategies and crops lends credence to the *ACRU* model's being able to simulate soil water content realistically. From this and several other verification studies on the soil water regime it is believed that the model can be used with confidence in irrigation soil water budget calculations, either for simulating soil water status *per se* or for using soil water status as a critical determinant in runoff production.

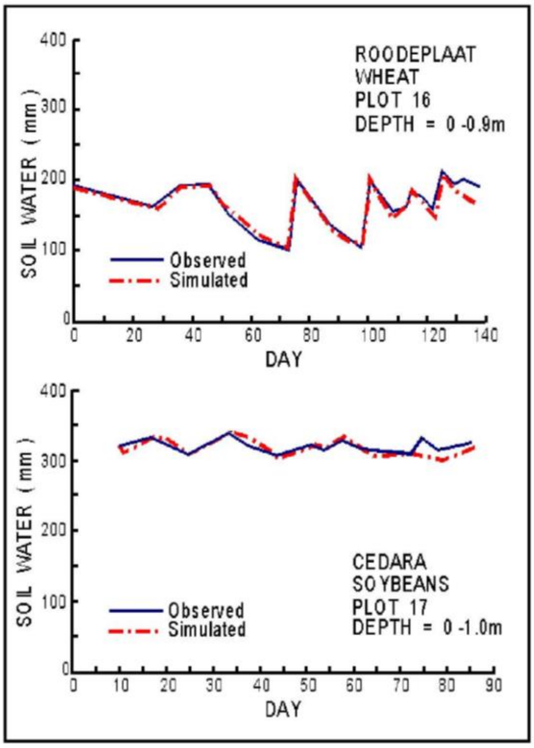

Figure 6.2.1 *ACRU* model simulated vs observed soil water content for irrigated wheat at Roodeplaat in Gauteng and irrigated soybeans at Cedara in KwaZulu-Natal (After Dent *et al*., 1988)

Reference

Dent, M.C., Schulze, R.E. and Angus, G.R. 1988. Crop water requirements, deficits and water yield for irrigation planning in southern Africa. *Water Research Commission*, Pretoria, RSA, *Report* 118/1/88. pp 183.

6.3 Verification of Actual Evapotranspiration: Example from a Lysimeter (Original Researchers: R.E. Schulze and A. Pike)

Background

Conventionally in water balance studies actual evapotranspiration, now often termed "total evaporation", is the residual between total rainfall and total runoff made up of surface/near surface runoff and drainage beyond the root zone which largely manifests itself as baseflows. In the overall long-term water budget equation, the various components of total runoff, worldwide, constitute only 35% of the total rainfall with actual evapotranspiration making up the remaining 65%. Averaged over a generally semi-arid South Africa, however, the long-term total runoff makes up only 9% of total rainfall with the remaining 91% being actual evapotranspiration. In many hydrological models, actual evapotranspiration is an internal state variable and is not modelled explicitly, although it makes up the largest component of the water budget. Its accurate assessment is therefore considered of paramount importance.

In the *ACRU* model, however, it is simulated on a day-by-day basis from four components, *viz*.

- *transpiration from the topsoil horizon* which depends, *inter alia*, on the day's atmospheric demand, the vegetation's water use (i.e. crop) coefficient, its active root fraction in that soil horizon and the soil water content of that horizon, which determines whether or not the crop/vegetation is stressed,
- *transpiration from the subsoil horizon*, which depends on the same factors, but for the subsoil,

- *evaporation from intercepted water* by the plant after rainfall, and
- *soil water evaporation from the topsoil*, which will depend also on the surface material covering the topsoil horizon.

In this section a verification of actual evapotranspiration as simulated by the *ACRU* model is presented.

Measuring Actual Evapotranspiration

Mass measuring techniques, which accurately determine changes in the total mass of weighing lysimeters, are accepted as probably the most convenient, sensitive and accurate means of monitoring evapotranspiration, with accuracies up to 0.05 mm per day (Mottram and De Jager, 1973). Different designs have made possible the measurement of either actual evapotranspiration or potential evapotranspiration from lysimeters using continuous recording techniques (instead of instantaneous observations). Two such lysimeters were installed at the then University of Natal (now KwaZulu-Natal) in the 1970s (Mottram and De Jager, 1973), with **Figure 6.3.1** showing, from left to right, the weighing stem, the lysimeter's calibration, a 36-hour trace and a continuous trace in a non-windy period.

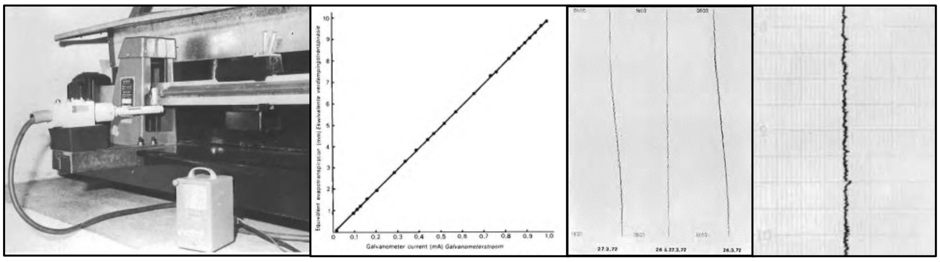

Figure 6.3.1 The University of Natal's weighing lysimeter, showing from left to right the weighing system, the lysimeter's calibration, a 36-hour trace and a continuous trace in a non-windy period (After Mottram and De Jager, 1973)

Results

In **Figure 6.3.2** results are shown of *ACRU* model simulations of actual evapotranspiration from the two lysimeters at the (then) University of Natal. With the exception of one month (February), when excessive drainage out of the lysimeters took place after a 130 mm rainfall event, simulations approximate the line of equality very well, considering that actual evapotranspiration was simulated under changing conditions from bare soil (with a LAI= 0,02) to sparse natural veld cover (LAI=0,7).

Conclusion

This verification of the *ACRU* model's ability to mimic actual evapotranspiration accurately from weighing lysimeter measurements engenders confidence that the water budget's largest output, frequently presented as a residual between rainfall and runoff, can be simulated accurately by the model.

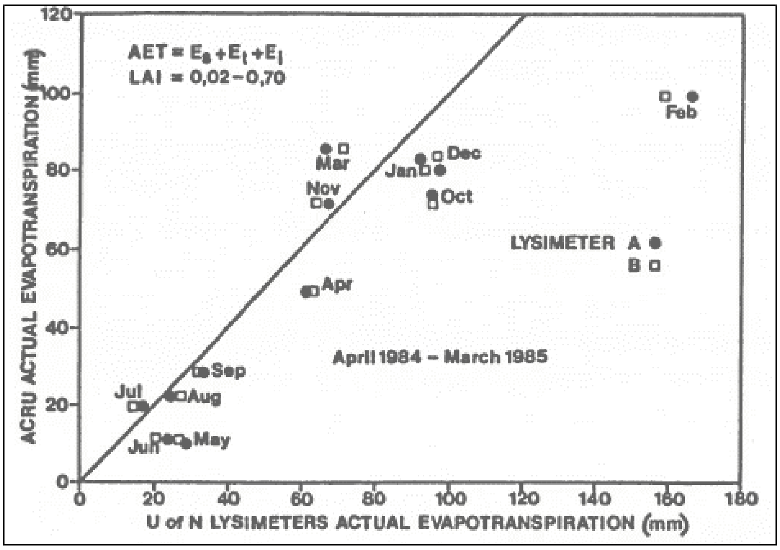

Figure 6.3.2 The *ACRU* model's verification of actual evapotranspiration base on lysimeter measurements (After Schulze, 1986)

References

Mottram, R. and De Jager, J.M. 1973. A sensitive recording lysimeter. *Agrochemphysica*, 5, 9-14.

Schulze, R.E. 1986. The *ACRU* Model for agrohydrological decision-making: Structure, options and application. *Proceedings, 2nd South African National Hydrology Symposium*, University of Natal, Department of Agricultural Engineering, *ACRU* Report, 22, 345-362.

6.4 Verification of Canopy Interception: Example from a *Pinus patula* Plantation (Original Researcher: R.E. Schulze)

The Von Hoyningen-Huene Interception Equation

Von Hoyningen-Huene (1983) developed a curvilinear equation of canopy interception loss per rainday for agricultural crops, given as

$$I_l = 0.30 + 0.27P_g + 0.13LAI - 0.013P_g^2 + 0.285P_g.LAI - 0.007LAI^2$$

in which I_l = interception loss (mm.rainday^{-1})

P_g = gross rainfall (mm)

LAI = Leaf Area Index of the crop,

with this equation "stable" up to a daily rainfall of 18 mm.

Application of the Equation and its Verification

With the need frequently arising to estimate canopy interception under afforested conditions, where its influence on the water budget may be highly pronounced, the Von Hoyningen-Huene equation was therefore tested on a stand 10-year old stand of *Pinus patula* at Cathedral Peak in KwaZulu-Natal (29°S, 29°E) in which canopy interception had been measured (Schulze *et al*., 1978) and the *LAI* had been estimated independently to be 4.5. **Figure 6.4.1** illustrates the excellent fit of the Von Hoyningen-Huene (1983) interception estimate (dots) against the line of best fit for the canopy interception experiment.

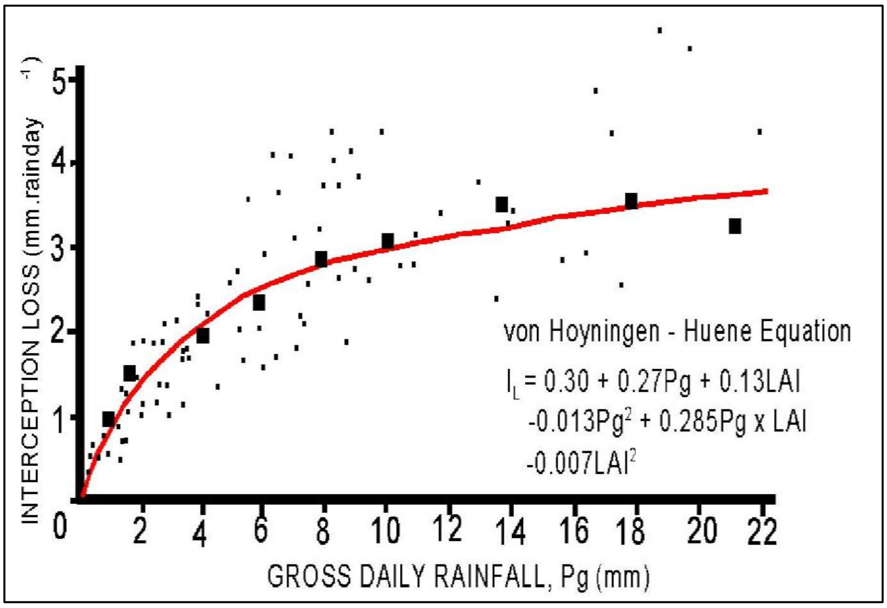

Figure 6.4.1 Simulations by the von Hoyningen-Huene (1983) equation of *Pinus patula* canopy interception

Conclusions

From **Figure 6.4.1** it is concluded that this equation may be used with confidence in simulations of canopy interception of *Pinus patula*. Care should, however, be exercised in using the equation on other commercial forest species, e.g. *Eucalyptus grandis*, because of their often very different canopy properties.

References

Schulze, R.E., Scott-Shaw, C.R. and Nänni, U.W. 1978. Interception by *Pinus patula* in relation to rainfall parameters. *Journal of Hydrology*, 36, 393-396.

Von Hoyningen-Huene, J. 1983. Die Interzeption des Niederschlages in landwirtschaftlichen Pflanzenbeständen. *Deutscher Verband für Wasserwirtschaft und Kulturbau*; Verlag Paul Parey-Hamburg, *Schriften*, 57, 1-66.

7 VERIFICATION STUDIES OF BIOMASS RELATED YIELDS

7.1 Verification of the *ACRU* Dryland Maize Yield Model (Original Researchers: R.E. Schulze and F.B. Domleo)

The Maize Yield Sub-Model in ACRU

With daily temperature information a generic phenologically based sub-model based on concepts proposed by Hanks (1974) and modified such that the phenological "clock" is driven by thermal time, *or* growing degree days (Domleo, 1990), has been developed and tested extensively under South African conditions. In this model, which has to operate when *ACRU* splits crop transpiration from soil water evaporation,

$$Y_m = Y_{pm} (E_{t1} / E_{tm1})^{\alpha m1} \times (E_{t2} / E_{tm2})^{\alpha m2} \times (E_{t3} / E_{tm3})^{\alpha m3}$$

where

Y_m	=	seasonal maize grain yield ($t.ha^{-1}$)
Y_{pm}	=	potential maize grain yield ($t.ha^{-1}$) for the season obtained from local information, in the 1990s defaulted to 9.0 $t.ha^{-1}$, but with modern hybrids now up to 16 $t.ha^{-1}$

with

E_{ti}	=	accumulated crop ("actual") transpiration for a given growth stage i, (mm) from all soil horizons
E_{tmi}	=	accumulated maximum transpiration for a given growth stage i, (mm) from all soil horizons
α_m	=	exponent to allow for weighting of different growth stages
1	=	growth stage 1: emergence to flower initiation
2	=	growth stage 2: flowering stage
3	=	growth stage 3: end of flowering to maturity.

Delimitation of Growth Stages by Accumulated Growing Degree Days

In order to model maize yield successfully using the above equation, the growth stages in the development of the maize plant need to be delimited such that account is taken of regional climatic differences and season-by-season as well as intra-seasonal climate/ soil water differences.

For this reason the concept of growing degree days, i.e. thermal time, was used. With this concept effective heat units for maize, between upper and lower threshold daily mean temperatures of10°C and 30°C respectively, are accumulated from date of planting and are used to delimit onset and end of growth stages. Default values of T_t for various states of phenological development are given in **Table 7.1.1**, derived by Domleo (1990) from a combination of data from the literature and from seed companies.

Table 7.1.1 Typical values of phenological states of maize related to accumulated growing degree days (T_t) after planting (Domleo, 1990)

Phenological State	T_t
Emergence	150
Onset of flowering	700
End of flowering	1150
Maturity	1700

Determination of Crop Coefficients by Accumulated Growing Degree Days

In order to be physically meaningful, crop coefficients (K_{cm}) need to be transferable to account for different climatic conditions between years at a given location, and between locations with different climatic conditions. The concept of relating K_{cm} to T_t is conceptually far superior to that of relating it to calendar data or using a fixed crop growth curve. Such a relationship, developed by Sammis *et al*. (1985), has been incorporated into the *ACRU* maize yield sub-model. The third order polynomial equation of Sammis *et al*. (1985) is shown in **Figure 7.1.1**. The solid line represents the "ideal" generated growth curve of K_{cm} when no water stress occurs, while the broken line deviates from the ideal curve under soil water stress conditions.

Crop Coefficients under Conditions of Plant Water Stress

In the *ACRU* maize yield model the $K_{cm} : T_t$ relationship proceeds as illustrated in **Figure 7.1.1** when actual transpiration E_t equals maximum transpiration E_{tm} . When, however, the $E_t : E_{tm}$ ratio is less than unity, and growth is in the vegetative phase, then the increase in "ideal" K_{cm} is reduced to the fraction E/E_{tm} , i.e. the crop coefficient advances at a reduced rate when the plant is under stress. When rainfall/ irrigation occurs and soil water deficit stress is relieved, K_{cm} will again resume at the "ideal" rate. When the threshold T_t for the onset of flowering is thus reached, *ACRU*'s maize crop will flower, as it would have under natural conditions, despite the K_{cm}'s possibly being at a reduced value. In the *ACRU* maize yield model there is no reduction of K_{cm} for stress during flowering, the reduction only being operative in the vegetative phase between plant emergence and the onset of flowering.

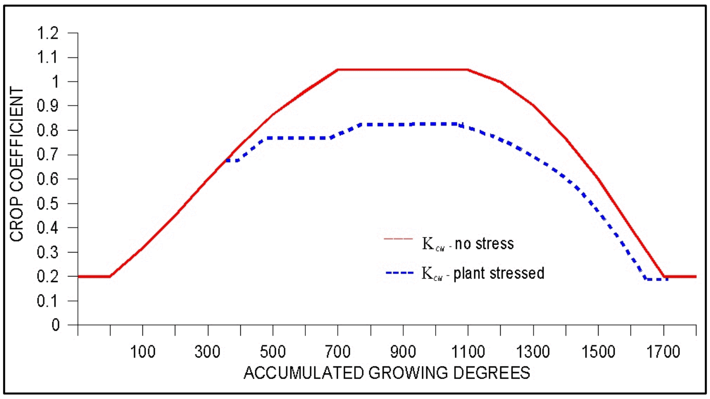

Figure 7.1.1 Crop coefficients for maize as related to accumulated growing degree days, T_t (After Domleo, 1990)

Planting Date and Length of Growing Season

The input variables to the maize sub-model include three options for the selection of planting dates applicable to South Africa, *viz*.

- by specifying day and month through the *ACRU Menubuilder*, or
- via the dynamic input file option, in which case they can be changed year-by-year, or
- by an *ACRU* defaulted computed planting dateoccurring after 1 October (before that, low soil temperature retards germination at most locations) on condition that a minimum of 25 mm rainfall has fallen within a period of five consecutive days after 1 October and if the threshold rainfall has not fallen, "planting" takes place on 23 December.

In regard to the length of the active growing season, this varies between 120 and 180 days depending on the hybrid and region, but 150 days is an average length in southern Africa.

Verifying the Maize Sub-Model in South Africa

The dryland maize sub-model embedded in *ACRU*, as described above, is driven by a yield potential which is reduced by stress weighted ratios of actual to maximum transpiration for three different phenological stages determined by thermal time, i.e. by accumulated growing degree days. Maize yields were verified at 10 research stations in South Africa (**Figure 7.1.2**) under a range of altitudes, mean annual precipitations (MAP), mean annual reference potential evaporations (MAE), soil conditions and seasonal climates. Selected location characteristics are given in **Table 7.1.2**.

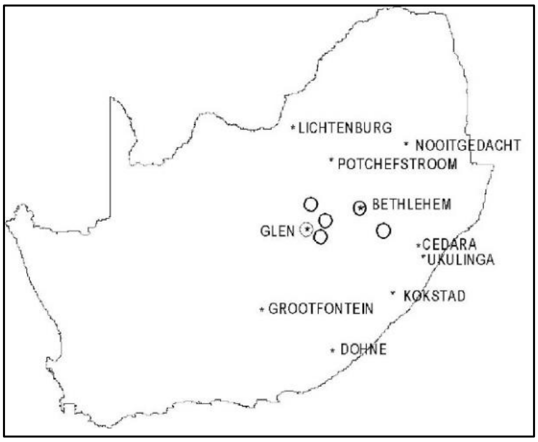

Figure 7.1.2 Locations of research stations from which data were used in verifications of maize (asterisk) and (circled) wheat (After Domleo, 1990)

Table 7.1.2 Locational and other characteristics of the stations selected for maize yield verifications

Station	Latitude (°S)	Longitude (°E)	Altitude (m)	MAP (mm)	MAE* (mm)	Soil Texture	Soil Depth (m)
Bethlehem	28°10'	28°18'	1638	667	1749	SaClLm	0.90
Cedara	29°32'	30°17'	1067	874	1467	SaCl	0.90
Döhne	32°31'	27°28'	899	780	1737	SaClLm	0.60
Glen	28°57'	26°20'	1304	542	2162	SaClLm	0.75
Grootfontein	31°29'	25°01'	1250	360	2451	SaClLm	0.80
Kokstad	30°31'	29°25'	1278	751	1543	SaCl	1.00
Lichtenburg	26°10'	26°10'	1460	520	2397	SaClLm	1.00
Nooitgedacht	26°31'	29°58'	1694	730	1911	SaClLm	0.80
Potchefstroom	26°44'	27°05'	1345	664	2068	SaCl	0.90
Ukulinga	29°40'	30°24'	765	705	1404	LmSa	0.70

* = MAE annual A-pan equivalent evaporation

Using the generic three growth stage phenological maize yield equation in *ACRU*, model predicted plots at all 10 locations together (69 yield events) are shown in **Figure 7.1.3** around the 1:1 line of best fit for a range of dryland yields from 0.9 to 7.9 t/ha/season. Overall goodness-of-fit statistics were highly satisfactory (**Table 7.1.3**) in terms of both means and variances. It should be noted that the simulations were not calibrated at all to account for management differences (e.g. row spacing, plant density, fertilisation) or for other possible crop damages (pests, hail).

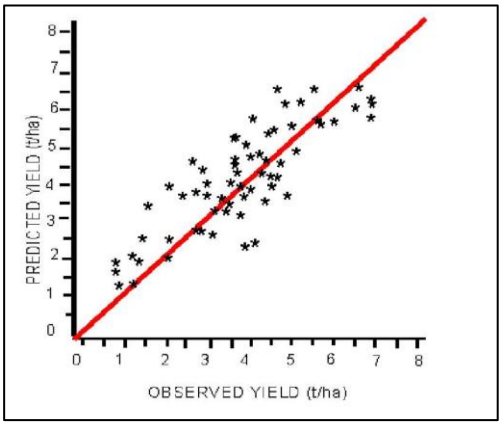

Figure 7.1.3 *ACRU* simulated vs observed maize yields at 10 locations in South Africa (After Domleo, 1990)

Table 7.1.3 Goodness-of-fit statistics for the verification of dryland maize yields at 10 locations in South Africa (After Domleo, 1990)

Statistic	Observed	*ACRU*
Mean (t)	3.72	3.93
CV (%)	40.49	36.02
Highest (t)	7.90	6.60
Lowest (t)	0.90	1.10

The relatively robust generic type maize model imbedded in *ACRU* may be classified as being of an intermediate level in terms of complexity. It therefore does not account for the variety of management options that more complex models (e.g. DSSAT, APSIM) do. The results are nevertheless highly successful, indicating that this crop yield model is likely to produce very acceptable estimates of season to season and location to location maize yield statistics. The major advantage of this imbedded model is that it can operate with the range of multi-purpose options available in *ACRU*, e.g. with or without irrigation or a reservoir, simply by "switching on" the crop yield option and responding to simple *ACRU Menubuilder* prompts, which include default values for all the important phenological information required. It should be stressed, however, that the model is driven by a yield potential which, with the advances of new hybrids since the early 1990s, has increases considerably from the 9.0 t/season which was used then.

References

Domleo, F.B. 1990. *Maize and wheat yield simulations with the ACRU model*. MSc dissertation, University of Natal, Pietermaritzburg, Department of Agricultural Engineering. pp 117.

Hanks, R.J. 1974. Model for predicting plant yield as influenced by water use. *Agronomy Journal*, 66, 660-665.

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7.2 Verification of the *ACRU* Winter Wheat Yield Model (Original Researchers: R.E. Schulze and F.B. Domleo)

The Winter Wheat Yield Sub-Model in ACRU

The winter wheat sub-model embedded in *ACRU* is driven by a yield potential which is reduced by stress weighted ratios of actual to maximum transpiration for different phenological (growth) stages. In the yield equation the phenology for wheat, grown in the eastern half of southern Africa as the winter variety in the essentially rainless season, changes more predictably and hence is by calendar days.

Winter wheat yields, under both dryland and irrigated conditions, were verified at seven locations, mainly in the Free State. The locations are clustered geographically (see **Figure 7.1.1** in the maize verification section) as well as by altitude (1158-1676 m), mean annual rainfall (490-760 mm) and potential evaporation (1749-2162 mm).

Results

Model predicted plots for winter wheat yields are given in **Figure 7.2.1**. Both dryland (asterisk) and irrigated (ringed) yields are predicted very well, as is also testified by the goodness-of-fit statistics in **Table 7.2.1**.

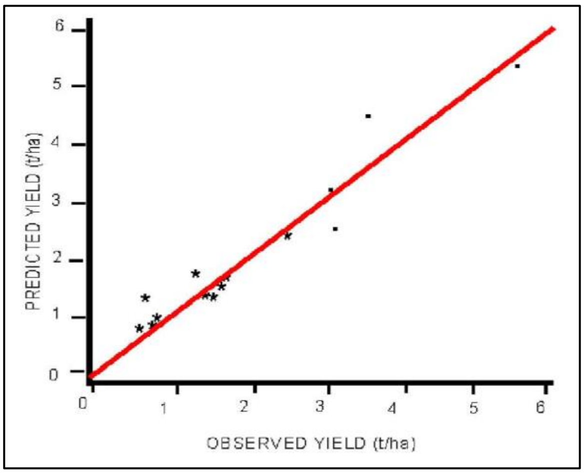

Figure 7.2.1 *ACRU* simulated vs observed winter wheat yields at 7 locations in South Africa, with asterisks denoting dryland and dots irrigated yields (After Domleo, 1990)

Table 7.2.1 Goodness-of-fit statistics for the verification of winter wheat yields at 7 locations in South Africa (After Domleo, 1990)

Statistic	Observed	*ACRU*
Mean (t)	2.07	2.10
CV (%)	64.45	66.24
Highest (t)	5.60	5.40
Lowest (t)	0.60	0.70

As in the case of maize, the relatively robust generic type winter wheat model imbedded in *ACRU* is classified as being of intermediate level in terms of complexity. It therefore does not account for the variety of management options that more complex models (e.g. DSSAT, APSIM) do. The results are nevertheless highly successful, indicating that this crop yield model is likely to produce very acceptable estimates of season to season and location to location yield statistics. The major advantage of this imbedded model is that it can operate with the range of multi-purpose options available in *ACRU*, e.g. with or without irrigation or a reservoir, simply by "switching on" the crop yield option and responding to simple *ACRU Menubuilder* prompts, which include default values for all the important phenological information required.

Reference

Domleo, F.B. 1990. *Maize and wheat yield simulations with the ACRU model*. MSc dissertation, University of Natal, Pietermaritzburg, Department of Agricultural Engineering. pp 117.

7.3 Verification of the Modified *ACRU*-Thompson Sugarcane Yield Model to Estimate Yields at Mill Supply Level (Original Researchers: T.G. Lumsden, R.E. Schulze, N.L. Lecler, and E.J. Schmidt)

Background

Imbedded within the *ACRU* model is a sugarcane yield model originally developed by Thompson (1976). This model was derived from a collation and regression analyses of experimental yields and evaporation data from Hawaii, South Africa, Mauritius and Australia. In the standard *ACRU-Thompson* sugarcane yield model (Schulze *et al.,* 1995), yields are estimated with Thompson's equation in which

$$Y = 9.53\ (AET_{sum}/100) - 2.36$$

where Y = sugarcane yield (t/ha/growing season) and

AET_{sum} = accumulated growing season total evaporation (actual evapotranspiration, mm)

The equation simulates sugarcane yields well, with a correlation coefficient was 0.95 and the standard error of yield estimates 15.1 t/ha.

In the *ACRU*-Thompson model, *ACRU* daily water budgeting routines are used to estimate accumulated growing season total evaporation. The *ACRU*-Thompson model computes an annual sugarcane crop from July to June. Water use by the crop is estimated through 12 monthly water use (crop) coefficients, the values of which may be set to 0.8 for average on-farm conditions (Schulze *et al.,* 1995).

Modifications to the ACRU model
Given the effect on sugarcane yields of growth cycles other than from July to June, it was considered important that the various growth cycles be represented in the modelling framework. In order to cater for a variety of growth cycle lengths and harvest dates, the *ACRU* model was modified through the introduction of dynamic equations relating crop water use to daily temperature, as reported in Lumsden *et al.* (1999). These equations, taken from the research of Hughes (1992), allow for the calculation of daily water use coefficients. The equations are as follows:

$K_c = 0.297 + (1.32 \times 10^{-6} \text{ X } GD_a^{2}) - (6.83 \times 10^{-10} \text{ X } GD_a^{3}) - K_{red}$
$K_{red} = 0.050 + (1.32 \times 10^{-6} \text{ X } GD_r^{2}) - (6.83 \times 10^{-10} \text{ X } GD_r^{3})$

where K_c = sugarcane water use (crop) coefficient
GD_a = accumulated degree days since planting and up to initiation of ripening at 1300 °*C* day *(*°C day)
GD_r = accumulated degree days after initiation of ripening (°C day)
K_{red} = reduction in water use coefficient after ripening
Degree day = (T_{max} + T_{min} / 2) - 12 (°C day)
T_{max} = daily maximum temperature (°C)
T_{min} = daily minimum temperature (°C).

Limits to K_c, taken from Hughes (1992), are:
K_c ≤ 1.00 for a plant crop
≤ 0.96 for a first ratoon crop
≤ 0.92 for second and subsequent ratoons
≥ 0.50 after initiation of ripening.

Daily observed maximum and minimum temperatures are input into the equations to allow for the calculation of the water use coefficients. If these temperatures are not available, then monthly long term means of temperatures may be specified, with these temperatures then being translated internally in the model to daily values by Fourier Analysis.

As the water use coefficients are related to temperature, they reflect the climate regime experienced by the crop during its growth cycle, thus allowing for the representation of different harvest dates. The use of temperature-based relationships also overcomes the limitation in the existing *ACRU* model, which restricts the length of growth cycles to 12 months. The influence of two different harvest dates on the seasonal water use coefficient curve of a 12-month crop are illustrated in **Figure 7.3.1**. The curves were derived from temperatures recorded in the Eston area of KwaZulu-Natal in South Africa.

The curve of the crop harvested in October (spring, with regrowth in summer) rises rapidly after growth commencement, reflecting the warm temperatures experienced by this crop in its initial growth stages during the summer months. In contrast, the curve of the crop harvested in April (autumn, with regrowth into winter months) rises slowly after growth commencement, reflecting the colder winter temperatures experienced in the early stages of this crop's growth cycle.

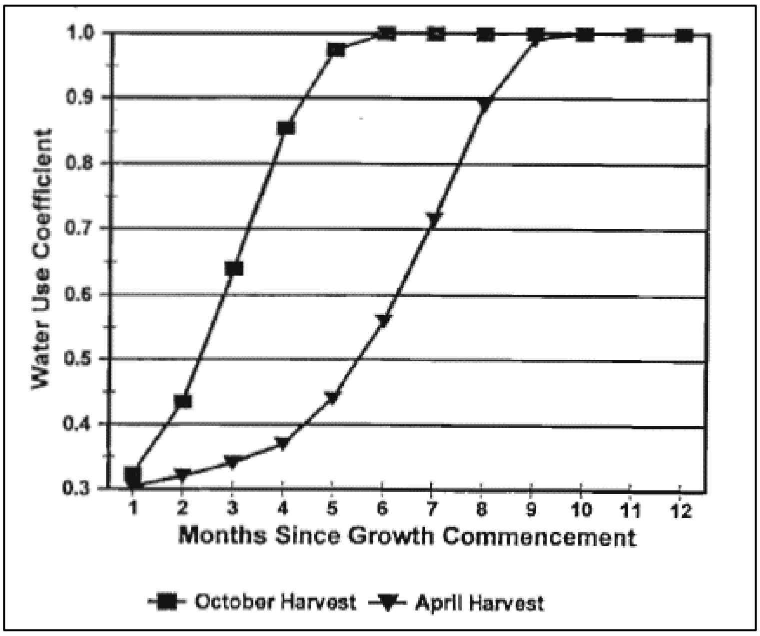

Figure 7.3.1 Seasonal water use (crop) coefficient curves of two 12-month sugarcane crops harvested in October and April (After Lumsden *et al*., 1999)

The Study Area: Eston Mill Supply Area

The Eston Mill Supply Area (MSA) is situated in the Midlands of KwaZulu-Natal Province, South Africa, and is located around latitude 29°55'S and longitude 30°30'E. It comprises of farms which generally supply cane to the Eston Sugar Mill. **Figure 7.3.2** shows the Eston MSA and indicates the boundaries of farms falling within the MSA. The roads and towns in the district are also shown. A small map is inserted to indicate the location of the Eston MSA within KwaZulu-Natal.

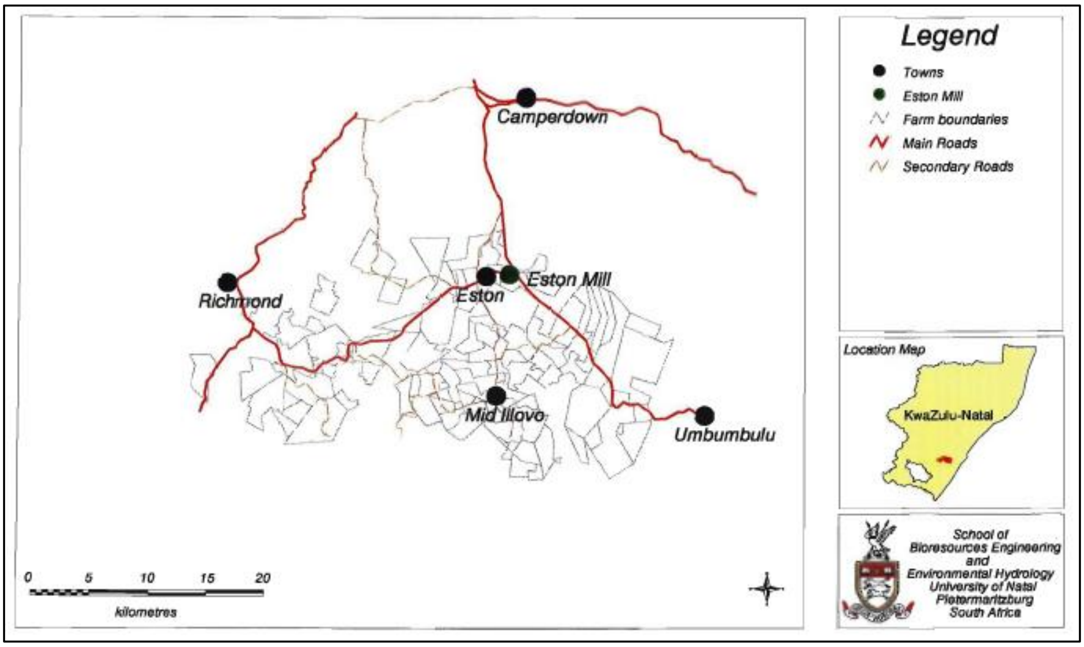

Figure 7.3.2 The Eston Mill Supply Area, with farm boundaries and other features (After Lumsden *et al*., 1999)

Not all farms in the MSA were included in analyses, as a result of difficulties in obtaining good quality observed yield data. The farms that were included (numbering 85) constituted a large proportion of the total number of farms, and were believed to be a representative sample of the MSA. Mean annual precipitation (MAP) in the MSA ranges from approximately 600 to 1000 mm. The annual means of daily maximum and minimum temperatures are 23.2°C and 13.2°C respectively. The range in altitude within the MSA is from ~ 400 to 1000 m.

Verification of Sugarcane Yields at Farm Scale

In order to assess the *ACRU*-Thompson yield simulations at farm scale, the mean simulated and observed yields over the period of yield simulation were calculated for each of the considered farms in the MSA. The percentage differences between the mean simulated and observed yields were then calculated and mapped (**Figure 7.3.3)**. Overall, the modified *ACRU*-Thompson model simulated yields well, with slight over- and under-simulations occurring, mostly within 10 to 20% of the observed.

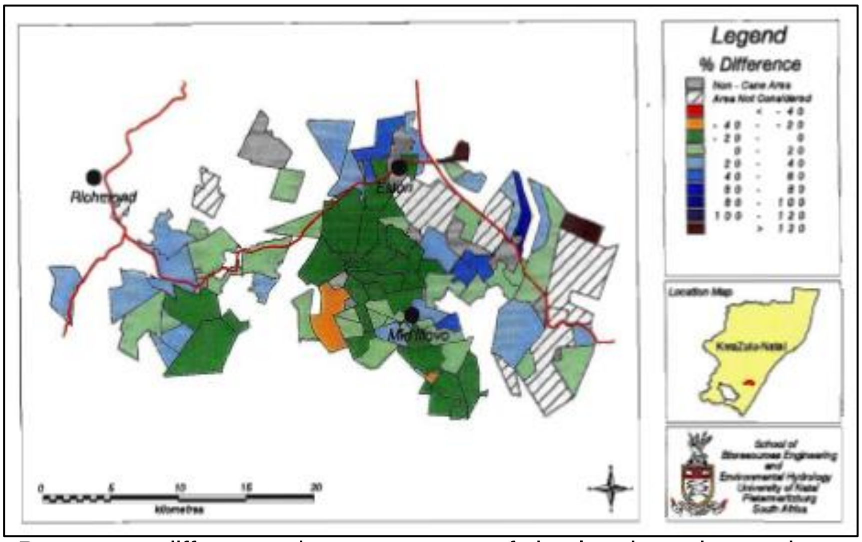

Figure 7.3.3 Percentage differences between means of simulated vs. observed sugarcane yields in the Eston MSA (After Lumsden *et al*., 1999)

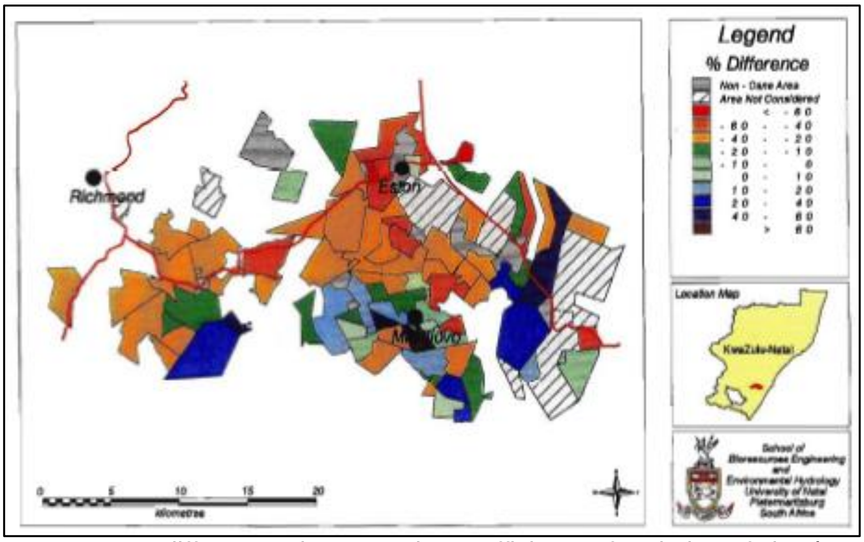

Figure 7.3.4 Percentage differences between the coefficients of variation of simulated vs. observed sugarcane yields in the Eston MSA (After Lumsden *et al*., 1999)

An analysis of the season to season variability of simulated yields in relation to the variability of observed yields was also conducted. Variation in yields was expressed through the coefficient of variation (CV). This statistic was calculated for yields simulated by the *ACRU-Thompson* model over the period of simulation, as well as for the corresponding observed yields. The percentage difference between the

CVs of simulated and observed yields was calculated on a farm-by-farm basis. These percentage differences were then mapped for the *ACRU*-Thompson (**Figure 7.3.4**). Again, the small percentage differences between simulated and observed CVs indicate that the variability of yields was, overall, captured successfully with the modified *ACRU*-Thompson model, with a slight tendency to under-simulate variability in yields.

The average MSA yields for the *ACRU*-Thompson (and for three other models) are plotted against time in **Figure 7.3.5**, along with the observed yields. These plots verify that the *ACRU*-Thompson model has generally captured the trend in the year to year variation of yield well – in fact, better than have the two more complex models.

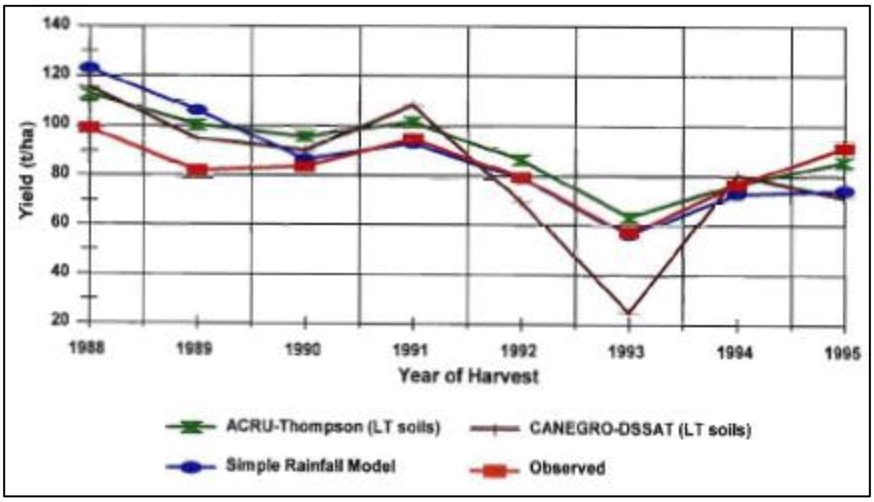

Figure 7.3.5 Average simulated and observed Eston MSA yields over time (After Lumsden *et al*., 1999)

The overall conclusion from this verification study is that the *ACRU*-Thompson model, modified by a dynamic and generic daily temperature-driven approach to account for different crop coefficient development for different harvest cycle lengths, and then used in an equation based on actual evaporation, which in turn is determined from a water budget dependent on daily temperature/potential evaporation and rainfall regimes on soils with specified characteristics, may be used with confidence in modelling sugarcane yields in South Africa.

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7.4 Verification of the *ACRU* Timber Yield Model (Original Researchers: D. Leenhardt and R.E. Schulze)

The Eucalyptus grandis Timber Yield Sub-Model in ACRU

The *Eucalyptus grandis* timber yield sub-model in *ACRU* uses accumulated actual transpiration, as computed by the *ACRU* model, on days with mean daily temperatures above the threshold of 14°C, to estimate tree height and diameter at breast height (DBH), from which timber volume may be calculated. Accumulated transpiration is determined for four different growth rates which depend on region (macro-climate), water holding properties of the soil and tree stocking densities (Schulze *et al*., 1995; Chapter 20). The equations developed for the *ACRU* timber yield sub-model are

$$\ln (HT) = 2.70269 + \ln (\sum E_r) \qquad r^2 = 0.89$$
$$\ln (DBH) = -2.46447 + 0.67087 \ln (\sum E_r) \qquad r^2 = 0.84$$

where

HT = tree height (m) and
DBH = diameter at breast height (10^{-2} m)

Testing the Timber Yield Model

Within the range of altitudes (50-1400 m), temperature parameters (e.g. January T_{max} 24-30°C; July T_{min} 4-12°C), *DBH* (2-23 10^{-2} m), tree heights (1-27 m) and tree stocking densities (1 230-2 050 stems.ha^{-1}) for which the *Eucalyptus grandis* timber yield model was developed (Schulze *et al*., 1995), the model was tested on two sets of independent data which were not available for model development, *viz*. one set of five Mondi Forest sites in Zululand and the other set from HL&H Mining Timber made up of two sites in Limpopo, two sites in southern Mpumalanga and two sites in the Midlands of KwaZulu-Natal. The results of the verification are summarised in **Table 7.4.1** while **Figure 7.4.1** depicts visually the observed *DBH* and tree height against the *ACRU* timber model for the two data sets.

Table 7.4.1 Bias, root mean squared error and standard deviation of the error of prediction of the yield model for the two *Eucalyptus grandis* verification sets (After Schulze and Leenhardt, 1995)

Variable	Mondi Forest Data Set			HL&H Mining Timber Data Set		
	Bias	RMSE	Standard Deviation	Bias	RMSE	Standard Deviation
DBH (10^{-2} m)	0.0002 m 0.2%	0.0144 m 12%	0.0144 m 12%	-0.0198 m 20%	0.0238 m 24%	0.0132 m 14%
Height (m)	1.56 m 13%	2.10 m 18%	1.41 m 12%	-2.04 m 19%	2.42 m 22%	1.30 m 12%

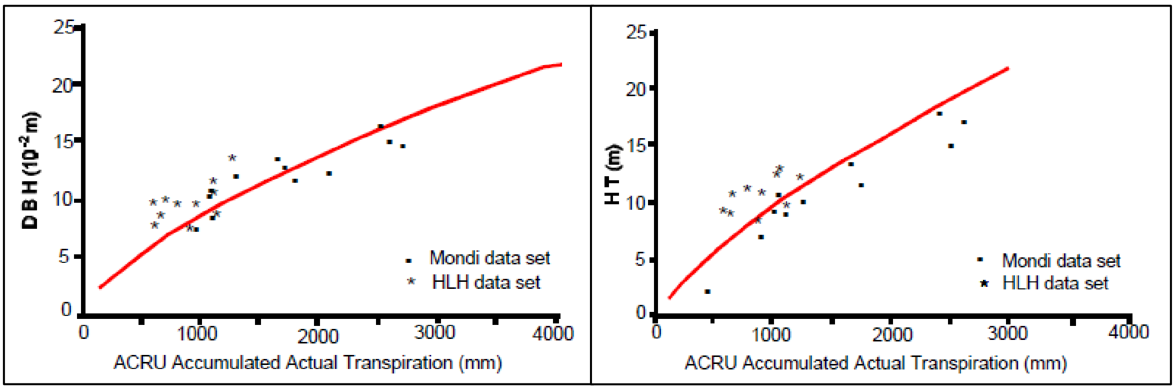

Figure 7.4.1 Verification of the *Eucalyptus grandis* tree height and DBH (i.e. volume) indices (After Schulze and Leenhardt, 1995)

Independent observations of the two timber yield indices follow the model trends well. The model under-predicts by about 20% at the HLH sites, where seedling were fertilised at planting. Within the range of climate, altitude soil and management conditions for which this model was developed, the authors are confident that the *ACRU Eucalyptus grandis* model will give highly acceptable timber yield predictions.

References

Schulze, R.E., Jewitt, G.P.W. and Leenhardt, D. 1995. Forestry Related Responses: Hydrological Impacts of Afforestation and a Timber Yield Model. *In*: Schulze, R.E. 1995. *Hydrology and Agrohydrology; A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, Report TT 69/95. Chapter 20.

Schulze, R.E. and Leenhardt, D. 1995. *Eucalyptus grandis* Timber Yield. *In*: Schulze, R.E. 1995. *Hydrology and Agrohydrology; A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, Report TT 69/95. Chapter 22.10.

8 VERIFICATION STUDIES OF LAND USE AND LAND MANAGEMENT IMPACTS ON RUNOFF

8.1 Verifying Impacts of Changes in Catchment Land Use over Time on Runoff (Original Researchers: K.C. Tarboton and R. Cluer)

Background

Hydrological analysis required for design and planning often fails to consider gradual catchment land cover and land use changes over time in long term simulations. It is important to consider land use change because one needs the ability to predict the runoff and other environmental impacts of such changes before they occur and hydrological modelling is the most useful tool by which the effects of such changes can be simulated realistically. Through its dynamic input option, the *ACRU* model has the facility of simulating hydrological response changes over time which result from land use changes. This case study assesses land use changes by comparing simulated streamflows using temporally static and then changing/dynamic land cover with observed streamflows for the 357 km^2 Lions river sub-system of the Mgeni catchment (**Figure 8.1.1**).

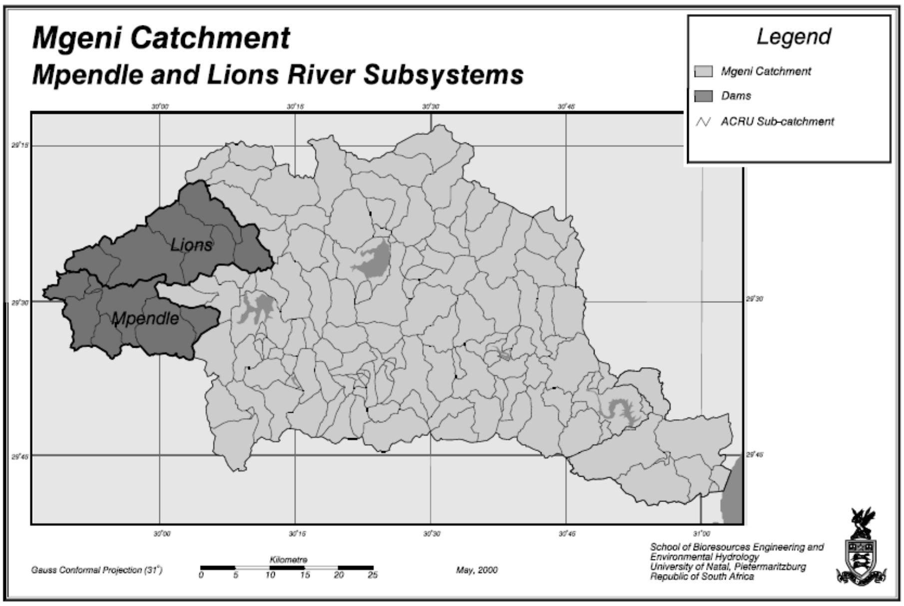

Figure 8.1.1 Location of the Lions river sub-system of the Mgeni catchment

Obtaining Land Cover Changes over Time

Black and white aerial photographs at scales ranging from 1:20 000 to 1:36 000 and dated 1959, 1967, 1978 and 1990 covering the Lions river sub-system were used to obtain the spatial distribution of land cover for each of these points in time. From the photographs land cover was delimited into:

- natural grassveld
- forestry (with a distinction between indigenous and commercial forests)
- contoured agriculture
- uncontoured agriculture
- farm dams and
- urban areas.

Care was taken to use only the central portion of each photograph to minimise distortion. In deriving the hydrological land cover variables at each point in time from 1959 to 1990, use was made of the land cover Decision Support System contained in the *ACRU Menubuilder*, which contains month-by-month values of the crop coefficient, canopy interception, per cent surface cover, root distribution and the coefficient of initial abstraction for over 200 land uses covering South Africa. After fieldwork in the catchment the following were assumed:

- the grassveld was in fair condition (i.e. lightly grazed, 50-75% cover),
- commercial forest was *Eucalyptus grandis*,
- contoured agriculture was dryland maize,
- uncontoured agriculture was dryland or irrigated pastures, and
- urban areas were informal residential areas, but more urban than rural in character.

By interpolating linearly between the spatial land cover distributions for each date of aerial photography, a dynamic land cover file was created for each of 6 sub-catchments of the Lions catchment. Temporal land cover trends are illustrated in **Figure 8.1.2** for the Lions sub-system as a whole, but the temporal land cover distributions for each of the 6 sub-catchments were actually used as model input. **Table 8.1.1** shows that individual sub-catchments had markedly different land covers over time.

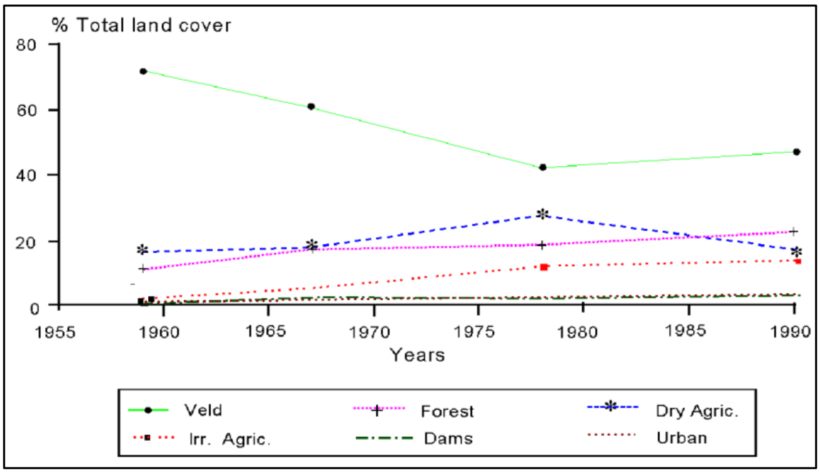

Figure 8.1.2 Land cover trends for the entire Lions river catchment over the period 1959-1990 (Tarboton and Cluer, 1991)

Table 8.1.1 Land cover distribution for Lions sub-catchments over time (Tarboton and Cluer, 1991)

Subcatchment Information	Year	Veld (km^2)	Forest (km^2)	Dryland Agric (km^2)	Irrigated Agric (km^2)	Dams (km^2)	Urban (km^2)
Subcatchment 1	1959	29.7	2.6	3.3	1.6	0.3	0.0
Area = 37.5 km^2	1967	28.0	4.9	2.2	2.0	0.3	0.1
M.A.P. = 1031 mm	1978	26.6	3.3	0.0	6.5	1.0	0.1
Altitude = 1151 m	1990	20.0	5.4	1.5	9.1	1.4	0.1
Subcatchment 2	1959	78.0	8.6	23.6	0.5	0.0	0.0
Area = 110.7 km^2	1967	51.7	15.6	34.5	7.0	0.7	1.2
M.A.P. = 928 mm	1978	44.4	12.0	37.4	14.3	1.1	1.5
Altitude = 1454 m	1990	61.7	14.0	13.1	18.9	1.8	1.2
Subcatchment 3	1959	47.9	3.7	7.8	1.6	0.1	0.2
Area = 61.3 km^2	1967	40.6	8.8	5.5	4.8	0.3	1.3
M.A.P. = 947 mm	1978	23.9	9.9	18.0	7.5	0.6	1.4
Altitude = 1378 m	1990	28.4	11.8	12.7	6.8	0.6	1.0
Subcatchment 4	1959	26.3	13.8	14.4	0.7	0.1	0.0
Area = 55.3 km^2	1967	35.0	13.1	5.7	1.4	0.1	0.0
M.A.P. = 1026 mm	1978	10.9	19.9	15.1	8.4	0.7	0.3
Altitude = 1254 m	1990	18.6	19.9	6.8	8.4	0.7	0.9

Subcatchment 5	1959	44.3	6.6	3.8	0.2	0.2	0.0
Area = 55.1 km^2	1967	36.0	10.4	6.9	0.9	0.9	0.0
M.A.P. = 966 mm	1978	22.9	13.5	16.7	0.9	0.9	0.2
Altitude = 1409 m	1990	21.5	18.3	13.5	0.7	0.7	0.4
Subcatchment 6	1959	22.7	2.1	4.3	0.3	0.0	0.0
Area = 29.4 km^2	1967	18.3	4.7	5.8	0.5	0.1	0.0
M.A.P. = 967 mm	1978	16.2	4.4	7.1	1.4	0.2	0.1
Altitude = 1214 m	1990	11.2	6.3	8.5	2.3	0.4	0.7

Streamflow Simulations

Streamflow was simulated from 1959 through 1990 and compared with streamflows observed at gauging station U2H007 at the catchment outlet. Two static simulations were carried out, the first assuming land cover temporally static from 1959 onwards (*59 Static*), and the second assuming 1990 land cover static throughout the simulation period (*90 Static*). The dynamic simulation accounted for gradual land cover changes by using a temporally varying dynamic land cover file (from 1959 to 1990) which was updated for each sub-catchment on an annual basis. Statistics of performance of monthly summaries of daily streamflow for the three simulations, compared with observed streamflow over the 31 year simulation period, are shown in **Table 8.1.2**. By assuming static land cover with a spatial distribution as in 1959, total observed streamflow was over-estimated by 17.7% with an increasingly divergent trend as illustrated in **Figure 8.1.3**. Simulation using static land cover was inadequate in mimicking the decreasing trend in observed streamflow as a result of the increased streamflow reducing activities in the catchment over time (**Figure 8.1.3**). Although the regression coefficient in the `*59 Static*' simulation was better than those of the other simulations, the variance of simulated values was greater and the high base constant offset the higher correlation coefficient and caused an over-simulation.

Table 8.1.2 Statistics of performance of monthly summaries of daily streamflow using *ACRU* for static and dynamic land covers (Tarboton and Cluer, 1991)

Statistic	***59 Static***	**Dynamic**	***90 Static***
Total observed streamflow (mm)	5243.84	5243.84	5273.84
Total simulated streamflow (mm)	6174.34	4810.36	3582.06
Correlation coefficient	0.79	0.77	0.75
Regression coefficient	0.87	0.80	0.74
Base constant for regression (mm)	4.59	1.70	-0.77
Variance of observed values (mm)	371.77	371.77	371.77
Variance of simulated values (mm)	451.45	398.45	357.36
Coefficient of Determination	0.62	0.60	0.56
Coefficient of Efficiency	0.54	0.57	0.50

When the temporally dynamic land cover file was used, the hydrological simulation was improved to the extent that the total simulated streamflow was only 8.3% less than the observed streamflow and variances in observed and simulated values were close to each other. The dynamic simulation mimicked observed streamflow almost exactly until 1972 (**Figure 8.1.3**), after which it under-simulated observed streamflow for five years before continuing parallel with observed streamflow for the remainder of the simulation period. This improved accuracy was obtained by recognising the physical changes in land cover illustrated in **Figure 8.1.2**, and using a temporally dynamic land cover file as an input to the *ACRU* modelling system without other changes or parameter calibration (Tarboton and Cluer, 1991).

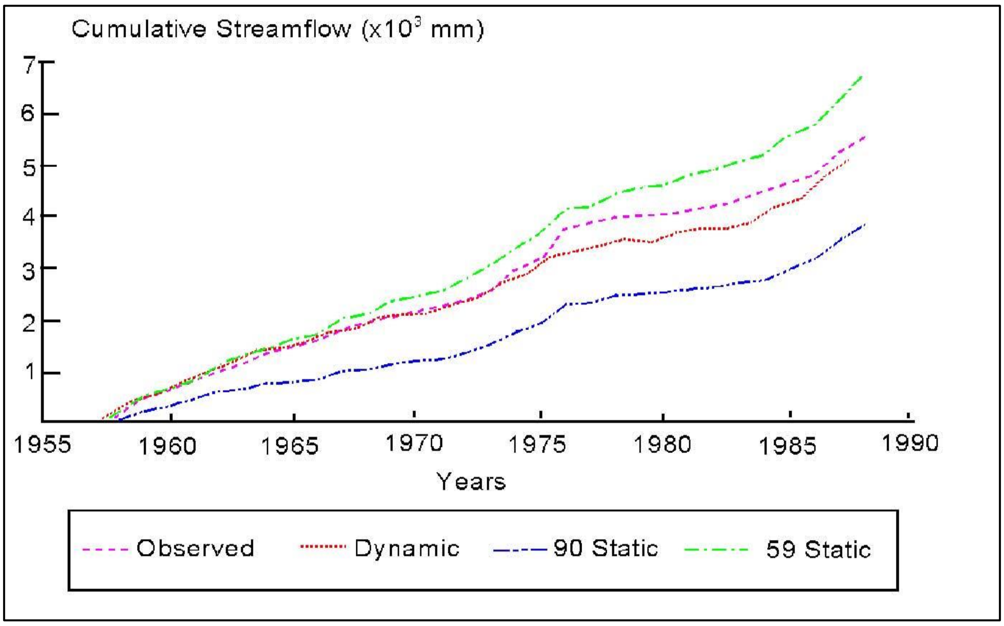

Figure 8.1.3 Comparison of long term cumulative observed streamflow with that simulated using static and temporally dynamic land cover (Tarboton and Cluer, 1991)

Conclusions

Frequently no historical land cover information is available and current land cover is used for long-term hydrological simulations with historical climate data. The significant under-estimation of observed streamflow by 37.7% (**Table 8.1.2**) when using the `*90 Static*' land cover highlights the inaccuracy of using current land cover information for long term hydrological simulations. Increasing divergence of the cumulative simulated streamflow from the cumulative observed streamflow when using `*90 Static*' land cover (**Figure 8.1.3**) indicates that by not considering temporal land cover trends in long term hydrological modelling, not only are the results likely to be inaccurate, but the inaccuracies are amplified in time and for longer term analysis.

Reference

Tarboton, K.C. and Cluer, R. 1991. Consideration of land cover changes over time for modelling long-term hydrological responses. *Agricultural Engineering in South Africa*, 23, 450-459.

8.2 Verifying Impacts of Afforestation on Streamflows with a Forest Decision Support System (Original Researchers: G.P.W. Jewitt and R.E. Schulze)

Setting the Scene

With intense competition for South Africa's sparse water resources, the potential impacts of afforestation, currently the only named streamflow reduction activity (SFRA) in the National Water Act of 1998, need to be assessed prior to planting. Increasing afforestation in South Africa and concern for its impact on water resources has led to increasing use of models to simulate the impacts of commercial afforestation on downstream water resources. The *ACRU* agro-hydrological modelling system has been used extensively in this regard. As a result, a Forest Decision Support System (FDSS) was developed in the 1990s for use when simulating hydrological impacts of afforestation with *ACRU*. This system simplifies the task of the model user a great deal by providing default values to land cover and soils input variables which may be affected by afforestation of a catchment. The user merely provides information regarding three tree genera (wattle vs pine vs eucalypt) and three ages relative to the genera (young vs intermediate vs mature) as well as three methods of site preparation used (intensive/ripping/ploughing vs intermediate vs poor/pitting). The development of this forest decision support system has been described and discussed in detail elsewhere (e.g. Jewitt and Schulze, 1991; Schulze *et al*., 2004).

Verification of *ACRU* for forested catchments was undertaken with the aim of showing that *ACRU's* FDSS can be used with confidence to simulate streamflow from catchments which are afforested with different species using different site preparation techniques and are at different stages of growth. This study presents a series of verifications described in more detail by Jewitt and Schulze (1999). Since it is the water yield of a forested catchment that is usually the focus of the water resources planner, assessing impacts of afforestation for monthly totals of daily simulated streamflows are presented. The South African catchments where streamflows from afforested catchments were simulated were:

- A University of KwaZulu-Natal research catchment at Cedara in KwaZulu-Natal, U2H018;
- A Department of Water Affairs and Sanitation operational catchment on the Marite River, X1H003, a tributary of the Sabie River, in Mpumulanga; and
- Three of the CSIR's Mokobulaan research catchments in Limpopo province.

Cedara Research Catchment U2H018

Total values of streamflow were simulated accurately (**Table 8.2.1**; **Figure 8.2.1**). Streamflow in this catchment is highly variable as a result of significant altitude differences within the catchment and the resultant rainfall variation within the catchment, which is well documented by Schulze and Schmidt (1989). The positive base constant for the regression equation implies that low flows tend to be slightly over-simulated and high flows slightly under-simulated. Despite altitude and rainfall differences the *ACRU* model has performed well on this complex catchment and statistics are good enough to allow the use of the model to simulate streamflows on similar catchments with a high degree of confidence.

Table 8.2.1 Selected features and goodness of fit statistics of the verification of streamflows on afforested research catchment U2H018 at Cedara (After Jewitt and Schulze, 1999)

SELECTED FEATURES OF CEDARA CATCHMENT U2H018	
Subcatchments	1
Latitude	29° 43'S
Longitude	30° 15'E
Altitude (m)	1 250
MAP (mm)	991
Area (km^2)	1.31
Aspect	North facing
Mean slope (%)	29.2
% afforested	92
Species	Mixed – *Pinus patula*, *Pinus radiata* and *Eucalyptus grandis*
Age (yrs)	Mixed – ranging from young to mature
Site preparation	Pitting

GOODNESS OF FIT STATISTICS FOR SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOWS IN CATCHMENT U2H018		
Statistics of performance of *ACRU* model, U2H018 Cedara: A comparison of simulated and observed streamflows for monthly totals of daily values 1977-1988		
Total observed flows (mm)	=	1 664.834
Total simulated flows (mm)	=	1 687.621
Mean observed flows (mm)	=	12.152
Mean simulated flows (mm)	=	12.313
Correlation coefficient	=	.861
Students "t" value	=	19.661
Linear regression coefficient	=	.807
Base constant for regression equation	=	1.783
Standard error of simulated flow	=	49.644
Variance of observed flow	=	724.266
Variance of simulated flow	=	636.132
Standard deviation of observed flow	=	26.912
Standard deviation of simulated flow	=	25.220
% difference in standard deviation	=	6.282
Coefficient of determination	=	.741
Coefficient of efficiency	=	.750
No systematic errors detected		

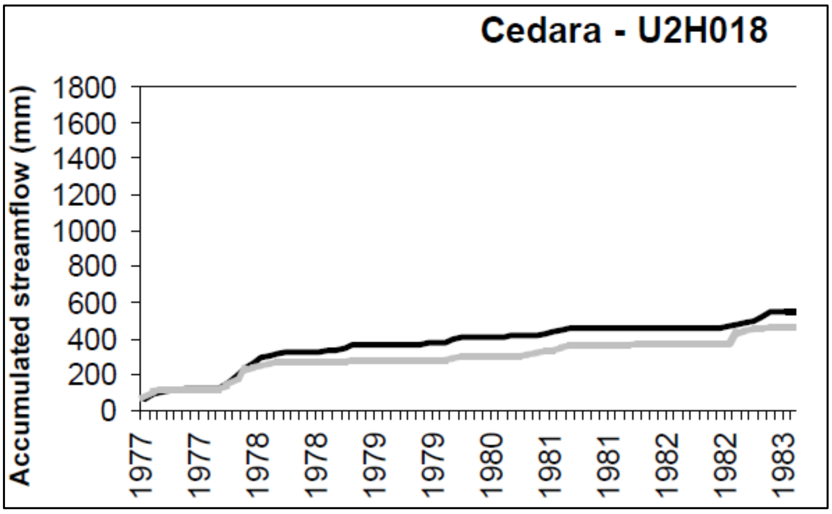

Figure 8.2.1 Verification of accumulated monthly streamflows at research catchment U2H018 at Cedara, with simulated flows in grey and observed flows in black (After Jewitt and Schulze, 1999)

Marite Operational Catchment X1H003

The catchment modelled is larger (212 km^2) than those usually used with *ACRU*. As such, it forms an important study in a non-research catchment and is more representative of the "typical" operational catchment on which modellers frequently have to make hydrological impact decisions.

Because of its size, the catchment was divided into three interlinked sub-catchments for purposes of hydrological modelling. A summary of sub-catchment information is contained in **Table 8.2.2**.

Table 8.2.2 Selected features and goodness of fit statistics of the verification of streamflows on the afforested operational catchment X1H003 on the Marite river in Mpumalanga (After Jewitt and Schulze, 1999)

Selected Physical Features of the Marite Subcatchments			
Subcatchment	**1 (Upper)**	**2 (Middle)**	**3 (Lower)**
Latitude	24° 49'S	24° 52'S	24° 50'S
Longitude	31° 00'E	31° 02'E	31° 05'E
Altitude (m)	950	900	880
MAP (mm)	1 413	1 287	908
Area (km^2)	67.01	88.95	56.45
% afforested	85	84	45
Main species	*Eucalyptus grandis*	*Pinus patula*	Mixed eucalypt and pine
Age (years)	12	20	15
Site preparation	Pitting	Pitting	Pitting

Goodness of Fit Statistics for Simulation of Monthly Totals of Daily Streamflows From the Marite River		
Statistics of performance of *ACRU* model, X1H003 Marite River: A comparison of simulated and observed streamflows for monthly totals of daily values 1980-1989		
Total observed flows (mm)	=	1857.944
Total simulated flows (mm)	=	1869.984
Mean observed flows (mm)	=	18.767
Mean simulated flows (mm)	=	18.889
Correlation coefficient	=	.889
Students "t" value	=	19.124
Linear regression coefficient	=	1.173
Base constant for regression equation	=	-3.131
Standard error of simulated flow	=	93.878
Variance of observed flow	=	246.331
Variance of simulated flow	=	429.113
Standard deviation of observed flow	=	15.694
Standard deviation of simulated flow	=	20.713
% difference in standard deviation	=	-31.796
Coefficient of determination	=	.790
Coefficient of efficiency	=	.605

Soils information was obtained from the Institute of Soil, Climate and Water soils Land Type maps for the area, with hydrological soil characteristics determined by methods described in Schulze (1995). The trees were planted between 1950 and 1989 and only minimal site preparation was used. Monthly means of maximum and minimum temperatures obtained from local temperature stations were used to estimate month-by-month potential evaporation values using the Linacre (1977) equation. Daily rainfall values were obtained through the University of Natal (now University of KwaZulu-Natal) Computing Centre for Water Research for three rainfall stations in the area, each station being used to "drive" a different sub-catchment. One arc minute values of median monthly rainfall were obtained (Dent, Lynch and Schulze, 1989) and used to adjust the rainfall to make it more representative of the respective sub-catchments. Daily observed streamflow records, generally of good quality, were obtained for the Department of Water Affairs and Forestry weir X3H011 for the period 1980 to 1989.

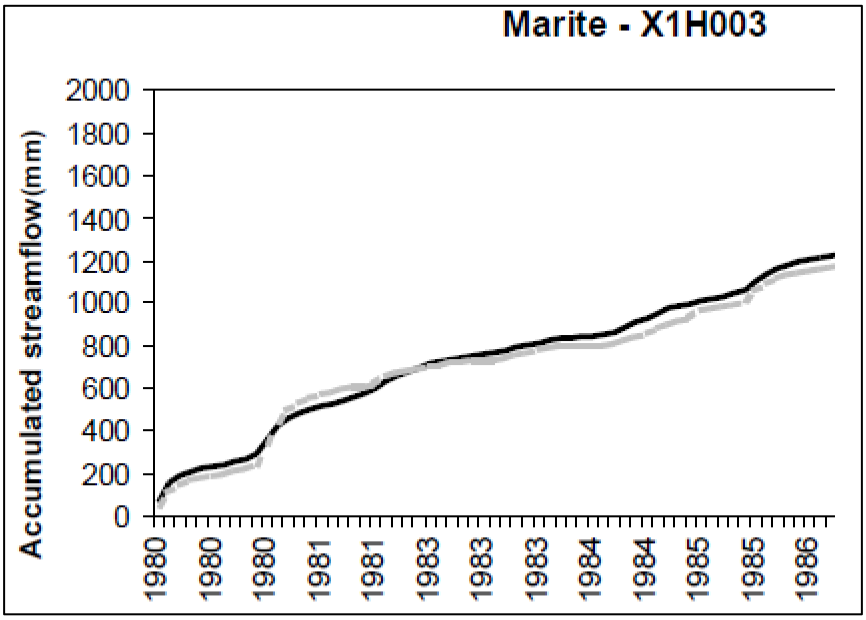

Figure 8.2.2 Verification of accumulated monthly streamflows at the operational catchment X1H003 on the Marite in Mpumalanga, with simulated flows in grey and observed flows in black (After Jewitt and Schulze, 1999)

As a practical application of the model on an operational catchment this simulation, and when using *ACRU* as a distributed model, very good results were produced, as shown in **Table 8.2.2** and **Figure 8.2.2**. The r^2 is high, showing good association between simulated and observed values. There are slight differences in the variance statistics, and the negative base constant with regression coefficient being higher than unity suggests that low flows are slightly under-simulated and higher flows slightly over-simulated. This is possibly a result of the timing of low and high flows not being well simulated as the flow routing option in *ACRU* was not invoked in this simulation.

These verification results, produced for an operational catchment which was not visited and thus was simulated completely “blindly”, nevertheless illustrate clearly that the application of *ACRU* in conjunction with the Forest Decision Support System is a viable tool in assessing impacts of afforestation on catchment water yield.

The Mokobulaan Research Catchments

The Mokobulaan small catchments forest hydrological experiment on the Drakensberg escarpment southeast of Lydenburg in Mpumalanga province, planned in 1956, has been described in detail by Van Lill *et al*. (1980), from whom catchment characteristics described below have been obtained. A summary of pertinent catchment characteristics of the three Mokobulaan catchments studied, *viz*. Catchments A and B, respectively under *Eucalyptus grandis* and *Pinus patula*, and Catchment C under natural grassland conditions, is presented in **Table 8.2.3**, while verification statistics of the two afforested catchments A and B are given in **Table 8.2.4**. A salient feature of the catchments affecting simulations are the very shallow soils.

Table 8.2.3 Selected features of the Mokobulaan research catchments in Mpumalanga province (After Jewitt and Schulze, 1999; original information Van Lill *et al*., 1980)

SELECTED FEATURES OF THE MOKOBULAAN RESEARCH CATCHMENTS			
Catchment	A	B	C
Latitude	25° 17'S	25° 17'S	25° 17'S
Longitude	30° 34'E	30° 34'E	30° 34'E
Altitude (m)	1 354	1 396	1 427
MAP (mm)	959	959	959
Area (km²)	2.62	3.46	3.69
Aspect	East facing	East facing	East facing
% slope	0.23	0.22	0.26
% afforested	100	100	0
Species	*Eucalyptus grandis*	*Pinus patula*	Grassland
Age (yrs)	0 - 12	0 - 10	N/A
Site preparation	Pitting	Pitting	N/A

Table 8.2.4 Goodness of fit statistics of the verifications of monthly totals of daily streamflows from the afforested Mokobulaan research catchments A and B in Mpumalanga (After Jewitt and Schulze, 1999)

GOODNESS OF FIT STATISTICS FOR SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOW FROM MOKOBULAAN CATCHMENT A		
Statistics of performance of *ACRU* model, Mokobulaan Catchment A: A comparison of simulated and observed streamflows for monthly totals of daily values 1963-1979		
Total observed flows (mm)	=	1992.271
Total simulated flows (mm)	=	1724.262
Mean observed flows (mm)	=	9.766
Mean simulated flows (mm)	=	8.542
Correlation coefficient	=	.419
Students "t" value	=	6.652
Linear regression coefficient	=	.532
Base constant for regression equation	=	3.258
Standard error of simulated flow	=	233.117
Variance of observed flow	=	201.879
Variance of simulated flow	=	324.818
Standard deviation of observed flow	=	14.208
Standard deviation of simulated flow	=	18.023
% difference in standard deviation	=	-26.845
Coefficient of determination	=	.176
Coefficient of efficiency	=	.554

GOODNESS OF FIT STATISTICS FOR SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOW FROM MOKOBULAAN CATCHMENT B		
Statistics of performance of *ACRU* model, Mokobulaan Catchment B: A comparison of simulated and observed streamflows for monthly totals of daily values 1969-1980		
Total observed flows (mm)	=	1913.084
Total simulated flows (mm)	=	1942.463
Mean observed flows (mm)	=	17.714
Mean simulated flows (mm)	=	17.986
Correlation coefficient	=	.731
Students "t" value	=	11.018
Linear regression coefficient	=	.902
Base constant for regression equation	=	2.011
Standard error of simulated flow	=	178.944
Variance of observed flow	=	421.405
Variance of simulated flow	=	641.990
Standard deviation of observed flow	=	20.528
Standard deviation of simulated flow	=	25.338
% difference in standard deviation	=	-23.428
Coefficient of determination	=	.534
Coefficient of efficiency	=	.282

No detailed rainfall or evaporation data for were available for any of the three catchments and consequently daily rainfall records for a nearby SA Weather Service rainfall station were obtained and applied to all three catchments. It was surmised that the small size of these catchments would render them to be particularly sensitive to accurate input data, and that some error was to be expected by applying coarse scale rainfall and evaporation data to a catchment under afforestation on very shallow soils. Furthermore, the simulation was a "blind" one in the sense that the catchments were not visited.

The streamflow in Catchment C was simulated first as a test of the performance of the *ACRU* model for a catchment under shallow rooted natural grassland. The model was found to simulate accumulated streamflows well, as shown in the top diagram of **Figure 8.2.3**.

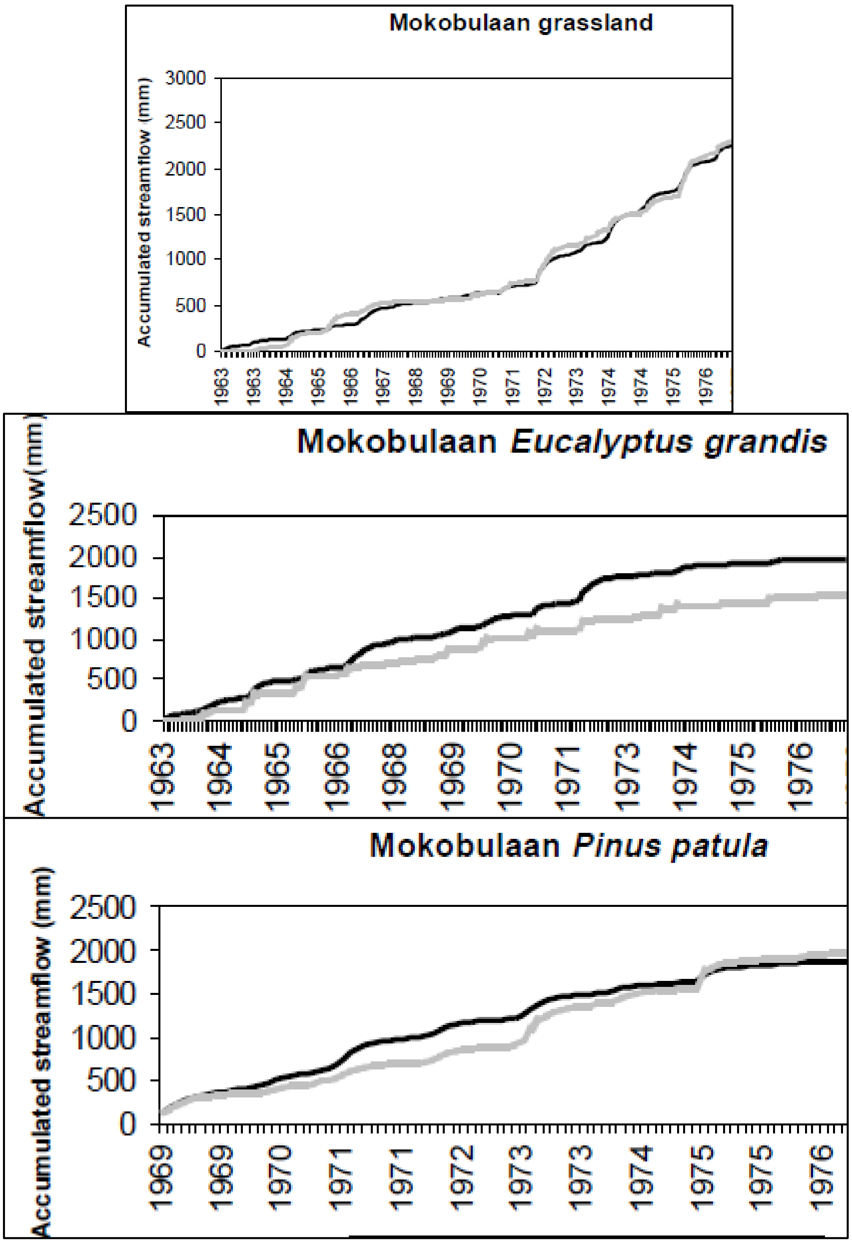

Figure 8.2.3 Monthly accumulations of daily streamflows from (top) Mokobulaan Catchment C under grassveld, (middle) Catchment A under *Eucalyptus grandis* and (bottom) Catchment B under *Pinus patula*, with simulated flows in grey and observed flows in black (After Jewitt and Schulze, 1999)

Streamflow from Catchments A and B was simulated utilising the dynamic land use facility (Schulze, 1995) in *ACRU*. This allows the modeller to change catchment land cover variables in the time series covering the simulation to account for vegetative changes resulting from growth of the trees, or management changes such as thinning of the stand.

Streamflow was simulated poorly in Catchment A which was planted to *E. grandis*. The plot of accumulated values of simulated and observed streamflow (**Figure 8.2.3** middle) indicates total streamflow to have been under-simulated. Statistics produced were consequently poor, as seen in

Table 8.2.4 (left). These results indicate the difficulties entailed in modelling a very small catchment with shallow soils and with a changing land cover. It is also possible that runoff events in this catchment do not correspond adequately to the rainfall record used and that better results would be expected if rainfall were measured within Catchment A and if the catchment had been visited in order to note more detail, *inter alia*, on soils or adjunct impervious areas.

Overall streamflow volume in Catchment B, planted to *Pinus patula* in 1971, is simulated well by *ACRU*, as illustrated in **Figure 8.2.3** (bottom) and the statistics of goodness of fit in **Table 8.2.4** (right). While higher variations and deviations of simulated values indicate that individual runoff events were likely not to have been simulated too well, the total water budget and periods of low flow, which are critical to the water resources planner, are simulated accurately.

Discussion and Conclusions

Based on the verifications presented above, it is suggested that the application of the *ACRU* model in conjunction with the forest decision support system to simulate streamflow from forested catchments is a useful tool for catchment decision makers in light of the National Water Act and the emphasis on Streamflow Reduction Activities. *ACRU* performed successfully on the forested catchments modelled, except for Catchment A at Mokobulaan where poor input data, problems of shallow soils and a lack of actual catchment knowledge were experienced.

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8.3 Verification of the Impact of a Wildfire on Streamflow Responses (Original Researchers: D.F. Scott and R.E. Schulze)

Fire and Hydrological Responses

In the past century large parts of South Africa's more humid eastern and southern catchment areas have seen commercial production afforestation to species such as *Pinus patula, P. taeda and P. elliottii,* as well as *Eucalyptus grandis* and other eucalyptus hybrids and *Acacia mearnsii*. This trend of afforestation continues to this day, albeit at a slower rate. The timber plantations are at risk of burning as they are surrounded by fire-prone and fire-maintained vegetation. The hydrological responses of these afforested catchments to fire may be different from that of the naturally vegetated catchments. It is important therefore to understand the risks and causes of different hydrological responses to forest fire in these high rainfall catchments.

Fire carries with it a risk of downstream flooding, mass failures (landslides, mudslides), increased soil erosion (hence a potential loss of site fertility and productivity), accelerated sedimentation of reservoirs and a consequent loss of storage capacity (Scott, 1994). Not all fires, however, have the same impact and several fire, fuel and vegetation characteristics may influence the effects of a fire. The role of fire in the hydrology of South African catchments is not well understood and, other than the long-term effect on water yield, has received relatively little research attention.

The Ntabamhlope Fire of August 1989

The high-intensity wildfire which burned a forested portion of the Ntabamhlope research catchment in August 1989 caused a marked change in the hydrological behaviour of the catchment during the first subsequent wet season (Scott, 1994; Chapter 7). The change in streamflow generation was postulated to have been caused by increased overland flow which resulted in shorter times of concentration and higher peak discharges during storms. Increased overland flows were linked to the widespread presence of water repellency in the soils of the plantation, which altered the mode of streamflow generation in the catchment.

This verification study describes the application of the *ACRU* agro-hydrological model to verify these hydrological effects in a relatively deterministic manner in order to utilise the findings of the detailed process studies so that catchment-specific results could be generalised for application to a broader geographical area, and to enable the impacts of wildfires on planted forests to be modelled where no observed hydrological data are available.

The *ACRU* model was set up to simulate, in distributed mode, the catchment which was delineated into five sub-catchments as shown in **Figure 8.3.1**. This allowed

- the sub-division of the catchment into relatively homogeneous segments which had different vegetation types (grassland or timber plantations),
- a check of the simulated flows in the upper, untreated research catchment V1H028, against its actual streamflow without the compounding effect of a fire, and
- confinement of the effects of the fire to only those sub-catchments which had actually been burned (Sub-catchments 3, 4 and 5 in **Figure 8.3.1**).

The Dynamic Information Menu to Account for the Effects of Fire

To account for the effect of fire within a single run of the model, *ACRU's* dynamic information input capability was invoked to alter certain variables to new values from September 1989, the first month following the fire. The changes of the monthly values of the above input parameters are plotted for the forested sub-catchments in **Figure 8.3.2** to illustrate the means by which *ACRU* was to account "dynamically" for the hydrological impact of the fire for the first nine months after the fire.

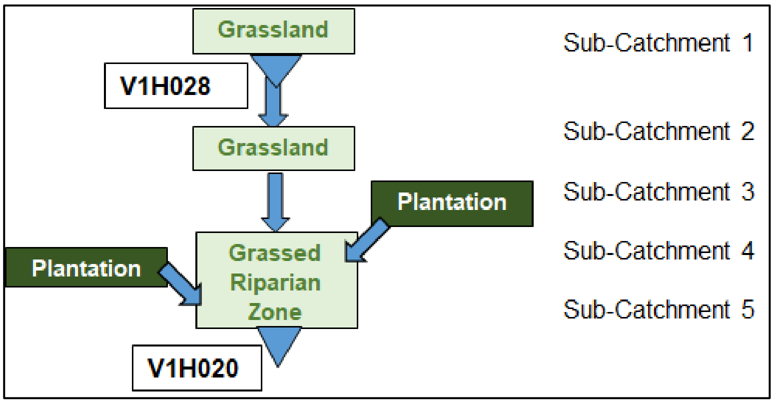


Figure 8.3.1 Layout and vegetation types of the sub-catchments within catchment V1H020 at Ntabamhlope for distributed modelling (After Scott, 1994)

The first and obvious effect of the fire was to kill all aerial parts of the vegetation, so that canopy and litter interception was removed, and transpiration halted. This was modelled by reducing interception to 0 mm per rainday in the first month after the fire (**Figure 8.3.2**) and increasing it gradually to account for the rapid re-growth of coppice that was observed in the catchment. Similarly, the crop coefficient was dropped to a minimum value of 0.45 after the fire and its recovery followed that of the canopy (**Figure 8.3.2**). All root activity in the model was re-set to be confined to the topsoil where initially only germinating seedlings were actively extracting soil-water for transpiration. The coefficient of initial abstraction (**Figure 8.3.2**), which accounts for rainfall abstractions by litter interception, initial infiltration and depression storage before runoff commences, was reduced to account for the removal of surface storage in the burned catchment (thereby increasing net rainfall).

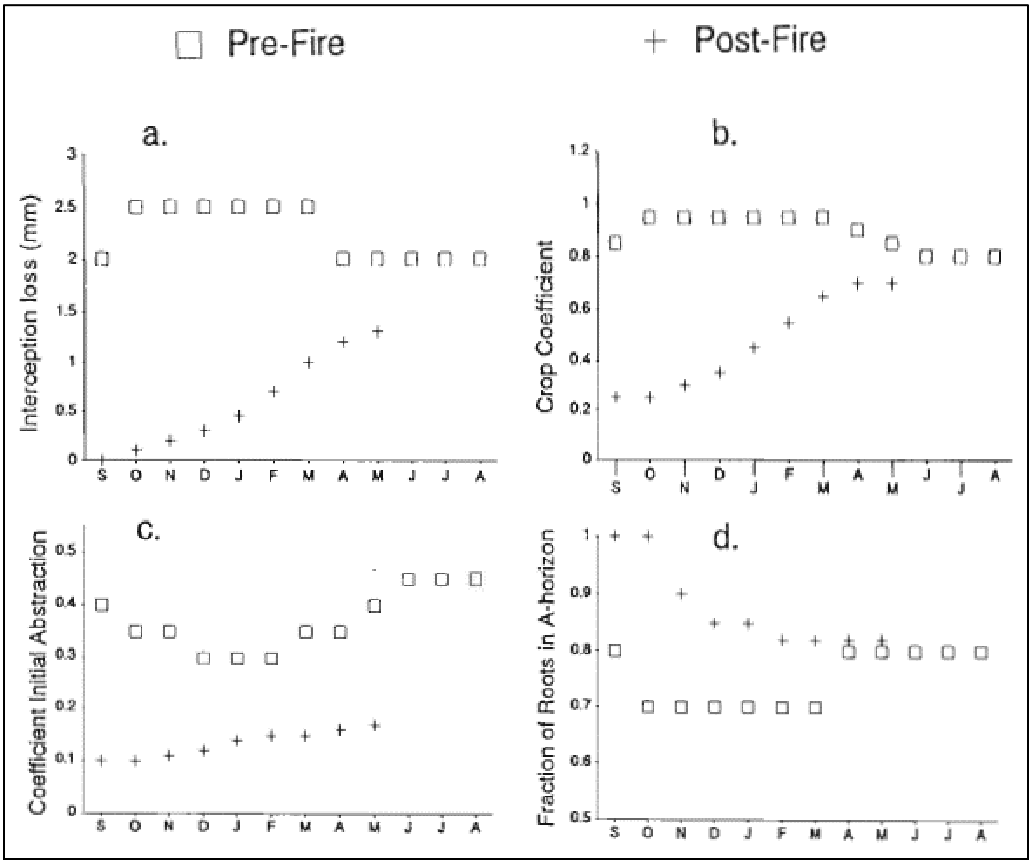


Figure 8.3.2 The monthly values of four *ACRU* model variables illustrating how they were set to accommodate before and after fire conditions in the burned sub-catchments at Ntabamhlope (After Scott, 1994)

The critical soil depth for which the soil water deficit is calculated for runoff generation procedures in *ACRU* was reduced from 0.4 m to 0.15 m in the burned plantation sub-catchments for the post-fire period to account for the influence of water repellency in the soils. Rainfall in excess of the daily water deficit in this critical soil depth depth is utilised in streamflow generating routines by the model. Neither the original value nor post-fire values reflect the actual depth of the water-repellent layer in the soil, but are an approximation in order to account for the spatial average of infiltration and the effect of litter to store water against overland flow over the plantation floor. While observation had shown that unburned soils were also water repellent, the effect of this phenomenon has limited impact on runoff generation while ground litter loads are high (Scott, 1994)

It should be noted that *ACRU,* as a physical-conceptual process-based model, is not calibrated to attain acceptable fits, but that all parameters which were affected were changed for physically accountable reasons. The direction and extent of an adjustment to a model parameter is therefore limited. However, as single parameter values have to be chosen to represent each sub-catchment, some averaging is done to account for scale and natural variability and, also, as some model parameters are conceptual rather than physical, a degree of experience is required of the modeller.

Observed Streamflow Effects

Fire changed all the stormflow variables from their expected behaviour based on the relationship with the control catchment (**Table 8.3.1**). In essence the storm hydrographs were larger and higher after the fire. The sample hydrographs plotted in **Figure 8.3.3** clearly illustrate the change in relationship between the two catchments which resulted from the fire. Before the fire, discharge per unit area was greater from the smaller, upper catchment, though the shape of the hydrograph was similar in both catchments, with a short delay in peaking at the lower station (**Figures 8.3.3 [a]** and **[b]**). After the fire, the larger catchment, of which the control is a part, had a relatively much greater discharge, with higher peaks and a very rapidly rising limb of the hydrograph. Storm duration was not markedly affected by fire; streamflow quickly returned to pre-storm levels, despite the greatly increased total stormflow volume (**Figures 8.3.3 [c]-[f]**).

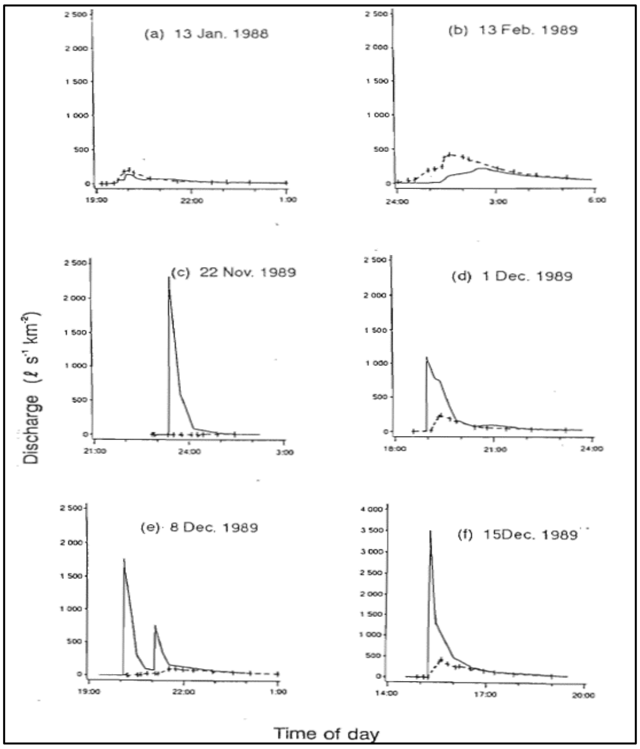


Figure 8.3.3 Sample hydrographs from Ntabamhlope catchments V1H020 (solid line) and V1H028 (stippled line) illustrating the change in the relationship between the catchments after the August 1989 fire, shown in plots [c] to [f] (After Scott, 1994)

Table 8.3.1 The mean pre-fire and post-fire values of the streamflow and stormflow variables, and the estimated change as a result of the passage of fire in catchment V1H020 at Ntabamhlope (After Scott, 1994)

Stream-flow Variable	Recorded Pre-Fire Mean	n	Recorded Post-Fire Mean	n	% Change Over Expected Value
Weekly streamflow (mm)	5.09	84	2.10	41	6% decrease
Weekly baseflow (mm)	3.47	137	0.92	71	48% decrease
Quickflow volume (mm)	4.69	31	2.08	13	92% increase
Peak discharge ($m^3.s^{-1}$)	0.66	31	1.21	13	1100% increase
Response ratio (%)	10.31	31	6.53	13	319% increase
Storm duration (min)	1464	28	690	13	12% increase
Time to peak (min)	193	23	54.9	10	53% decrease
Ratio of recession limb to rising limb stormflow	3.38	23	22.3	10	1206% increase

The results of the stormflow analysis show that after the fire rainfall inputs were reaching the stream very quickly, causing a rapid rise in stream levels. It is postulated that this quick delivery of water to the stream channel was by means of overland flow (surface runoff). If the whole of the post-fire increase in storm response is attributed to the plantation area, then after the fire stormflow volumes from this part of the catchment represented up to 42% of the rainfall inputs. Given the site conditions and the shortened time-to-rise of the hydrograph (**Figure 8.3.3**; **Table 8.3.1**), it is clear that a large proportion of this contribution must have been overland flow. Water repellent soils in the burned catchment are hypothesised to have played a part in generating overland flow from the burned areas.

Verification of the Effects of Fire

Daily and monthly streamflow totals were generated with *ACRU* and compared to the observed values. For all single rainstorms of above 15 mm, the stormflows simulated in each of the five sub-catchments of the model were summed to give a total stormflow volume from the catchment per storm.

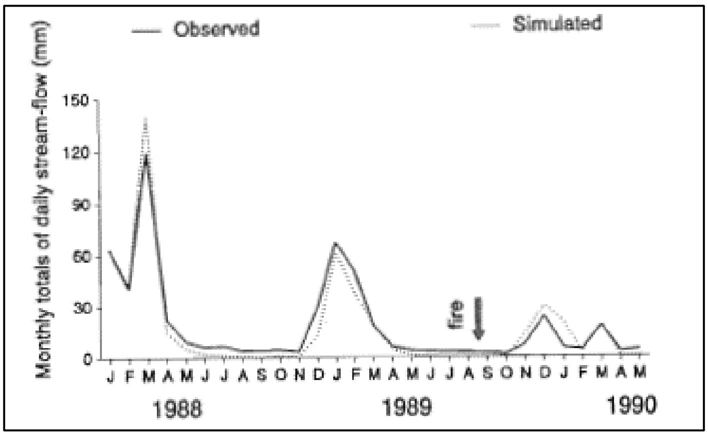


Figure 8.3.4 Time-plot of the observed and simulated monthly totals of daily streamflow for catchment V1H020 at Ntabamhlope.

The monthly totals of simulated daily streamflow were generally satisfactory (**Figure 8.3.4**), although baseflows in the dry winter months were consistently under-simulated, both before and after the fire. Daily streamflow volumes were also over-simulated during the dry season and during that the early part of the wet season when the catchment is wetting up after the long dry season (**Figure 8.5a** and **8.5c**). This is thought to be largely because of the problems of generally over-simulating flows from a "dry" catchment (a feature which has often been observed in the use of *ACRU*).

The over-simulations obtained in the post-fire months of December and January (**Figure 8.3.5** bottom right) stem from the over-simulation of stormflows in the period while the catchment was wetting up. A minor part of this error derives from the upstream grassland sub-catchments in the simulation. In the post-fire period baseflows were again over-simulated (**Figure 8.3.5** bottom right).

The simulated stormflow volumes were generally slightly higher than the observed stormflows, and more so after the fire (**Figure 8.3.5** right vs left). Before the fire, moderate to large storms (25-100 mm rainfalls) seem to have been over-simulated because the actual storm had been generated by low intensity rainfall events (*ACRU* as a daily model, does not account explicitly for rainfall intensity). These storms are of minor importance for planning purposes, and from this perspective such an error is considered acceptable. After the fire almost all the storms were over-simulated. This is thought to be partly because of the afore-mentioned problem of generally over-simulating flows from a "dry" catchment, and partly because of over-adjustments to account for the effects of fire.

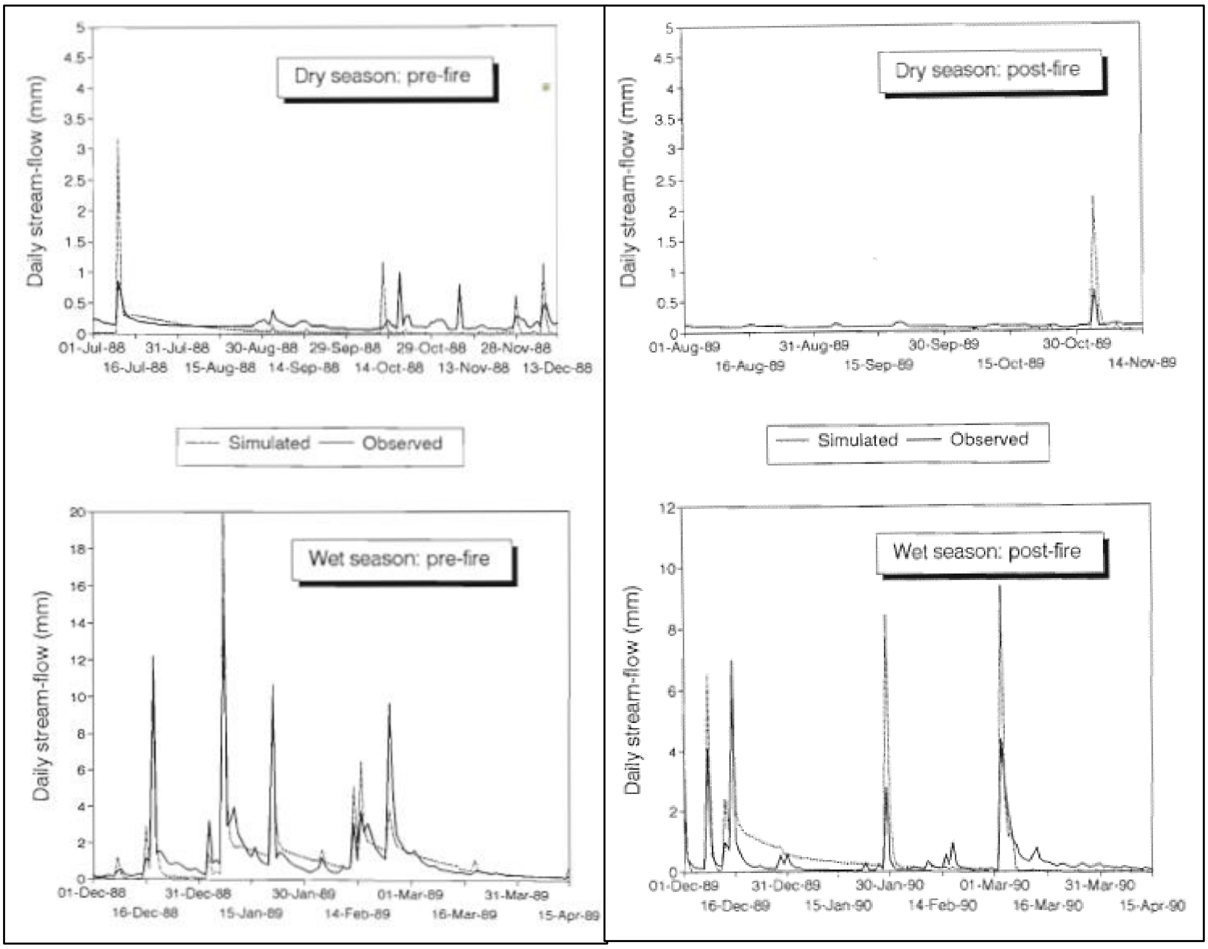


Figure 8.3.5 Time plots of the observed and simulated daily streamflow volume in Ntabamhlope catchment V1H020 for dry and wet periods (left) before the fire, and (right) after the fire, noting also scale differences in the vertical axes (After Scott, 1994)

Discussion and Conclusions

This verification has illustrated the *ACRU* model's versatility in that an abrupt hydrological impact such as a fire can be modelled with moderate success, and that the impact can be confined to the actual parts of the catchment which are affected. Consequently, realistic sub-catchment values for the hydrological control parameters could be used in the model, i.e. without areal averaging across the largely unaffected catchment.

The results show that the model is relatively sensitive to certain input parameter values. In particular it seemed that small changes to the critical soil depth for generating stormflow could easily lead to over-estimates in stormflow volumes. However, the realistic way in which total streamflow from the catchment was simulated after the fire is encouraging. The modelling of stormflow generation appears to mimic the likely process in the field, in that large rainstorms caused overland flow and storm runoff without necessarily recharging the whole profile. Consequently, baseflows remained low. This lends support to the hypothesis that overland flow contributes to stormflow generation in those wildfire sites where water repellency occurs in the soils. Before the fire little rain water would have reached the stream as overland flow, but after the fire, water repellent soils in the burned eucalypt plantation would have generated a considerable overland flow contribution to stormflows. Yet the soil water store was still not fully recharged, and consequently baseflows generally remained low during the wet season. These points are in agreement with the finding in the regression analysis that streamflow in the post-fire period became more responsive to rainfall depth.

This verification exercise has demonstrated the potential for using *ACRU* as a planning tool in regards impacts of fires on hydrological responses. It has been shown that the magnitude of floods, i.e. the increased size of floods following a wildfire in a catchment, can be predicted with some success. This finding is desirable for catchments for which suitable records are not available, and will find particular application where forested catchments are situated upstream of other key land uses such as flood prone urban developments.

Reference

Scott, D.F. 1994. *The Hydrological Effects of Fire in South African Catchments*. PhD Thesis, University of Natal, Pietermaritzburg, RSA. pp 168.

8.4 Verification of the *ACRU* Model's Flow Routing Module (Original Researchers: J.C. Smithers and R.E. Caldecott)

Introduction

The ability to simulate, on a continuous basis, the peak flow rate, streamflow volume and the entire hydrograph from a catchment is important in planning, design and operation of hydraulic structures and in the solution of a wide range of problems associated with water use. In South Africa, commonly used techniques for modelling the runoff hydrograph shape include the unit hydrograph, the kinematic and the time-area methods (Campbell *et al*., 1986). An advantage of applying any of these methods in a spatially distributed model when simulating the runoff from a large heterogeneously responding catchment, is that such a catchment can be sub-divided into relatively homogenous response units, thus accounting for the catchment's spatial heterogeneity, rather than operating simply a spatially lumped model. The *ACRU* modelling system, which originally was developed as a small catchments daily time step hydrological model, is being applied increasingly in distributed mode to larger and/or complex catchments where the river network plays an important role in transporting the water to the catchment outlet.

The assumption in *ACRU* that stormflow generated on a particular day passes the catchment outlet on the same day is valid for small catchments, but is not so of larger catchments. Thus, when *ACRU* is applied in distributed mode on larger catchments, the temporal distribution of streamflow passing the catchment outlet does not reflect the translation of the hydrograph taking place through river reaches and reservoirs encountered *en route* to the catchment outlet.

The development of a flow routing sub-model both for reservoirs and for river reaches, which has been incorporated as an option into the *ACRU* model and which enables continuous hydrograph simulation and flow routing to improve the temporal distribution of the daily streamflows generated by *ACRU*, has been presented in detail by Smithers and Caldecott (1995). A summary of results from verifications of the flow routing sub-model undertaken on the 175 km^2 catchment upstream of the Henley Dam in KwaZulu-Natal, as well as on the Ntabamhlope wetland in western KwaZulu-Natal, are presented below. More details are given in a paper by Smithers and Caldecott (1993).

Henley Catchment Verification

The *ACRU* model, in a typical operational type of situation, was applied with and without the flow routing sub-model invoked to the 175 km^2 catchment upstream of Henley Dam in the Mgeni catchment. An example of the improvement in the temporal distribution of the simulated daily runoff is given in **Figure 8.4.1** (left).

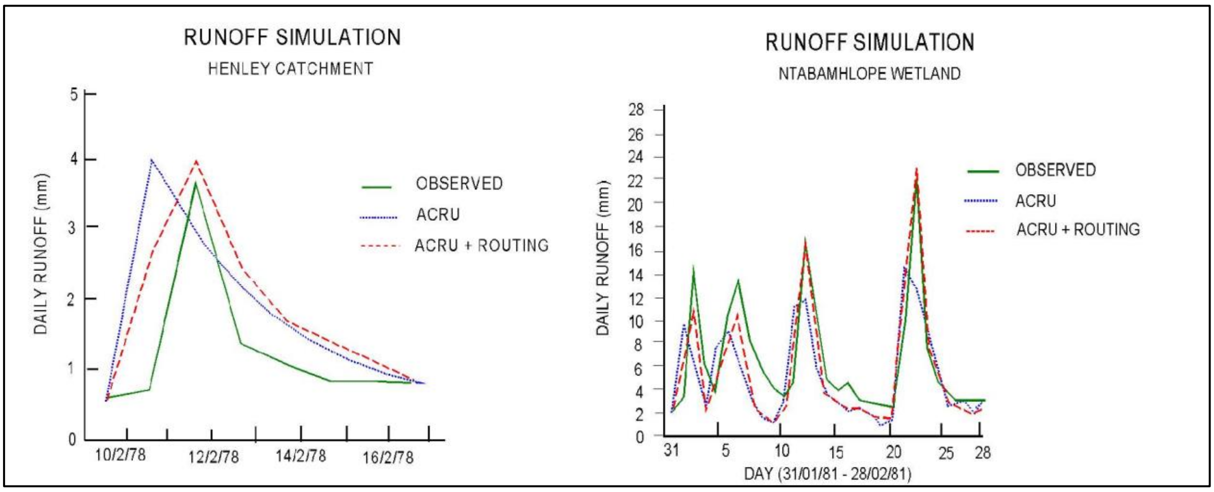


Figure 8.4.1 Verifications of the *ACRU* model's flow routing option from (left) the Henley catchment and (right) the Ntabamhlope wetland (After Smithers and Caldecott, 1993)

Verification of Flow Routing through the Ntabamhlope Wetland

The Ntabamhlope wetland is located at latitude 29°04'S and longitude 29°39' E, at an altitude of 1 440 m above sea level. The wetland surface area is approximately 1.8 km^2 and it has an upstream catchment area of approximately 34 km^2. Smithers (1991), in verifying the developments to the *ACRU* wetland sub-model, which is described in detail in Smithers and Schulze (1995), applied the *ACRU* model to the Ntabamhlope wetland. The results obtained indicated that the model simulated monthly totals of daily flows well, but without flow routing did not simulate the translation of flows which occurred in the observed daily flow. The model was re-run with the flow routing sub-model invoked and selected statistics of performance are presented in **Table 8.4.1** for the streamflow simulations with and without the routing sub-model invoked.

Differences in the simulated runoff depths with and without the routing sub-model are due to the finite difference approximation of the runoff hydrograph. The improvement in performance of the model with the flow routing sub-model invoked is evident from the improvement in the correlation coefficient and regression coefficient, as shown in **Table 8.4.1**. **Figure 8.4.1** (right) clearly shows the effect of the routing sub-model during a period of high flow conditions.

Table 8.4.1 Statistics of performance of daily *ACRU* runoff simulations from the Ntabamhlope wetland, without and with the flow routing options (years 1977-1987)

Statistic	*ACRU*	*ACRU* + Routing
Total observed runoff (mm)	881	881
Total simulated runoff (mm)	842	854
Correlation coefficient	0.64	0.79
Regression coefficient	0.62	0.81
Regression intercept	0.17	0.08

Conclusions

Visually, from **Figure 8.4.1**, it is already evident by invoking the flow routing option in the *ACRU* model that the simulation is an improvement on not using the option. This observation is corroborated by the statistics of model performance in **Table 8.4.1** which show that when the flow routing option is used all four statistics are improved, with the simulated runoff closer to the observed, the correlation coefficient better, the regression coefficient closer to the ideal 1.0 and the regression intercept closer to the ideal zero.

References

Smithers, J.C. 1991. Modelling the Ntabamhlope wetland: Initial results. *Agricultural Engineering in South Africa*, 23, 440-449.

Smithers, J.C. and Caldecott, R.E. 1993. Development and verification of hydrograph routing in a daily simulation model. *Water SA*, 19, 263-267.

9 SELECTION OF INTERNATIONAL VERIFICATION STUDIES ON THE *ACRU* MODEL

9.1 Australasia: Verification Studies of Streamflows in the Operational Manuherikia Catchment in Otago, New Zealand (Original Researchers: S.W. Kienzle, University of Lethbridge, Canada and J. Schmidt, National Institute of Water and Atmospheric Research, New Zealand)

Setting the Scene

As in many parts of the world, in New Zealand water for irrigation is becoming an increasingly critical component of the country's rural economy, with increased future water demands and a reliable water supply needed. However, little is known about the impacts of intensified irrigated practices on catchment hydrology and water resources such as potential changes to river flow rates, in particular low flows, and lowering of groundwater levels as a result of abstraction and changes in recharge rates.

In an ideal setting, the evaluation of the impacts of land use change and the introduction of irrigated agriculture, large reservoirs, irrigation canal systems (races), farm dams and inter-basin transfer, would be based on long-term streamflow observations both upstream and downstream of such a development. However, in New Zealand, available streamflow records are often not long enough nor dense enough to allow the quantitative assessment of the impact of irrigated agriculture. Therefore, as an alternative approach, the streamflow can be simulated for pre- and post-development scenarios.

This case study focuses on estimating the pre-irrigation development hydrology in the Manuherikia catchment in New Zealand as a verification study with the daily time-step and process based *ACRU* model under natural conditions and, depending on the model's performance, its subsequent application under modified conditions.

The Manuherikia Catchment

The Manuherikia catchment of 3 035 km^2 is located in Central Otago, New Zealand (**Figure 9.1.1**). Owing to its distance from the sea and the high altitude in Central Otago, the climate is the mostly continental with temperatures ranging from a maximum of 35°C in summer to a winter minimum of -20°C. Rainfall varies from 330 mm/y to 1500 mm/y and occurs throughout the year, with ~ 60% falling in spring and summer. In the valleys only 3% of annual precipitation falls as snow, while on the highest ridges snowfall can constitute up to ~ a third of the annual precipitation.

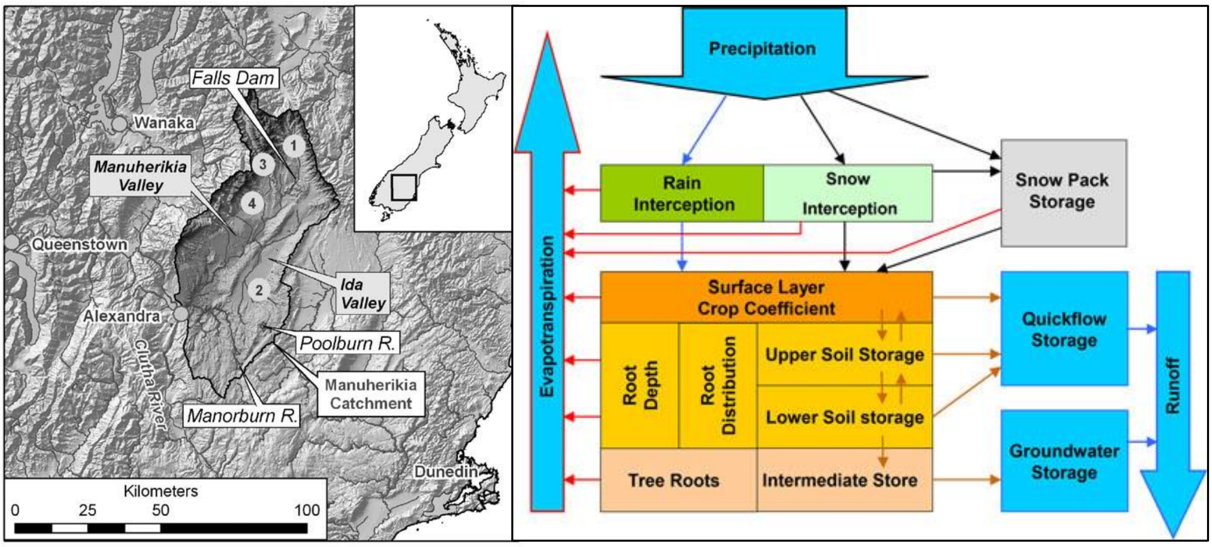


Figure 9.1.1 (Left) Map of Manuherikia catchment, with numbers 1 to 4 indicating the locations of the four gauging stations at which verifications were undertaken, and (right) a schematic of the major elements of the *ACRU* model which includes snow related modules (After Kienzle and Schmidt, 2008)

Verification of Simulated Hydrological Outputs

Model verification is important to establish if the behaviour of the simulation model is consistent with the behaviour of the hydrological system. As the aim of this investigation was to provide water yield information to water resources managers and local catchment management agencies, the verifications undertaken were focused on the total generated streamflow and its seasonal behaviour as well as the standard deviation and correlation statistics.

Simulated streamflows were verified for various periods between 1975 and 2005 at gauged outflows of four sub-catchments (locations and periods shown in **Figure 9.1.1** and **Table 9.1.1**). These four sites represent upstream headwaters of the Manuherikia catchment in a range of different environments (high altitude/rainfall to low altitude/rainfall), which are uninfluenced by water abstractions and irrigation. **Table 9.1.1** lists the various objective functions used to evaluate the success of the simulations, while **Figures 9.1.2** and **9.1.3** show the cumulative and seasonal streamflows for observed and simulated scenarios.

Table 9.1.1 Attributes of the four Manuherikia sub-catchments and statistical results of the verification analyses (After Kienzle and Schmidt, 2008)

Number in Figure 1	**1**	**2**	**3**	**4**
Station Number	75251	75255	75257	75256
Station Name	Manuherikia at D/S Forks	Dovedale Creek at Willows	Dunstan Creek at Gorge	Woolshed Creek at Lauder Station
Catchment size [km^2]	172.9	39.3	157.8	10.9
Verification period	1978-1993 1999-2004	1978-1993	197 -1994	1973-1979
Sample size (# of months)	244	156	202	97
Mean observed flows (mm)	45.66	10.14	38.73	29.31
Mean simulated flows (mm)	44.98	9.87	39.29	27.69
Difference between the means [%]	**1.48**	**2.70**	**–1.45**	**5.51**
t statistic for comparing means	0.281	0.216	–0.233	0.532
Standard deviation observed	26.19	12.49	24.20	21.38
Standard deviation simulated	26.91	9.8	24.23	20.90
Difference between standard deviations [%]	**–2.74**	**21.51**	**–0.10**	**2.23**
Coefficient of determination	0.667	0.519	0.618	0.509
Coefficient of efficiency	0.642	0.211	0.573	0.858

Accumulated streamflows compare very well for three sites, while site 75255 (#2 in **Figure 9.1.1**) exhibits the largest deviations. The fact that the accumulated streamflows do not deviate by a large margin is evidence that both wet and dry years are simulated realistically.

Results of monthly totals of modelled versus observed streamflows show that simulations for all four gauged sub-catchments produced an accumulated streamflow yield within an accuracy of 5.5%, and for three sub-catchments within 3%. The variance of monthly streamflows is well represented for three sub-catchments, with a difference in standard deviations of less than 3%. Only one sub-catchment (associated with gauging station 75255, #2 in **Figure 9.1.1**) was simulated with a difference in standard deviations of 21.5%. The relatively poor simulations at sub-catchment 75255 are attributed to uncertainties in precipitation, climate, and soil variables, where inconsistencies between the soils database and field observations were found (Kienzle and Schmidt, 2010).

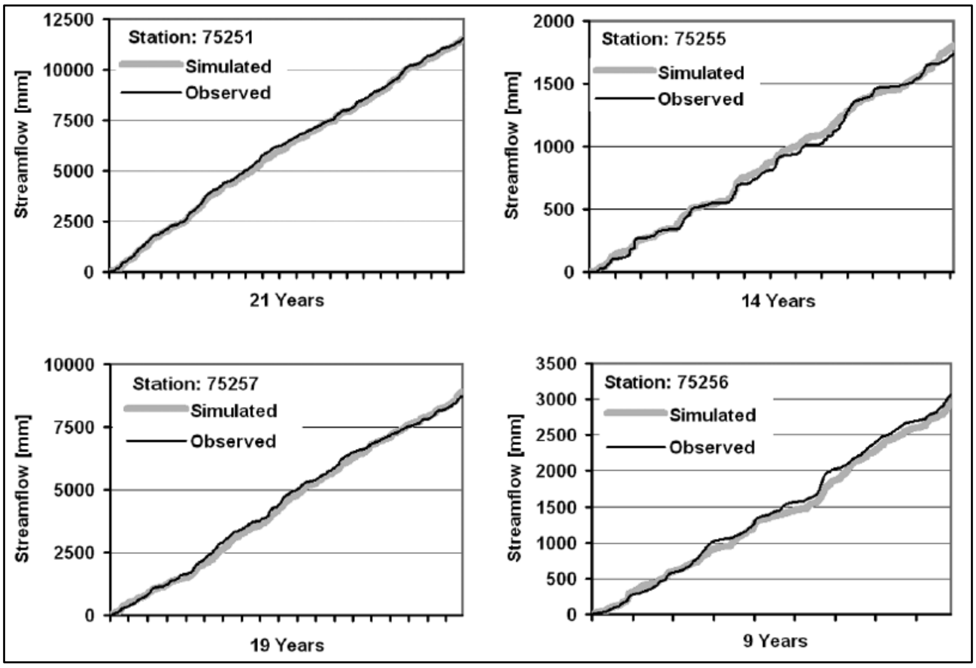


Figure 9.1.2 Simulated and observed streamflows for the four Manuherikia sub-catchments at which verification analyses were undertaken (After Kienzle and Schmidt, 2008)

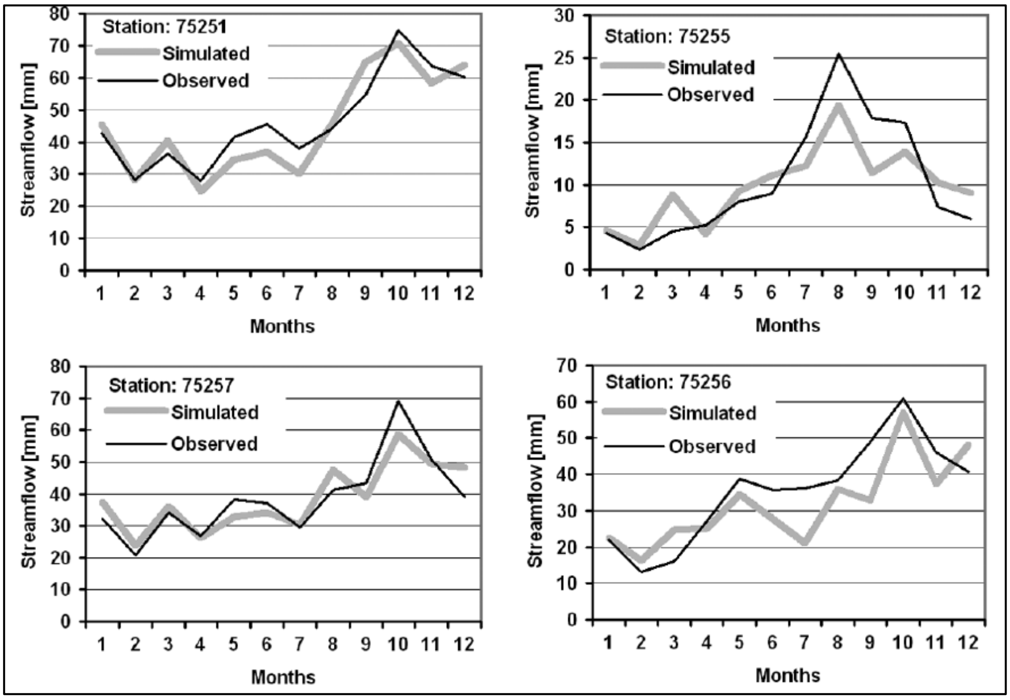


Figure 9.1.3 Simulated and observed monthly streamflows for the four sub-catchments at which verification assessments were undertaken (After Kienzle and Schmidt, 2008)

Coefficients of determination are all above 0.5, and the coefficient of efficiency (Nash-Sutcliffe efficiency) is high for two sub-catchments (#1 and #4 in **Figure 9.1.1**) and low for one sub-catchment (#2 in **Figure 9.1.1**). The range for the coefficient of efficiency lies between 1.0 (perfect fit) and $-\infty$. The largest disadvantage of both the coefficient of determination and the coefficient of efficiency is the fact that the differences between the observed and simulated values are squared, so differences in higher streamflow values have a much larger effect on the coefficients than differences during low streamflows.

Conclusions

Based on the uncertainty of many input parameters and variables, in particular climate data, which was interpolated from sparsely distributed climate stations, the simulations can, overall, be regarded as representing the natural system acceptably well for the *ACRU* model to be used with confidence in New Zealand when assessing impacts of future land use and irrigation practices.

Reference

Kienzle, S.W. and Schmidt, J. 2008. Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand. *Journal of Hydrology (NZ)*, 47 (2), 67-83.

9.2 Africa 1: Verification of the *ACRU* Streamflow Modelling Approach on a Small Research Catchment in Eritrea (Original Research: Y.B. Ghile, R.E. Schulze)

Introduction

The highlands of Eritrea, Ethiopia, Kenya and Uganda are some of the most highly populated areas in Africa facing complex problems of severe poverty, low productivity and severe water constraints. Conflicts over water are increasing in the region, caused mainly due to the increase of population size and lack of economic and technical means to distribute the limited available water to a wide range of users. Water managers need, therefore, to pay attention to adaptation of appropriate modelling and decision aid tools that facilitate the assessment of quantity and quality of water resources. This chapter focuses on a small Eritrean research catchment, the Afdeyu, with some general hydrological background first given on the catchment, followed by an outline of the research methodology, the verification results and conclusions on the suitability of the model for application in countries such as Eritrea.

Background on the Afdeyu Research Catchment

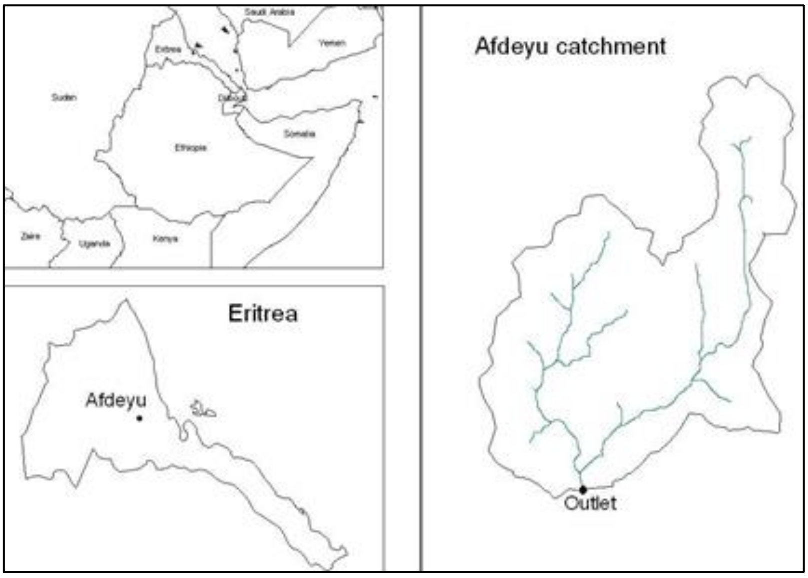


Figure 9.2.1 Geographic location of the eastern part of Africa and the Afdeyu research catchment

Eritrea, a semi-arid country with a complex series of landscape and climatic features giving give rise to a wide variety of agro-ecological zones, is located in the eastern part of Africa between 12˚42'N and 18°20'N and 36°30'E and 43°20'E (**Figure 9.2.1**).

Only one research catchment, *viz.* the Afdeyu, with a relatively good streamflow record as well as soils and land use information, is available for verifying outputs from the *ACRU* model. The Afdeyu research catchment covers an area of 1.77 km^2 has an altitudinal range of 160 m from 2300 to 2460 m above sea level, a mean annual rainfall estimated to be 556 mm, a bimodal rainfall regime with a short and longer rain season, but with the variability during the short rainy season high with rainfall often erratic and convective, and the period from November to April as well as June experiencing little to no rain.

Research Methodology and Model Inputs

The *ACRU* stormflow modelling approach has proved to be successful in many parts of southern Africa and elsewhere, but had not yet been verified on East African catchments. Owing to the limited observed streamflow data currently available in Eritrea, only the Afdeyu catchment was found suitable for this verification. Being a small catchment, the model was run on the Afdeyu assuming it to be one spatial entity, without subdivisions into sub-catchments. Data and information on rainfall, temperature, potential evaporation, soils and land uses, which are required by the *ACRU* model for streamflow simulations, were obtained, and are described in detail, by Ghile (2004).

Following field work in the Afdeyu catchment by Ghile, and recommendations contained in the *ACRU* User Manual (Smithers and Schulze, 1995), the catchment's quickflow response was set at 0.99, thereby implying that essentially all stormflow generated from a rainfall event exited the small catchment's outlet on the same day as the rainfall event. The effective depth of the soil from which stormflow generation is computed was set to the value of the thickness of the topsoil horizon at 0.3 m. Baseflow was excluded from the simulated total streamflow because none has been observed to occur over the years, and no adjunct impervious areas were connected directly to the watercourse. However, 4% of the catchment was occupied by disjunct impervious areas not adjacent to a watercourse, with the impervious surface storage capacity being set at 1 mm.

Results and Discussions

Figure 9.2.2 shows a plot of monthly totals of daily values from the *ACRU* model simulations vs observations on a month-by-month basis for the period of observation at the Afdeyu catchment from 1985-1999. Data from 1991-1993 are missing because no runoff observations were made during that period. Despite the relatively limited level of information on climate, soils and land use for the Afdeyu catchment, the monthly totals of simulated daily flows from the *ACRU* mimicked the corresponding observed flows excellently, with the one exception of August 1998, where the model overestimated by around 28%.

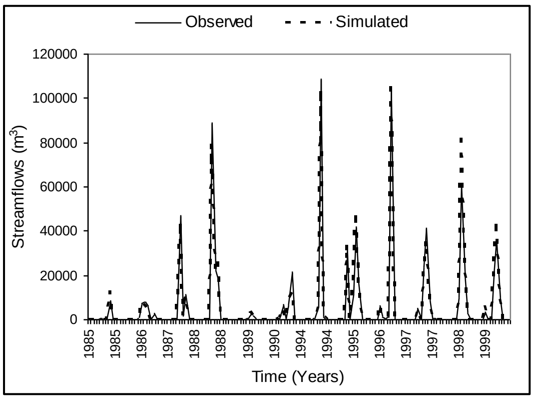


Figure 9.2.2 Monthly totals of daily *ACRU* simulated versus observed flows (m^3) in the Afdeyu catchment in Eritrea for the period of 1985-1999, with missing observed data from 1991-1993 (After Ghile, 2004)

A plot of simulated versus observed daily flows, as well as monthly totals of daily flows, reveals a very high performance of the model, with $r^2 = 0.94$ for the analysis daily flows (**Figure 9.2.3 a**) and $R^2 = 0.97$ for the analysis of monthly totals of daily flows (**Figure 9.2.3 b**).

The relationship is especially strong for less extreme events, while there is slightly more scatter at high flows. While there might have been occasional misreading of the raingauge, or wind flow causing turbulent eddies around the raingauge orifice, which occurs commonly in the torrential and erratic storm events experienced at Afdeyu, only one inlier point was found in the daily analysis (cf. **Figure 9.2.3 a**).

The excellent simulations of the *ACRU* model are confirmed by the accumulated monthly and annual flows, as shown in **Figure 9.2.4**, which illustrate clearly that the total values of flows were simulated correctly.

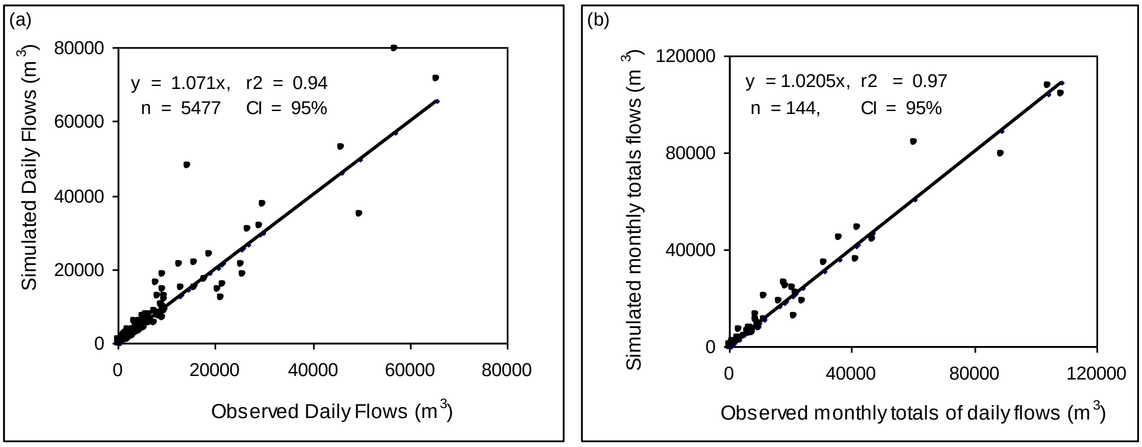


Figure 9.2.3 Scattergrams of *ACRU* simulated daily flows (a) and monthly totals (b) versus observed flows for the Afdeyu catchment for the period 1985-1999 (After Ghile, 2004)

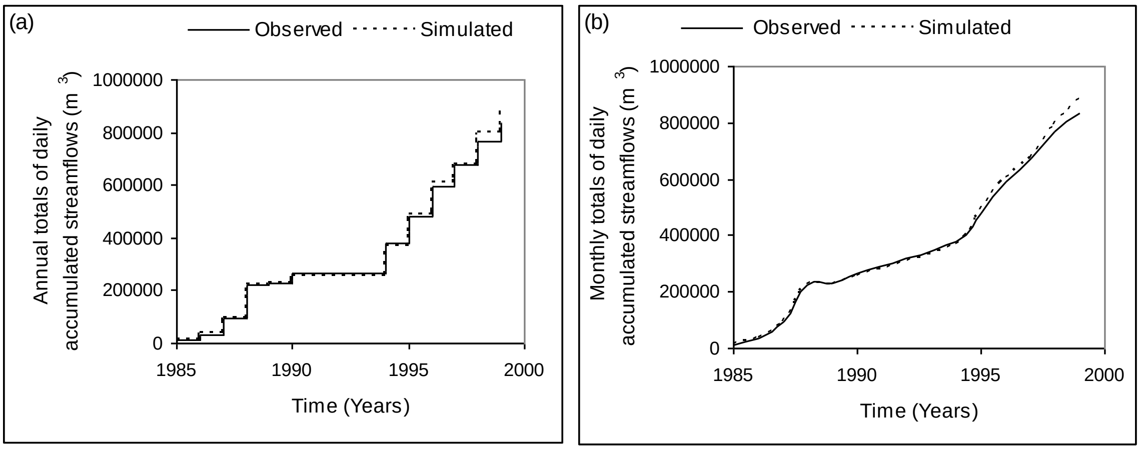


Figure 9.2.4 Annual (a) and monthly (b) simulated versus observed accumulated flows for the Afdeyu catchment for the period 1985-1999, with missing observed data from 1991-1993 (After Ghile, 2004)

A statistical summary of the performance of the *ACRU* model (**Table 9.2.1**) has been conducted in order to obtain an indication of how well the estimated values fit the observed values and to check whether any systematic errors were evident in the estimations. The model has shown excellent relationships between total flows (difference < 7%), as well as between variances (difference in standard deviations only 3.3%), as may be seen in **Table 9.2.1**. The slope of the regression is acceptably close to unity, while the degrees of association between the observed and simulated values (both the coefficient of determination and coefficient of efficiency) are also very close to unity.

Conclusions

Despite the relatively limited levels of information on certain climate parameters as well as on soils and land use for the Afdeyu research catchment, the *ACRU* model simulated both daily and monthly flows well. It has been shown by the statistics presented in **Table 9.2.1** that the *ACRU* soil water budgeting procedures produce highly acceptable performance statistics for stormflow simulations on the Afdeyu research catchment. The success of the model results implies that, in hydrologically heterogeneous regions such as Eritrea, given the observed daily rainfall values, the application of a soil water budgeting technique can provide excellent stormflow volumes, largely because through such models the soil water status antecedent to a rainfall event has been accounted for explicitly. The above results, although from only one research catchment in Eritrea, illustrate that the *ACRU* model may be adapted as a tool to provide realistic estimates of, for example, streamflows, peak flows, reservoir levels in east Africa, following further testing of the model across a wider range of catchment characteristics than those found at Afdeyu.

Table 9.2.1 Statistics of performance of the *ACRU* model for the stormflows produced from daily rainfall amounts of each year for the period 1985-1999, with missing data from 1991-1993 (After Ghile, 2004)

Conservation Statistics	
Total observed flows (m^3)	832 158
Total simulated flows (m^3)	886 030
Percentage difference in total flows	6.47
Standard deviation of observed flows (m^3)	1930
Standard deviation of simulated flows (m^3)	1994
Percentage difference in standard deviations	3.31
Regression Statistics	
Correlation coefficient (Pearson' s)	0.97
Slope of the regression line	0.82
Base constant for regression equation	11.19
Coefficient of efficiency	0.92
Total sum squares (SST)	2.449E+10
Sum of squares due to regression (SSR)	2.304E+10
Residual sum of squares (SSE)	1.444E+09
Coefficient of determination	0.94

References

Ghile, Y. 2004. An adaptation of the SCS-*ACRU* hydrograph generating technique for application in Eritrea. MSc Dissertation, University of KwaZulu-Natal, Pietermaritzburg, RSA.

Smithers, J.C. and Schulze, R.E., 1995. *ACRU Agrohydrological Modelling System: User Manual Version 3.00*. *WRC Report* TT 70/95, Water Research Commission, Pretoria, RSA.

9.3 Africa 2: Verification of Streamflows from Large Operational Catchments within the Mbuluzi System in eSwatini (Original Researchers: D.J.M. Dlamini and R.E. Schulze)

Geographical Location

The Mbuluzi river, eSwatini's (Eswatini's) only major river which originates within the country, has its source in the north-western part of the country close to the border with South Africa. It drains an area of 2 958.9 km^2 area before crossing into Mozambique in the east, and stretches latitudinally from 25°54' to 26°30'S and longitudinally from 31°02' to 32°06'E, as shown in **Figure 9.3.1**.

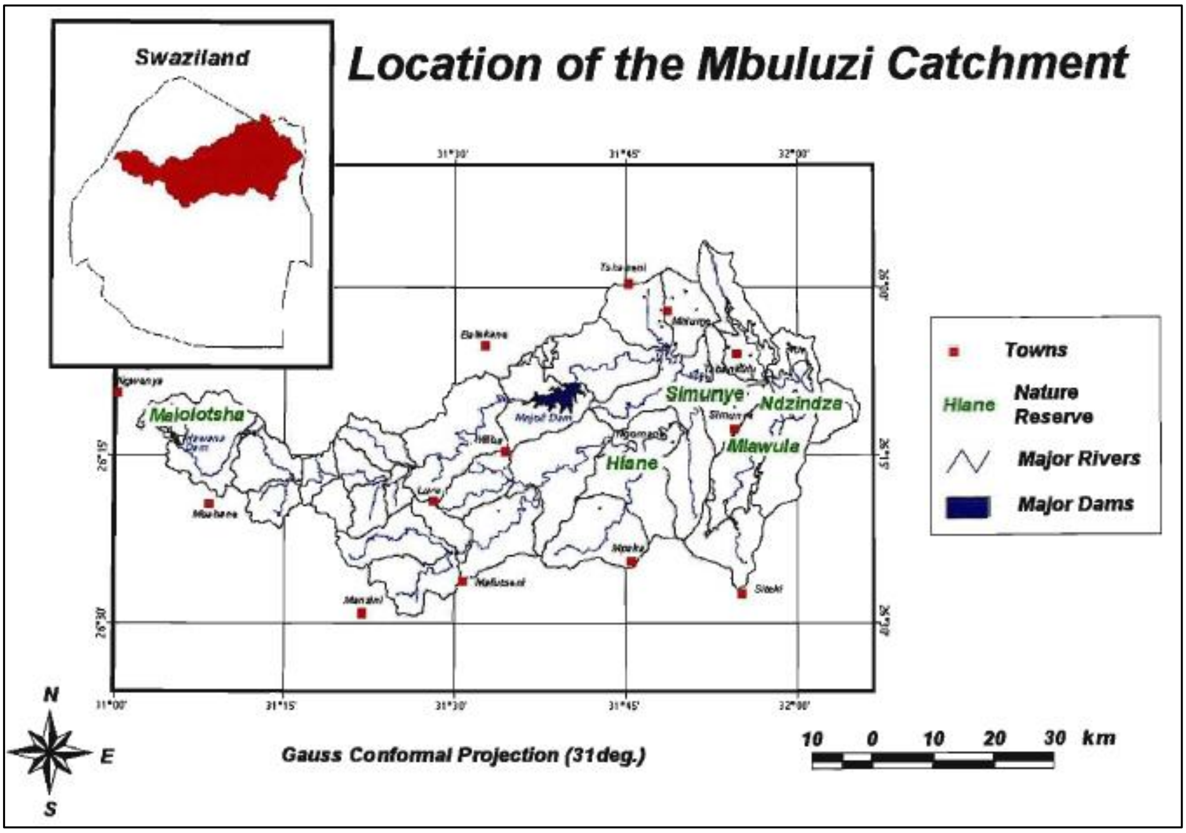


Figure 9.3.1 Location of the Mbuluzi Catchment within Eswatini

Catchment Attributes

The western part of the catchment is mostly highveld at altitudes ranging from 800 to 1 800 m, is generally mountainous, while the middleveld consists of undulating topography at altitude from 400 to 1 000 m and the lowveld in the east is largely flat land. Except for the lowveld which is semi-arid, most of the catchment has a sub-humid temperate climate, receiving most of its rainfall during the wet summer season October to March. Mean Annual Precipitation (MAP) ranges from 700 mm in the eastern lowveld to > 1 200 mm in parts of the western highveld. Temperatures vary with altitude, with the lowveld the hottest region in the catchment with minimum and maximum temperatures respectively exceeding 11°C and 26°C in winter (July) and 22°C and 33°C in summer.

Verification Studies

Verification studies were undertaken to assess the performance of *ACRU* model's streamflow output in the Mbuluzi catchment. For the verification studies, it was assumed that the present land cover was static and representative of the entire simulation period. The length of the verification period was limited by continuity of the observed data. Monthly totals of simulated daily streamflows were matched against observed data from the streamflow gauging stations GS4, GS3 and GS32, with summaries of the results of the verification studies presented **Figures 9.3.2**, **9.3.3** and **9.3.4**, each showing:

- time series plots of simulated and observed monthly totals of daily streamflows,
- comparisons of accumulated monthly totals of daily streamflows for simulated and observed values,
- scatter plots of simulated vs observed monthly totals of streamflows, and
- summaries of statistical comparisons of simulated and observed monthly totals of daily streamflows.

Note at the outset that these were "blind" verifications with no calibrations to force good fits.

Verification of Modelled Streamflows at GS4
The gauging weir at GS4 commands a 173.7 km^2 area at the upstream end of the Mbuluzi catchment (**Figure 9.3.1**). Other than the Hawana Dam, this part of the catchment is least impacted by humans. From this station, flow records are available from 1960 to 1984 when the weir was washed away by the Cyclone Domonia floods.

The verification results indicate that the intra- and inter-annual high and low flow trends are well matched (**Figure 9.3.2**). The coefficient of determination R^2 is 77%. The sum of simulated monthly streamflows differs from that of observed values by only 9.2%. From the time series and scatter plots (**Figure 9.3.2**), it can be seen that while the total streamflows and baseflows are well reproduced, the peak flows or floods are slightly exaggerated by the model. The standard deviation of the simulated monthly totals is 27% higher than the observed values, indicating a more attenuated natural hydrograph than that modelled.

Verification of Modelled Streamflows at GS3
The GS3 weir has a contributing area of 713 km^2 (**Figure 9.3.1**). It is less than 5 km upstream of the Mnjoli Dam. The land upstream of the weir is predominantly occupied by rural communities, used mainly for subsistence agriculture and communal grazing on poorly managed pastures. Verification studies at GS3 were undertaken for the period beginning in 1971 to 1983. This is the longest spell of continuous recording available for the weir.

In **Figure 9.3.3** it can be seen that the model mimics the seasonal and annual trends of streamflow relatively well. The correlation coefficient between the observed and simulated values of streamflow is 0.85, giving a coefficient of determination of 71%. However, the model appears to consistently under-simulate baseflows. The sum of simulated monthly totals of streamflows is 14.2% less than the sum of the observed values, with the difference between the standard deviations 20.3%.

Verification of Modelled Streamflows at GS32
The GS32 station is located strategically at Mlawula as the last gauging weir before the Mbuluzi river crosses the international boundary into Mozambique **(Figure 9.3.1**). Its contributing area of 2 597 km^2 constitutes more than 87% of the total area of the Mbuluzi catchment. Streamflow measured at this point is heavily impacted by the expansive irrigated agriculture practised upstream.

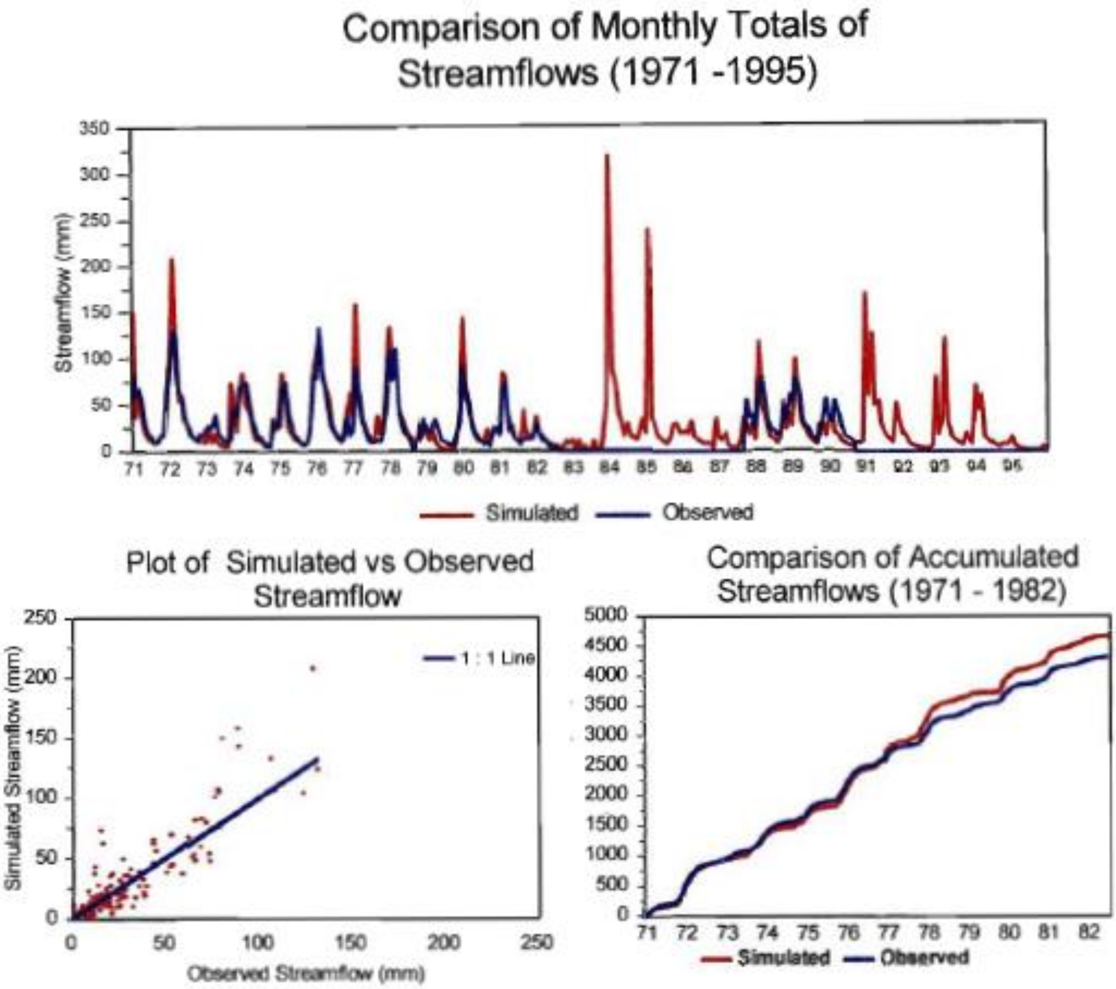
A summary of the results of the verification studies at Mlawula is presented in **Figure 9.3.4**. The analysis is for a total of 76 months from 1979 to 1984. Although the trends were well modelled ($r = 0.89$ and $r^2 = 0.80$), there are marked deviations on some statistics, with the difference between the sums of the monthly totals of streamflow is 25%, while the standard deviations of the simulated streamflow is about twice that of observed streamflow.

Comments on the Mbuluzi Verification Studies
Given that these verifications on the Mbuluzi system were “blind” simulations with no calibration having been undertaken, and given

- the inevitable simplification of representing each sub-catchment's daily rainfall by data from a single rainfall station, as well as
- averaging the heterogeneous soil properties to obtain representative values for an entire sub-catchment, and considering
- systematic and random errors associated with the monitoring of both rainfall and streamflow,
- the assumption that the land cover did not change significantly during the period of simulation, and
- simplifications having had to be made in regard to river/dam abstractions and return flows because no detailed data were available,

the verifications on these three operational catchments making up the Mbuluzi system may be considered acceptable, and while a near perfect match between the observed and simulated streamflows is desirable, the discrepancies noted above were not unexpected.

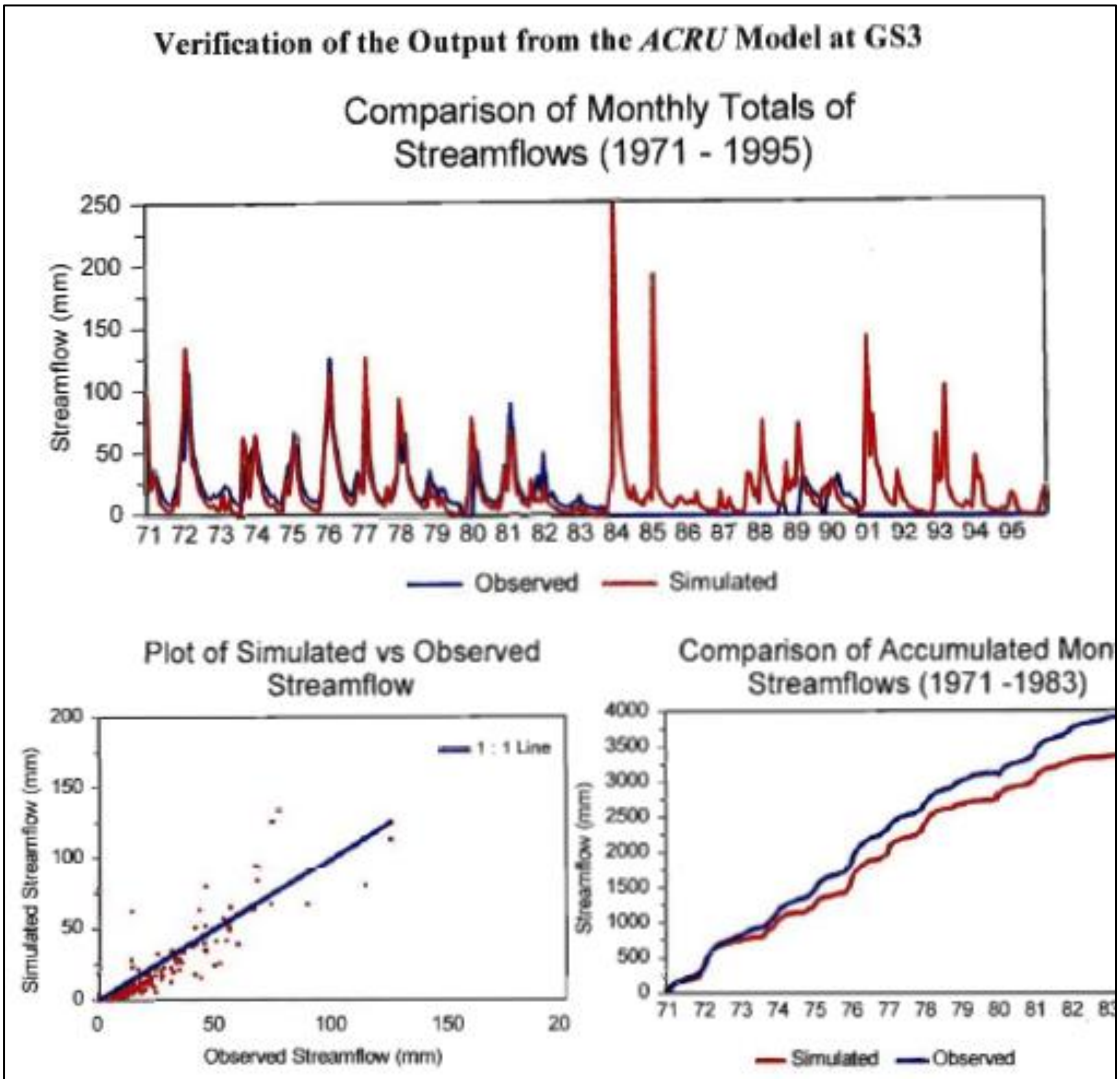
Verification of Output from *ACRU* Model at GS4



Statistical Comparison of Monthly Totals of Daily Simulated and Observed Streamflows

Catchment Area (km^2)	=	173.0
Mean Annual Precipitation (mm)	=	1219.0
Mean Annual Runoff (mm)	=	301.9
Runoff Coefficient (MAR / MAP, %)	=	24.8
Number of months of observations	=	140
Sum of observed values (mm)	=	44433.2
Sum of simulated values (mm)	=	48539.0
% difference between the sums	=	9.2
Correlation coefficient (r)	=	0.88
Coefficient of determination (r^2)	=	0.77
Standard deviation of observed values (mm)	=	28.2
Standard deviation of simulated values (mm)	=	35.8
% difference between standard deviations	=	27.1
Kurtosis of observed values	=	2.0
Kurtosis of simulated values	=	5.1
Skewness coefficient of observed values	=	1.6
Skewness coefficient of simulated values	=	2.1
1 mm streamflow	=	$173 \times 10^3 m^3$

Figure 9.3.2 Results from streamflow verifications at Gauge GS4 on the Mbuluzi in Eswatini (After Dlamini, 2001)

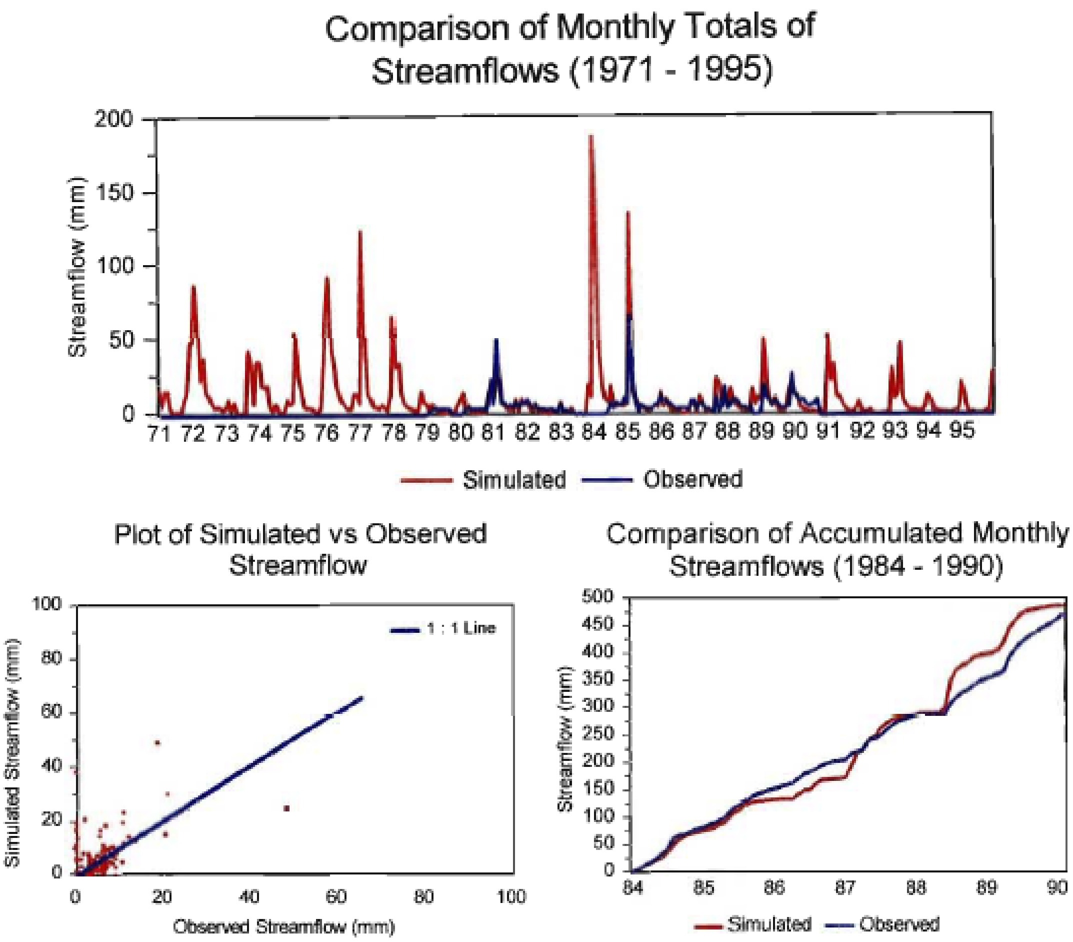


Statistical Comparison of Monthly Totals of Daily Simulated and Observed Streamflows

Catchment Area (km²)	=	713.0
Mean Annual Precipitation (mm)	=	895.4
Mean Annual Runoff (mm)	=	222.5
Runoff Coefficient (MAR / MAP, %)	=	24.8
Number of monthly observations	=	153
Sum of observed values	=	3938.7
Sum of simulated values	=	3379.9
% difference between the sums	=	-14.2
Correlation coefficient (r)	=	0. 85
Coefficient of determination (r^2)	=	0.71
Standard deviation of observed values (mm)	=	21.1
Standard deviation of simulated values (mm)	=	25.4
% difference between standard deviations	=	20.3
Kurtosis of observed values	=	4.6
Kurtosis of simulated values	=	4.7
Skewness coefficient of observed values	=	1.9
Skewness coefficient of simulated values	=	2.1
1 mm streamflow	=	713×10^3 m³

Figure 9.3.3 Results from streamflow verifications at Gauge GS3 on the Mbuluzi in Eswatini (After Dlamini, 2001)

Verification of the Output from the *ACRU* Model at GS32



Statistical Comparison of Monthly Totals of Daily Simulated and Observed Streamflows

Catchment Area (km²)	=	2597.0
Mean Annual Precipitation (mm)	=	747.6
Mean Annual Runoff (mm)	=	111.4
Runoff Coefficient (MAR / MAP, %)	=	14.9
Number of monthly observations	=	76
Sum of observed values	=	542.2
Sum of simulated values	=	677.7
% difference between the sums	=	25.0
Correlation coefficient (r)	=	0. 89
Coefficient of determination (r^2)	=	0.80
Standard deviation of observed values (mm)	=	8.1
Standard deviation of simulated values (mm)	=	16.4
% difference between standard deviations	=	102.1
Kurtosis of observed values	=	36.0
Kurtoses of simulated values	=	46.5
Skewness coefficient of observed values	=	5.3
Skewness coefficient of simulated values	=	6.3
1mm streamflow	=	2.597×10^6 m ^{3}

Figure 9.3.4 Results from streamflow verifications at Gauge GS32 on the Mbuluzi in Eswatini (After Dlamini, 2001)

Reference

Dlamini, D.J.M. 2001. *Integrated Water Resources Management Studies in the Mbuluzi Catchment, Eswatini*. MSc Hydrology Dissertation, University of KwaZulu-Natal, Pietermaritzburg, RSA. pp 147.

9.4 Africa 3: Verification of Long-term Groundwater Level Fluctuations in the Romwe Catchment in Zimbabwe due to Variations in Rainfall (Original Researchers: J.A. Butterworth, R.E. Schulze, L.P. Simmonds, P. Moriarty and F. Mugabe)

Background

Observations suggest that large perturbations in groundwater levels are a normal feature of the response of a shallow aquifer to variations in rainfall, with long-term trends in groundwater levels apparently reflecting the effects of cycles in rainfall (rather, in this case, than impacts of land uses or abstractions). A modelling approach may thus be applied in the development of guidelines for groundwater schemes to help ensure safe long-term yields and to predict future stress on groundwater resources in low rainfall periods.

To evaluate the effects of variations in rainfall on groundwater, long-term rainfall records were used to simulate groundwater levels over the period 1953-96 at the Romwe experimental catchment in south-eastern Zimbabwe, 86 km south of Masvingo, with one of the methods adopted to predict groundwater levels as a function, *inter alia*, of drainage being the *ACRU* model. The 4.6 km^2 Romwe Catchment is located at 20°45'S, 30°46'E and includes areas of rainfed cultivation on the valley floor and miombo woodland on the surrounding hillslopes. Average annual rainfall at a rainfall station 12 km from the catchment is 585 mm, with rainfall being strongly seasonal with 84% received on average in the summer rainy season between November and March.

The Approach Used

Water balance measurements were made on a 2.4 ha surface water sub-catchment in the northern part of the area where the freely draining red clay soils overlie a weathered aquifer, with this sub-catchment comprising two fields of a cropped area of 1.7 ha, with the remaining area being scrub and sparse woodland vegetation on the flanks of the fields, with groundwater level measurements done close by.

In this study, the soil water balance component of *ACRU* Version 323 was used in lumped mode to calculate drainage, with some modifications made to account for Romwe's aquifer being disconnected from surface water courses for most of the year and discharges to streams occurring for only limited periods during wet years.

On days when drainage out of the B-horizon was simulated from the soil water balance model, groundwater level rise was predicted using the equation

$$h2 - h1 = D/S_y$$

where $h2 - h1$ is the groundwater rise between times t_1 (start of day) and t_2 (end of day) due to an amount of drainage D at a site with specific yield S_y expressed as a fraction (Price, 1996). Owing to the difficulty of obtaining reliable measurements of S_y for the Romwe aquifer (Macdonald *et al*., 1995), this quantity was optimised over the period for which observed groundwater levels were available.

Groundwater discharge was predicted using a groundwater recession function parameterised from measurements of falling groundwater levels during periods when recharge was assumed to be zero, following established.

With the exception of leaf area index, all *ACRU* model parameters were determined from measured or published sources, without calibration against observations. Leaf area index was determined from the fractional radiation intercepted by the canopy using a modified light extinction coefficient of 0.25, because plant uptake for the sparse crop in widely-spaced rows was overestimated when simulated using published coefficients. Soil water redistribution factors according to textural properties and streamflow parameters were taken from values given by Smithers and Schulze (1995).

Comparison Between Observed and Simulated Groundwater Levels

Observed groundwater levels over the period 1992-96 and simulated levels using *ACRU* are shown in **Figure 9.4.1**. Groundwater levels simulated using *ACRU* follow the observed levels closely over the four years of comparison. Both the timing and magnitude of the groundwater level rise are accurately represented and the pattern of recession is well described (**Figure 9.4.1**). There are, however, two notable differences between observed and simulated levels. Towards the end of December 1992, simulated groundwater levels rise considerably before the observed main rise in levels in mid-February 1993, the most likely explanation being that up to November 1993 rainfall data were taken 12 km away, rather than in the catchment itself. Considerable spatial variation in rainfall over distances of a few kilometres is common due to the convectional nature of rainfall. The second major difference between observed and simulated water levels occurs in the 1994/95 rainy season. In February 1995, a rise in groundwater levels of 0.94 m is simulated compared to an observed rise of 2.40 m. One possible explanation for the underestimation of groundwater rise in the 1994/95 season is under-estimation of drainage from the unsaturated zone.

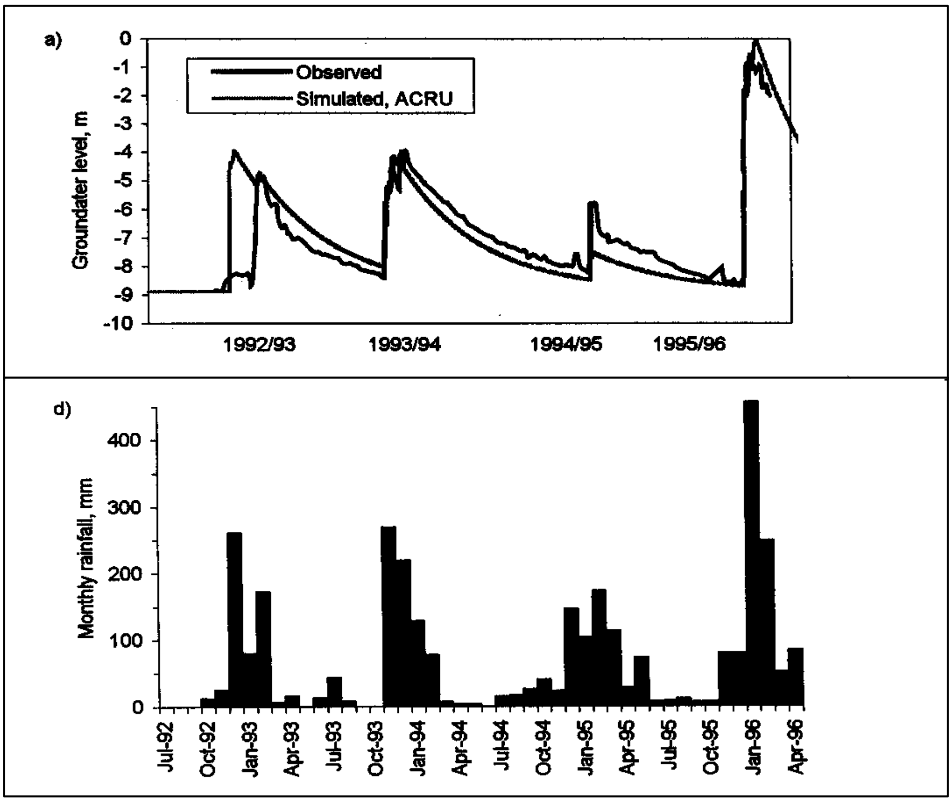


Figure 9.4.1 Observed (thicker line) and *ACRU* simulated (smoother line) groundwater levels from 1992 to 1996 (top) and monthly total rainfalls (bottom)

Overall Conclusion

The overall conclusion of this verification study was that the *ACRU* model could simulate groundwater levels, certainly in the Romwe catchment, successfully, even over short periods of time.

References

Butterworth, J.A., Schulze, R.E., Simmonds, L.P., Moriarty, P., and Mugabe, F. 1999. Hydrological processes and water resources management in a dryland environment IV: Long-term groundwater level fluctuations due to variation in rainfall. *Hydrology and Earth System Science*, 3, 353-361, https://doi.org/10.5194/hess-3-353-1999.

Smithers, J.C. and Schulze, R.E., 1995. *ACRU Agrohydrological Modelling System: User Manual Version 3.00*. *WRC Report* TT 70/95, Water Research Commission, Pretoria, RSA.

9.5 Americas 1: Verification of the *ACRU* Model on an Operational Catchment with Snowmelt in Alberta, Canada (Original Researchers: K.A. Forbes, S.W. Kienzle, C.A. Coburn, J.M. Byrne and J. Rasmussen)

Setting the Scene

The availability of water resources in the province of Alberta in Canada is of particular concern due to growing water demands by agriculture, industry and a rapidly increasing population. This is coupled with the current body of research in western Canada that indicates that water resources in southern Alberta are vulnerable to climate change impacts.

The objective of this research was to first parameterize and then verify the streamflow of the *ACRU* agro-hydrological modelling system on the operational Beaver Creek catchment in southern Alberta under current climatic conditions, prior to simulating impacts of projected climate change on the catchment.

The Study Area

The 254 km^2 Beaver Creek catchment (**Figure 9.5.1**), centred at latitude 49°44’N and longitude 113°52’W, is a so-called hybrid stream with perennial streamflow and a bimodal inter-annual hydrograph indicating the influence of both snowmelt and rainfall processes. The headwaters of Beaver Creek stem from the higher elevation slopes of the Porcupine Hills in the northwest, part of the Rocky Mountains, and are characterized by the rapid spatial transition from montane coniferous / deciduous forest to aspen parkland and prairie grasslands / rangelands and cultivated areas (cf. **Figure 9.5.2** left).

For purposes of modelling with *ACRU*, the Beaver Creek catchment was run in distributed mode with the catchment discretised inti 5 distinct hydrological response units (HRUs) each with relatively homogenous hydrological responses (**Figure 9.5.2 right**). The major physiographic attributes of the HRUs in regards to sub-catchment areas, percentages of each HRU of the total area, mean elevation, dominant soil type and generalized land cover (**Figure 9.5.2 left**) are given in **Table 9.5.1**.

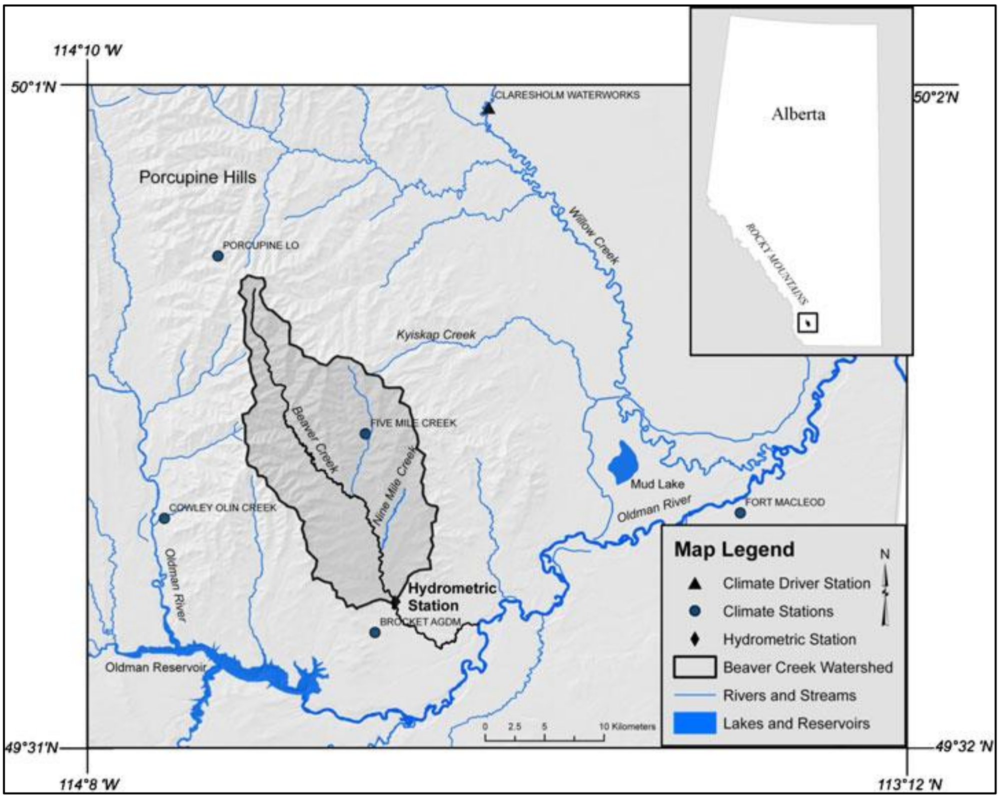


Figure 9.5.1 Map of the Beaver Creek catchment in Alberta, Canada (After Forbes *et al*., 2008)

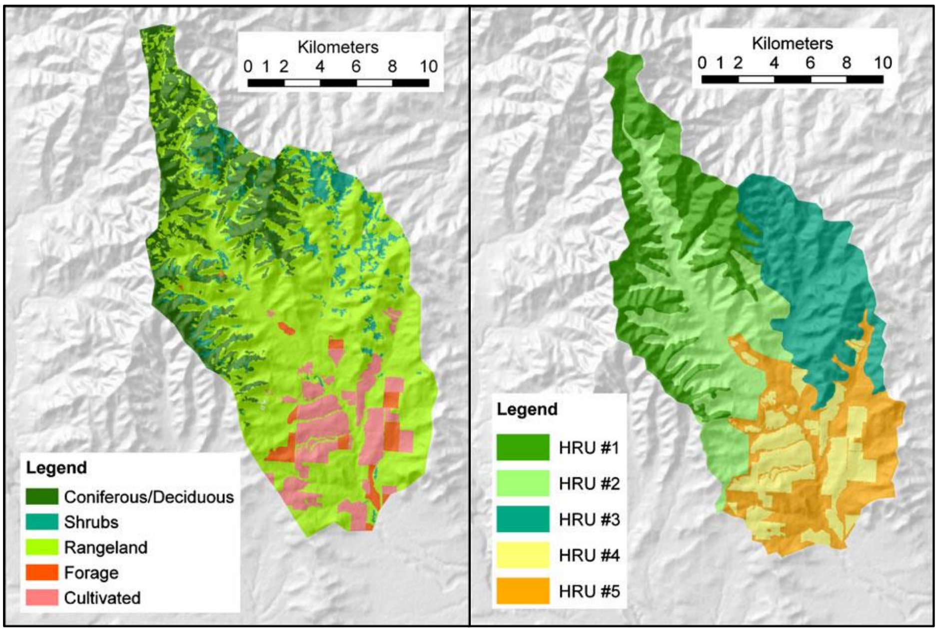


Figure 9.5.2 Land cover (left) and (right) the hydrological response units delineated for the Beaver Creek catchment (After Forbes *et al*., 2010)

Table 9.5.1 Major physiographic characteristics of hydrological response units of the Beaver Creek catchment (After Forbes *et al*., 2008)

HRU	Area (km^2)	Area %	Elevation (m)	Soil type	Land cover
1	60.03	23.63	1,500	Clay loam	Mixed forest
2	55.88	21.99	1,400	Loam	Rangeland
3	61.31	24.13	1,400	Clay loam	Shrub and rangeland
4	46.42	18.27	1,300	Clay loam	Forage
5	30.43	11.98	1,200	Sandy clay loam	Cultivations

The Version of the ACRU Model Used

The version of the *ACRU* model includes a new method to separate rain and snow precipitation (**Figure 9.5.3**; Kienzle, 2008).

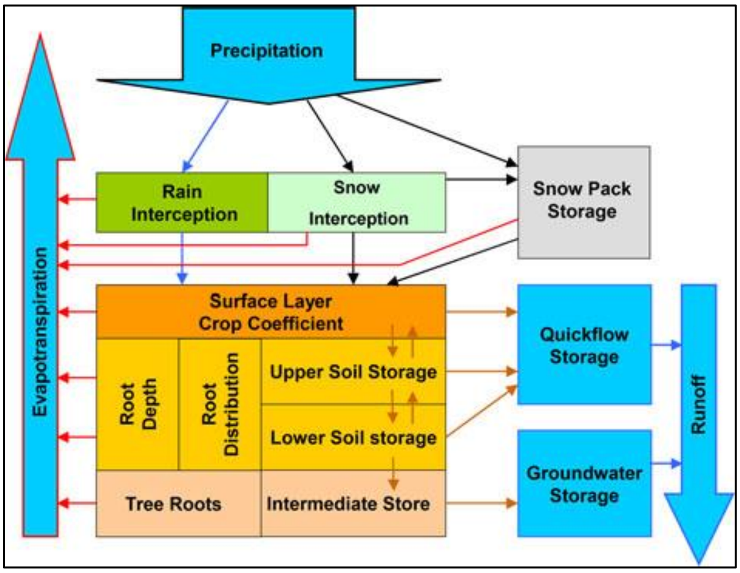


Figure 9.5.3 The snowmelt version of the *ACRU* model used in the Beaver Creek verification (After Kienzle, 2008)

This version *ACRU* simulates the principal hydrological processes of rain and snow interception, infiltration, snowpack accumulation, snowmelt, soil water storages, unsaturated and saturated soil water redistribution, total evaporation (a daily summation of snow sublimation, plant transpiration from the root zone and evaporation from the soil surface, as well as interception) and temporally discrete runoff generation. Multi-layer soil water budgeting is retained from “standard” *ACRU* routines (Schulze, 1995) with the total evaporation routine partitioned between growth-stage specific transpiration and soil water evaporation, making it sensitive to changes in crop phenology and seasonal temperature.

Verification of ACRU Model Output

The *ACRU* model simulated the observed streamflow record in the Beaver Creek with acceptable accuracy over a 27-year verification period. What matters for climate change impact studies, however, is not the exact duplication of runoff events, but a realistic representation of the hydrological behaviour of seasonal changes, water yield, and the magnitude and frequency of extreme events such as floods and low flow periods.

Figure 9.5.4 presents a typical simulation for a 12-month period. A comparison of simulated and observed hydrographs in **Figure 9.5.4** shows that magnitudes of floods and low flows are very similar, that the seasonal timing was well simulated, and that the recession of the hydrographs was captured. Observed streamflows were not available for November to March due to freezing of Beaver Creek.

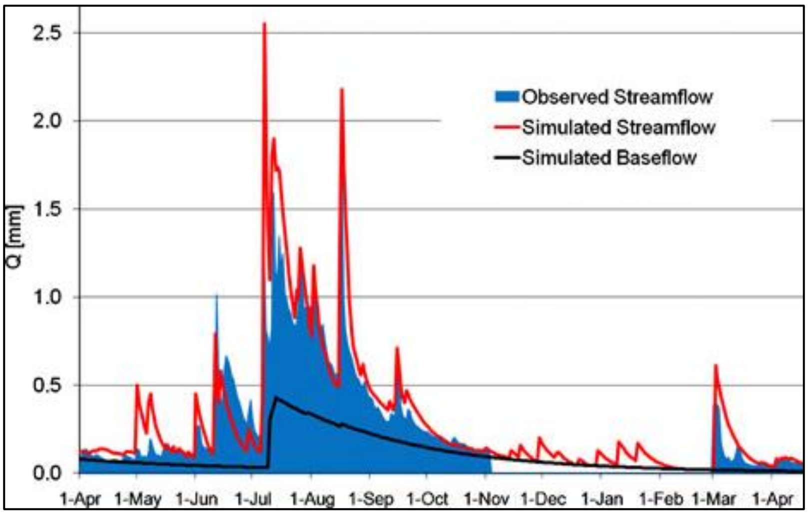


Figure 9.5.4 Simulated and observed hydrograph for the period April, 1993, to April, 1994 (After Forbes *et al*., 2008)

Conclusions

This verification has illustrated that on an operational catchment in Canada the snowmelt modifications made to the “standard” version of the *ACRU* model have been able to capture the post-winter snowmelt runoff well, and that the model is thus appropriate to use at high latitudes/altitudes where snow is a major contributor to total precipitation in the water budget.

References

Forbes, K.A., Kienzle, S.W., Coburn, C.A., Byrne, J.M. and Rasmussen, J. 2008. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change*, DOI 10.1007/s10584-010-9890-x.

Kienzle, S.W. 2008. A new temperature-based method to separate rain and snow. *Hydrological Processes*, 22, 5067-5085.

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9.6 Americas 2: Verifications on the Swan River in Canada from Daily through Monthly to Annual Streamflows, Ranked Daily Streamflows, and Exceedance Probabilities of "Extreme" Flood Events (Original Researcher: S.W. Kienzle)

Background

The Swan River Watershed of 1 885 km^2 is located in central Alberta, Canada with its main streamflow gauging station, 07BJ003, near Kinuso. The watershed consists predominantly (73%) of forest (both natural and planted), with 10% covered by herbaceous plants, 5% by wetlands, and 3% by agriculture and the remaining 9% by developed areas, rock outcrops and rocky areas, open water, and other vegetation types.

The watershed has an elevation range from 574 m at the gauging station to 1 357 m (**Figure 9.6.1** left), a MAP ranging from ~ 500 mm to over 650 mm (**Figure 9.6.1** right), with annual precipitation varying from 265 mm to 896 mm, between 70 and 150 days per year with precipitation of over 2 mm per year, and up to 9 days per year with a precipitation exceeding 20 mm per day. While snowfall constituted about 36% of annual precipitation in the 1950s, that proportion has declined in recent years to about 27% with today's shorter and much warmer winters.

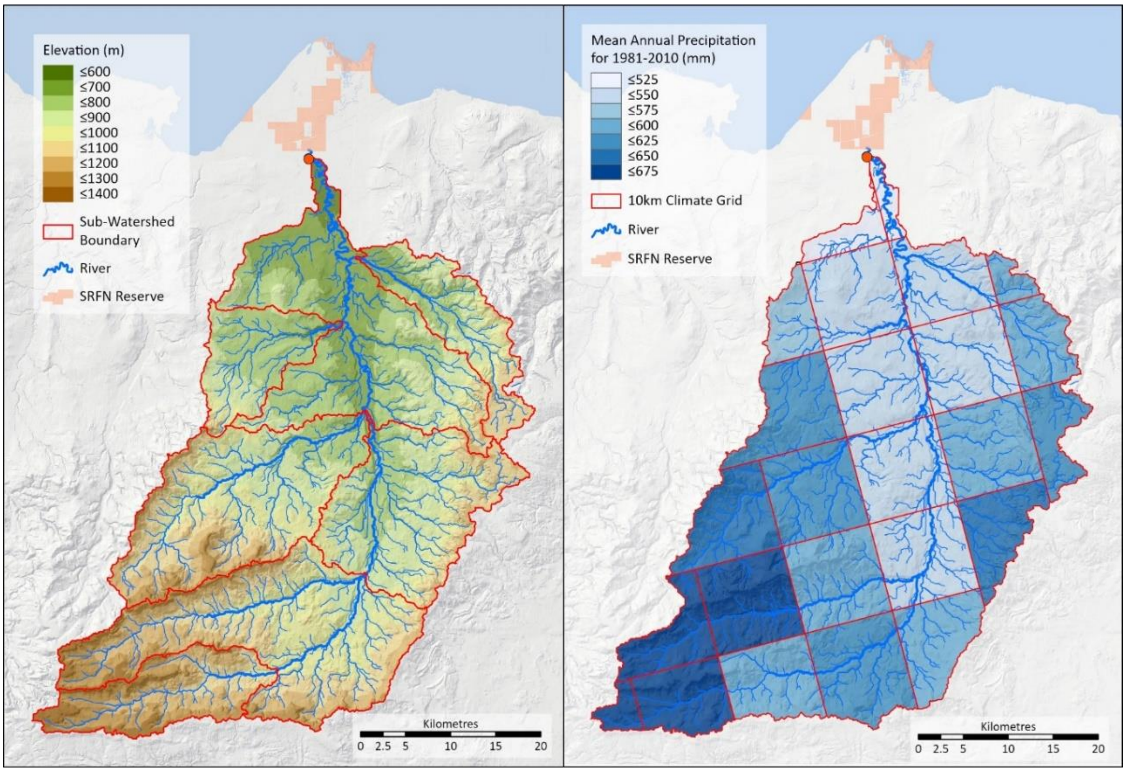

Figure 9.6.1 The Swan River watershed with (left) elevation bands used to delineate HRUs to represent changes in temperatures and (right) mean annual precipitation for the climate normal period 1981-2010, based on a 10 km by 10 km climate grid

With physically-based, spatially distributed hydrological models being the only effective means to assess the impacts of climate change on hydrological response, as they are able to capture the spatial variability of hydrological processes throughout complex watersheds, the *ACRU* agro-hydrological modelling system, modified to be responsive to snowmelt (**Figure 9.6.2** left), was selected for this study, also because it can adjust daily minimum and maximum air temperatures by intra-annual lapse rates using monthly lapse rates, with the lapse rate corrected temperatures further adjusted as a function of daily incoming solar radiation (representing exposition) and land cover. This is considered to be critical for the separation of rain and snow, evapotranspiration and snow melt, and allows for more realistic estimation of local hydrological behaviour. *ACRU*, as the model of choice, was applied to simulate historical (1951-2017) and projected future (2041-2070) streamflows, focusing on peak flows, generated by the entire Swan River Watershed upstream of gauging station 007BJ003 near Kinuso.

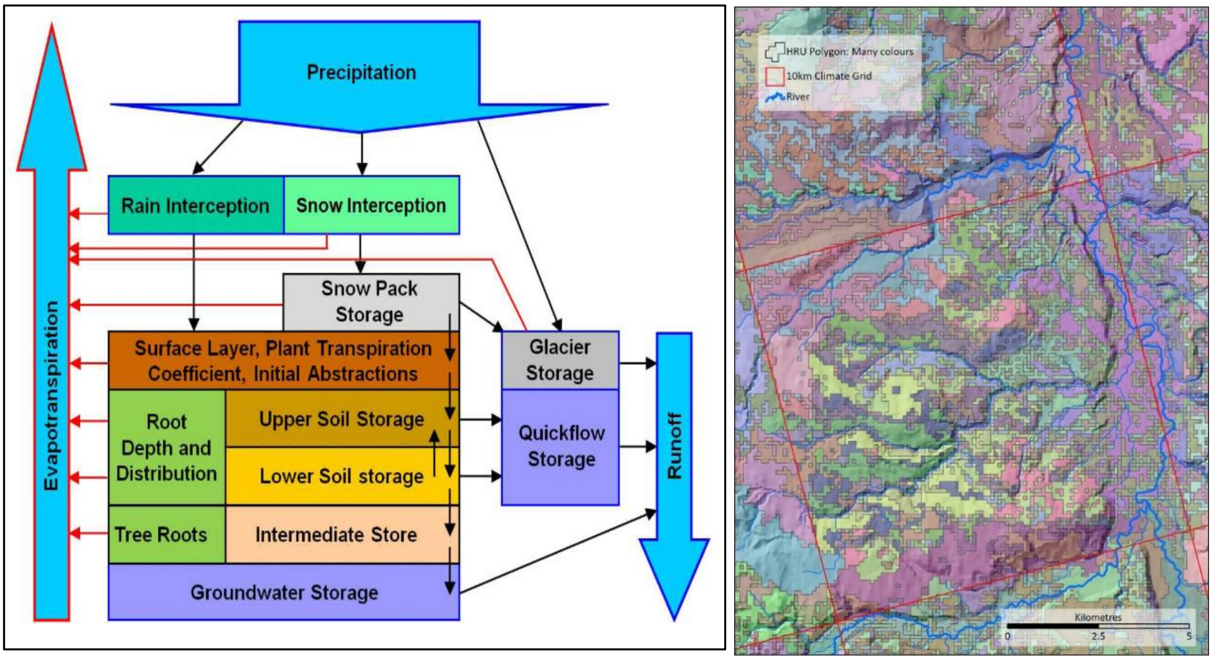

Figure 9.6.2 The modified *ACRU* agro-hydrological modelling system (left) and (right) a detailed view of hydrological response units identified, each with its own colour and with one HRU found in many separate locations

Datasets Required for Modelling

As is the case with every integrated/multi-purpose hydrological modelling system applied to simulate hydrological responses in large and heterogeneous watersheds, *ACRU* requires a wide range of bio-physical and hydro-climatological variables and parameters. In this case the spatial organization of *ACRU* was based on hydrological response units (HRUs), each having a unique combination of elevation, land cover, and climate. Motivated by the lack of readily available hydro-climatological data for the calculation of potential and actual evapotranspiration, soil moisture deficits, or groundwater recharge, the range of hydro-climatological data that were processed spatially for each HRU included solar radiation, sunshine hours, wind and relative humidity. Recently available climate data sets of daily minimum and maximum temperatures and precipitation for the period 1950-2017, at a spatial resolution of 10 km by 10 km, were processed to be directly available for input into *ACRU*. This enabled the calculation of daily and spatially explicit estimates of potential evapotranspiration using the Penman-Monteith approach.

The final number of HRUs was 506. Each HRU was then parameterized to have a unique combination of hydrological variables, most of which were derived by GIS overlay analysis. The area of each HRU was calculated based on its true, sloped area, as the planimetric area derived from a GIS is under-estimated in steeply sloped terrain, which would affect interception volumes, soil moisture storages, groundwater recharge rates, actual evapotranspiration volumes, and runoff coefficients (Kienzle, 2010). An impression of the detailed landscape representation, showing an enlarged perspective of the spatial distribution of the HRUs, is presented in **Figure 9.6.2** (right).

After initial parameterization, using default values for some unknown variables such as groundwater outflow rate, *ACRU* was run, and the daily streamflow time series was statistically compared to the observed ones using a wide range of verification methods.

The Approach to Verification Methods

Since there are currently no universally accepted guidelines for evaluating hydrological models, especially in climate change studies, a combination of evaluation approaches was used to rigorously quantify the *ACRU* model performance, with the key objective of hydrological simulations being for simulated values to "mimic" as closely as possible corresponding observed values, where

- the simulated values should correspond to observed values as closely as possible on a 1:1 basis,
- means and variances of simulated values should be conserved when compared with means and variances of observed values,
- simulated and observed values exhibit a close association with one another,
- with there being no systematic under- or over-simulation error, i.e. no bias, between simulated and observed trends,
- with the streamflow probabilities being similar, and where
- the degree of closeness of simulated and observed streamflow values is measured by a collection of specific goodness-of-fit criteria, or objective functions.

Each resulting verification statistic is classed into four categories, ***Excellent***, ***Good***, ***Satisfactory*** and ***Unsatisfactory***, so as to allow for easier evaluation of the overall simulation success. The classifications are based mainly on recommendations by Moriasi *et al*. (2007) with, however, the evaluation criteria of the percentage difference of simulated and observed water yields being based on the Schulze and Smithers (1995) criteria, because they are stricter than those suggested by Mosiasi *et al*. (2007).

The objective functions tested included (**Table 9.6.1**):

- the percentage difference between the sum of simulated daily flows and observed daily flows, which is equivalent to the Percent Bias,
- the percentage difference between standard deviations of simulated daily flows and observed daily flows,
- The coefficient of determination (r^2) for both daily and monthly flows,
- The regression coefficient (slope as a ratio),
- The ratio of the root mean square error to the standard deviation of measured data, and
- the Nash-Sutcliffe efficiency coefficient.

In addition to strict statistics, a visual comparison of daily and monthly flows using scatterplots, was made, as these aid in the evaluation of recession curves, the shape of flood peaks and overall similarities of simulated and observed daily streamflows. They also offer insights into the annual hydrograph, thus comparing the timing of snowmelt, the timing and magnitude of the freshet (the spring melt runoff), as well as the gradual decline during summer and fall.

Verification Results 1: From Daily through Monthly to Annual Streamflows

A summary of the verification statistics is provided in **Table 9.6.1**. In addition to statistical results, visual analyses are presented in **Figure 9.6.3**.

With an overall under-simulation of 3.53%, the simulation of annual water volumes is classed as "Excellent". The overall runoff coefficient, i.e. the proportion of precipitation that runs off, is represented realistically. This, together with other statistics presented in **Table 9.6.1**, implies that the *ACRU* model can replicate the overall flow regime of the watershed. The comparison of simulated against observed standard deviation in daily streamflows resulted in a "Good" simulation (**Table 9.6.1**). The fact that the value is under-simulated is expected, as the most severe floods are typically under-simulated as shown in **Figure 9.6.3**, which directly affects this statistic.

Table 9.6.1 Verification criteria (Excellent, Good, Satisfactory and Unsatisfactory) and performance of simulated vs. observed streamflows for the Swan River Watershed at Kinusu, 1971-2000

Statistic	Excellent	Good	Satis-factory	Unsatis-factory	Swan River at Kinusu
% Difference of Mean Annual Flow	≤ 5	≤ 10	≤ 15	> 15	-3.53
Difference in Standard Deviation	≤ 5	≤ 15	≤ 25	> 25	-12.59
r^2 Daily flows	≥ 0.80	≥ 0.70	≥ 0.60	< 0.60	0.52
r^2 Monthly Flows	≥ 0.85	≥ 0.75	≥ 0.65	< 0.65	0.82
Slope of the Regression Line	≥ 0.90	≥ 0.80	≥ 0.60	< 0.60	0.63
Percent Bias	≤ 10%	≤ 15	≤ 25	> 25	3.53
RMSE-Observations Std Deviation Ratio	≤ 0.50	≤ 0.60	≤ 0.70	> 0.70	0.70
Nash-Sutcliffe Coefficient of Efficiency	≥ 0.75	≥ 0.65	≥ 0.50	< 0.50	0.50

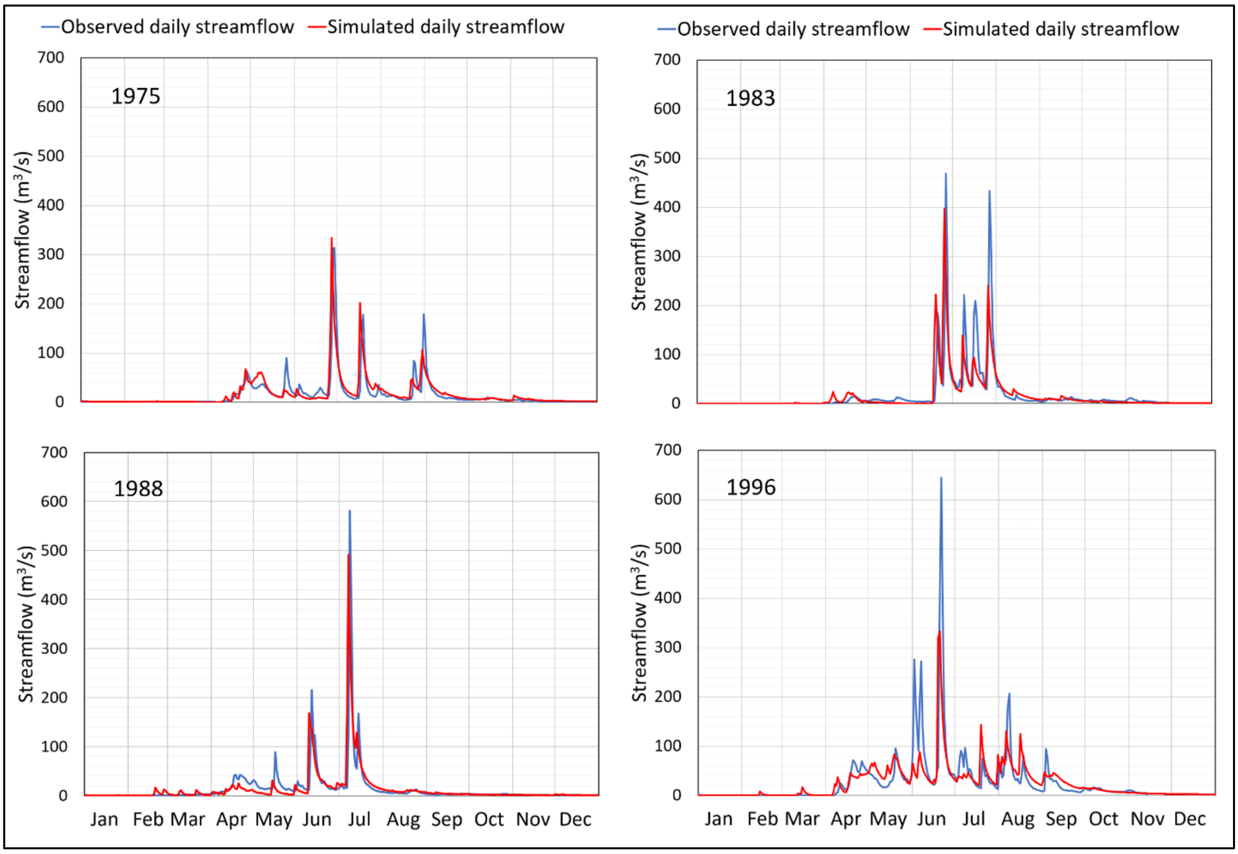

Figure 9.6.3 Visual comparisons of daily hydrographs for four years

While the coefficient of determination (r^2) between *daily* simulated and observed flows is classed as "Unsatisfactory", the *monthly* flow simulations are classed as "Good". A high r^2 for the monthly flows is an indicator that the annual streamflow regime and the annual flow fluctuations are, overall, well simulated. With **Figure 9.6.3** presenting four annual hydrographs based on daily streamflows, it is evident from all four hydrographs that the streamflow simulations at times differ substantially from the observed ones. It is equally evident from all four hydrographs, however, that the general streamflow regime is well simulated. In many years, such as 1975 and 1988, flow peaks are represented well, but not always their timing (which is the reason for the low r^2 value, as the coefficient of determination, r^2, uses the square of the differences). The years 1983 and 1996 in **Figure 9.6.3** show how the largest flood flows are consistently under-simulated.

The Nash-Sutcliffe coefficient of efficiency (NSE), often used in hydrology to evaluate the streamflow simulation, is rated as “Satisfactory”, due to the same reason that the r^2 value is low. The watershed simulation is successful in simulating the overall flow regime, where all physical parameters are within physically meaningful ranges. Therefore, a low coefficient of determination (r^2) and NSE value are of low concern for this specific study, as in water resources management the daily timing of streamflow is not important, but rather the successful simulation of the frequency and magnitudes of daily flows is.

Verification Results 2: Ranked Daily Simulated vs. Observed Streamflows

In **Figure 9.6.4** a comparison is made between the simulated and observed daily streamflows for the period 1971-2000, where flows from all 10 958 days are ranked from lowest to highest. Simulated and observed streamflow occurrences up to about the 1% exceedance probability (equalling the 1:100-day return period) are very similar. Only the highest 1% of flows are under-simulated.

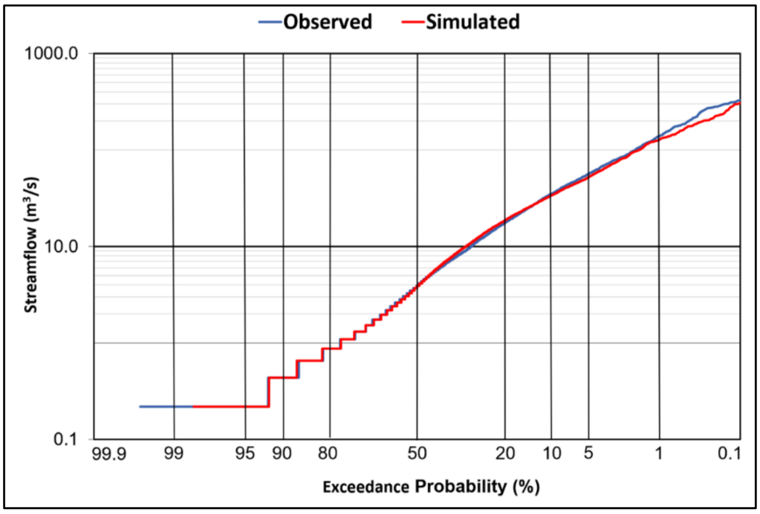

Figure 9.6.4 Comparison of exceedance probabilities of simulated and observed daily streamflows for the period 1971-2000 at Gauging Station 07JB001 on the Swan River at Kinuso

Verification Results 3: Exceedance Probabilities of Observed vs. Simulated “Extreme” Floods

When the *ACRU* model was set up to test annual maximum series and “extreme” events, using graphical representations, the theoretical distributions versus the plotting positions of four selected frequency distributions were plotted for the ***observed*** annual flood values vs. the annual ***flood values generated by the ACRU model*** (**Figure 9.6.5**).

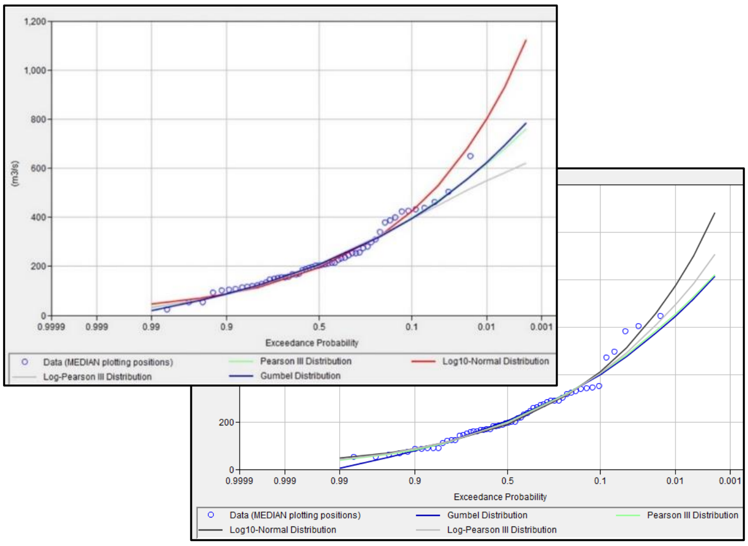

Figure 9.6.5 Exceedance probability graphs from the Swan River of observed flood values (top) and the simulated flood values (bottom) for four selected extreme value distributions

Note that since hydrological time series data are generally distributed non-normally, log transformations such as the Log-Pearson III distribution and the Log10-Normal should be considered. Based on purely graphical interpretation from distributions displayed in **Figure 9.6.5**, all four distributions investigated fit the observed flood data quite well. However, for extreme flood analyses, distributions that under-estimate the largest observed flood values should be avoided, as the subsequent estimation of the 1% exceedance probability (0.01 in **Figure 9.6.5**) may under-estimate the 100-year floods, because the estimated 100-year flood value is lower than the largest flood observed during the 56-year observation period. Therefore, only the Log-Pearson III and the Log10-Normal distributions were considered for further analysis, and statistically the Log10-Normal distribution was found to be the best.

If the Log10-Normal distribution values in **Figure 9.6.5** are compared, i.e. the red line in the top graph derived from the observations and the grey line in the bottom graph of simulated values derived from *ACRU*, then it is seen that for the 1:2 year flood (i.e. the 0.5 probability of exceedance) both observed and simulated value are at ~ 200 $m^3.s^{-1}$ while for the 1:10 year flood (0.1 probability of exceedance) both values are at ~ 400 $m^3.s^{-1}$ and for the 1:100 year flood (0.01 exceedance probability) the simulated and observed values are almost identical at ~ 800 $m^3.s^{-1}$, indicative that the *ACRU* derived design floods mimic the observed ones excellently.

Concluding Thoughts

The *ACRU* model has been shown to generally mimic observations excellently on the Swan River in Canada, i.e. in a climatic regime under which the model was not developed, from daily through monthly to annual streamflows, as well as mimicking ranked daily streamflows well and also exceedance probabilities of annual design floods – thus covering a wide range of typical hydrological applications.

References

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Moriasi, D., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions ASABE*, 50(3), 885-900.

10 ON SPATIAL SCALE AND OTHER ISSUES IN HYDROLOGICAL VERIFICATIONS WITH THE *ACRU* MODEL

10.1 Seeking Approaches and Solutions to Scale Problems in Hydrology (R.E. Schulze)

Superpositioning: The Fundamental Problem to the Scale Issue in Hydrological Modelling
The fundamental problem to the scale issue in hydrological modelling is that the hydrological system consists of a super-positioning of

- spatially and temporally varying climatic forcing at
  - space scales varying from point to hillslope (e.g. differences due to aspect) to region (e.g. synoptic influences) and continents (e.g. global patterns such as El Niño) and
  - time scales varying from minutes (e.g. thunderstorms) to days (e.g. from frontal systems), months, seasons (e.g. wet or dry seasons) and years (e.g. inter-annual variability of climate/runoff), plus
- spatially variable soils whose hydrological responses depend on
  - hillslope position, geology, macro- and microclimatic conditions and which may be further complicated by
  - impacts of humans by tillage or grazing practices, plus
- varying land uses with varying evaporative rates which display seasonal trends and are modified by anthropogenic activities, plus
- varying topographic features, including interlinked hillslope elements, with their slope, aspect and position which, however, remain invariant over time resulting in highly non-linear rates of hydrological responses with different physical laws emerging and dominating at different space and time scales,
- all of which a hydrological model such as *ACRU* tries to encapsulate, often by simplifications of processes and by spatially aggregating parameters (or in the case of some other types of models, by calibration procedures).

Key Critical Time and Space Scale Questions
In modelling this hydrological response system at a variety of time and space scales face a number of critical questions:

- What is the preferred time and space scale for a specific model used in assessing specific hydrological problems, given the simple conceptualization we have of the hydrological system?
- How best does one integrate, link and scale up knowledge of microscale hydrological processes operating and measured at point, plot or field scales to form a causal chain in order to facilitate modelling of hydrological processes unambiguously at catchment scale?
- How does one couple technologies such as radar (for areal rainfall derivation) or satellite imagery (for rainfall and land use information) operationally at the appropriate time and space scales as input to distributed models?
- How does one account for the spatial integration of heterogeneous non-linearly interacting processes, including effects of preferential flow paths at the scale at which one is modelling?
- How does one account for the fact that not all processes are susceptible to changes of scale beyond a certain area, e.g. that up to a certain length scale the saturated source area has been found to be highly variable, but that it remained stable beyond that threshold area?

Modelling at Small Catchments' Scale: Some General Comments

- A small catchment may be defined as one small enough that individual non-transient attributes such as land use, soils or physiography can be identified and isolated as having potentially dominant influences on the shape and magnitude of the hydrograph.
- They are also small enough that other processes such as areal reduction factors of rainfall or hydrograph routing can be ignored in modelling their hydrological responses.
- Because they are small they can be intensively instrumented to help identify and understand the main hydrological processes occurring, with that, however, implying an accurate gauging structure for both high and low flows.

- Modelling hydrological responses from small catchments is, however, more complex than modelling responses from larger catchments, because intra-daily processes take on significance. This apparent hydrological paradox occurs because in larger catchments considerable spatial self-correction, averaging, attenuation and hence smoothing of the runoff hydrograph have taken place. It is the significance of the intra-daily processes which will be shown in some of the verification studies which follow to be the cause of relatively poor verification results.
- Small catchments can be either
  - ***experimental research catchments***, in which case land use and its management are controlled/ determined/ selected by the researchers, as is physiography (slope, aspect), so that their influences can be understood and parameterized, or they can be
  - ***representative research catchments***, in which case typical land uses, soils and physiographies are selected in an attempt to understand general local or regional rainfall/runoff relationships.
- For model development, experimental catchments provide more useful insights and information than representative catchments. This was the case with the *ACRU* model, where high reliance was placed on inputs to and outputs from experimental catchments in the USA and South Africa in the model's development.

Modelling at Medium-Sized to Operational Catchments' and Regional Scales: Some General Comments

- At these scales modelling attains importance in aiding
  - national water policy making
  - regional operational hydrology, including water security assessments
  - the equitable distribution of water to various competing demand sectors, including the agriculture, irrigation, HEP, urban and environmental sectors, or
  - the establishment of international water rights.
- Medium to larger to operational catchments are relatively straightforward to model as entities when using conceptually simple parameter calibrating models, because the generally slowly responding hydrographs lend themselves to curve fitting approaches.
- However, it is at this scale that "what if" scenarios relating to changing policies, land uses, water demands and climate most often have to be modelled.
- From a South African national database perspective these medium-sized operational catchments approximate the size of Quinary catchments for which detailed climate, topographic, soils and vegetation/land use data are available.
- That raises problems/challenges relating to
  - the heterogeneity of the catchments in their natural state in regards to physiography and hence rainfall and temperature, as well as soils,
  - the human influences already existing in the catchments, e.g. influences of dams, abstractions, return flows, irrigation, or hydrologically influential major land uses
  - hence the level of discretisation/subdivision of the catchments becomes an important issue, also
  - the representation of hydrological processes at this scale and the complexities of data collection at this scale and
  - the necessity for flow routing through channels and reservoirs.
- These challenges have been largely addressed in the structure/multi-purposeness of *ACRU*.

Background to a Suite of Small and Medium Sized Catchment Verification Studies and Experiences from Those

In an important study on trying to establish improved parameter estimations for use with the *ACRU* model (Royappen, 2002), published also as a WRC Report (Royappen *et al*., 2002), a suite of verification studies was carried out on small experimental and representative research catchments as well as on a set of medium-sized operational catchments from across a wide range of Köppen-Geiger Climate Zones, altitudes and vegetation/land use types, from which important lessons were learned on model verification. Findings are discussed in sections below.

Characteristics of the small experimental and representative research catchments and those of the medium-sized operational catchments assessed below are summarised in **Tables 10.1.1** and **10.1.2**, with locations shown in **Figure 10.1.1**. What is evident from the tables/map is that a wide range of overall climate types from semi-desert to sub-tropical to sub-humid and Mediterranean, hence a range of Köppen-Geiger climate zones (eight of the 14 found in South Africa), of MAPs, vegetation types and areas in the summer as well as winter and all year rainfall regimes are covered by this assessment.

Table 10.1.1 Characteristics of the small experimental and research catchments used in this suite of verification studies

Map Symbol and Name	Area (km^2)	MAP (mm)	Other Climate Attributes	Altitude Range (m)	Cover	Köppen-Geiger Zone
SD Safford AZ, USA	2.10	225	Semi-desert	990-1050	Sparse shrubs	BWk
ZU Zululand	3.32	1310	Sub-tropical	205- 325	Ngongoni grassland	Cfa
CP Cathedral Peak	0.99	1420	Summer rainfall	1345-2225	Short grassveld	Cwb
DH De Hoek	1.03	1115	Summer rainfall	1450-1630	Short grassveld	Cwb
WK Witklip	1.08	1110	Sub-humid trop	1000-1340	Plantation-*P. patula*	Cwb
WF Westfalia	0.33	1250	Sub-humid	1140-1420	Indigenous forest/shrub	Cwa
LB Lamprechtsbos B	0.66	1145	Mediterranean	300-1070	Plantations/fynbos	Csb

Table 10.1.2 Characteristics of the medium-sized operational catchments used in this suite of verification studies

Map Symbol and Name	Area (km^2)	MAP (mm)	Other Climate Attributes	Altitude Range (m)	Cover	Köppen-Geiger Zone
WV Watervalsrivier	36	660	Winter rainfall	120-1085	Shrubland; low fynbos	Csb
KR Kruisrivier	50	645	Winter rainfall		Shrubland; low fynbos	BSk
BK Bloukransrivier	57	1005	All year rainfall		Thicket & Bushveld	Cfb
TR Treurrivier	92	790	Summer rainfall	1200-1835	Grassveld; Plantations	Cwb
DR Dieprivier	72	710	All year rainfall		*Pinus* Plantations	BSk
BS Beestekraalspruit	14	980	Summer rainfall	980-2190	NE Mountain Sourveld	Cwb
GN Groot Nylsrivier	75	655	Summer rainfall	1215-1510	Thicket & Bushveld	BSh

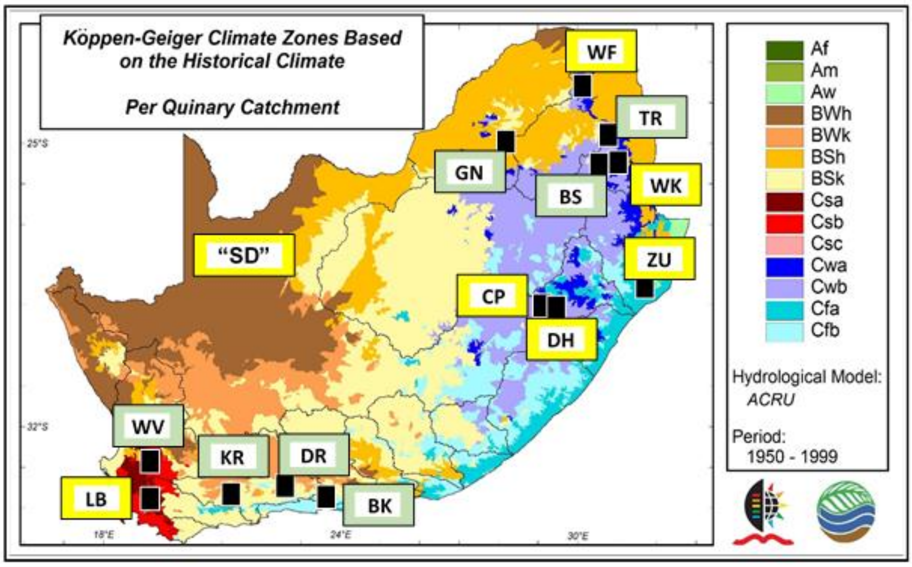


Figure 10.1.1 Locations within South Africa of the small experimental research catchments (in the yellow blocks) and the medium-sized operational catchments (light green blocks) used in the assessment below, superimposed on a map of Köppen-Geiger climate zones, with "SD" denoting Safford in Arizona, USA

10.2 Verification Studies on Small Research Catchments (M.Royappen and R.E. Schulze)

Please note that the figures in this section where reproduced from Royappen (2002), and no high resolution maps were available.

Small Research Catchment 1: Safford Arizona, USA

The 2.10 km^2 Safford research catchment ARS No. 4501 is located in Arizona, USA at 32°55' N and 109°48' W at altitudes ranging from 990 to 1052 m.a.s.l. (**SA** in **Figure 10.1.1**; **Figure 10.2.1** below). It is relatively flat, has shallow soils and sparse succulent vegetation as it experiences an arid climate with a MAP of 225 mm mainly of high intensity convective events and mean annual runoff (MAR) of only 9.1 mm (~ 4% of MAP) consisting primarily of flashy and discontinuous stormflow (**Figure 10.2.2** left) much of which is lost to channel and bank transmission losses.

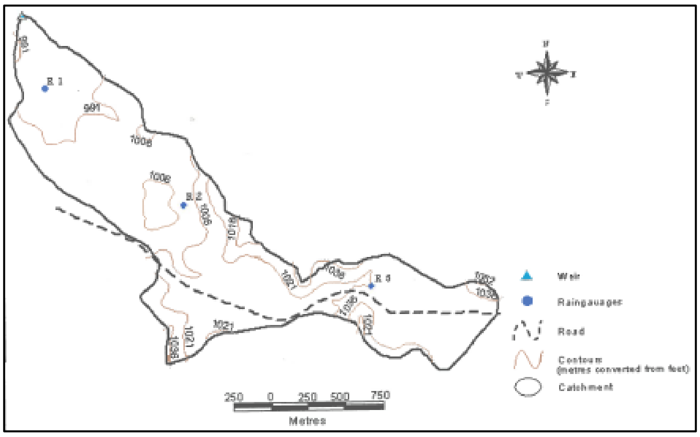


Figure 10.2.1 Safford research catchment ARS 4501 in Arizona, USA (After Royappen, 2002)

In **Figure 10.2.2** (left) time series of observed and simulated monthly totals of daily streamflows from this arid catchment are shown, as are accumulated flows. The patterns of flow observed are typical of those from arid and semi-arid catchments, with markedly discontinuous flows, virtually non-existent/transient baseflows, and occasional very high quickflows. The diagram of accumulated observed and simulated flows illustrates that large discrepancies may occur around the time of high rainfall events. Variations in rainfall intensity and streamflow transmission losses into banks and the channel bed are the main causes of inconsistent runoff responses to rainfall in this catchment. More detailed analysis of hourly data (not shown here) illustrates an under-simulation of quickflow with high intensity rainfalls, whereas an over-simulation of quickflow occurs in association with low intensity rainfall events. The scatter plot of observed versus simulated monthly totals of daily flows (**Figure 10.2.2** right) reveals a relatively poor fit (R^2 =0.56), and this is borne out by the statistics of fit in **Table 10.2.1**. Clearly, *ACRU,* as a daily time step model, is not structured in detail enough to predicting flows in arid catchments where low soil infiltration rates, short rainfall events of highly variable rainfall intensity and significant transmission losses occur.

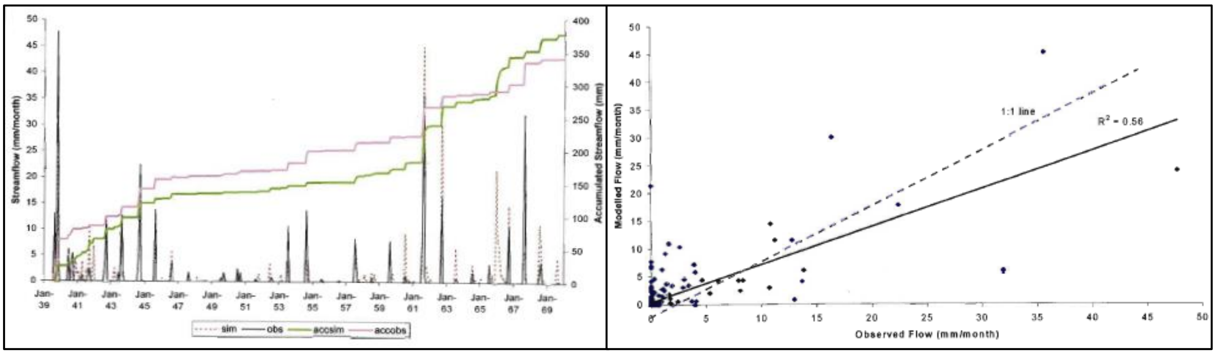


Figure 10.2.2 Time series of observed (obs) and simulated (sim) monthly totals of daily streamflows for the Safford research catchment ARS 4501, with accumulated flows (accsim; accobs) also shown (left), and (right) a scatter plot of monthly totals of daily simulated and observed streamflows from 1939 to 1969 (After Royappen, 2002)

Table 10.2.1 Statistical analysis of monthly totals of daily observed and simulated streamflows for Safford ARS 4501 from 1939 to 1969 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	0.92		Coefficient of Determination R^2	0.56
Mean of Simulated Values	1.02		Slope of Regression Line	0.68
% difference Between Means	-10.74		Y-Intercept of Regression Line	0.40
% Difference Between Std Dev	9.69		Coefficient of Efficiency	0.43
% Difference between CVs	18.45		Coefficient of Agreement	0.84

Small Research Catchment 2: Zululand

The Ngongoni grassed Zululand research catchment W1H016 (**ZU** in **Figure 10.1.1**; **Figure 10.2.3** below) is situated around 28°50' S and 31°46' E on a coastal plain with gently undulating terrain in KwaZulu-Natal, South Africa. W1H016 includes catchment W1H017 nested within its area of 3.32 km^2, and has an altitudinal range from 205 to 325 m.a.s.l. It is one of few small, sub-tropical research catchments in RSA and experiences significantly higher temperatures and humidities than the other catchments studied, with heavy orographic rainfall sometimes induced with rising moisture laden air. The results from this catchment also illustrate very good relationships between observed and simulated streamflows, as shown in **Figure 10.2.3** (right), with a very high correlation coefficient of 0.98. Deviations between observed and simulated streamflows are minimal and result mainly from differences between isolated events. In **Figure 10.2.4** (right) the excellent association between observed and simulated streamflows, along the 1:1 line, with a high correlation coefficient of 0.99, is shown. Daily streamflows from the Zululand research catchment W1H016 are very "flashy", as shown in **Figure 10.2.3** (right), with baseflow recessions receding very rapidly, approaching near zero flows. The excellent statistics shown in **Table 10.2.2** confirm that simulated streamflows are highly correlated to observed streamflows from W1H016, having a low percentage difference between standard deviations of 2.37%, and a high coefficient of agreement of 0.98.

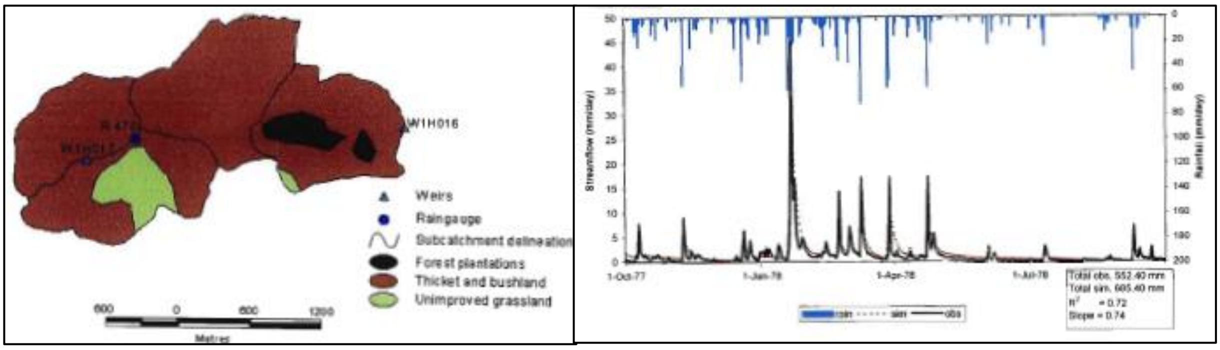


Figure 10.2.3 Zululand research catchment W1H016 with nested catchment W1H017 and location of rainfall station (left), and (right) a time series of observed (obs) and simulated (sim) daily streamflows from October 1977 to September 1978 (After Royappen, 2002)

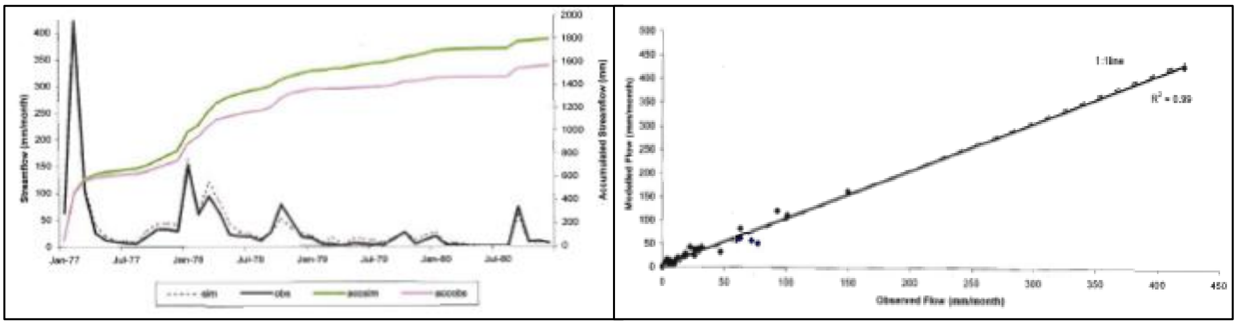


Figure 10.2.4 Time series of observed (obs) and simulated (sim) monthly totals of daily streamflows from 1977 to 1980, with accumulations over time (accsim; accobs) also shown (left), and a scatter plot of simulated and observed monthly totals of daily streamflows for the Zululand research catchment W1H016 (After Royappen, 2002)

Table 10.2.2 Statistical analysis of monthly totals of daily observed and simulated streamflows for Zululand research catchment W1H016 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	36.09		Coefficient of Determination R^2	0.93
Mean of Simulated Values	36.16		Slope of Regression Line	0.94
% difference Between Means	-5.72		Y-Intercept of Regression Line	4.11
% Difference Between Std Dev	2.37		Coefficient of Efficiency	0.93
% Difference between CVs	-6.45		Coefficient of Agreement	0.96

Small Research Catchment 3: Cathedral Peak IV

Cathedral Peak grassland catchment IV (V1H005; **CP** in **Figure 10.1.1**; **Figure 10.2.5**) of 0.99 km^2 is located around 29°00'S, 29°25'E on the Little Berg plateau of the Drakensberg of KwaZulu-Natal, RSA at altitudes from 1 845-2 226 m. It has a MAP of 1 420 mm, with approximately 49% converting to streamflow. Rain on this catchment with very deep dystrophic soil falls in summer with ~ 85% of the rainfall occurring between October and March, and with ~ half of all rainfall events being convective. Winters are cold and dry (occasional snowfalls occur at high altitude) while summers are hot and wet.

Excellent relationships exist between observed and simulated streamflows for this Cathedral Peak research catchment, as shown in **Figure 10.2.5** (right) and **Figure 10.2.6** for both accumulated and scatter plots. Excellent statistics are achieved between observed and simulated monthly streamflows (**Table 10.2.3**), with very high coefficients of correlation and agreement between simulated and observed flows of 0.94 and 0.98 respectively.

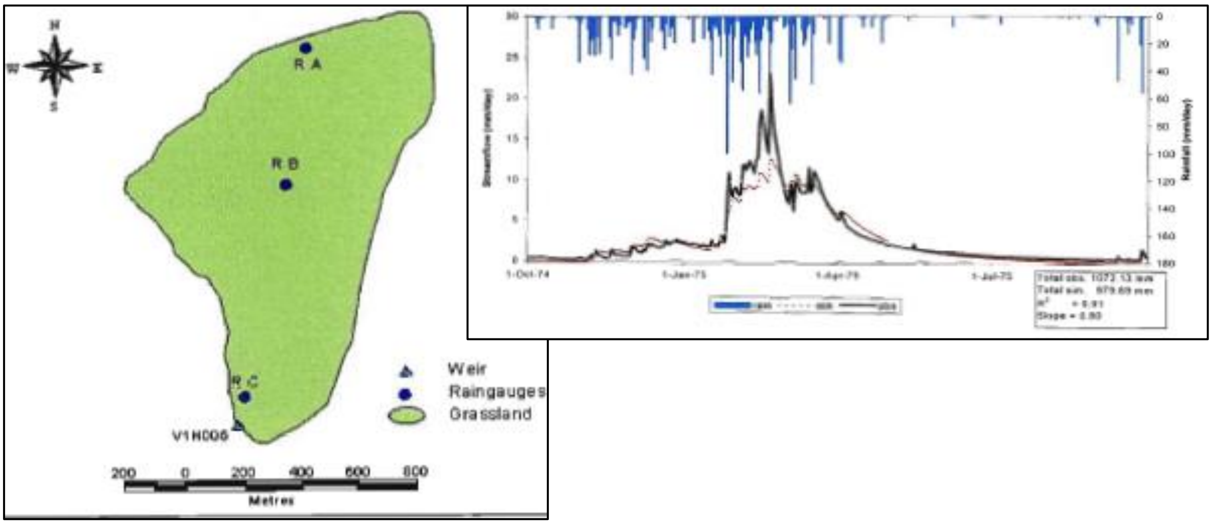


Figure 10.2.5 Cathedral Peak IV research catchment, with the positions of the rainfall stations and gauging weir shown (left), and (right) a time series of observed (obs) and simulated (sim) daily streamflows from October 1974 to September 1975 (After Royappen, 2002)

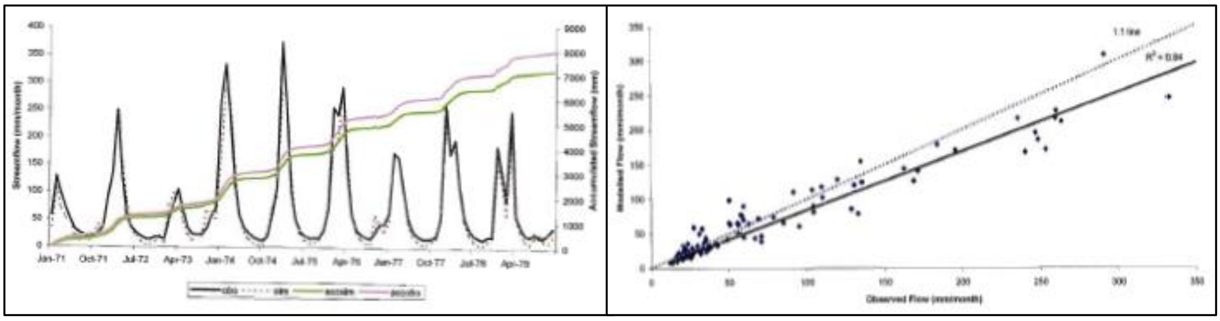


Figure 10.2.6 Time series of observed (obs) and simulated (sim) monthly totals of daily streamflows from 1971 to 1979 for Cathedral Peak research catchment IV, with accumulated flows (accsim; accobs) also shown (left), and a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Table 10.2.3 Statistical analysis of monthly totals of daily observed and simulated streamflows for Cathedral Peak V1H005 from 1971 to 1979 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	74.20		Coefficient of Determination R^2	0.94
Mean of Simulated Values	66.77		Slope of Regression Line	0.88
% difference Between Means	10.02		Y-Intercept of Regression Line	1.28
% Difference Between Std Dev	6.66		Coefficient of Efficiency	0.91
% Difference between CVs	-1.26		Coefficient of Agreement	0.96

Small Research Catchment 4: De Hoek

The De Hoek grassland research catchment V1H015 of 1.03 km^2 (**Figure 10.2.7**) is located in the foothills of the Drakensberg mountain range in KwaZulu-Natal, South Africa around 29°58'S and 30°20'E. With an altitudinal range from 1 450 to 1 630 m.a.s.l. it has relatively steep slopes averaging 12° and deep dystrophic apedal soils. Nested within this catchment are sub-catchments V1H010, V1H011 and V1H012. MAP is 1 115 mm with a majority of the summer rainfall events being convective, although low intensity frontal events occur in autumn and spring. Average maximum temperatures are 24.5°C and 19.2°C and average minimum temperatures 12.9°C and 0.3°C for January and July, respectively, and annual reference potential evaporation is ~ 1 660 mm.

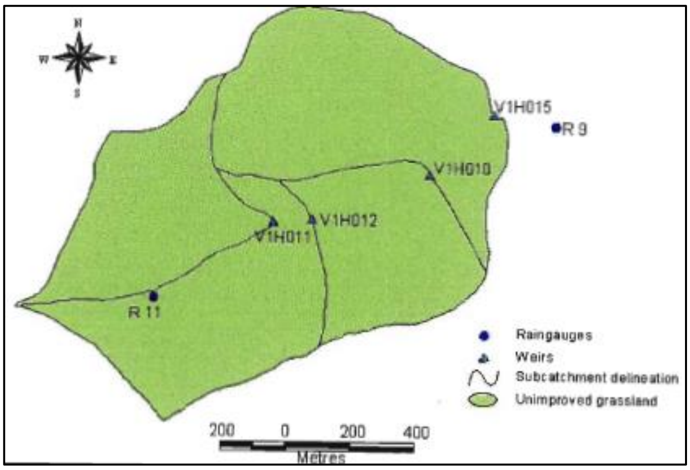


Figure 10.2.7 De Hoek research catchment V1H015, showing nested catchments V1H011, V1H012 and V1H010 and positions of raingauges R9 and R11 (After Royappen, 2002)

Very high flows are simulated well by the model, and a good relationship exists between accumulative observed and simulated flows over the entire simulation period (**Figure 10.2.8** left). An acceptable correlation coefficient of 0.78 is achieved between simulated and observed monthly totals of daily streamflows (**Figure 10.2.8** right). This catchment is highly responsive to rainfall intensity. Statistics in **Table 10.2.4** indicate good relationships between simulated and observed streamflows, with a difference between the means of only 0.22%.

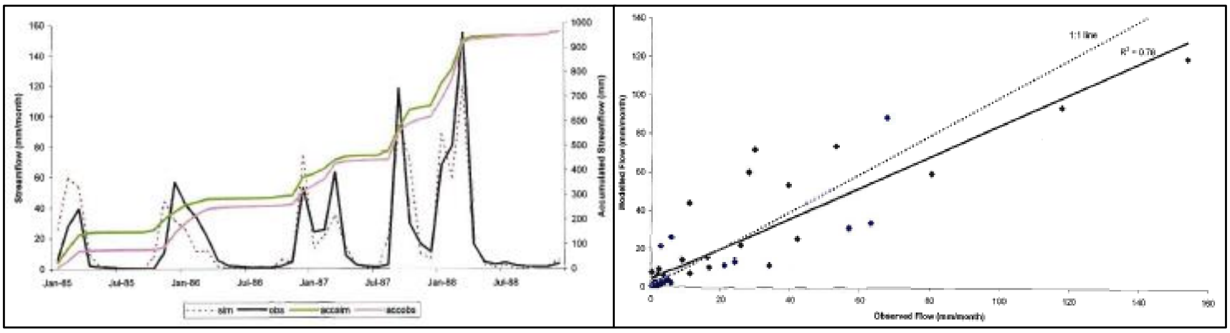


Figure 10.2.8 Time series of observed (obs) and simulated (sim) monthly totals of daily streamflows from 1985 to 1988 for the De Hoek research catchment V1H015, with accumulated flows (accsim; accobs) also shown (left), and (right) scatter plots of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Table 10.2.4 Statistical analysis of monthly totals of daily observed and simulated streamflows for De Hoek V1H015 from 1985 to 1988 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	20.08		Coefficient of Determination R^2	0.78
Mean of Simulated Values	20.12		Slope of Regression Line	0.80
% difference Between Means	-0.22		Y-Intercept of Regression Line	4.06
% Difference Between Std Dev	9.39		Coefficient of Efficiency	0.73
% Difference between CVs	9.59		Coefficient of Agreement	0.94

Small Research Catchment 5: Witklip

The 1.08 km^2 Witklip research catchment V (X2H038; **WK** in **Figure 10.1.1**; **Figure 10.2.9** left), located around 25°14'S and 30°53'E located in the Eastern Drakensberg escarpment within the Mpumalanga province of South Africa, has an elevation range from 1 000 to 1 340 m, a MAP of 1 100 mm and a MAR of 362 mm (33% of MAP) and experiences a humid sub-tropical climate, with predominantly summer rainfall. Most of the catchment is under plantation forestry of *Pinus* and *Eucalyptus* species (**Figure 10.2.9** left) on deep weathered soils.

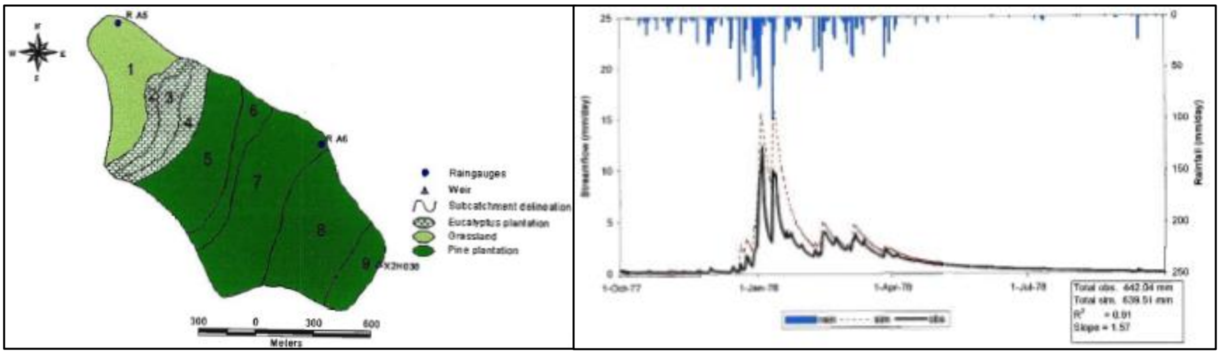


Figure 10.2.9 Witklip catchment V (V2H038), showing land uses and the location of rainfall stations A5 and A6 (left), and (right) detailed hydrographs of observed (obs) and simulated (sim) daily streamflows from October 1977 to September 1978 (After Royappen, 2002)

Results show highly acceptable trends between observed and simulated streamflows. As is seen in **Figure 10.2.10** (left), differences in accumulated flows over the entire simulation resulted from a single event in January 1978. High correlation exists between simulated and observed streamflows, with a R^2 of 0.91 (**Table 10.2.5**). Daily streamflows are over-simulated (**Figure 10.2.9** right), possibly from the soil profile not being defined deep enough. Regression statistics of monthly totals of daily observed and simulated streamflows are excellent (cf. **Table 10.2.5**), having a high coefficient of agreement of 0.98.

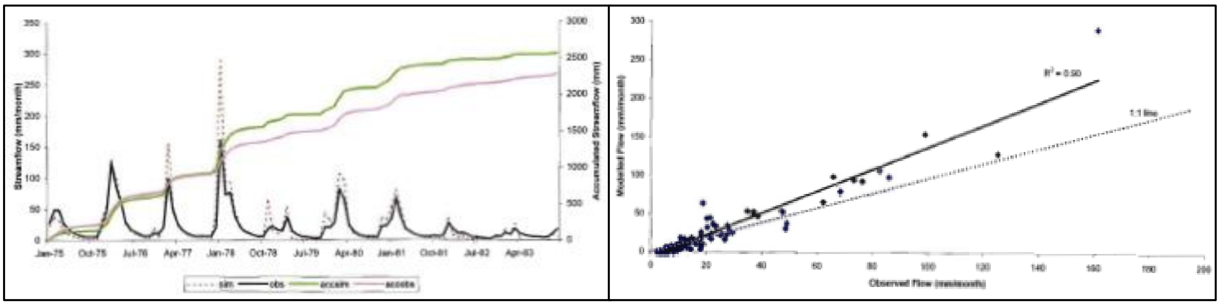


Figure 10.2.10 Time series of observed (obs) and simulated (sim) monthly totals of daily streamflows from 1975 to 1983 for Witklip V, with accumulated flows (accsim; accobs) also shown (left), and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Table 10.2.5 Statistical analysis of monthly totals of daily observed and simulated streamflows for Witklip V from 1975 to 1983 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	21.16		Coefficient of Determination R^2	0.91
Mean of Simulated Values	23.70		Slope of Regression Line	1.43
% difference Between Means	-12.04		Y-Intercept of Regression Line	-6.64
% Difference Between Std Dev	-50.07		Coefficient of Efficiency	0.83
% Difference between CVs	-33.94		Coefficient of Agreement	0.98

Small Research Catchment 6: Westfalia

The 0.33 km^2 Westfalia research catchment B, officially B8H022 (23°43'S and 30°04'E; **WF** in **Figure 10.1.1**; **Figure 10.2.11**) forms part of a paired catchment experiment in Mpumalanga Province of South Africa. At an altitudinal range from 1 140 to 1 420 m, a MAP of 1 253 mm made up predominantly of orographic summer rains and a vegetal cover of ~ 10 m high indigenous shrubs, the catchment is underlain by deep, dystrophic clayey soils.

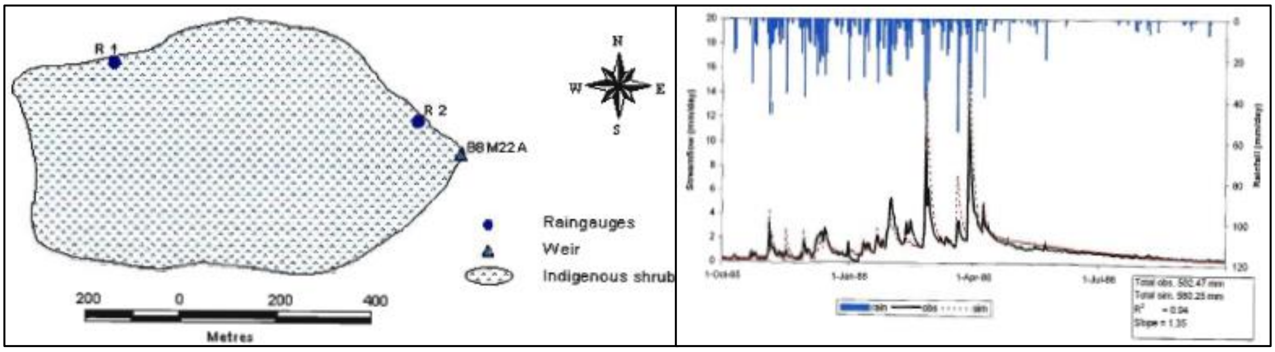


Figure 10.2.11 Westfalia B research catchment, illustrating the land use and the locations of rainfall stations (left) and (right) a time series of observed (obs) and simulated (sim) daily streamflows from October 1985 to September 1986 (After Royappen,2002)

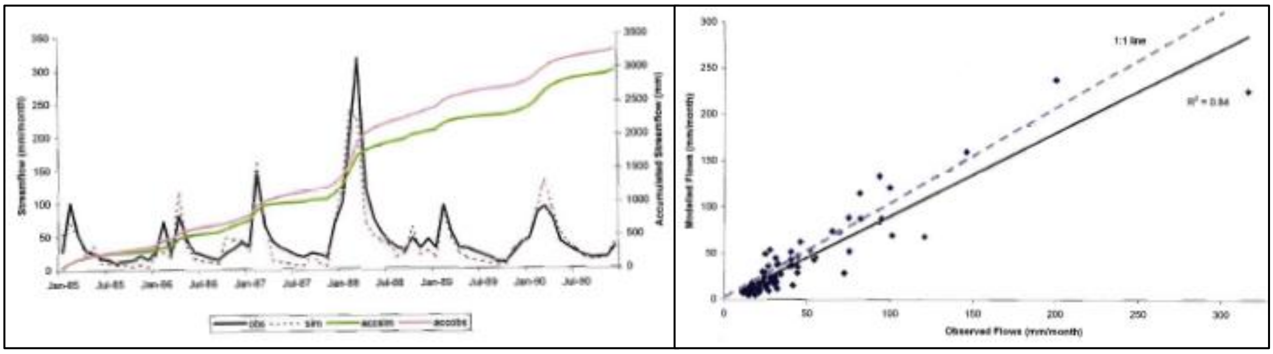


Figure 10.2.12 Time series of observed (obs) and simulated (sim) monthly totals of daily streamflows from 1985 to 1990 for Westfalia B, with accumulated flows (accsim; accobs) also shown (left), and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Streamflows for Westfalia B are slightly under-simulated by the model, as shown by the accumulated flows in **Figure 10.2.12** (left). A distinct under-simulation of flow occurs in June 1987, which suggests that there may have been problems with the rainfall records for this period, while the possibility of leaks across the catchment boundary of Westfalia B has long been suspected, potentially affecting the streamflow records from this catchment. However, bearing in mind the small catchment area (0.33 km^2) of Westfalia B, streamflows are simulated within acceptable limits for the period 1985 to 1990, and this is substantiated by the high correlation of $R^2 = 0.84$ shown in **Figure 10.2.12** (right) and the statistics in **Table 10.2.6**. Excellent model fit between observed and simulated daily streamflows from October 1985 to September 1986 are illustrated in **Figure 10.2.11** (right).

Table 10.2.6 Statistical analysis of monthly totals of daily observed and simulated streamflows for Westfalia B from 1985 to 1990 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	45.36		Coefficient of Determination R^2	0.84
Mean of Simulated Values	41.02		Slope of Regression Line	0.90
% difference Between Means	9.57		Y-Intercept of Regression Line	0.42
% Difference Between Std Dev	2.57		Coefficient of Efficiency	0.82
% Difference between CVs	-7.74		Coefficient of Agreement	0.96

Small Research Catchment 7: Lamprechtsbos B

The 0.66 km^2 Lambrechtsbos B research catchment (33°57'S; 18°57'E; **LB** in **Figure 10.1.1**), official designation G2H010, with a humid meso-thermal Mediterranean type climate of warm dry summers and cool wet winters, is situated in the long, narrow Jonkershoek valley (**Figure 10.2.13** left) in the Western Cape province of South Africa. Minimum elevation is 300 m and the maximum is at 1 067 m, the areal mean of MAP is 1 145 mm and MAR is 518 mm, i.e. ~ 45% of MAP. The catchment experiences a steep, orographic rainfall gradient. Daily rainfalls at raingauge R15 at low altitude were adjusted upwards by the monthly catch at raingauge R10, considered more representative of the average rainfall over the catchment. With complex acidic dystrophic and deep sandy loam soils of low organic matter content, these well-drained soils largely control baseflows. By 1964 the catchment had been afforested to 82% with *Pinus radiata,* with 20 m buffer strips left unplanted on either side of the stream banks. The simulation period was from 1969 to 1974.

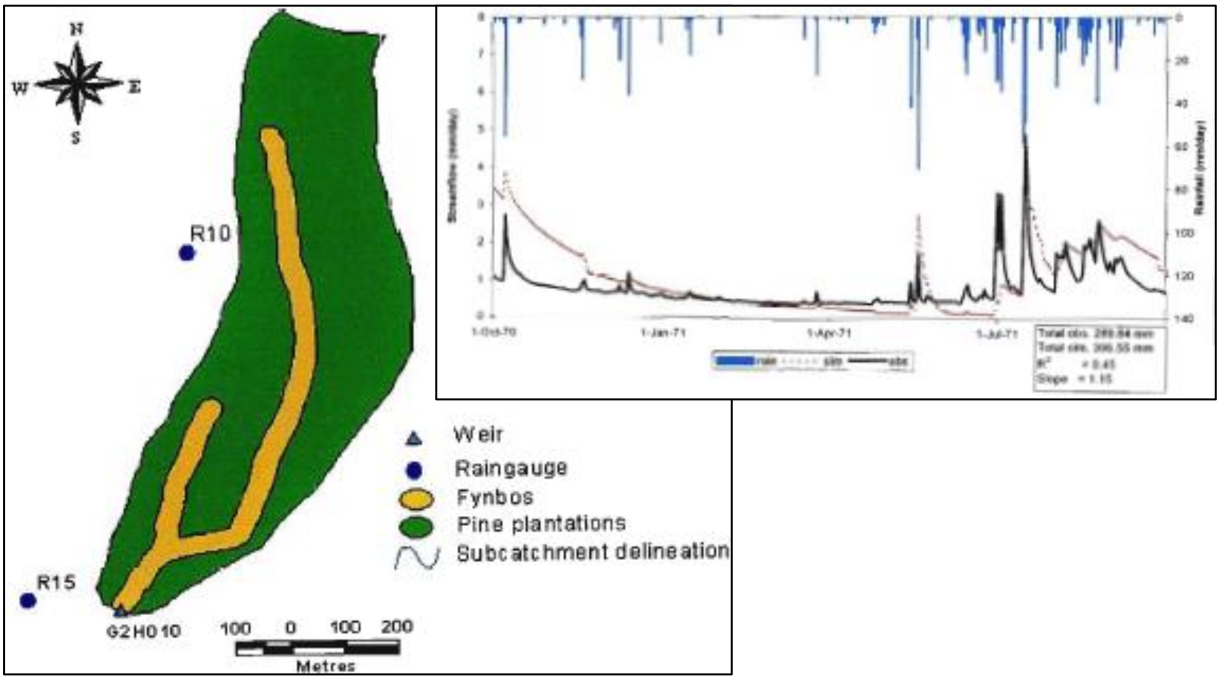


Figure 10.2.13 The Lambrechtsbos B catchment (left) and (right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily streamflows from October 1970 to September 1974 for t.ambrechtsbos B, with summary statistics of model fit to observed data for this period are also shown (After Royappen, 2002)

Streamflows for Lambrechtsbos B are over-simulated, as shown in **Figures 10.2.14** (left and right), with the slope of the regression line nearly 2. This may be due to the rainfall values which were used not being representative of the entire catchment, bearing in mind that this catchment extends upwards altitudinally by nearly 800 m into the Jonkershoek Mountains. Correlations between observed and simulated streamflows along the 1:1 line are poor, as shown in **Figure 10.2.14** (right).

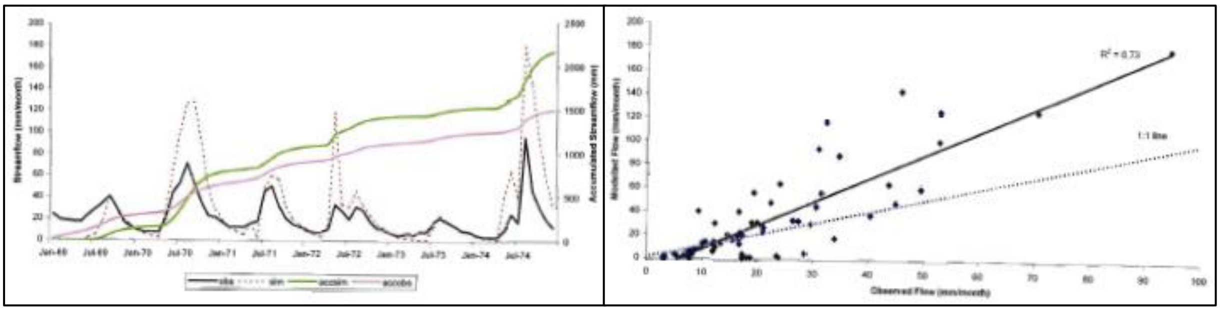


Figure 10.2.14 Time series of observed (obs; solid black line) and simulated (sim; stippled) monthly totals of daily streamflows from 1969 to 1974 for Lambrechtsbos B, with accumulated flows (accsim in green; accobs in purple) also shown (left), and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Baseflow recessions are generally over-simulated, with the simulated baseflows receding slower that the those of the observed flows, as shown in **Figure 10.2.13** (right). These differences between observed and simulated streamflows are also evident from the large differences in standard deviations of 135.35% shown in **Table 10.2.7**.

Table 10.2.7 Statistical analysis of monthly totals of daily observed and simulated streamflows for Lambrechtsbos B from 1969 to 1974 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	20.79		Coefficient of Determination R^2	0.73
Mean of Simulated Values	30.12		Slope of Regression Line	1.99
% difference Between Means	-44.90		Y-Intercept of Regression Line	-11.23
% Difference Between Std Dev	-135.35		Coefficient of Efficiency	0.49
% Difference between CVs	-60.35		Coefficient of Agreement	0.92

Lessons Learned from These Verification Studies on Small Research Catchments

- ***Modelling in Arid to Semi-Arid Catchments with a Daily Time-Step Model is Fraught with Problems***
  - This was borne out from the simulations at Safford.
  - The patterns of flow observed show markedly discontinuous flows, virtually non-existent/transient baseflows, and occasional very high quickflows.
  - The diagram of accumulated observed and simulated flows illustrated that large discrepancies may occur around the time of high rainfall events.
  - Variations in rainfall intensity and streamflow transmission losses into banks and the channel bed were the main causes of inconsistent runoff responses to rainfall in this catchment.
  - More detailed analysis of hourly data (not shown in this document) illustrated an under-simulation of quickflow with high intensity rainfalls, whereas an over-simulation of quickflow occurred in association with low intensity rainfall events.
  - The scatter plot of observed versus simulated monthly totals of daily flows (**Figure 10.2.2** right) revealed a relatively poor fit (R^2 =0.56), and this was borne out by the statistics of fit in **Table 10.2.1**.
  - Clearly, *ACRU,* as a daily time step model, is not structured in detail enough to predicting flows in arid catchments where low soil infiltration rates, short rainfall events of highly variable rainfall intensity and significant transmission losses occur.
- ***Excellent Verification Results are Generally Achieved in Catchment with High Rainfall***
  This was illustrated by the verifications from Zululand and Cathedral Peak. In Zululand **Figure 10.2.4** (right) illustrated the excellent association between observed and simulated streamflows, along the 1:1 line, with a high correlation coefficient of 0.99. Similarly, for Cathedral Peak excellent relationships were shown to exist between observed and simulated streamflows, as illustrated in

Figure 10.2.5 (right) and **Figure 10.2.6** for both accumulated and scatter plots, as were the good relationships between accumulative observed and simulated flows over the entire simulation period at De Hoek (**Figure 10.2.8** left).

- ***Different Catchments can Nevertheless Display Certain Uniquenesses in their Runoff Responses.*** For example:
  - At De Hoek the catchment was highly responsive to rainfall intensity.
  - Daily streamflows from the Zululand research catchment W1H016 are found to be very "flashy", as shown in **Figure 10.2.3** (right), while baseflow recessions receded very rapidly, approaching near zero flows.
- ***Rainfall and Runoff Observations are not Always Perfect, Even in Research Catchments***
  This was shown at Westfalia B, where a distinct under-simulation of flow occurred in June 1987, suggesting that there may have been problems with the rainfall records for this period, while the possibility of leaks across the catchment boundary of Westfalia B has long been suspected, potentially affecting the streamflow records from this catchment.
- ***A Single Large Event can Distort Verification Results***
  As can be seen for Witklip in **Figure 10.2.10** (left), where differences in accumulated flows over the entire simulation resulted from a single event in January 1978 not having been simulated well. This could have resulted from a heavy convective storm over a part of the catchment where no rainfall gauging exists.
- ***Consistent Over- or Under-Simulation can Result from Incorrect Soils Inputs***
  A case in point is Witklip, where over-simulations (**Figure 10.2.9** right) are thought to result from the soil profile not having been defined as deep enough.
- ***Good Simulation Results from Catchments with High Altitude Ranges and Steep Rainfall Gradients are Difficult to Achieve***
  This was well illustrated by results from Lambrechtsbos B, where the minimum elevation is 300 m and the maximum is 1 067 m, the catchment experiences a steep orographic rainfall gradient and the raingauge distribution is not representative of elevation. In the case of Lambrechtsbos B the streamflows were over-simulated, as shown in **Figures 10.2.14** (left and right), with the slope of the regression line nearly 2, correlations between observed and simulated streamflows along the 1:1 line being poor, as shown in **Figure 10.2.14** (right), and large differences in standard deviations being evident. In such steep catchments, baseflow recessions also tend to be poorly modelled.

Thus, even in research catchments model verifications are not always as good as one would wish them to be.

References

Royappen, M. 2002. Towards improved parameter estimation in streamflow predictions using the ACRU Model. Unpublished MSc Thesis, University of Natal, Pietermaritzburg.

Royappen, M., Dye, P.J., Schulze, R.E. and Gush, M.B. 2002. *An Analysis of Catchment Attributes and Hydrological Response Characteristics in a Range of Small Catchments*. Water Research Commission, Pretoria, WRC Report 1193/1/02. pp 142.

10.3 Verification Studies on Medium-Sized Operational Catchments (M. Royappen and R.E. Schulze)

Please note that the figures in this section where reproduced from Royappen (2002), and no high resolution maps were available.

Medium-Sized Operational Catchment 1: Watervalsrivier

The Watervalsrivier catchment G1H012 (**Figure 10.3.1** left; **WV** in **Figure 10.1.1**) of 36 km^2 is situated in the winter rainfall region of the Western Cape province around 33°21'S and 19°06'E, is bordered by mountains and has an altitudinal range from 120 to 1 086 m.a.s.l. The MAP, based on raingauge 0042201 W situated ~ 1 km from the weir and ~ 8 km from the outermost boundary, is 664 mm. Over

81% of the catchment is covered with shrubland and low fynbos and ~ 17% forest by plantations. The period of simulation was from 1968 to 1974. Streamflows are simulated well, as shown in **Figures 10.3.2** (left) and **10.3.1** (right), with a good correlation indicated by *ACRU* between observed and simulated streamflows (**Figure 10.3.2** right; **Table 10.3.1**). Comparisons of the total observed and simulated streamflows in **Table 10.3.1** indicate a slight over-simulation of streamflows, which may be attributed to rainfall values used being too high. Typically, *ACRU* over-simulates early rainfall season streamflows, as shown in **Figure 10.3.1** (right), and this is usually associated with low intensity frontal rainfall.

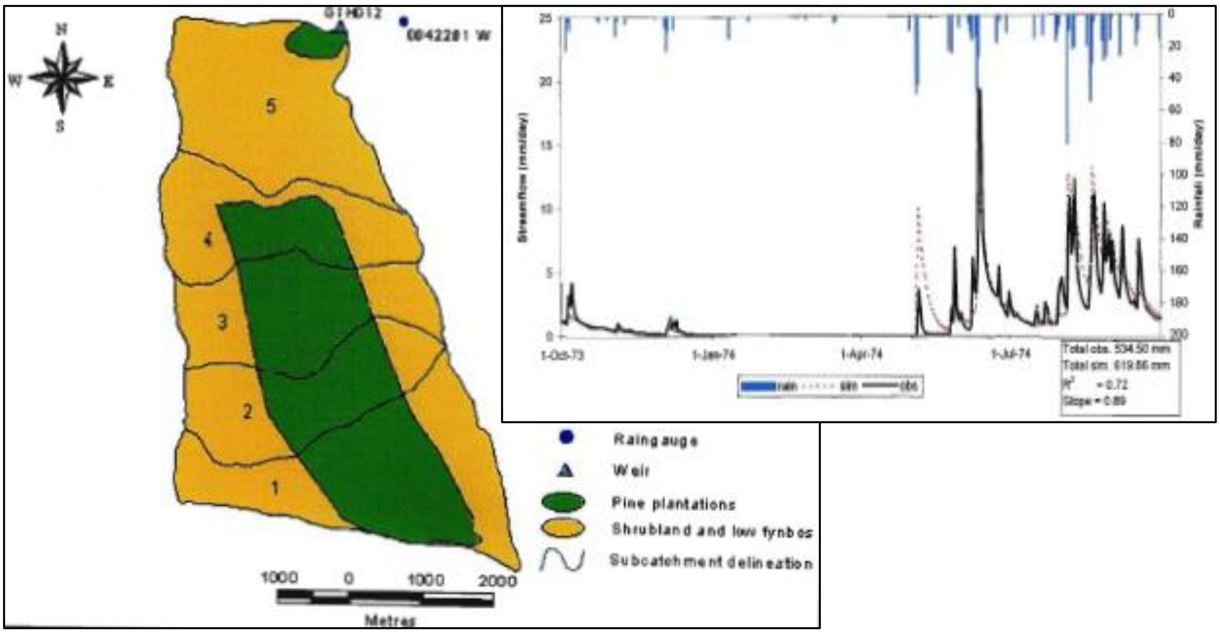


Figure 10.3.1 The Watervalsrivier catchment showing sub-catchment delineations, land cover and the location of the rainfall station used (left), and (right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily streamflows from October 1973 to September 1974 (After Royappen, 2002)

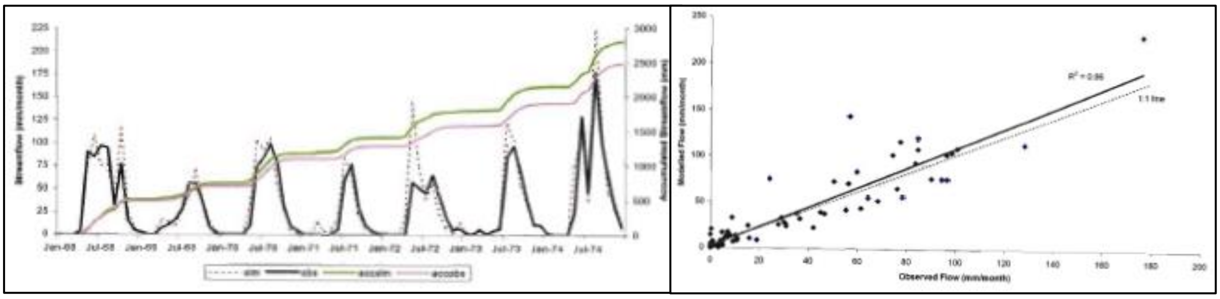


Figure 10.3.2 Time series of observed (obs; solid black line) and simulated (sim; stippled) monthly totals of daily streamflows from 1968 to 1974 for Watervalsrivier (left), with accumulated flows (accsim in green; accobs in purple) also shown, and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Table 10.3.1 Statistical analysis of monthly totals of daily observed and simulated streamflows for Watervalsrivier from 1968 to 1974 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	29.46		Coefficient of Determination R^2	0.86
Mean of Simulated Values	33.33		Slope of Regression Line	1.07
% difference Between Means	-13.07		Y-Intercept of Regression Line	1.86
% Difference Between Std Dev	-15.21		Coefficient of Efficiency	0.85
% Difference between CVs	-1.89		Coefficient of Agreement	0.96

Medium-Sized Operational Catchment 2: Kruisrivier

The Kruisrivier catchment H9H004 of 50 km^2 **(Figure 10.3.3** left; **KR** in **Figure 10.1.1**) is situated at 34°00'S and 21°16'E near Riversdale in the Western Cape province.

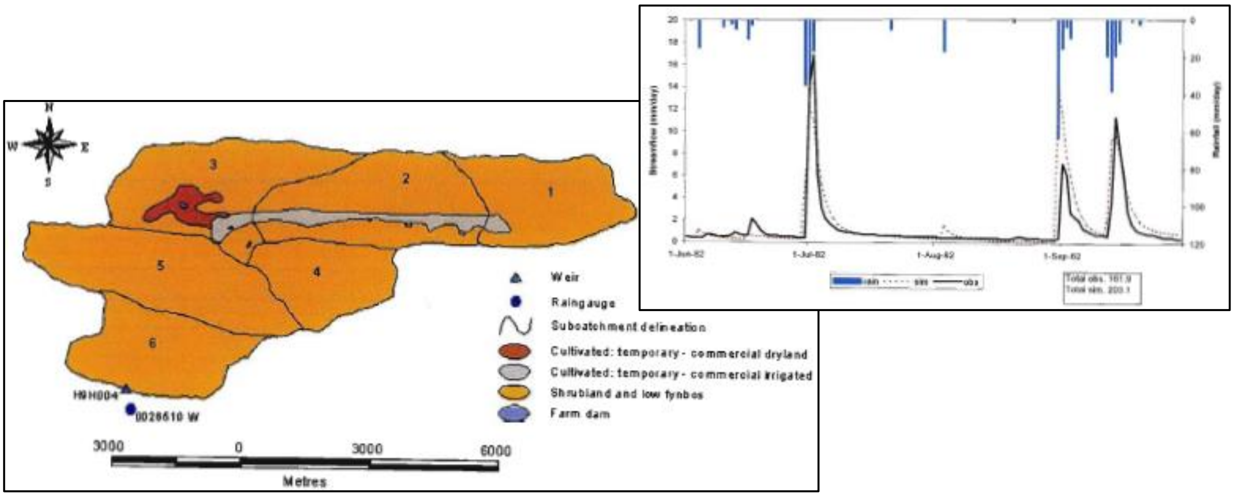


Figure 10.3.3 The Kruisrivier catchment illustrating the sub-catchment delineation, land uses and the location of the rainfall station (left) with (top right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily streamflows from June 1982 to September (After Royappen, 2002).

Rainfall is concentrated in the winter months from June to September, with a MAP of 645 mm from raingauge 0026510 W located near the outlet of the catchment and used in modelling. The dominant vegetation is shrubland and low fynbos, with a small percentage of cultivated commercial dryland and orchards irrigated in the dry summers from October to March from the six small farm dams. The simulation period was from 1981 to 1990. As a result of irrigation in the catchment during summer months, focus of the simulations were the winter months June to September, during which time there were no abstractions. Streamflows during non-abstraction months are simulated relatively well, as shown in **Figure 10.3.4** (left), and if the first season (1981) were omitted, the accumulated flows over the entire simulation period would be nearly identical.

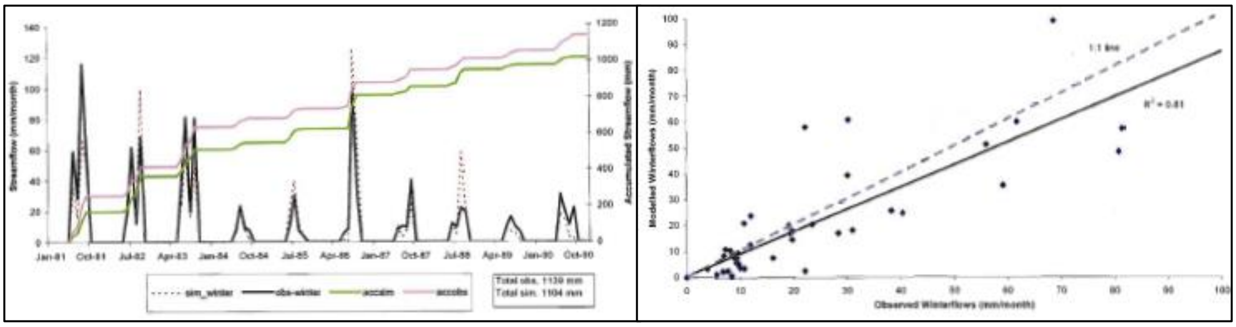


Figure 10.3.4 Time series of observed (obs_winter; solid black line) and simulated (sim_winter; stippled) monthly totals of daily winter (June to September) flows from 1981 to 1990 for Kruisrivier, with accumulated winter flows (accsim, green line; accobs, purple) also shown, and (right) a scatter plot of simulated and observed monthly totals of daily winter flows (After Royappen, 2002)

Figure 10.3.4 (right) shows a relatively good trend between modelled and observed streamflows, with a slight under-simulation of flows as shown by the regression line. A good model fit between observed and simulated daily streamflows is shown in **Figure 10.3.3** (right).

Medium-Sized Operational Catchment 3: Bloukransrivier

The 57 km^2 Bloukransrivier operational catchment **(Figure 10.3.5** left; **BK** in **Figure 10.1.1**), monitored at weir K7H001, is located around 33°57'S and 23°37'E near Nature's Valley Reserve in the Western Cape Province of South africa. It has a MAP range from 685 to 1 350 mm and is in the all year rainfall region.

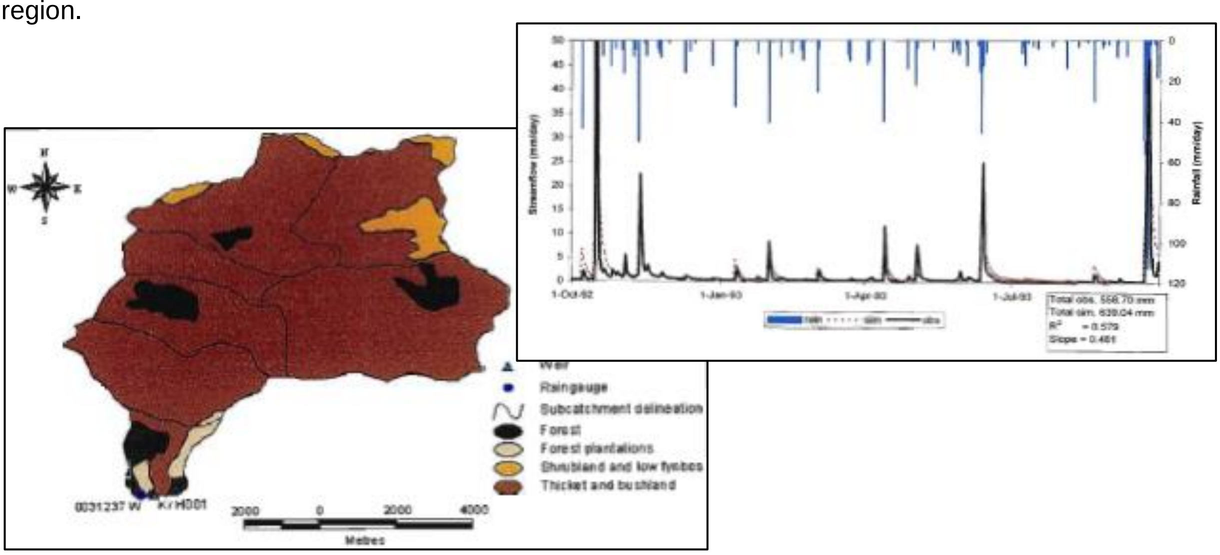


Figure 10.3.5 The Bloukransrivier catchment, showing land uses and the location of the rainfall station used (left) and (right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily streamflows from October 1992 to September 1993, with statistics of model fit to observed data for this period also shown (After Royappen, 2002)

A large percentage of the catchment with 0.4-0.5 m deep sandy soils is shrubland and low fynbos, with scattered plots of indigenous and plantation forest and indigenous forest on the steep slopes. The simulation period was from 1989 to 1995.

Good relationships between observed and simulated streamflows for the Bloukransrivier are shown in **Figure 10.3.6**, with general over-simulation in months with high flows. The results also illustrate very good associations between observed and simulated streamflows, along the 1:1 line, as shown in **Figure 10.3.6** (right). Baseflow recessions are rapid, reaching to near zero flows (**Figure 10.3.5** (right). The low percentage differences between standard deviations (7.43%) and coefficients of variation (8.96%) shown in **Table 10.3.2** confirms the good relationships between observed and simulated streamflows.

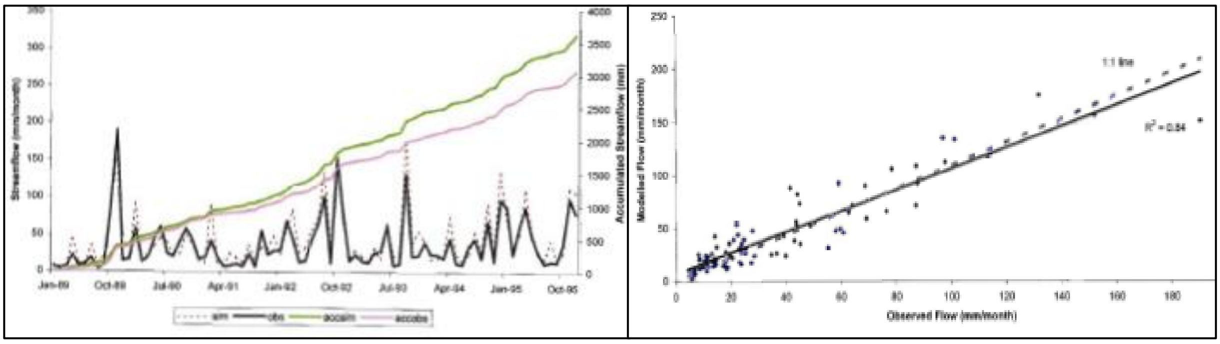


Figure 10.3.6 Time series of observed (obs; solid black line) and simulated (sim; stippled) monthly totals of daily streamflows from 1989 to 1995 for the Bloukransrivier, with accumulated flows (accsim in green; accobs in purple) also shown left), and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Table 10.3.2 Statistical analysis of monthly totals of daily observed and simulated streamflows for the Bloukransrivier from 1989 to 1995 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	36.60		Coefficient of Determination R^2	0.84
Mean of Simulated Values	43.19		Slope of Regression Line	0.99
% difference Between Means	-18.01		Y-Intercept of Regression Line	7.11
% Difference Between Std Dev	-7.43		Coefficient of Efficiency	0.84
% Difference between CVs	8.95		Coefficient of Agreement	0.81

Medium-Sized Operational Catchment 4: Treurrivier

The 92 km^2 Treurrivier catchment in Mpumalanga province, RSA, streamflow from which is monitored at weir B6H003, is located around 24°41'S, 30°48'E (**Figure 10.3.7** left; **TR** in **Figure 10.1.1**). Three rainfall gauges (0594494 W, 0594590 W and 0594764 W), located outside the catchment, but providing good quality data, were used. Rainfall is concentrated in the summer months November to April. Estimated MAP near the outlet of the catchment is ~ 790 mm, but rises to ~ 1 595 mm in its upper reaches. The altitudinal range exceeds 600 m from 1 200-1 835 m. The catchment has a mixed vegetation (**Figure 10.3.7**). Simulation period was from 1981 to 1986.

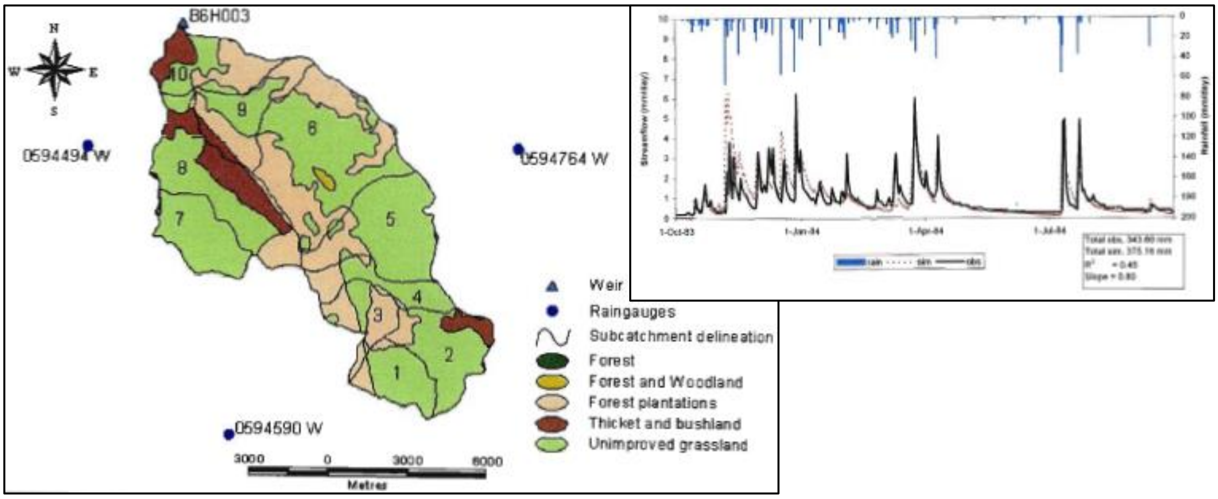


Figure 10.3.7 The Treurrivier catchment, illustrating land uses, sub-delineation and locations of rainfall stations (left), and (right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily streamflows from October 1983 to September 1984, including summary statistics of model fit for this period (After Royappen, 2002)

The results for the Treurrivier catchment illustrate excellent relationships between observed and simulated streamflows (**Figure 10.3.8** left), with good correlation trends shown in **Figure 10.3.8** (right). **Figure 10.3.8** (right) shows the typical over-simulation by the model of the first relatively high rainfall event of the rainy season. However, baseflow recessions are simulated well here. The results for the Treurrivier catchment are borne out by the excellent statistics of fit (R^2 = 0.95), shown in **Table 10.3.3**.

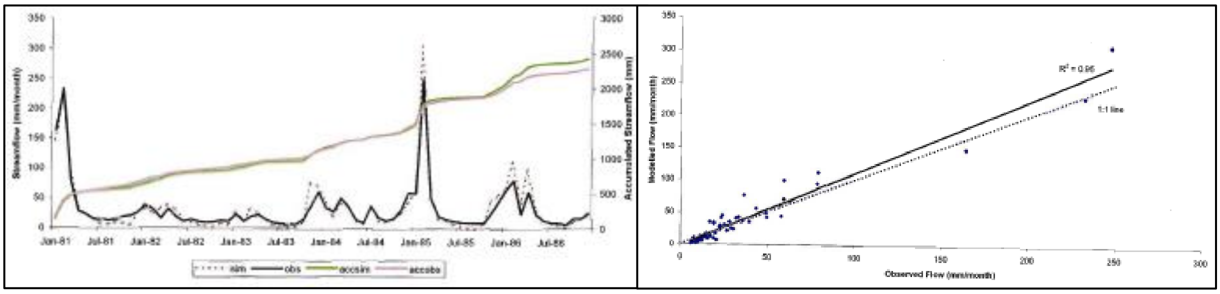


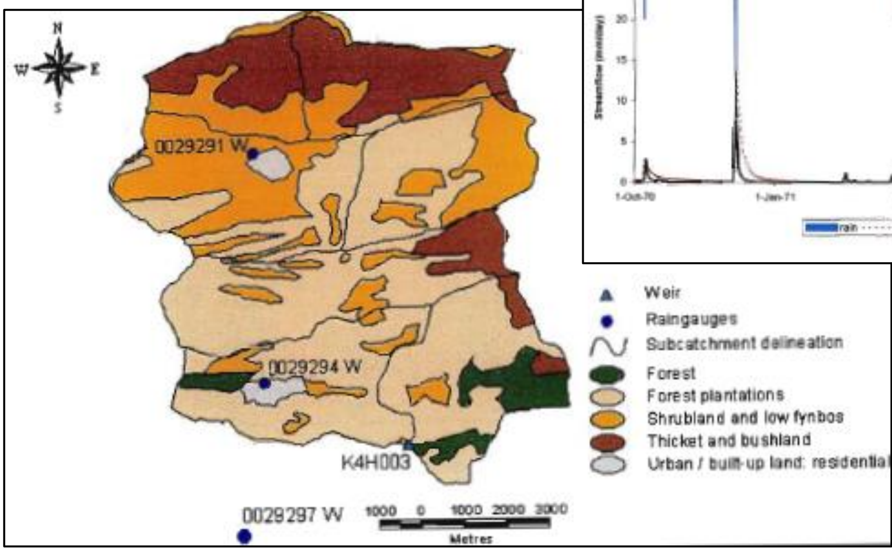
Figure 10.3.8 Time series of observed (obs; solid black line) and simulated (sim; stippled) monthly totals of daily flows from 1981 to 1986 for the Treurrivier catchment, with accumulated flows (accsim in green; accobs in purple) also shown, and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Table 10.3.3 Statistical analysis of monthly totals of daily observed and simulated streamflows for the Treurrivier catchment B6H003 from 1981 to 1986 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	31.74		Coefficient of Determination R^2	0.95
Mean of Simulated Values	33.64		Slope of Regression Line	1.11
% difference Between Means	-6.04		Y-Intercept of Regression Line	-1.56
% Difference Between Std Dev	-14.11		Coefficient of Efficiency	0.93
% Difference between CVs	-7.63		Coefficient of Agreement	0.99

Medium-Sized Operational Catchment 5: Dieprivier

The Dieprivier operational catchment of 72 km^2 (**Figure 10.3.9** left; **DR** in **Figure 10.1.1**) of highly variable soils and a mix of pines, shrubland and low fynbos, is monitored at weir K4H003. It is situated in the Western Cape Province around 33°54'S and 22°42'E with the Outeniqua Mountains to the west. The catchment falls within the all-year rainfall region, has a MAP of 711 mm with rainfall data from raingauges 0029291W, 0029294W and 0029297W used for this study. The simulation period was from 1968 to 1975.



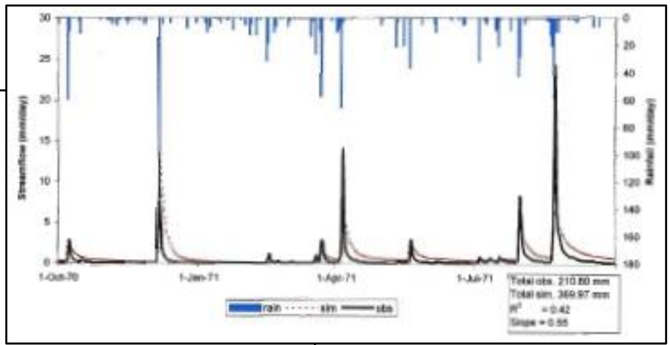


Figure 10.3.9 The Dieprivier catchment showing land cover, catchment delineation and positions of rainfall stations (left) and (right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily flows from October 1970-September 1971, with a summary of modelled statistics to observed data for this period (After Royappen, 2002)

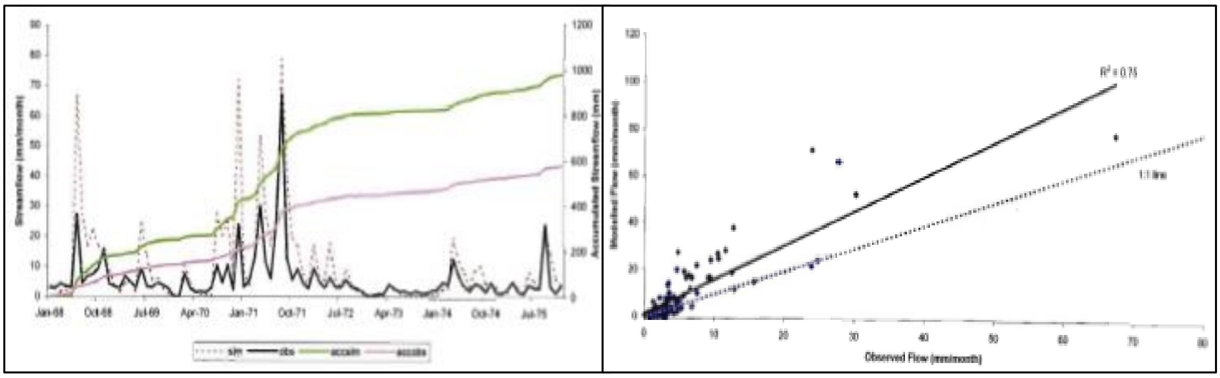


Figure 10.3.10 Time series of observed (obs; solid black line) and simulated (sim; stippled) monthly totals of daily streamflows from 1968 to 1975 for Dieprivier, with accumulated flows (accsim in green; accobs in purple) also shown (left), and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Trends between observed and simulated streamflows for Dieprivier are poor, with large deviations between accumulated flows, as shown in **Figure 10.3.10** (left) and relatively poor comparative statistics (**Table 10.3.4**). Streamflows from the Dieprivier catchment are very flashy, as shown in **Figure 10.3.9** (right). Associated with that are baseflow recessions which are very rapid, approaching near zero flows. Over-simulations indicate that the soils of this catchment may be much deeper than used in simulations, and that the two rainfall stations may not have been representative of the entire catchment rainfall.

Table 10.3.4 Statistical analysis of monthly totals of daily observed and simulated streamflows for Dieprivier from 1968 to 1975 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	6.02		Coefficient of Determination R^2	0.75
Mean of Simulated Values	10.21		Slope of Regression Line	1.48
% difference Between Means	-69.58		Y-Intercept of Regression Line	1.33
% Difference Between Std Dev	-70.84		Coefficient of Efficiency	0.59
% Difference between CVs	-0.74		Coefficient of Agreement	0.92

Medium-Sized Operational Catchment 6: Beestekraalspruit

The Beestekraalspruit operational catchment of 14 km^2 (**Figure 10.3.11** left; **BK** in **Figure 10.1.1**) is located around 25°17'S and 30°34'E in Mpumalanga province and is monitored at weir X2H026. It ultimately flows into the Crocodile River. MAP is 977 mm and the altitudinal range is from 980 to 2190 m. Data from the nearby Mokobulaan research catchments' raingauges have been used to represent the higher rainfall regions of the catchment. Raingauge 0555137 W, located within the catchment, was used to represent the remaining catchment area. The natural vegetation is Northeast Mountain Sourveld, with ~ 24% of the catchment consisting of forest plantations. The simulation period was from 1971 to 1975.

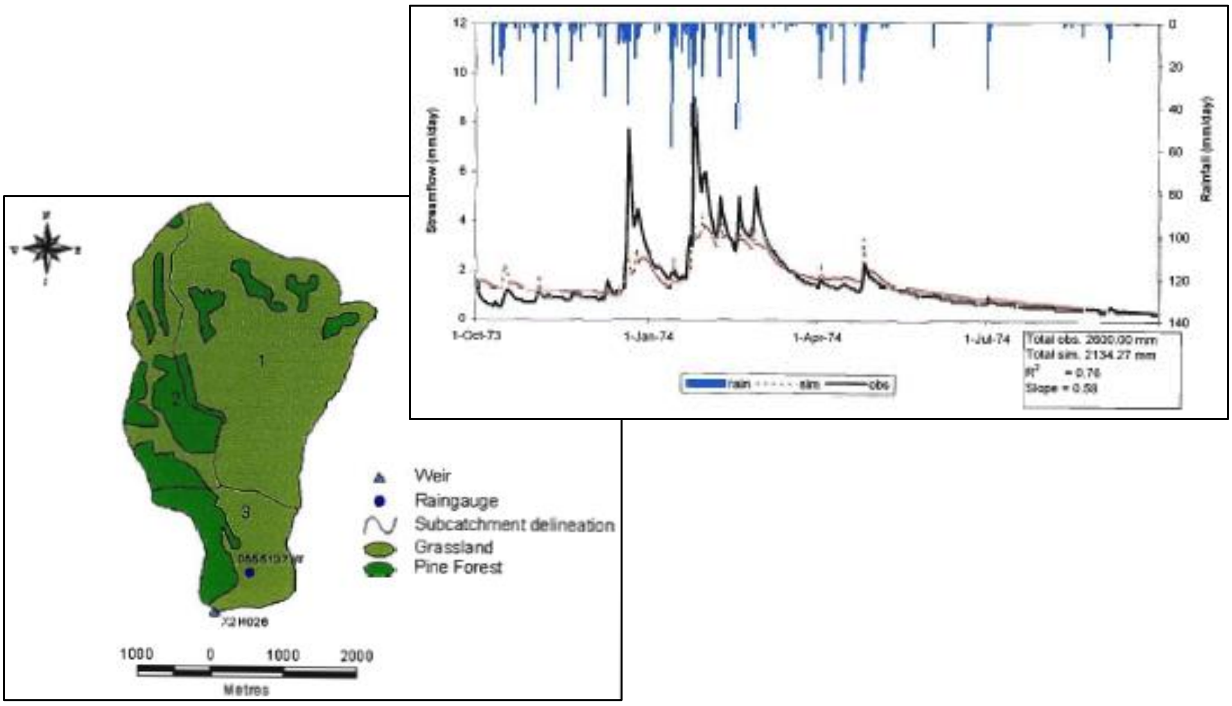


Figure 10.3.11 Beestekraalspruit catchment, illustrating land uses and the location of the rainfall station (left) and (right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily streamflows from October 1973 to September 1974, with summary statistics of model fit for this period also shown (After Royappen, 2002)

Trends between observed and simulated streamflows are satisfactory, with the deviations between accumulated flows, shown in **Figure 10.3.12** (left), arising from large differences between observed and simulated flows in the first year of the simulation, possibly due to a large baseflow store from the previous season. Streamflows are predominantly under-simulated (regression slope = 0.58), possibly caused by rainfall values not being representative of the entire catchment. However, baseflow recessions are simulated well through the 1973 and 1974 hydrological years (**Figure 10.3.11** right). An acceptable correlation of $R^2 = 0.76$ was calculated from the regression of simulated streamflows against observed monthly streamflows, shown in **Figure 10.3.12** (right) and associated statistics in **Table 10.3.5**. **Figure 10.3.11**(right) shows that the model does not mimic the flashy responses of daily observed streamflows from the Beestekraalspruit catchment satisfactorily. However, the "steps" in the observed baseflow recessions indicate measurement errors or poor digitizing of recorder charts.

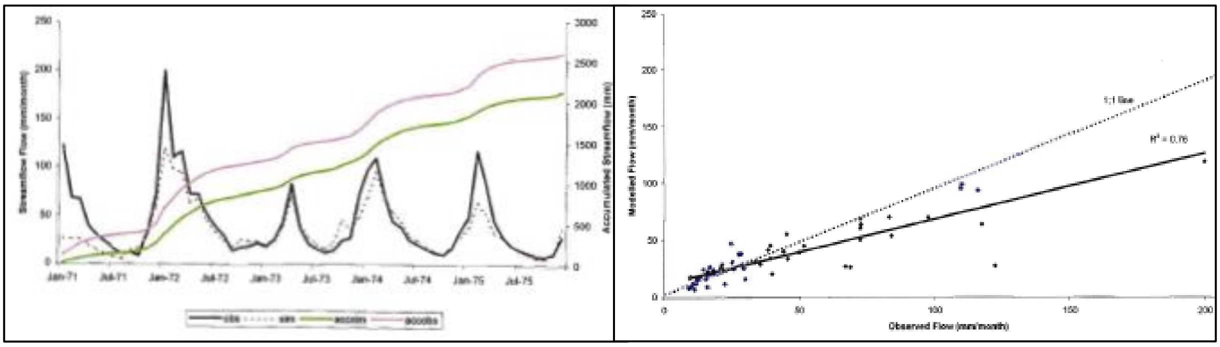


Figure 10.3.12 Time series of observed (obs; solid black line) and simulated (sim; stippled) monthly totals of daily streamflows from 1971 to 1975 for Beestekraalspruit, with accumulated flows (accsim in green; accobs in purple) also shown, and (right) a scatter plot of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Table 10.3.5 Statistical analysis of monthly totals of daily observed and simulated streamflows for Beestekraalspruit from 1971 to 1975 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	43.33		Coefficient of Determination R^2	0.76
Mean of Simulated Values	35.57		Slope of Regression Line	0.58
% difference Between Means	17.91		Y-Intercept of Regression Line	10.52
% Difference Between Std Dev	33.58		Coefficient of Efficiency	0.26
% Difference between CVs	19.08		Coefficient of Agreement	0.93

Medium-Sized Operational Catchment 7: Groot Nylsrivier

The Groot-Nylrivier catchment A6H011 (**Figure 10.3.13** left; **GN** in **Figure 10.1.1**) of 74.8 km^2 in southern Limpopo province of South Africa is situated around 24°45'S and 28°44'E, has a MAP of 655 mm, an altitudinal range from 1 213 to 1 508 m and a natural vegetation of thicket and bushland. Four very small dams within the catchment have very little influence on flows recorded at the weir. Records from raingauges 0589586 W and 0589670 W were selected for modelling. Rainfall is concentrated in the summer months from November to April and occurs predominantly in the form of thunderstorms.

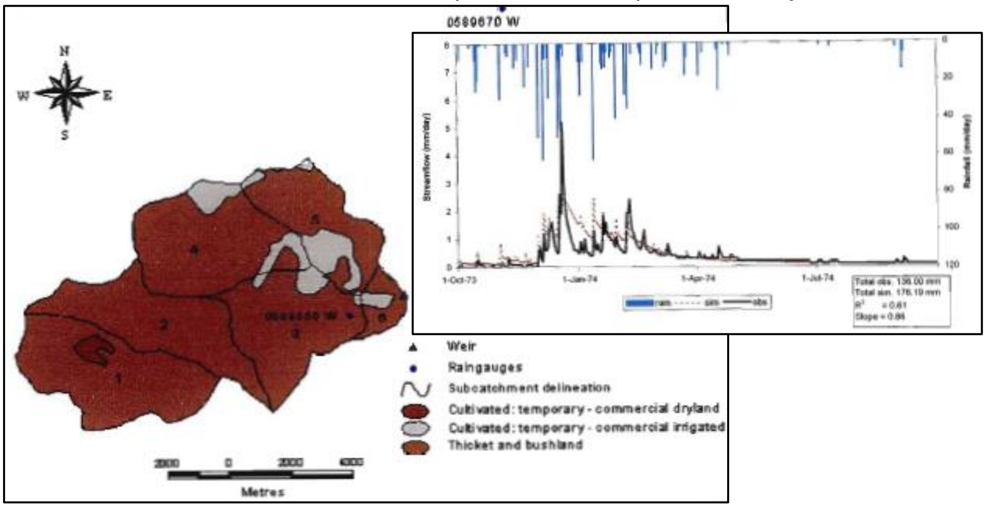


Figure 10.3.13 The Groot-Nylrivier catchment, illustrating land uses and locations of rainfall stations (left) and (right) a time series of observed (obs; solid black line) and simulated (sim; stippled) daily streamflows from October 1973 to September 1974, with summary statistics of model fit to observed data also shown (After Royappen, 2002)

Soils are highly variable, but are predominantly acidic sands, loams or gravels with a maximum depth of 1.2 m. The simulation period was from 1968 to 1978.

Observed streamflows of the Groot-Nylrivier are over-simulated quite considerably (**Figure 10.3.14** left), probably owing to the rainfall values used from two gauges located in this area being unrepresentative of the entire catchment rainfall. The poorly simulated streamflows events during 1972 and 1977 are also possibly a result of problems with the rainfall data sets used. **Figure 10.3.14** (right) shows an acceptable correlation along the 1:1 line for an operational catchment, with an R^2 of 0.76.

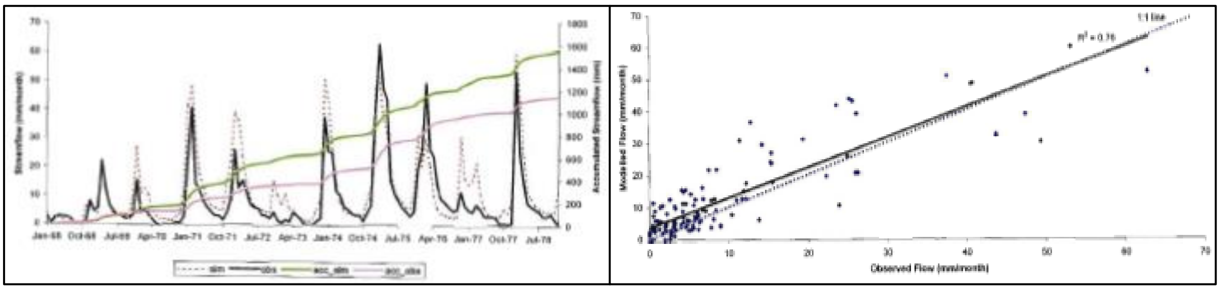


Figure 10.3.14 Time series of observed (obs; solid black line) and simulated (sim; stippled) monthly totals of daily streamflows from 1968 to 1978 for Groot-Nylrivier, with accumulated flows (accsim in green; accobs in purple) also shown, and (right) scatter plots of simulated and observed monthly totals of daily streamflows (After Royappen, 2002)

Daily streamflows shown in **Figure 10.3.13** (right) indicate that observed stormflow peaks are not simulated too well, however the "steppy" responses in the observed data set towards the end of the season is evidence of measurement errors or poor digitizing. Statistics calculated on monthly totals of daily observed and simulated streamflows (**Table 10.3.6**) show only a small difference between standard deviations of 6.84%, and a high coefficient of agreement of 0.93.

Table 10.3.6 Statistical analysis of monthly totals of daily observed and simulated streamflows for Groot-Nylrivier A6H011 from 1968 to 1978 (After Royappen, 2002)

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	6.70		Coefficient of Determination R^2	0.76
Mean of Simulated Values	11.77		Slope of Regression Line	0.93
% difference Between Means	-35.46		Y-Intercept of Regression Line	3.67
% Difference Between Std Dev	-6.84		Coefficient of Efficiency	0.70
% Difference between CVs	21.13		Coefficient of Agreement	0.93

Lessons Learned from These Verification Studies on Medium-Sized Operational Catchments

- ***Early Season Over-Simulation***
  Typically, *ACRU* over-simulates early rainfall season streamflows in the summer rainfall region, as shown for Watervalsrivier in **Figure 10.3.1** (right). This is often associated with low intensity frontal rainfalls occurring in spring and early summer. This was also shown in the Treurrivier catchment, where over-simulation by the model of the first relatively high rainfall event of the rainy season occurred.
- ***Irrigation and Other Abstractions in Operational Catchments can Confound Verifications***
  Irrigation and other abstraction patterns are very difficult to estimate, and they can be highly inconsistent during and between seasons. Thus, for example, as a result of irrigation abstractions in the Kruisrivier catchment during summer months the focus of simulations was in the winter months June to September, during which time there were no abstractions. Streamflows during non-abstraction months were simulated relatively well, as shown in **Figure 10.3.4** (left).
- ***A Warm-Up Year is Recommended for Simulation Studies***
  Initial catchment conditions for a model, e.g. regards the baseflow store or soil water content, are not always estimated well. A warm-up year (or even longer) is thus recommended for simulation/verification studies. This was shown to be the case for the Kruisrivier where, had the first season been omitted, the accumulated flows over the entire simulation period would have been nearly identical. Conversely, large differences between observed and simulated flows in the first year of the Beestekraalspuit simulation were possibly due to a large baseflow store from the previous season.

- ***Raingauges Need to be Strategically Located Within and Around Catchments***
  This is an absolute necessity for model verification studies, as a severe convective event in one part of a catchment may not be captured by gauges which measure rainfall at a point in space, but may reflect strongly in runoff which cascades down to its point of measurement. However, even if raingauges are located outside of a catchment's boundaries, if strategically located they may yield good verification results, as was the case of three rainfall gauges (0594494 W, 0594590 W and 0594764 W), located outside the Treurrivier catchment boundaries but provided good quality data and yielded excellent relationships between observed and simulated streamflows (**Figure TR1.2** left), with good correlation trends shown in **Figure 10.3.8** (right). On the other hand, streamflows in Beestekraalspruit were predominantly under-simulated (regression slope = 0.58), postulated to have been caused by rainfall values not being representative of the entire catchment, while in the Groot-Nylsrivier the considerable over-simulations (**Figure 10.3.14** left) are probably a result of the rainfall values used from two gauges located in this area being unrepresentative of the entire catchment rainfall.
- ***Observed Rainfall and/or Runoff Records May Contain Errors***
  Poor digitization of runoff recorder charts in the Beestekraalspruit catchment, for example, are believed to be the cause of "steps" in observed runoff records. Furthermore, in the Groot-Nylsrivier the daily streamflows shown in **Figure 10.13** (right) indicate "steppy" responses in the observed data set towards the end of the season, believed to be evidence of measurement errors or poor digitizng. On the other hand, the poorly simulated streamflows events during 1972 and 1977 in the Groot-Nylsrivier are thought to be a result of problems with the rainfall data sets used.
- ***Accurate Soils Input can be Vital to Good Simulations***
  As an example, streamflows from the Dieprivier catchment were very flashy, as shown in **Figure 10.3.9** (right), and associated with that were baseflow recessions which were very rapid, approaching near zero flows. Over-simulations indicate that the soils of this catchment may be much deeper than used in simulations.

As was the case with streamflow verifications on research catchments, on medium-sized operational catchments the verifications are frequently not as good as one would have them given "perfect" data, information and initial conditions, and in verification studies one needs to check inputs very carefully before making any insinuations on the hydrological model per se.

References

Royappen, M. 2002. Towards improved parameter estimation in streamflow predictions using the ACRU Model. Unpublished MSc Thesis, University of Natal, Pietermaritzburg.

Royappen, M., Dye, P.J., Schulze, R.E. and Gush, M.B. 2002. *An Analysis of Catchment Attributes and Hydrological Response Characteristics in a Range of Small Catchments*. Water Research Commission, Pretoria, WRC Report 1193/1/02. pp 142.

10.4 Verification Studies on Larger Operational Catchments 1: Crossing Major Hydro-Climatic Regions with *ACRU* Model Confirmations in the Mgeni, Luvuvhu and Breede Catchments (Original Researchers: M.L. Warburton-Toucher, R.E. Schulze and J.P.W. Jewitt)

Introduction

Together, land use change and climate change form a complex and interactive system, whereby both are human influences which can perturb hydrological responses which, in turn, can feed back to influence the climate system. An appropriate daily time step and multi-soil-layer water budget hydrological model such as *ACRU*, which is conceptualized to accurately represent hydrological processes, is sensitive to land use and adequately accounts for climate change drivers provides a means of assessing these complex interactions. At an operational water resource management scale within South Africa the suitability of *ACRU* must, however, be confirmed by assessing its ability to predict output when compared against observed data sets. The objective of this verification study, therefore, was to confirm the ability of the model through comparisons of its output with observed data sets in three hydro-climatically highly diverse operational catchments, *viz.* the Mgeni, the Luvuvhu and the Upper Breede catchments in South Africa, to be used to assess the hydrological responses to land use and its change, and in another study, to climate change. This confirmation was undertaken without field visits or calibration on these hydro-climatically diverse operational catchments in order to support the notion that *ACRU* can to be applied with confidence on catchments where streamflow data are not available and when using national databases of climate, soils, and land use as sources of information in conjunction with experience-based default parameterization of variables.

The Study Catchments in Broad Overview

The Mgeni, Luvuvhu and Upper Breede catchments were selected for this study as they vary considerably in both climate and land use in ranging in climates from the dry sub-tropical regions of the country in the north-east, to the winter rainfall areas of the Western Cape and the wetter eastern seaboard areas of the country with summer rainfall (**Figure 10.4.1**). The Mgeni catchment is a complex catchment, both in terms of its land use and water engineered system and while occupying only 0.33% of South Africa's land surface, is economically and strategically important in providing water resources to ~ 15% of South Africa's population and producing *ca*. 20% of the country's GDP. The Luvuvhu catchment contains large areas of subsistence agriculture, but is also important in regards to conservation in including parts of the Kruger National Park. The Upper Breede catchment forms part of the headwaters of the Breede River Catchment in the Western Cape, where commercial orchards and vineyards, mostly under irrigation, are the primary activity.

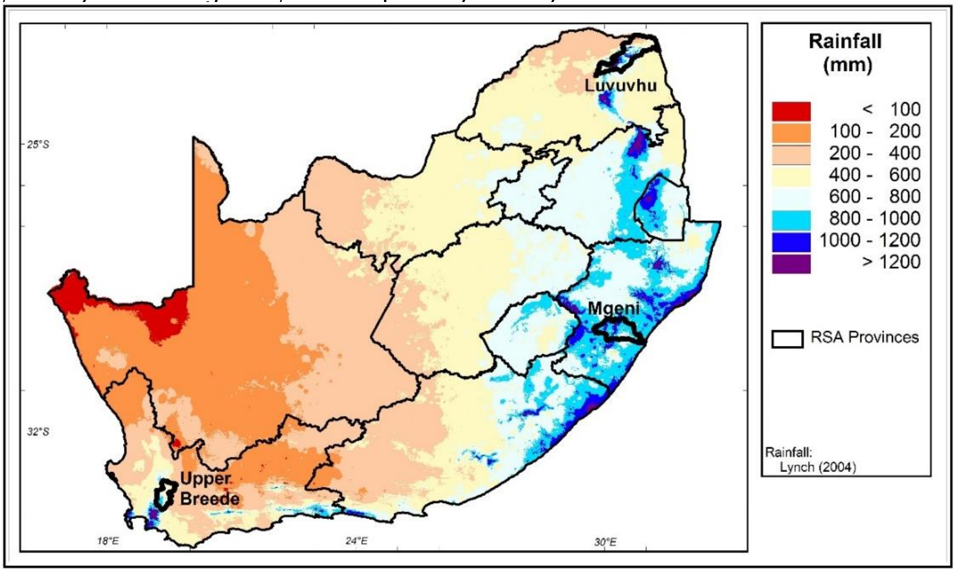


Figure 10.4.1 Location of the study catchments superimposed on a map of the mean annual precipitation (MAP) of South Africa (Warburton *et al*., 2010; MAP after Lynch, 2004)

The Mgeni Catchment: Key Modelling Related Features

The Mgeni catchment of 4 349 km^2 is located in the KwaZulu-Natal province (**Figure 10.4.1**). The altitude in the catchment ranges from 1 913 m a.s.l. in the western escarpment to sea level at its outlet into the Indian Ocean (**Figure 10.4.2**). The catchment has a summer rainfall and generally experiences a warm subtropical climate. MAP varies from 1 550 mm p.a. in the west to 700 mm p.a. in the drier middle reaches of the catchment. Rainfall throughout the catchment is, however, highly variable, both inter- and intra-annually. The mean annual potential evaporation ranges from 1 567 mm p.a to 1 737 mm p.a. The water engineered system within the Mgeni currently consists of four main dams (**Figure 10.4.2**), *viz*. Midmar (full supply capacity of 237 million m^3) supplying Pietermaritzburg and parts of Durban, as well as Albert Falls (289 million m^3), Nagle (23 million m^3) and Inanda (242 million m^3) dams supplying Durban. Additionally, there are 300 farm dams supplying water for 18 500 ha of irrigation. It is, thus, a stressed system now closed to new streamflow reduction activities for the foreseeable future.

The Mgeni catchment consists of 13 water management units (WMUs; **Figure 10.4.2**) delineated according to altitude, topography, soils properties, land cover, water management (water inputs and abstractions), inter-basin transfers, water quality sampling points and streamflow gauging. In this study the comparison of model output against observed data was undertaken at the gauged outlets of the Mpendle, Lions River and Karkloof WMUs and at a gauge point within the Henley WMU (**Figure 10.4.2**) as these WMUs had no major dams upstream of the gauging weirs for which off-takes are not known. The WMUs differ in land use, and observed streamflow data of good quality and reasonable length was available for the time period that corresponds to the available land use data. A summary of the areas, MAPs and land uses in the Mgeni catchment as a whole, as well as the Mpendle, Lions River, Karkloof and Henley WMUs is given in **Table 10.4.1**.

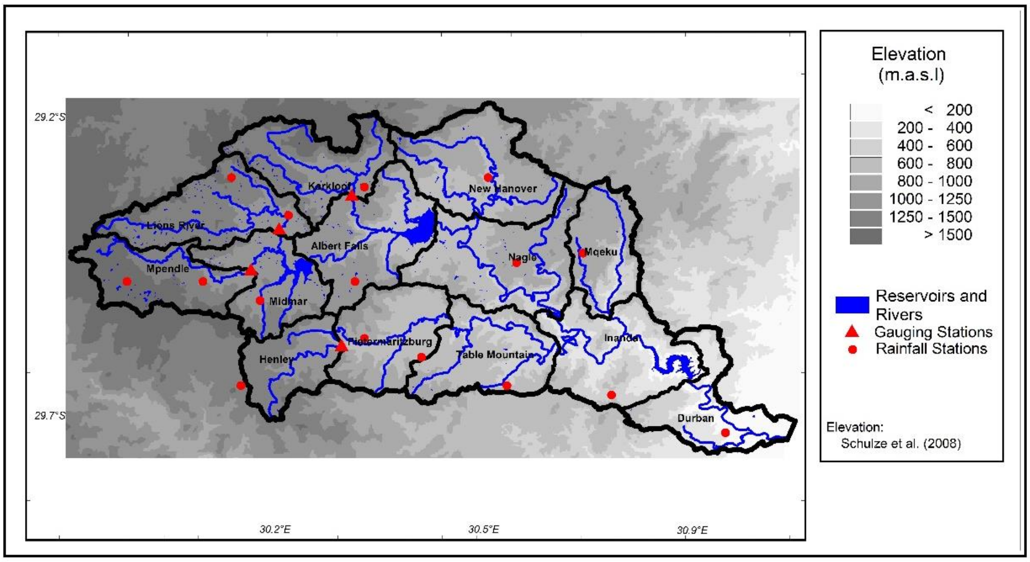


Figure 10.4.2 Water Management Units of the Mgeni catchment Africa (After Warburton *et al*., 2010)

Table 10.4.1 Summary of selected features and land uses of the Mgeni Catchment and the WMUs selected for the confirmation studies Africa (After Warburton *et al*., 2010)

Attribute	Mgeni Catchment	Mpendle WMU	Lions River WMU	Karkloof WMU	Henley WMU
Area (km^2)	4 349.42	295.69	362.02	334.29	219.98
MAP (mm p.a)	918.18	963.48	963.72	1044.96	947.77
Average Altitude (m.a.s.l)	923.30	1556.00	1387.29	1302.54	1280.05
Gauging station	-	U2H013	U2H007	U2H006	U2H011
Land uses (% of area)					
Natural vegetation	57.1	68.2	54.4	50.3	50.9
Water bodies	1.9	1.5	1.8	0.7	0.1
Alien vegetation	0.7	2.7	2.0	1.0	1.7
Degraded areas	2.4	4.1	2.1	0.5	2.7
Commercial forestry	16.0	15.4	15.8	33.6	5.2
Commercial agriculture					
- Sugarcane	5.8	0.0	0.0	0.0	0.0
- Irrigated	4.4	6.2	16.5	11.1	1.8
- Dryland	1.0	1.1	7.1	2.6	0.4
Subsistence agriculture	2.1	0.7	0.0	0.0	12.7
Urban areas					
- Commercial	0.7	0.0	0.0	0.0	0.0
- Formal residential	2.9	0.1	0.3	0.0	0.0
- Informal residential	4.9	0.0	0.0	0.0	24.4

The Luvuvhu Catchment: Key Modelling Related Features

The Luvuvhu catchment of 5 940 km^2, situated in the north-east of the Limpopo province (**Figure 10.4.1**), is drained by the Luvuvhu and Mutale Rivers flowing in an easterly direction to the confluence with the Limpopo River on the RSA-Mozambique border. The climate of the catchment is variable, both spatially and temporally, with MAP ranging from 1 870 mm p.a. in the mountainous regions (1 360 m.a.s.l) of the upper reaches to 300 mm p.a. in the drier, lower (200 m.a.s.l.) regions. The mean annual potential evaporation ranges from 1 905 mm p.a. to 2 254 mm p.a. The lower reaches of the Luvuvhu fall within the boundaries of Kruger National Park. A large proportion of the catchment is under subsistence agriculture (**Table 10.4.22**). The Luvuvhu consists of 14 WMUs (**Figure UB1.3**) which were delineated according to the Quaternary Catchments and adjusted to accommodate streamflow gauging stations. The Upper Mutale WMU (**Figure 10.4.3**) presented an ideal opportunity for a confirmation study with high quality streamflow data available and the land use and climate representative of the larger Luvuvhu catchment (**Table 10.4.2**).

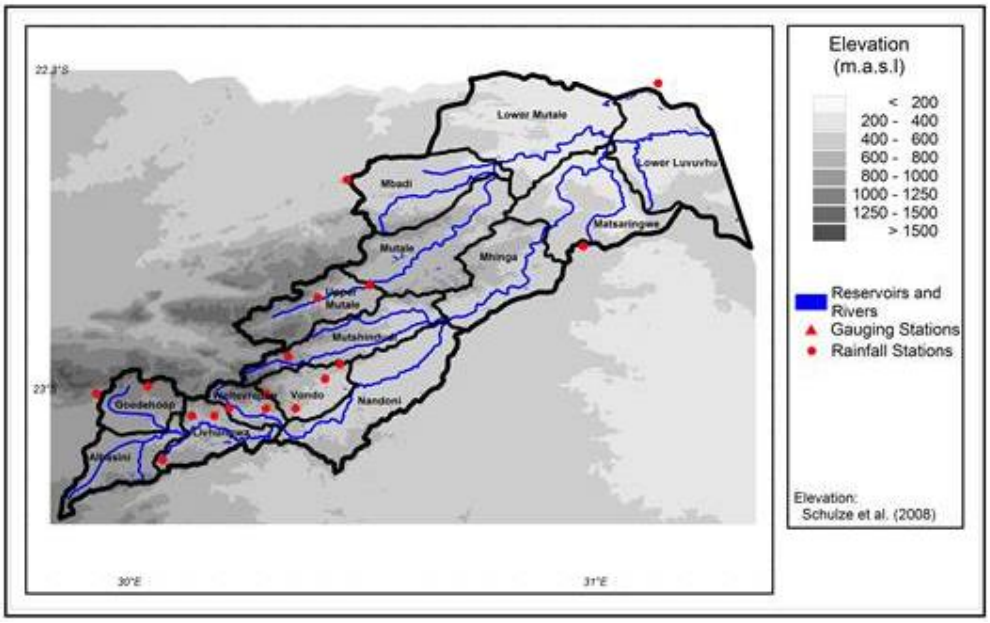


Figure 10.4.3 Luvuvhu Water Management Units (After Warburton *et al*., 2010)

Table 10.4.2 Summary of selected features and land uses of the Luvuvhu Catchment and the Upper Mutale WMU (After Warburton *et al*., 2010)

Attribute	Luvuvhu Catchment	Upper Mutale WMU
Area (km^2)	5940.35	328.91
MAP (mm p.a)	684.49	961.02
Average Altitude (m.a.s.l)	589.45	932.92
Gauging Station	-	A9H004
Land use (% of area)		
Natural vegetation	62.5%	60.8%
Water bodies	0.2%	0.0%
Degraded areas	8.1%	4.3%
Commercial forestry	6.0%	12.7%
Commercial agriculture (Irrigated)	3.0%	2.6%
Subsistence agriculture	15.8%	13.4%
Informal residential areas	4.4%	6.2%

The Upper Breede Catchment: Key Modelling Related Features

The Upper Breede catchment of 2 046 km^2 is located in the mountainous region of the Western Cape province of South Africa (**Figure 10.4.1**). The catchment is topographically rugged, with altitude ranging from > 1 990 to 200 m a.s.l. The catchment falls within the winter rainfall region of the RSA and is highly variable due to the topography, with MAP varying between 1 190 mm in the higher to 350 mm p.a. in the lower areas of the catchment. Irrigated commercial agriculture is the primary economic activity, with the main crop being high value vineyards for wine production. Other farming products include deciduous fruit, dairy and wheat. The catchment is also rich in biodiversity, which has led to conflicts between clearing of land for farming and conserving biodiversity. In the lower reaches of the catchment there are two inter-basin transfer schemes from the Upper Breede into the neighbouring Berg catchment for irrigation purposes. The Upper Breede consists of 11 WMUs, delineated into Quaternary Catchments by accounting for topography, land cover and streamflow gauging stations.

Table 10.4.2 Summary of selected features and land uses of the Luvuvhu Catchment and the Upper Mutale WMU (After Warburton *et al*., 2010)

Attribute	Upper Breede Catchment	Koekedou WMU	Upper Breë WMU
Area (km^2)	2046.44	48.17	655.74
MAP (mm p.a)	619.66	788.28	573.54
Average Altitude (m.a.s.l)	716.96	934.00	810.07
Gauging Station	-	H1H013	H1H003
Land use (% of area)			
Natural vegetation	75.8%	78.8%	66.4%
Water bodies	2.2%	2.5%	2.5%
Commercial forestry	0.5%	0.2%	0.4%
Commercial agriculture (Irrigated)			
- Permanent	12.7%	18.5%	16.2%
- Temporary	7.9%	0.0%	12.9%
Residential & Urban areas	0.8%	0.0%	1.5%

For the confirmation study the Koekedou and Upper Breë WMUs were chosen (**Figure 10.4.4**) as they have good quality streamflow data of reasonable length, the land uses are representative of that of the catchment as a whole (**Table 10.4.3**) and they are not affected by the inter-basin transfer schemes.

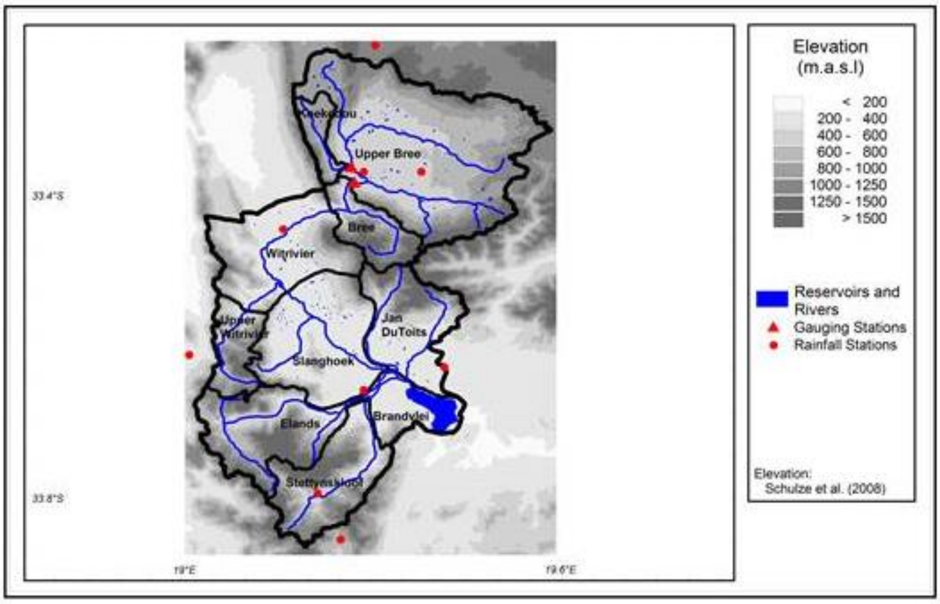


Figure 10.4.4 Upper Breede Water Management Units (After Warburton *et al*., 2010)

Model Input 1: Sub-catchment Delineation and Configuration

The WMUs were delineated into sub-catchments reflecting altitude, topography, soils properties, land cover, water management (inputs and abstractions), and location of gauging stations, with the Mgeni catchment subdivided into 145 sub-catchments, the Luvuvhu into 52 and the Upper Breede into 31 sub-catchments. These sub-catchments were considered relatively homogeneous in regards to climate and soils, but with land use within each sub-catchment varying. For this reason, each sub-catchment was further divided into major land use units for modelling purposes, with these units configured such that their streamflows cascade into each other in a logical sequence representative of river flow, and per the example of flow sequences of a sub-catchment in the Mgeni shown in **Figure 10.4.5**.

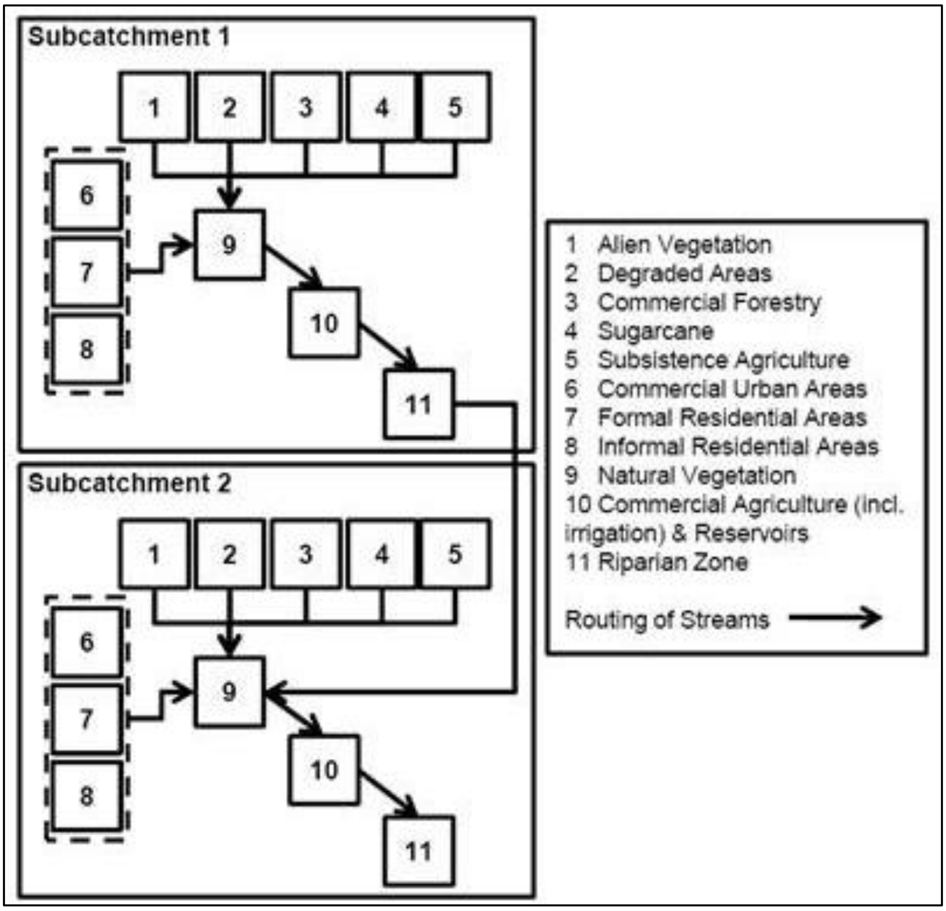


Figure 10.4.5 An example from the Mgeni catchment of cascading (i.e. routing) of flows between sub-catchments and land use units within each sub-catchment (After Warburton *et al*., 2010)

Model Input 2: Climatological and Soils Data and Information

For the Mgeni catchment 15 representative rainfall stations were selected, 16 for the Luvuvhu and 9 for the Upper Breede catchment, on the basis of reliability of the record, the altitude of the rainfall station in relation to that of the streamflow gauge, and the rainfall station's location in respect of the catchment. For each of the chosen stations a 40-year record (1960-1999) of daily rainfall was extracted from the Lynch (2004) rainfall database for South Africa. The Hargreaves and Samani (1985) daily A-pan equivalent reference evaporation equation was used to estimate daily values.

Detailed soils values required by *ACRU* were obtained for the three study areas from the electronic data accompanying the "South African Atlas of Climatology and Agrohydrology" (Schulze, 2008), while streamflow related variables and coefficients were obtained from the *ACRU* User Manual.

Surface areas of the reservoirs in the Mgeni, Luvuvhu and Upper Breede catchments were obtained from 1:50 000 topographic map sheets, with surface area to capacity relationships taken from the ACRU User Manual, with environmental flows were assumed to be equal to seepage from the farm dams. Irrigation areas were identified from the NLC (2000), with scheduling set at 20 mm applied in a fixed 7-day cycle, with the cycle interrupted only after 20 mm of rain on a given day. Standard *ACRU* spray evaporation and wind drift losses were assumed.

Background to Results of Confirmation Studies

The ability of the model to simulate the variability of streamflows as well as accumulated flows was considered. The objectives for an adequate simulation were set as a percentage difference between the sum of simulated flows ($\sum Q_s$) and of observed flows ($\sum Q_o$) of less than 15% of $\sum Q_o$, a percentage difference between the standard deviation of simulated daily flows (σ_s) and standard deviation of observed flows (σ_o) of less than 15% of σ_o, and an R^2 value in excess of 0.7 for daily simulated flows, as suggested for daily simulations by Smithers and Schulze (2004) given the high spatial variability of rainfall in the catchments. Furthermore, the Nash and Sutcliffe (1970) efficiency index (E_f) was used.

Mgeni Catchment Results

For the period of gauged flow data (1987-1998) statistics of performance on the four Mgeni WMUs are shown in **Table 10.4.4**, graphs of observed and simulated streamflow, with the daily values accumulated to monthly totals, are shown in **Figure 10.4.6** and flow duration curves of daily simulated and observed streamflows in **Figure 10.4.7**. For the Mpendle WMU the low flows and the high flows were marginally under-simulated (**Figure 10.4.6** and **10.4.7**), with the simulated stormflows not being responsive to actual events, this being attributed to the portion of degraded land in the WMU which, being scattered, makes its simulation difficult. As the total flows are adequately simulated, the percentage difference between the observed and simulated standard deviation is less than 15%, the R^2 of daily values is 0.836 and the Nash-Sutcliffe E_f is 0.802 (**Table 10.4.4**), the simulation of streamflow in the Mpendle WMU can be considered highly acceptable.

The Lions River WMU similarly produced good results with an R^2 of 0.882 (**Table 10.4.4)**. Total values of streamflow were slightly under-simulated, with the rates of baseflow (**Figure 10.4.7**) and, consequently, the hydrograph recessions providing the reason for the under-simulation (**Figure 10.4.6**). Both high flows and low flows were under-simulated in the Karkloof WMU (**Figure 10.4.6** and **Figure 10.4.7**), resulting in a difference of 13.05% between the daily means of the simulated and observed streamflows. However, the simulation was considered reasonable given that the Nash-Sutcliffe E_f is 0.655 and the other statistics (**Table 10.4.4**) fell within the objectives outlined for this confirmation study. The large portion of the Henley WMU under informal residential areas made this WMU a problematic catchment to model, as informal residential areas in the RSA are unstructured and diverse in their nature. In modelling these areas, it is not possible to fully capture the diversity of land uses and soil compaction. Thus, owing to this difficulty the results of the confirmation study for the Henley WMU can be considered reasonable as all statistics, except for the percentage difference between the standard deviations were within the objectives set for the confirmation study, and flow duration curve (**Figure 10.4.7**) indicates that the variability of streamflow was adequately simulated. The range of land uses represented in the catchment as a whole, and within the individual WMUs, made it difficult to achieve very good simulations, with this difficulty reflected in the statistics produced study. Overall, however, the *ACRU* model performed well on each of the four WMUs included, and the above results show that the *ACRU* model can be used to simulate streamflows of the Mgeni catchment, with its highly diverse land uses, with reasonable confidence.

Table 10.4.4 Statistics of performance of the *ACRU* model Mgeni Catchment: Comparison of daily observed and simulated values (After Warburton *et al*., 2010)

WMU (1987-1998)	Mpendle	Lions River	Karkloof	Henley
Total observed flows (mm)	3444.068	2507.196	3456.985	2635.724
Total simulated flows (mm)	3171.486	2257.643	3005.969	2533.988
Ave. error in flow (mm/day)	-0.063	-0.058	-0.105	-0.024
Mean observed flows (mm/day)	0.796	0.582	0.803	0.629
Mean simulated flows (mm/day)	0.733	0.524	0.698	0.605
% Difference between means	7.91%	9.95%	13.05%	3.86%
Std. Deviation of observed flows (mm)	1.823	1.734	1.228	1.246
Std. Deviation of simulated flows (mm)	2.011	1.947	1.305	1.541
% Difference between Std. Deviations	-10.34%	-12.31%	-6.26%	-23.67%
Correlation Coefficient: Pearson's R	0.915	0.939	0.844	0.886
Regression Coefficient (slope)	1.009	1.055	0.897	1.095
Regression Intercept	-0.070	-0.090	-0.022	-0.084
Coefficient of Determination: R^2	0.836	0.882	0.713	0.785
Nash-Sutcliffe Efficiency Index (E_f)	0.802	0.847	0.655	0.654

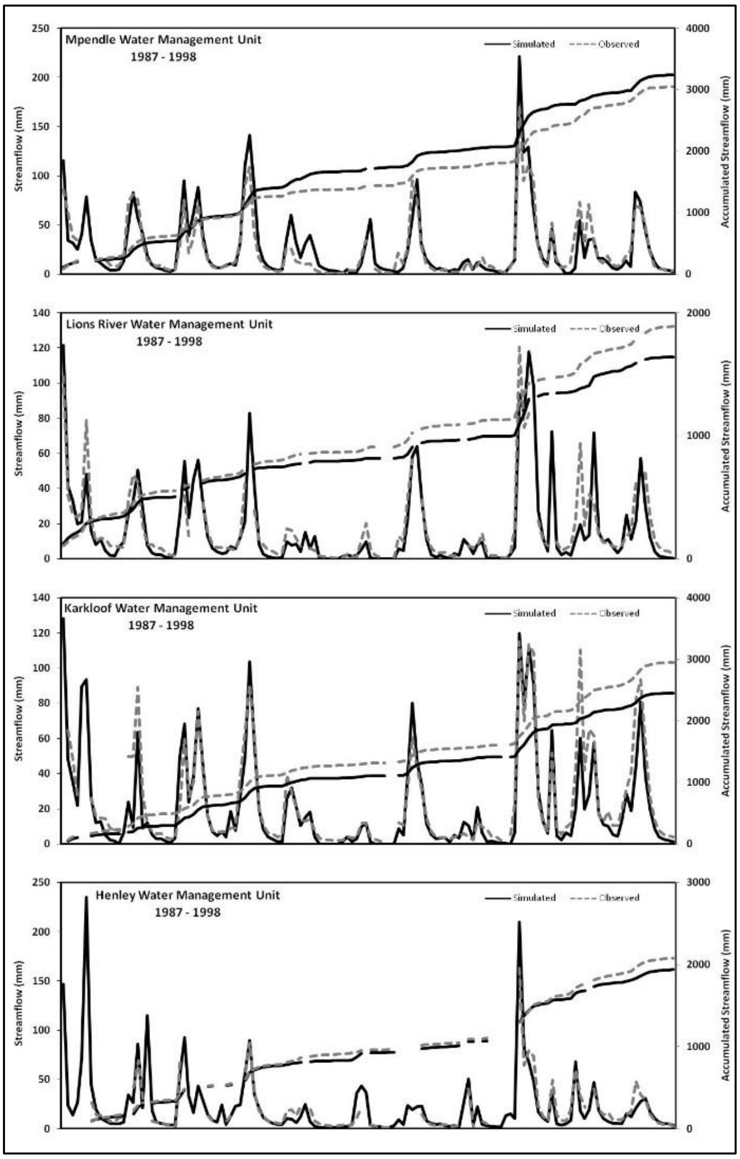


Figure 10.4.6 Comparison of monthly totals of daily simulated and observed streamflows for (from top to bottom) the Mpendle WMU, Lions River WMU, Karkloof WMU and the Henley WMU of the Mgeni Catchment (After Warburton *et al*., 2010)

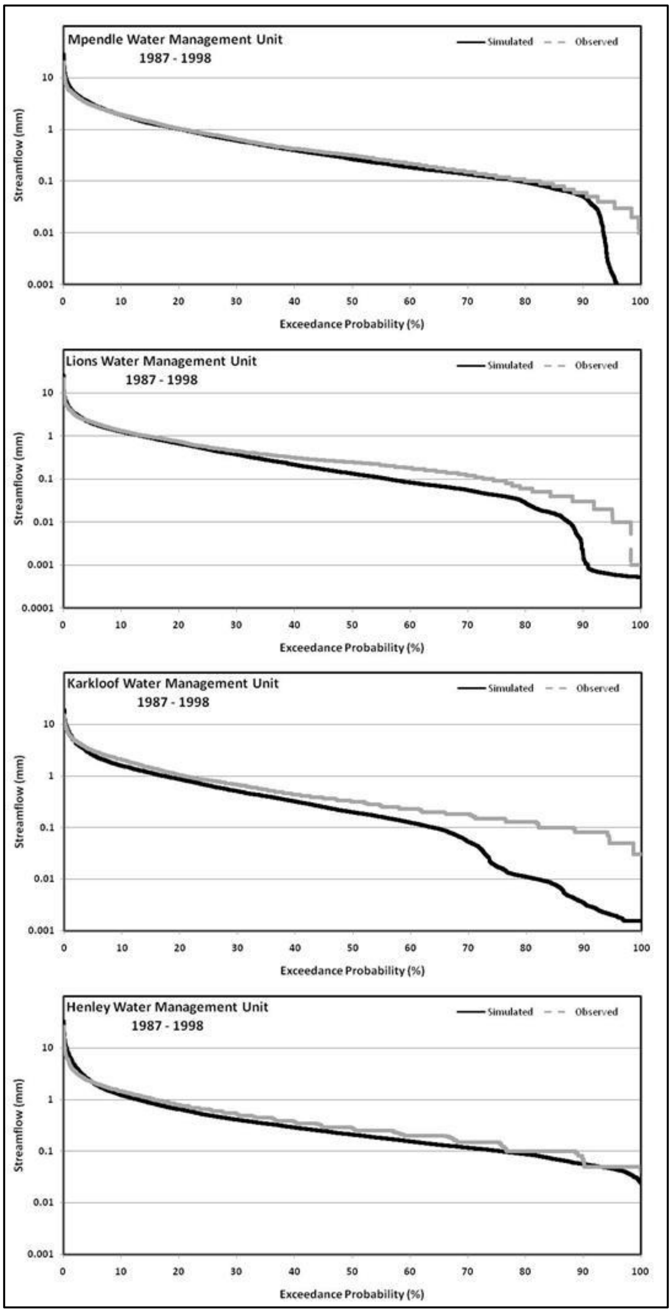


Figure 10.4.7 Comparison of flow duration curves of daily simulated and observed streamflows for (from top to bottom) the Mpendle WMU, Lions River WMU, Karkloof WMU and the Henley WMU of the Mgeni Catchment (After Warburton *et al*., 2010)

Luvuvhu Catchment Results

Observed streamflow data of appropriate quality in the Luvuvhu Catchment were available for one gauging station, *viz*. A9H004, located at the outlet of the Upper Mutale WMU, for 1970-1990. Statistics of goodness-of-fit (**Table 10.4.5**) for the Upper Mutale WMU are highly acceptable. Total values of streamflow are simulated well, with accumulated totals of observed and simulated streamflows following similar patterns (**Figure 10.4.8**). The high flows are slightly under-simulated, median flows slightly over-simulated and the low flows are well simulated (**Figure 10.4.9**), this being further indicated by the regression coefficient of 0.859 and intercept of 0.177. The Nash-Sutcliffe E_f of 0.715 supports the acceptability of the results (**Table 10.4.5**). The satisfactory goodness-of-fit statistics produced for the Upper Mutale WMU imply that streamflows of the larger Luvuvhu Catchment can also be simulated with confidence using the *ACRU* model.

Table 10.4.5 Statistics of performance of the *ACRU* model Luvuvhu Catchment: Comparison of Daily Observed and Simulated Values (After Warburton *et al*., 2010)

WMU (1970-1990)	Upper Mutale
Total observed flows (mm)	6689.166
Total simulated flows (mm)	7056.196
Ave. error in flow (mm/day)	0.050
Mean observed flows (mm/day)	0.904
Mean simulated flows (mm/day)	0.954
% Difference between means	-5.49%
Std. Deviation of observed flows (mm)	2.631
Std. Deviation of simulated flows (mm)	2.635
% Difference between Std. Deviations	0.16%
Correlation Coefficient: Pearson's R	0.858
Regression Coefficient (slope)	0.859
Regression Intercept	0.177
Coefficient of Determination: R^2	0.736
Nash-Sutcliffe Efficiency Index (E_f)	0.715

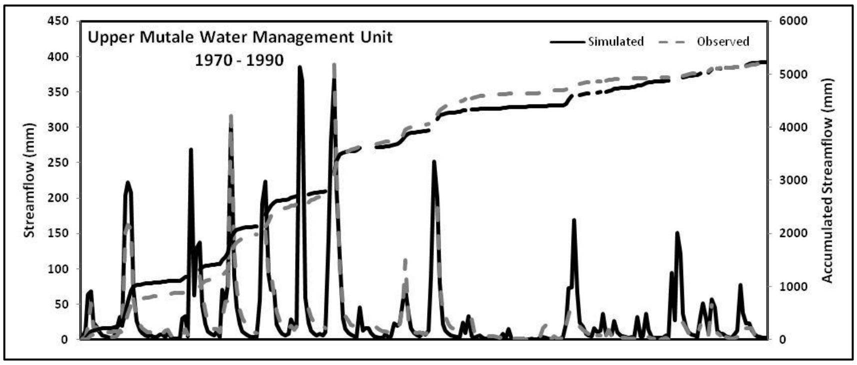


Figure 10.4.8 Comparison of monthly totals of daily simulated and observed streamflows for the Upper Mutale WMU of the Luvuvhu Catchment (After Warburton *et al*., 2010)

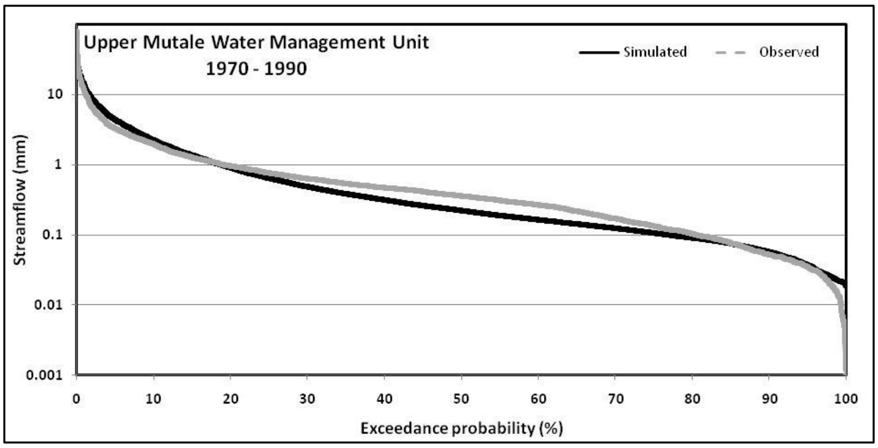


Figure 10.4.9 Comparison of flow duration curves of daily simulated and observed streamflows for the Upper Mutale WMU of the Luvuvhu Catchment (After Warburton *et al*., 2010)

Upper Breede Catchment Results

The verification study in the Upper Breede Catchment was carried out on two WMUs for the period 1987-1998 for which observed streamflow data were available. Goodness-of-fit statistics produced for the Koekedou WMU are highly acceptable (**Table 10.4.6**), with a Nash-Sutcliffe E_f of 0.785. Total accumulated flows (**Figure 10.4.10**, top) were well simulated, with the simulated pattern closely matching that of the observed. However, the regression intercept, regression coefficient (**Table 10.4.6**) and comparison of flow duration curves of daily observed and simulated streamflows (**Figure 10.4.11**, top) indicate an over-simulation of baseflows and a slight under-simulation of high flows.

Statistics for the Upper Breë show that the R^2 value of 0.712, the percentage difference of means and the percentage difference of standard deviations between simulated and observed flows fall within the acceptable limits outlined for the confirmation study (**Table 10.4.6**). However, total accumulated flows were over-simulated (**Figure 10.4.10**, bottom), high flows under-simulated and low flows over-simulated (**Figure 10.4.11**, bottom). One reason for this is that the Upper Breë contains steep topography rendering capturing the responsiveness of high flows difficult. However, since statistics are within the acceptable limits for the study, the simulation for the Upper Breë is considered acceptable. As *ACRU* performed well on the Koekedou and satisfactorily on the Upper Breë WMU, it is concluded that streamflows for the Upper Breede Catchment can be simulated with reasonable confidence.

Table 10.4.6 Statistics of performance of the *ACRU* model Upper Breede Catchment: Comparison of Daily Observed and Simulated Values (After Warburton *et al*., 2010)

WMU (1987-1999)	**Koekedou**	**Upper Breë**
Total observed flows (mm)	4209.394	1663.064
Total simulated flows (mm)	4496.732	1642.908
Ave. error in flow (mm/day)	0.070	-0.005
Mean observed flows (mm/day)	1.021	0.376
Mean simulated flows (mm/day)	1.091	0.372
% Difference between means	-6.83%	-1.21%
Std. Deviation of observed flows (mm)	5.323	0.812
Std. Deviation of simulated flows (mm)	5.639	0.768
% Difference between Std. Deviations	-5.94%	5.39%
Correlation Coefficient: Pearson's R	0.929	0.844
Regression Coefficient (slope)	0.956	0.798
Regression Intercept	0.114	0.071
Coefficient of Determination: R^2	0.864	0.712
Nash-Sutcliffe Efficiency Index (E_f)	0.785	0.516

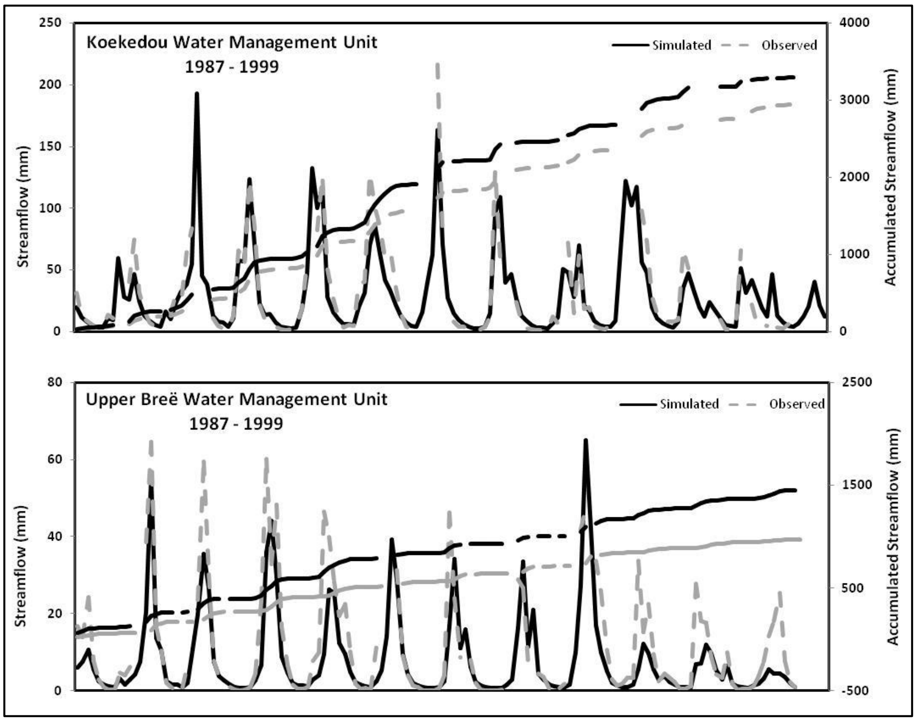


Figure 10.4.10 Comparison of monthly totals of daily simulated and observed streamflows for (from top to bottom) the Koekedou WMU and the Upper Breë WMU of the Upper Breede Catchment (After Warburton *et al*., 2010)

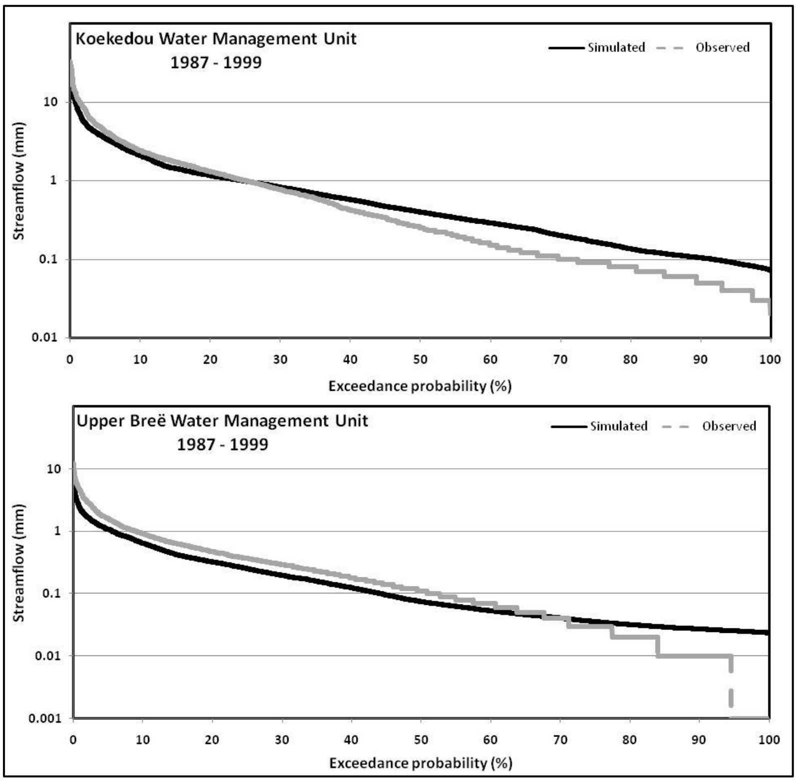


Figure 10.4.11 Comparison of flow duration curves of daily simulated and observed streamflows for (from top to bottom) the Koekedou WMU and the Upper Breë WMU of the Upper Breede Catchment (After Warburton *et al*., 2010)

In the Final Analysis

No fieldwork was carried out in the three catchments to determine values of input variables, with the simulation results produced in this confirmation study being based on national land use and soils information, together with default input values obtained from the *ACRU* User Manual where no better information was available. Based on the simulation results and with the E_f ranging between 0.847 and 0.597, it is suggested that the *ACRU* model can be used with confidence to simulate the streamflows of the Mgeni, Luvuvhu and Upper Breede Catchments. The *ACRU* model has been used many times to aid decision-making in South Africa, and applied in many hydrological designs, water resource assessments and research projects both in South Africa and internationally. To demonstrate the model's ability and acceptance, confirmation studies such as this one need to be undertaken, and this study adds to the literature confirming that the model's process representation appears to be a relatively accurate reflection of reality at a daily time step and over a range of climates.

By covering the range from the dry sub-tropical Luvuvhu to the wetter and sub-humid Mgeni in a summer rainfall region and the Upper Breede catchment with winter frontal rainfall, the confidence in the model's ability to represent hydrological responses under a range of climates has increased. Thus, in effect by using a space-time study with a process-based model, the uncertainty of *ACRU*'s ability to cope with the projected future climate scenarios is reduced. Furthermore, as the model was shown to be sensitive to diverse land uses which included commercial forestry, natural vegetation, urban areas and subsistence agriculture, uncertainties and questions regarding the model's ability to be sensitive to land use change are also seen to have been constrained. An advantage of *ACRU* over many other models, in regard to land use and climate change studies, is that it explicitly simulates the stormflow and baseflow components of runoff, with this being important because the partitioning of rainfall into different flow components may change under future climatic conditions.

Having been undertaken without calibration on these hydro-climatically diverse operational catchments, this study furthermore supports the notion that *ACRU* can to be applied with confidence on operational catchments where streamflow data are not available and when using national databases of climate, soils and land uses as sources of information, with this being the case not only under present climatic conditions, but because processes are modelled explicitly, also under projected future climates.

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10.5 Verification Studies on Larger Operational Catchments 2: Verifications on Operational Catchments from the WRC's Water Flows Project (Original Researchers: M.L. Toucher, M. Shabalala, N. Malevu, R. Sutcliffe, S. Thornton-Dibb; Edited by R.E. Schulze)

Background

With South Africa experiencing a rapidly changing landscape, and needing to support a growing population and economy, it is necessary to make increasing changes to the land's surface to ensure adequate economic growth and food production. However, with such rapid and widespread changes in land use and management, vast changes in water availability are inevitable, with these including

- Conversion of areas of natural vegetation to industrial or residential areas,
- Conversion of natural vegetation to croplands, to biofuel crops and/or to commercial forestry,
- Over-exploitation of grasslands for livestock grazing,
- Introduction of alien invasive species due to human movements and economic activities,
- Unsustainable and/or irregular fire regimes, detrimental to the ecological health of the system, and
- Misuse and degradation of riparian zones and wetlands which are vital ecological infrastructure,

all of which combine to impact upon the hydrological system at different spatial and temporal scales.

This prompted the Water Research Commission to fund the project ***Modelling of Water Flows with Change in Land Management in Selected River Catchments*** (2017-2021), with a focus on the Thukela, Waterberg, Mzimvubu and Breede catchments, and including streamflow verifications in each. Land uses needed to include at least one of alien invasion, agricultural land, bush encroachment, wetlands, denuded land or an area where non-sustainable burning regimes are practised. The ideal sub-catchment size was considered to be between 10-50 km^2 as this would allow for detailed modelling to understand the impacts of land management on flows and would prevent the masking of impacts through the accumulation of flows from different land uses. The objective of each verification study was to obtain, at a daily resolution, a percentage difference between the sum of simulated flows ($\sum Q_s$) and sum of observed flows ($\sum Q_o$) < 15% of $\sum Q_o$, a percentage difference between the standard deviation of simulated daily flows (σ_s) and standard deviation of observed flows (σ_o) < 15%, a percentage difference between the variance of simulated daily flows and observed flows < 15%, an R^2 value > 0.7 and the Nash-Sutcliffe efficiency index (E_f) close to the R^2.

The Thukela Catchment Verification Study

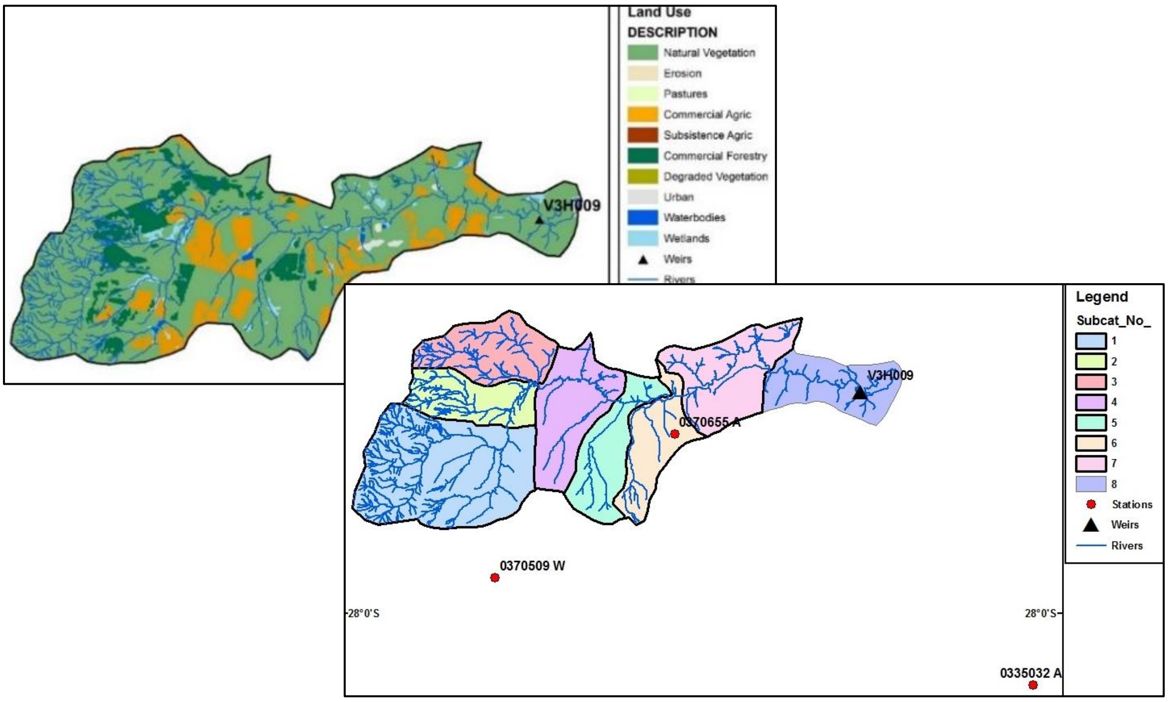

Figure 10. 5.1 Land uses and rivers (top) of Thukela sub-catchment V3H009 located in Quaternary V31F within the Thukela catchment, and (bottom) the sub-catchment delineation and locations of rainfall stations and the weir

The 148.0 km² catchment V31F monitored by weir V3H009 was selected due to the combination of wetlands and commercial agriculture/forestry (**Figure 5.1** top) which would allow for the opportunity to investigate, through modelling, the impacts of different agricultural management decisions on the functioning of the wetlands.

Catchment V31F was delineated into eight sub-catchments (**Figure 10.5.1** bottom), with each of these further sub-delineated in homogenous response units according to the land uses present. For each sub-catchment a driver rainfall station from those shown in **Figures 10.5.1** was allocated. Following extensive analysis and error checking of the streamflow and rainfall records, the verification period selected for V31F was January 1975 to December 1994. The *ACRU* model was found to simulate the flows of V31F excellently (**Table 10.5.1**), with the percentage difference between the means, variances and standard deviations being within the objectives set.

The simulated flows for V31F mimicked the observed peak and low flow periods well; similarly, the accumulated simulated flow matched the accumulated observed flows both in magnitude and trend (**Figure 10.5.2**). The flow duration curve for V31F (**Figure 10.5.3**) indicated that the high flows were well simulated, however the tail end of the low flows are over-simulated. This may be the reason for the R^2 that was obtained being slightly below the target of 0.7 (**Table 10.5.1**).

Table 10.5.1 Statistics of performance of the *ACRU* model at Thukela catchment V31F: Comparison between daily observed and simulated values

Catchment	V31F; V3H009 1975-1994
Total observed flows (mm)	2531.213
Total simulated flows (mm)	2512.622
Ave. error in flow (mm/day)	-0.003
Mean observed flows (mm/day)	0.367
Mean simulated flows (mm/day)	0.364
% Difference between means	0.735
% Difference between Variances	-0.065
% Difference between Std. Deviations	-0.032
Regression Coefficient (slope)	0.824
Regression Intercept	0.062
Coefficient of Determination: R^2	0.679
Nash—Sutcliffe Efficiency Index (E_f)	0.648

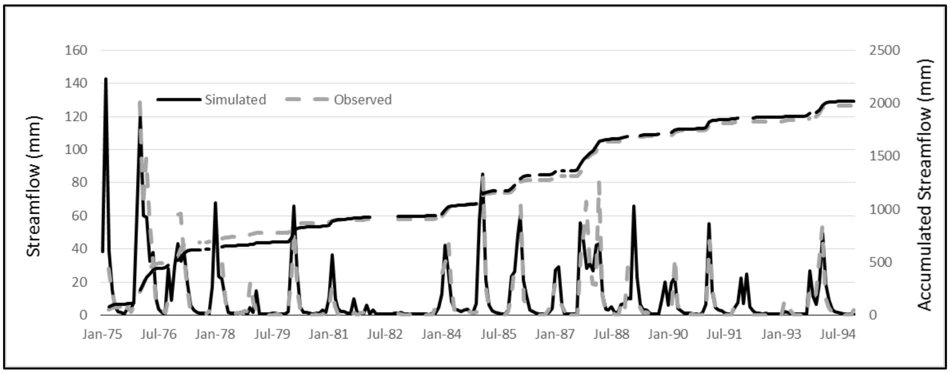

Figure 10.5.2 Comparison of monthly totals of daily simulated and observed streamflows for Thukela catchment V31F and the accumulated flows over the verification period (1975-1994)

The regression limb of the hydrographs for V11K were well simulated. However, there appeared to still be an under-simulation of the peak flows at times and the low flow months were generally over-simulated (**Figure 10.5.2**). This under-simulation of the low flows for V11K was also evident in the flow duration curve (**Figure 10.5.3**). The accumulated flows, however, showed a good correspondence in magnitude over the verification period. The R^2 value obtained for V11K was 0.361 which was below the target objective, and the Nash-Sutcliffe efficiency did not match this value (**Table 10.5.1**). This may be due to the shortness of the verification period together with the missing values in the period and, especially, the distance of the rainfall driver station from the catchment (**Figure 10.5.3**).

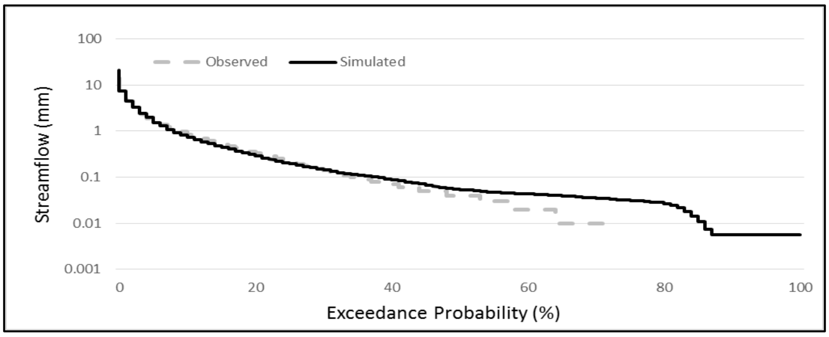

Figure 10.5.3 Comparison of flow duration curves of daily simulated and observed streamflows (1975-1994) for Thukela catchment V31F

Overall the simulation for V31F was considered to be highly acceptable and the *ACRU* model was shown to be able to simulate the flows for the land uses present.

The Mzimvubu Catchment Verification Study

The sub-catchments on which the comparison of observed and simulated streamflow could be undertaken were Quaternary catchment T35C monitored by weir T3H009 (307.0 km^2; 1964-2005) and Quaternary catchments T32C, T32B and T32A monitored by weir T3H004 (1 029 km^2; 1985-1999). Sub-catchment T35C has large tracts of commercial forestry, a number of small wetlands and small isolated areas of subsistence agriculture (**Figure 10.5.4** top right). The larger selected sub-catchment comprising of Quaternaries T32A, T32B and T32C has areas of commercial agriculture and wetlands, as well as degraded areas (**Figure 10.5.4** top left).

Catchments T32 and T35C were further delineated to reflect the altitude, topography, soils properties, land cover, water management (water inflows; abstractions), and location of gauging stations, resulting in 33 (**Figure 10.5.4** bottom left) and 17 sub-catchments (**Figure 10.5.4** bottom right), respectively. These sub-catchments are considered relatively homogeneous in terms of climate and soils; however, the land use within each one varies. Thus, each sub-catchment was further delineated into homogenous response units according to the land uses present. For each sub-catchment a driver rainfall station from those shown in **Figure 10.5.4** (bottom maps), was allocated. The sub-catchments were numbered as in **Figure 10.5.4** (bottom) and were configured to flow into each other in a logical flow path.

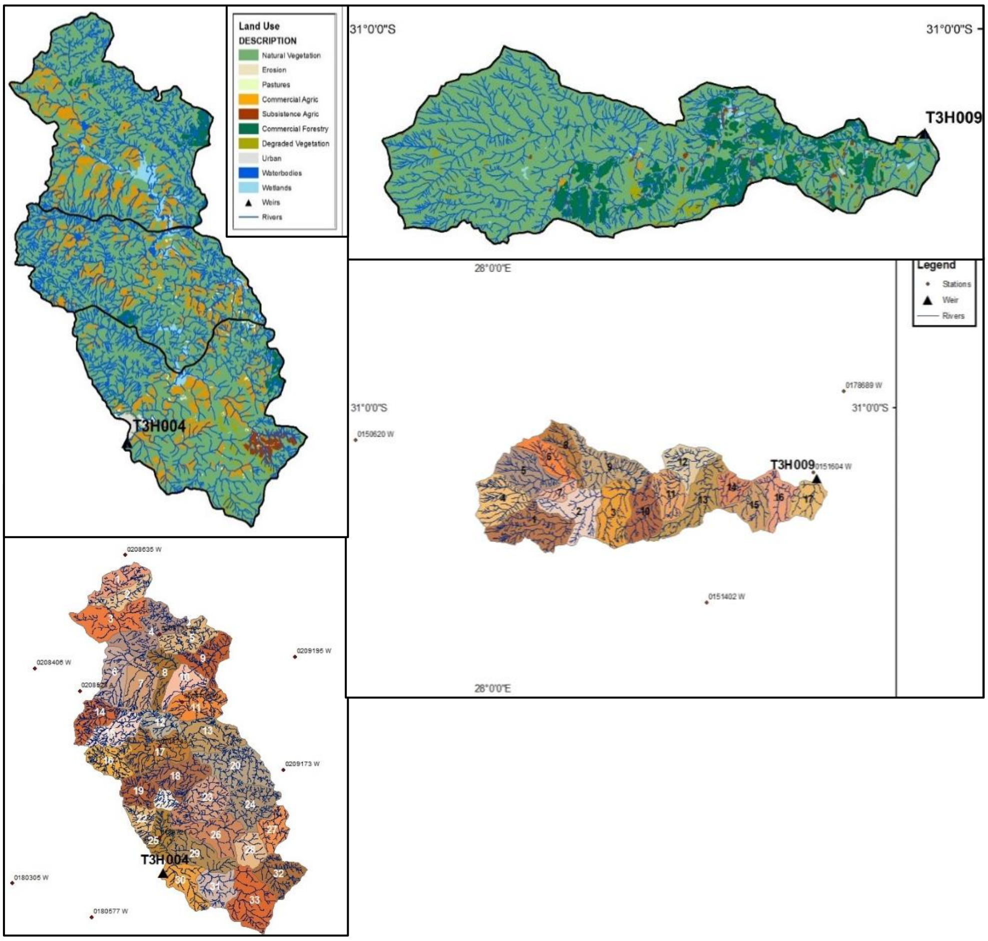

Figure 10.5.4 Land uses and rivers of sub-catchment T32A-T32C upstream of weir T3H004 (top left) and of sub-catchment T35C upstream of weir T3H009 (top right) within the Mzimvubu system, as well as their respective sub-catchment delineations, rainfall stations and the weir locations (bottom left and right)

Following an analysis of the observed streamflow data available for T32, the period with the least missing records was identified as 1965-1980, while for T35C the verification period selected was 1985-1999. After an initial simulation, several adjustments were made to the streamflow response variables and soil depths for both catchments. However, despite these adjustments, the flows in T32 were over-simulated by 22% and the flows in T35C were under-simulated by 22% (**Table 10.5.2**), which is greater than the target objectives set. However, the differences between observed and simulated variances and standard deviations were well within the desired range of < 15% for both sub-catchments, and the R^2 and E_f factors, though not exceeding 0.7, were relatively close to each other and were deemed acceptable (**Table 10.5.2**). Note that there was not a single rainfall station within the catchment.

The monthly time series of observed and simulated flows for T32 showed a generally good simulation of the peaks and the low flow periods (**Figure 10.5.5**), with a good correspondence in the regression limbs of both the simulated and observed hydrographs. This was further supported in the flow duration curve for T32 (**Figure 10.5.6**) where a good simulation of both the high and low flows is evident. The monthly flow time series of observed and simulated flows over the verification period from 1985-1999 for T35C showed a generally good simulation of the low flows, with some of the peak flows being well simulated and others under-simulated (**Figure 10.5.7**). The accumulated simulated and observed flows over the verification period were further evidence of the under-simulation, although the pattern of the accumulated flows showed good correspondence (**Figure 10.5.7**). The flow duration curve for T35C (**Figure 10.5.8**) showed that the under-simulation was due to an under-simulation of the higher end of the flow magnitudes. It also showed a tendency for the low flow magnitudes to be over-simulated. It should be noted that there was not a single rainfall station within the actual catchment.

Table 10.5.2 Statistics of performance of the *ACRU* model at Mzimvubu catchments T32A-C and T35C: Comparison between observed and simulated values

Statistics	T32A-C; Weir T3H004 1965-1980	T35C; Weir T3H009 1985-1999
Total observed flows (mm)	1377.07	4146.79
Total simulated flows (mm)	1689.46	3216.97
Ave. error in flow (mm/day)	0.064	-0.176
Mean observed flows (mm/day)	0.281	0.786
Mean simulated flows (mm/day)	0.345	0.609
% Difference between means	-22.685	22.423
% Difference between Variances	6.259	3.219
% Difference between Std. Deviations	3.18	1.622
Regression Coefficient (slope)	0.632	0.564
Regression Intercept	0.167	0.166
Coefficient of Determination: R^2	0.426	0.329
Nash—Sutcliffe Efficiency Index (E_f)	0.317	0.147

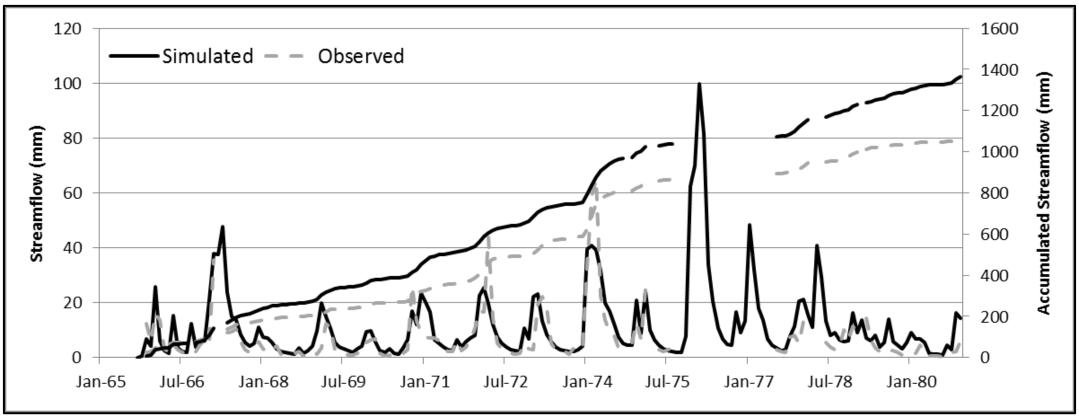

Figure 10.5.5 Comparison between monthly totals of daily simulated and observed streamflows for Mzimvubu catchment T32 and accumulated flows over the period 1965-1980

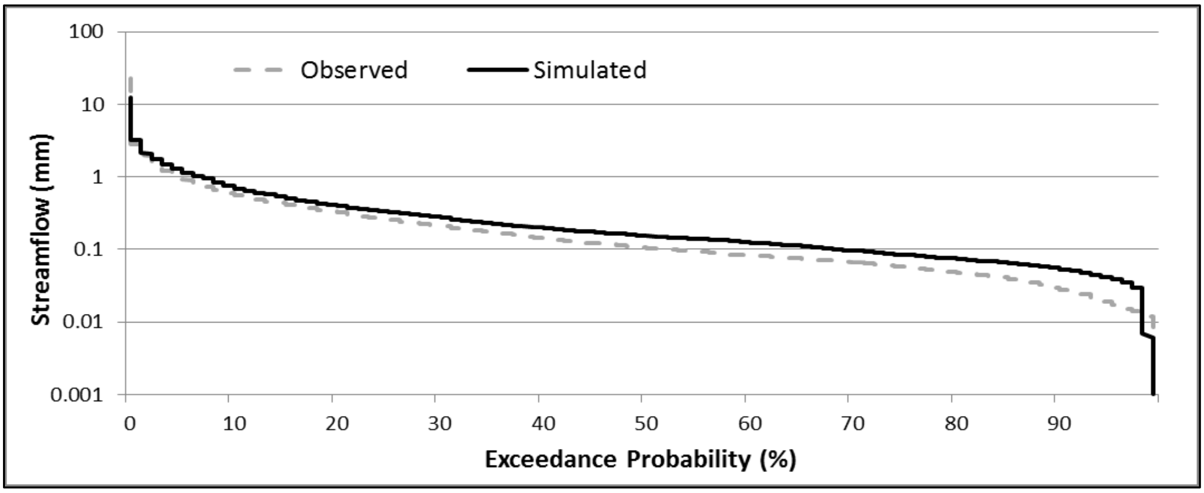

Figure 10.5.6 Comparison of flow duration curves of daily simulated and observed streamflows (1965-1980) for Mzimvubu catchment T32

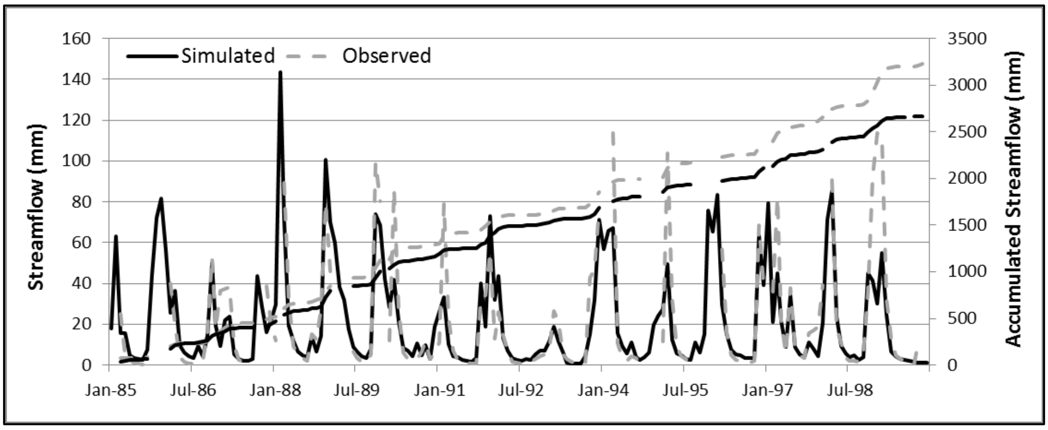

Figure 10.5.7 Comparison between monthly totals of daily simulated and observed streamflows for Mzimvubu catchment T35C and accumulated flows over the verification period (1985-1999)

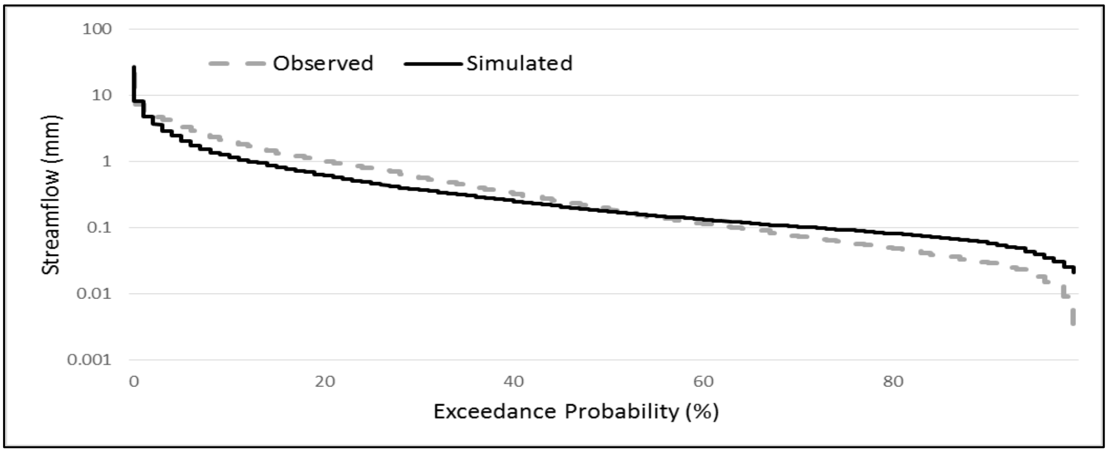

Figure 10.5.8 Comparison of flow duration curves of daily simulated and observed streamflows (1985-1999) for Mzimvubu catchment T35C

Despite the differences between the means and the R^2 value (**Table 5.2**) not being within the target objectives, these results were deemed acceptable given the data constraints for both T32 and T35C.

For the gauging weir T3H004, which monitored at the outlet of T32, it was observed that so-called 'over-topping' was taking place, and no daily average flows exceeded 38 $m^3.s^{-1}$. However, when the weir's Ratings Table was consulted, the most recent Ratings Table was from 1951 and that no allowance was made for flows in excess of 1.07 m deep. Despite best efforts to extend the ratings curve there, this was still problematic. For weir T35C the data were mostly of an acceptable quality.

One of the biggest problems faced with the sub-catchments was that of finding acceptable rainfall data. Whilst numerous stations were available in the area, many had either highly unreliable data or large percentages of patched data, implying that the driving rainfall stations for the simulations were limited to very few of stations, some of which were at a distance to the sub-catchment (see **Figures 10.5.5** and **10.5.7**). Given that much of the Mzimvubu catchment is made up of the former Transkei homeland, it is not surprising that there is such a sparse network of monitoring systems in place. However, despite this, the very small differences in variance and standard deviation between observed and simulated streamflows for the T32 and T35C catchments, and the monthly time series of flows showing that, should more acceptable data have been available, the differences in total observed and simulated streamflow would have improved the verification simulations. Thus, it is believed that the *ACRU* model is able to realistically mimic the conditions present within the sub-catchments.

The Limpopo-North Water Management Area Verification Study

Following eliminations of weirs within the Limpopo-North WMA with sub-catchments larger than 200 km^2 and with a record length shorter than 15 years, as well as weirs which ceased recording prior to 1960, two weirs remained, with the details given in **Table 10.5.3**. The land uses upstream of the weirs were mapped in order to determine whether the sub-catchments met the land use requirements, which they did. For simplicity, the portion of Quaternary catchment A61A above weir A6H010 will at times be referred to as catchment A61A and the portion of Quaternary catchment A61C above weir A6H011 will at times be referred to as catchment A61C. The catchment delineation resulted in three sub-catchments in A6H010 (**Figure 10.5.9** left) and six in A6H011 (**Figure 10.5.9** right). These sub-catchments were numbered and configured to flow into each other according to the river flow in the catchment (from 1 through to the outlet sub-catchment, being the highest number). The land uses still differed within the sub-catchments, thus they were further broken down into homogenous land use units. The locations of the rainfall stations used to drive the hydrology of the sub-catchments are shown in **Figures 10.5.9**.

Table 10.5.3 Weirs selected within the Limpopo-North WMA and catchment sizes, weir monitoring period and evaluation of the catchment land uses

Weir	Sub-Catchment Area (km^2)	Monitoring Period	Evaluation of Sub-catchment Land Uses
A6H010 in A61A	70.0	1967-1986	Commercial agriculture; degraded areas
A6H011 in A61C	73.0	1966-2005	Commercial agriculture; degraded areas

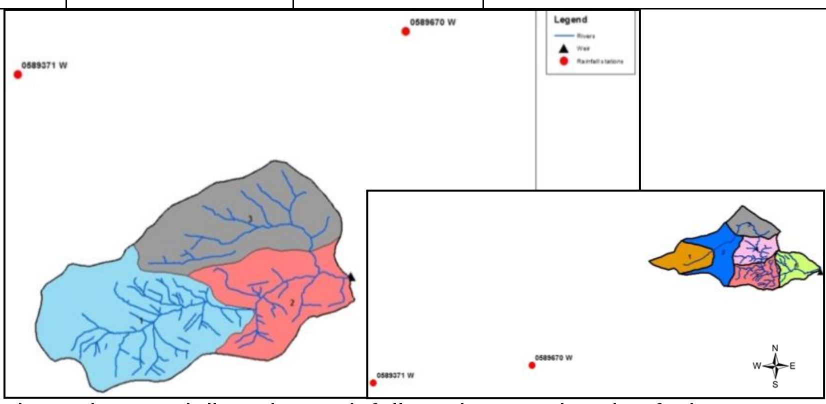

Figure 10.5.9 Sub-catchment delineation, rainfall stations and weir of Limpopo-North catchment A61A (left) and catchment A61C (right)

The initial simulation for both sub-catchments provided what was deemed to be an adequate simulation. The differences between the means, variances and standard deviations were all within the target objectives of a difference of less than 15% (**Table 10.5.4**). The regression statistics were poor for both A6H010 and A6H011, with the R^2 obtained below the target objectives and a marked difference between the R^2 and the Nash Sutcliffe efficiency (**Table 10.5.4**).

Table 10.5.4 Statistics of performance of the *ACRU* model at gauging stations within Limpopo-North catchments A61A and A61C: Comparison between observed and simulated values

Catchment	A6H010 1967-1986	A6H011 1965-1985
Total observed flows (mm)	1039.11	704.66
Total simulated flows (mm)	1117.03	679.74
Ave. error in flow (mm/day)	0.349	-0.003
Mean observed flows (mm/day)	4.66	0.09
Mean simulated flows (mm/day)	5.01	0.09
% Difference between means	-7.498	3.536
% Difference between Variances	-5.669	-6.560
% Difference between Standard. Deviations	-2.795	-3.228
Regression Coefficient (slope)	0.60	0.54
Regression Intercept	2.19	0.04
Coefficient of Determination: R^2	0.346	0.274
Nash—Sutcliffe Efficiency Index (E_f)	0.149	0.015

The monthly time series of observed and simulated daily flows for A61A shows a good representation of the observed flow peaks and low flows by the simulation in the early part of the verification period (**Figure 10.5.10**). However, the simulated accumulated flows appear to be a better representation in the latter part of the verification. The flow duration curve for A61A **(Figure 10.5.11**) shows a good representation of the high flows by the simulation, but marked over-simulation of the low flows is evident.

The time series of the monthly totals of daily simulated and observed flows for A6H011 (**Figure 10.5.12**) showed that the peaks were not simulated well in magnitude, but were in timing, and the regression limbs of the hydrographs were well simulated except for the two largest events. The accumulated simulated flows matched the pattern and magnitude of the accumulated observed flows well (**Figure 10.5.12**). However, the flow duration curve for A6H011 showed clearly the under-simulation of the low flows (cf. **Figure 10.5.13**).

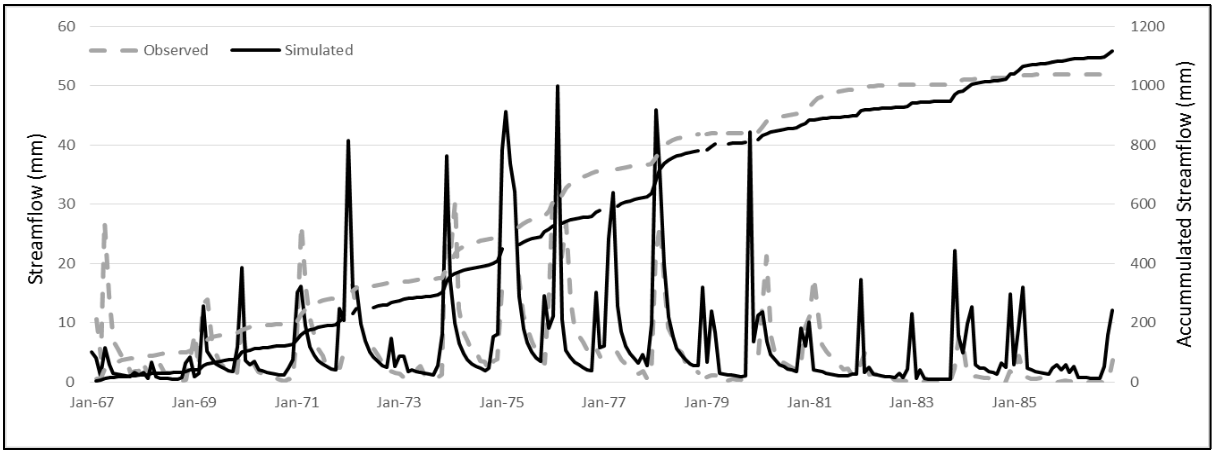

Figure 10.5.10 Comparison of monthly totals of daily simulated and observed streamflows within Limpopo-North catchment A61A and accumulated flows over the verification period

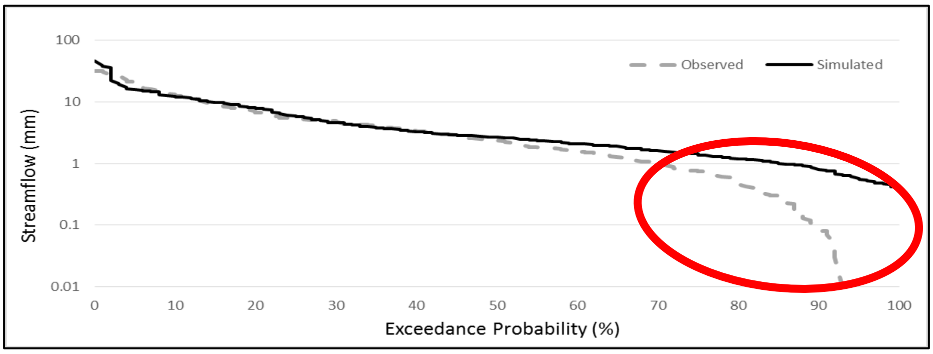

Figure 10.5.11 Comparison of flow duration curves of daily simulated and observed streamflows for Limpopo-North catchment A6H010, showing also the marked over-simulation of the low flows

The time series of the monthly totals of daily simulated and observed flows for A6H011 (**Figure 10.5.12**) showed that the peaks were not simulated well in magnitude, but were in timing, and the regression limbs of the hydrographs were well simulated except for the two largest events. The accumulated simulated flows matched the pattern and magnitude of the accumulated observed flows well (**Figure 10.5.12**). However, the flow duration curve for A6H011 showed clearly the under-simulation of the low flows (cf. **Figure 10.5.13**).

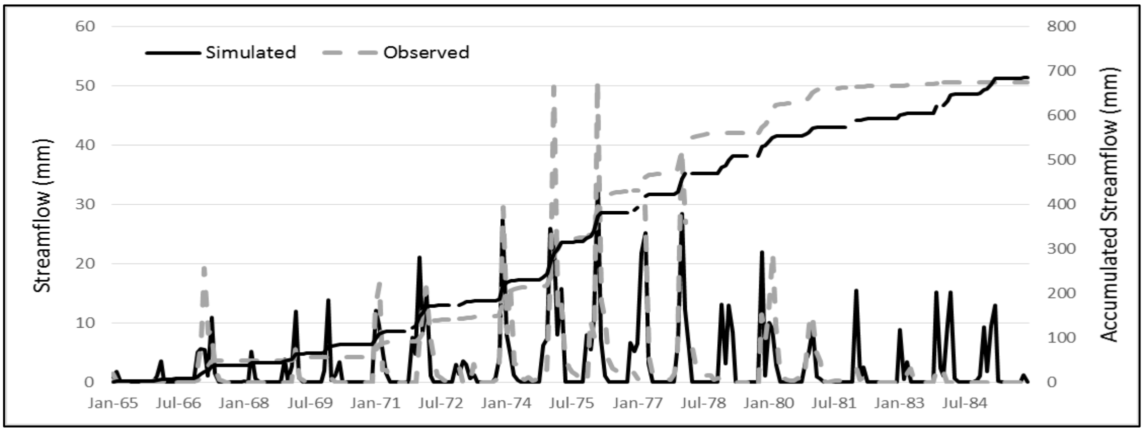

Figure 10.5.12 Comparison of monthly totals of daily simulated and observed streamflows for Limpopo-North catchment A61C and the accumulated flows over the verification period (1965-1985)

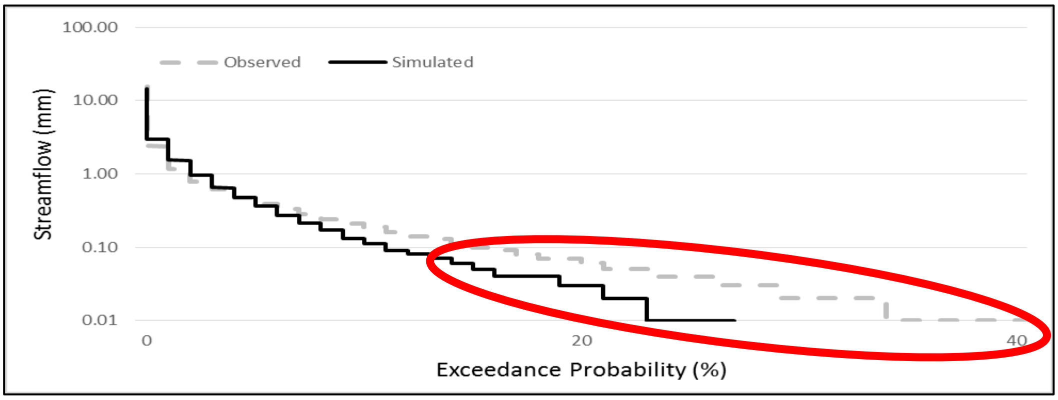

Figure 10.5.13 Comparison of flow duration curves of daily simulated and observed streamflows (1965-1985) for Limpopo-North catchment A61C, showing clearly the under-simulation of the low flows

Despite the poor R^2 values for both catchments, the simulations were considered to be adequate given the quality of the observed streamflow records for both sub-catchments. A further contributing factor was the distance of the driver rainfall stations from the sub-catchments (**Figures 10.5.9**), although statistically the rainfall stations appeared to be a good match based on the gridded monthly surfaces, the actually daily values may not be a good representation particularly given the convective nature of rainfall in the Limpopo area. Together the comparisons between the observed and simulated flows in catchments A6H010 and A6H011 provided evidence that the *ACRU* model is able to simulate the flows of the Limpopo-North WMA.

The Breede Water Management Area Verification Study

Key criteria for the selection of catchments in the Breede WMA were the presence of commercial agriculture and the size of the sub-catchments. After the start and end dates of the streamflow records for all weirs within the Breede WMA had been obtained, and weirs with sub-catchments larger than 400 km^2 had been eliminated, as were those with a record length shorter than 15 years, weirs which had ceased recording prior to 1960 as well as those with very suspect runoff to rainfall relationships, and after an evaluation of land uses within sub-catchments had been undertaken, the chosen weir was H1H003 which is located downstream of H1H013 (area 53 km^2). While weir H1H013 monitors flows generated from a tributary in Quaternary H10C, weir H1H003 monitors the flows generated from H10A, H10B and H10C. This thus it provided a unique opportunity for a nested study, across spatial scales. The hypothesis used in this specific verification study was that by demonstrating the ability of the *ACRU* model to adequately simulate various land uses at a small spatial scale, the model would adequately simulate at larger spatial scales. The use of weirs H1H013 and H1H003 for the verification study in the Breede catchment allowed for this hypothesis to be tested.

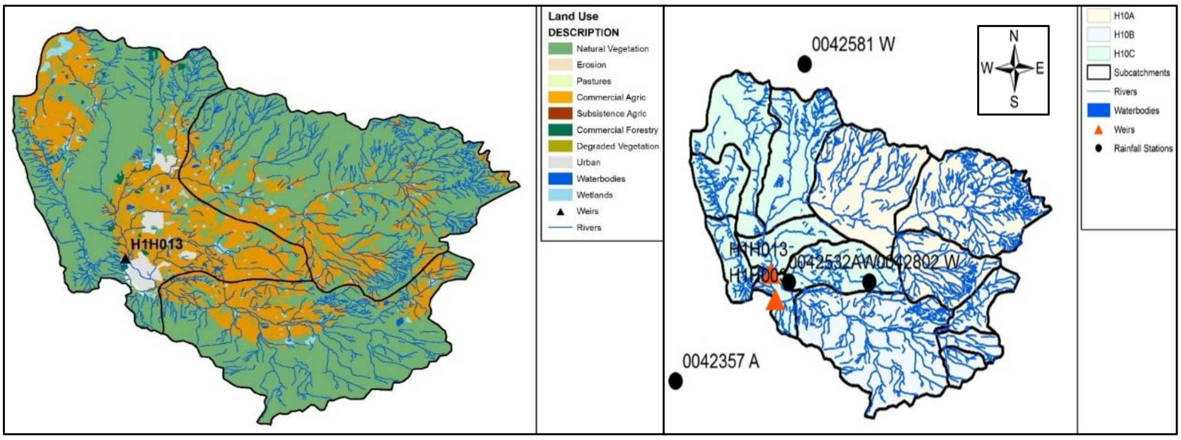

Figure 10.5.14 Land uses and rivers of the catchment comprising of Breede Quaternaries H10A, H10B and H10C within which the sub-catchment monitored by weir H1H013 falls (left) and (right) the sub-catchment delineation, rainfall stations, rivers and weirs

The catchments' sub-delineations resulted in 3 sub-catchments in H10A, 4 sub-catchments in H10B and 7 sub-catchments in H10C (**Figure 10.5.14**, right). Two of the sub-catchments in H10C formed the sub-catchment used in the verification study. These sub-catchments were numbered and configured to flow into each other according to the river flow in the catchments. The land uses still differed within the sub-catchments, thus they were further broken down into homogenous land use units. The locations of the rainfall stations used to drive the hydrology are also shown in **Figure 10.5.14** (right).

The goodness-of-fit statistics produced from weir H1H013, the sub-catchment within H10C, were considered to be highly acceptable (**Table 10.5.5**), with all the statistics falling within the objective range set. The percentage difference between the mean and standard deviations was well below the threshold objective of 15% (**Table 10.5.5**). A Nash-Sutcliffe E_f of 0.785 was attained. Total accumulated flows (**Figure 10.5.15**), were well simulated, with the simulated pattern closely matching that of the observed.

A R^2 of 0.864 for the comparison of daily observed and simulated flows was achieved, which is well above the objective of 0.7. However, the regression intercept, regression coefficient (**Table 5.4**) and comparison of flow duration curves of daily observed and simulated streamflows (**Figure 10.5.16**) indicated an over-simulation of the baseflows and a slight under-simulation of the high flows.

Table 10.5.5 Statistics of performance of the *ACRU* model at Breede sub-catchment H10C and outlet of H10C: Comparison between daily observed and simulated values

Catchment	Sub-Catchment in H10C Weir H1H013; 1987-1999	Outlet H10C Weir H1H003; 1987-1999
Total observed flows (mm)	4209.394	1663.064
Total simulated flows (mm)	4496.732	1642.908
Ave. error in flow (mm/day)	0.070	-0.005
Mean observed flows (mm/day)	1.021	0.376
Mean simulated flows (mm/day)	1.091	0.372
% Difference between means	-6.83%	-1.21%
% Difference between Standard Deviations	-5.94%	5.39%
Regression Coefficient (slope)	0.956	0.798
Regression Intercept	0.114	0.071
Coefficient of Determination: R^2	0.864	0.712
Nash—Sutcliffe Efficiency Index (E_f)	0.785	0.516

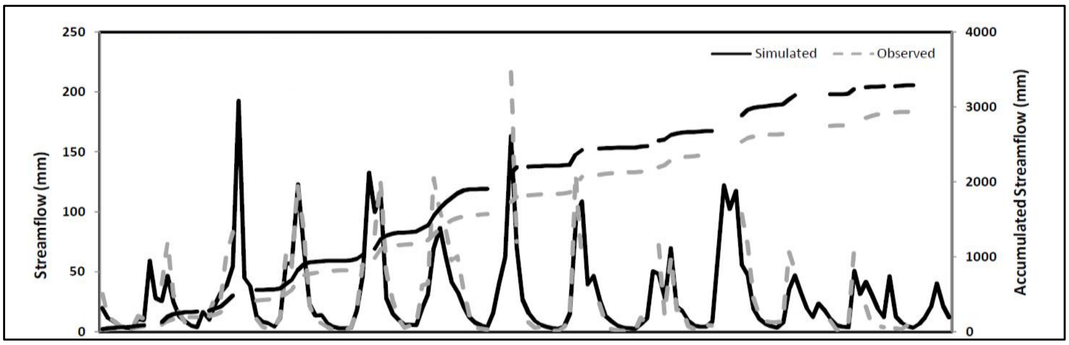

Figure 10.5.15 Comparison between monthly totals of daily simulated and observed streamflows from weir H1H013 in Breede sub-catchment H10C and the accumulated flows over the verification period 1987-1999

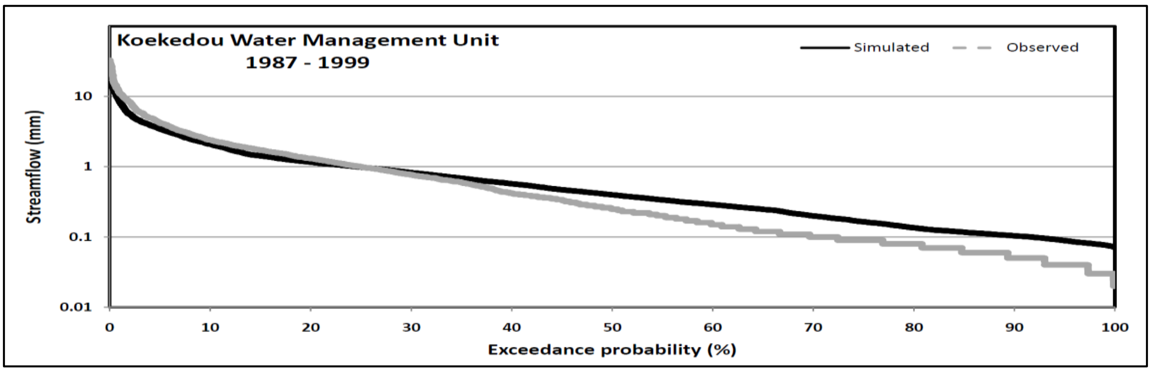

Figure 10.5.16 Comparison between flow duration curves of daily simulated and observed streamflows for Breede sub-catchment H10C for the period 1987-1999

The statistics of performance at the outlet of H10C show an R^2 value of 0.712 (**Table 10.5.5**), and the percentage difference of the means and the percentage difference of the standard deviations between simulated and observed flows fall within the target objectives outlined (**Table 10.5.5**). However, the total accumulated flows at the outlet of H10C were over-simulated (**Figure 10.5.17**). Contrary to this the time series of monthly simulated and observed flows shows a consistent under-simulation of the peaks (**Figure 10.5.17**). The flow duration curve (**Figure 10.5.18**) shows systematic over-simulation of the low flows.

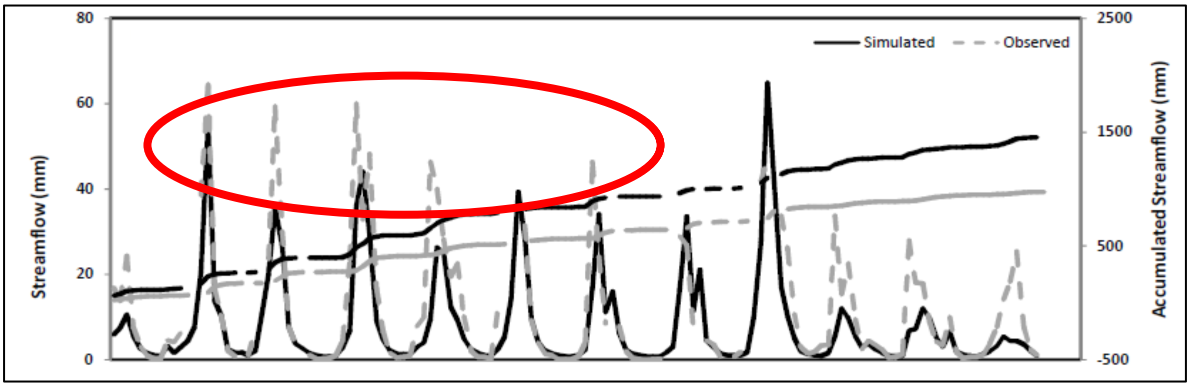

Figure 10.5.17 Comparison of monthly totals of daily simulated and observed streamflows at weir H1H003 at the outlet of Breede Quaternary catchment H10C and the accumulated flows over the verification period 1987-1999

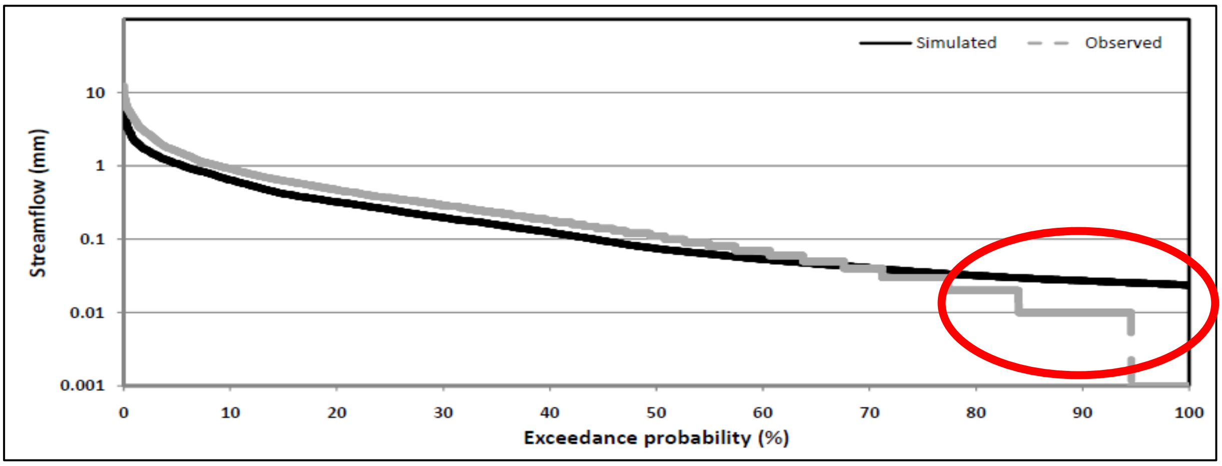

Figure 10.5.18 Comparison of flow duration curves of daily simulated and observed streamflows at the outlet of Breede Quaternary catchment H10C for the period 1987-1999

The under-simulation of the high flows and over-simulation of the low flows was consistent between the two locations. One reason for this is that the H10A, H10B and H10C Quaternaries have steep topography in places, which drop from high mountainous areas to low-lying narrow, flat river plains. This makes capturing the responsiveness of high flows difficult. However, since statistics of performance were within the acceptable limits for both considered sites, the simulation for the site within H10C and the site at the outlet of H10C can be considered acceptable. Thus, it is concluded that streamflows for the Breede Catchment can be simulated with reasonable confidence using the *ACRU* model. The *ACRU* model is able to accommodate the permanent irrigated agriculture well, with the only caution being the under-simulation due to the steepness of some of the areas.

Reference

Shabalala, M., Malevu, N., Sutcliffe, R., Thornton-Dibb, S. and Toucher, M.L. 2021. Verification Studies of the *ACRU* Model Within the Study Catchments. In Schulze, R.E. and Toucher, M.L. 2021. *Modelling of Water Flows with Change in Land ManagementIn Selected River Catchments: Report 1: Setting the Scene.* Water Research Commission, Pretoria, RSA, Report 2560/1/21. Chapter 5, 105-118.

10.6 A Verification Study on Operational Catchments that Provided More Questions than Answers: The Case of the Sabie (Researchers: A Pike and R.E. Schulze)

Please note that some figures could unfortunately not be reproduced in a desired high resolution.

Location

The 6 260 km^2 Sabie catchment in South Africa's in Primary Catchment X (**Figure 10.6.1** top) is located in Mpumalanga province and stretches latitudinally from 24°E30' to 25°E15' S and longitudinally from 30°E40' to 32°E10' E. With an altitudinal range from 150 m in the east to over 1 800 m in the west, and with patterns of MAP directly related to altitude, MAPs range over nearly 1 000 mm from 440 mm in the east to 1 425 mm in the west (**Figure 10.6.2**). The catchment consists of two major river basins, from north to south the

- Sand river basin (1 910 km^2) made up of QCs X32A to X32J and the
- Sabie river basin (4 350 km^2) made up of QCs X31A to X31M and below the confluence with the Sand, QCs X33A to X33D

with a dolomitic area runs from north to south through the upper reaches of the Sand and Sabie catchments. Runoff processes associated with karst hydrology were therefore expected to dominate the production of streamflows in sub-catchments falling within this area.

Delineation of the Area into Sub-Catchments

The 25 DWS Quaternary Catchments making up the basic spatial units of the Sand and Sabie systems were sub-delineated into 130 more homogeneous hydrological response units, HRUs, on the basis of the range of soils, land uses, reservoir locations and climatic variation found, with the HRUs ranging in area from 0.05 to 266.52 km^2 (**Figure 10.6.2** bottom right). Catchment details are given in Pike and Schulze (2001).

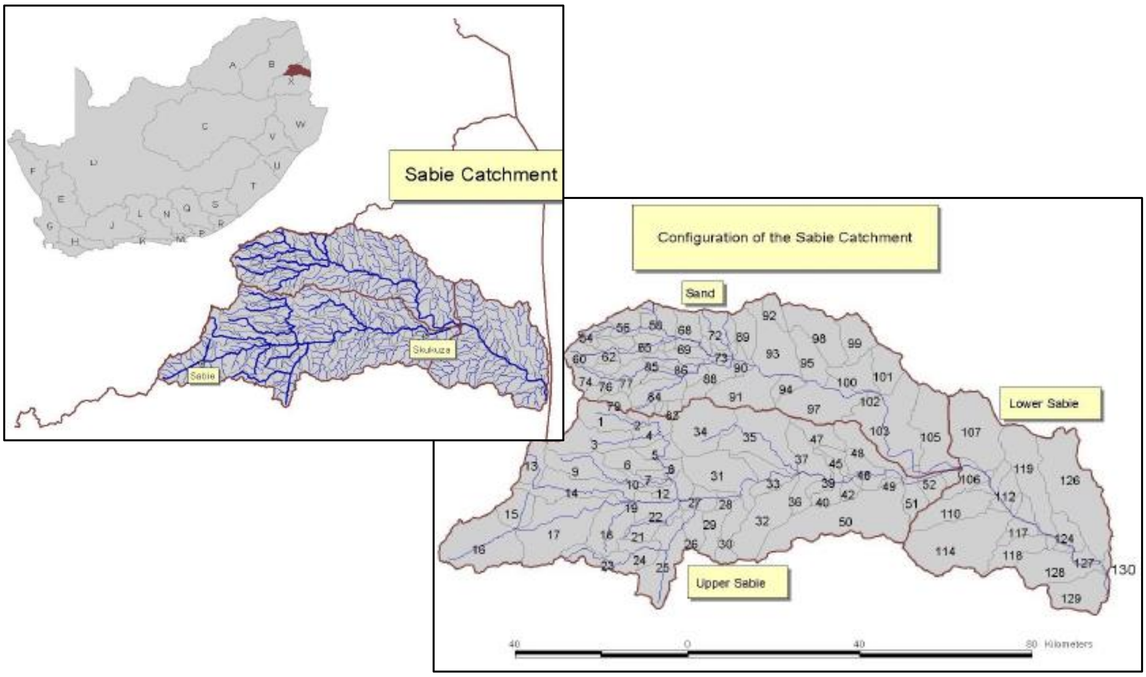

Figure 10.6.1 Primary and major sub-catchment boundaries and stream networks in the Sabie catchment (top left) as well as the sub-catchment delineation of the Sabie catchment into HRUs (bottom right), with some sub-catchment numbers omitted for sake of clarity and (After Pike and Schulze, 2001)

Model Input

In total 25 daily rainfall stations were selected to "drive" the hydrology of the 130 sub-catchments (**Figure 10.6.2** top left). Month-by-month sub-catchment area-weighted values of monthly means of daily maximum and minimum temperatures and monthly mean totals of A-pan equivalent potential evaporation were determined from 1' x 1' of a degree latitude by longitude gridded values using techniques described in Schulze (1997). The GIS coverage of soil Land Types for the Sabie catchment was obtained from the Institute for Soil, Climate and Water (ISCW) and *ACRU* related hydrological soils attributes were assigned. Land uses (**Figure 10.6.2** bottom right) were based on the CSIR's 1999 National Land Cover (NLC) Database's classification as a basis from which to derive land cover related hydrological variables for the *ACRU* model in South Africa. Additional model inputs were on irrigation, afforestation, dams (irrigation, domestic and livestock abstractions), inter-basin transfers and on sediment yield modelling. Details of the model inputs are given in detail in Pike and Schulze (2001).

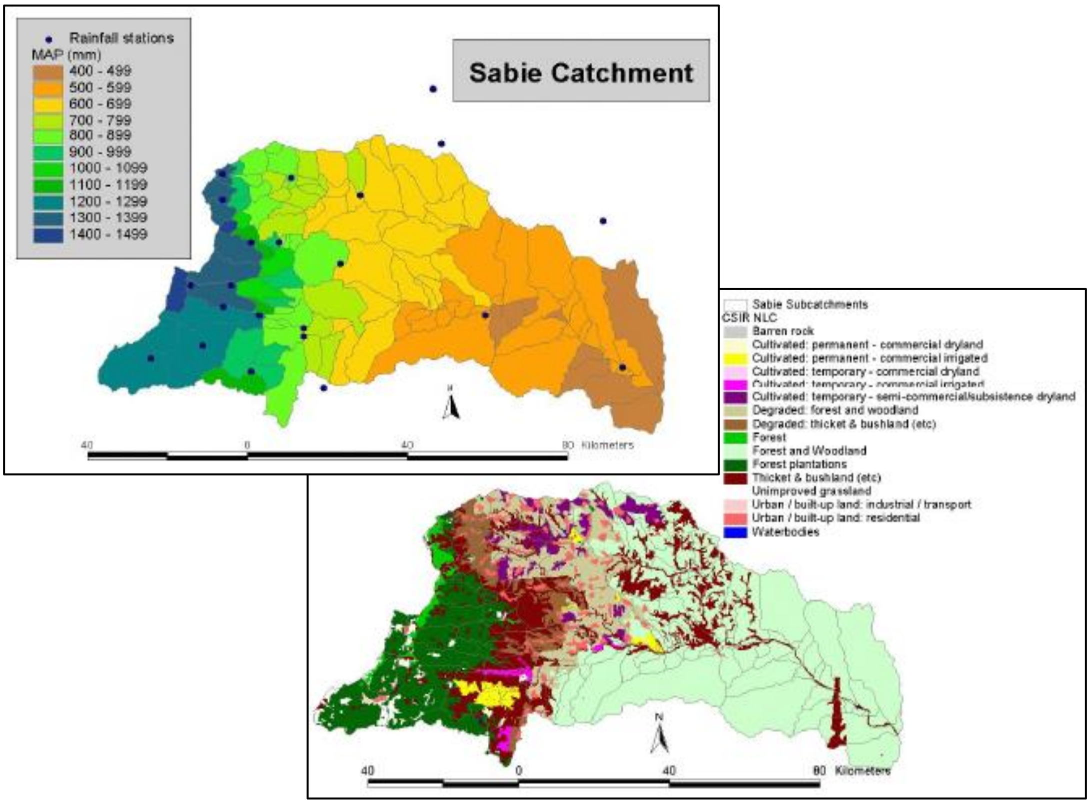

Figure 10.6.2 Sabie catchment showing the 25 daily driver rainfall stations selected for this study and the range in MAP (top left) as well as the major CSIR (1999) land use classes (After Pike and Schlze, 2001)

Why Can We Not Verify Streamflows at Every Gauging Station in a Catchment?

From **Figure 10.6.3** it is seen that in the Sand and Sabie catchments streamflow data were collected from the 10 gauging stations, with the station locations also shown in the figure.

Catchment	Sub-catchment	Station Identification Code	Contributing Area (km^2)	Monitoring Period
Sand Catchment	94	X3H008	1071.98	07/09/1967-31/05/1998
Sabie Catchment	16	X3H001	173.21	16/03/1948-30/06/1998
	15	X3H002	55.87	01/02/1964-30/06/1998
	13	X3H003	46.11	17/03/1948-30/06/1998
	25	X3H004	215.94	22/02/1948-30/06/1998
	22	X3H006	676.59	04/09/1958-30/04/1998
	23	X3H007	60.94	13/11/1963-15/09/1991
	4	X3H011	212.48	29/11/1978-31/01/1998
	125	X3H015	5783.71	03/02/1987-31/05/1998
	44	X3H021	2426.56	16/11/1990-30/06/1998

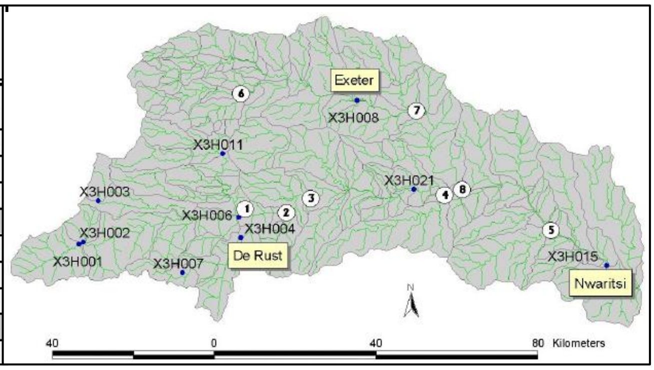

Figure 10.6.3 Monitoring periods of observed daily streamflow records for the 10 gauging stations in the Sand and Sabie catchments (left) with (right) the station locations (After Pike and Schulze, 2001)

However, numerous gauging stations had unsuitable records, and those stations needed to be systematically eliminated in order that the verification be conducted against acceptable streamflow data. The problems associated with the data measured at the various stations in the Sand and Sabie Catchment included overtopping of some of the structures occurs during flows exceeding a certain threshold, for example at gauging stations X3H007, X3H008 and X3H015 respectively. By way of example, the non-stationarity of the record in X3H007 together with the problem of the gauging station overtopping rendered those records unsuitable for verification purposes, as is illustrated in **Figure 10.6.4**.

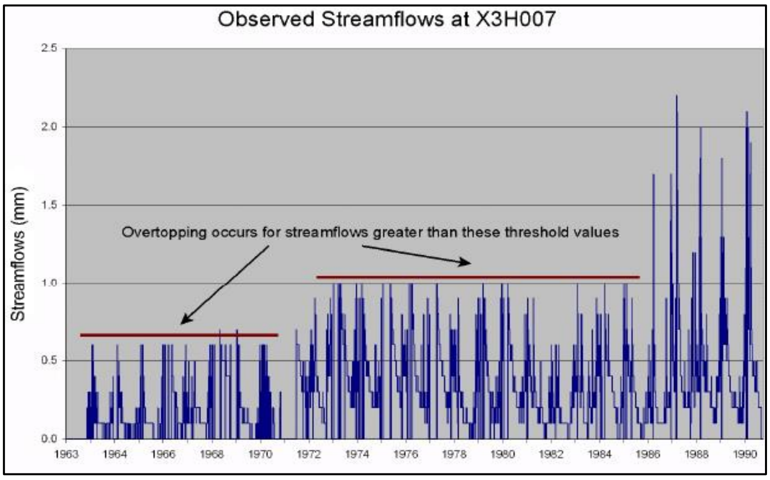

Figure 10.6.4 Plot of available observed daily streamflow data at gauging station X3H007 for the period November 1963 to September 1991, showing the non-stationarity of the record up to 1986 because of overtopping of the structure (After Pike and Schulze, 2001)

In addition to overtopping at X3H015 (see **Figure 10.6.5** where overtopping of the gauging structure is indicated by green arrows), the comparison with observations reveals another important aspect of the runoff producing processes. During the drought of 1990, the lag between the observed and simulated flows suggests that the Dolomitic (karst) areas alluded to earlier may influence the timing of flows in the Sabie. It is thus important for the user to note that *ACRU* does not model karst hydrological responses and this should be considered when selecting a catchment for verification studies.

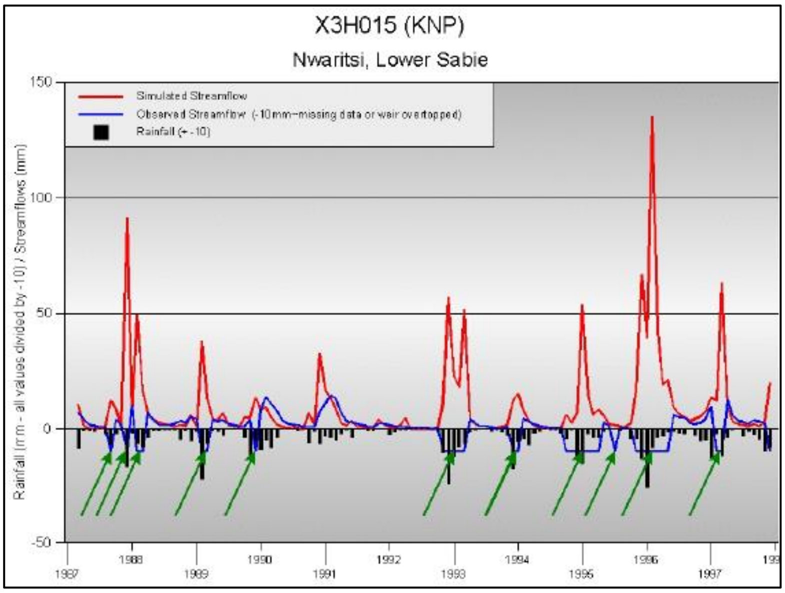

Figure 10.6.5 Monthly totals of daily simulated and observed streamflows at gauging station X3H015 for the period 1987 to 1997 showing the problem not only of overtopping (indicated by green arrows), but also the lag effect of the upstream karst hydrological processes (After Pike and Schulze, 2001)

Verifications of Streamflows in the Sabie Catchment at Gauging Stations X3H004 and X3H015

In **Figures 10.6.6** and **10.6.7** double mass plots are shown of monthly totals of daily simulated and observed streamflows at gauging stations X3H004 (Area: 215.9 km^2; 1965 to 1997) and X3H015 (Area: 5 783.7 $km^{2;}$ 1987 to 1997), with statistics of model performance given in **Tables 10.6.1** and **10.6.2**. In the interests of transparency, and to add credibility to the results of this verification study, any observed data which were excluded from the analyses are shown in **Figures 10.6.8** and **10.6.9**. The decision to discard these data points was taken when it became evident that the volume of runoff recorded by the gauging instrument was disproportionate to the amount of rainfall occurring in that month, with the problem resulting from one or more of the following factors:

- either the rainfall or streamflow records included serious observational errors which had not been flagged as unreliable data, or
- an inaccuracy occurred in process of converting the stage data to runoff data via a rating table, or
- these so-called “rogue” data points were records of flows which were generated by rainfall events which were not recorded at the raingauges selected for this study.

While the simulated flow accumulations over time mimicked the observations well, and months with high flows are well simulated on a monthly totalled basis, some of the conservation and regression statistics in **Tables 10.6.1** and **10.6.2** not satisfactory. The verification identifies potential problems in the timing the monthly flows, where some of the simulated monthly flows precede the observed flows (e.g. the summers of 1975, 1976 and 1980). However, the timing of some of the other monthly flows seems to be in phase (1972, 1978, 1985 and 1989). The inconsistency of the timing of the flows and the fact that this phenomenon is evident from monthly totals seems to suggest that the problem is of a hydrological nature as opposed to inaccuracies in the data. The *ACRU* model tends to underestimate autumn and winter low flows in the Sabie.

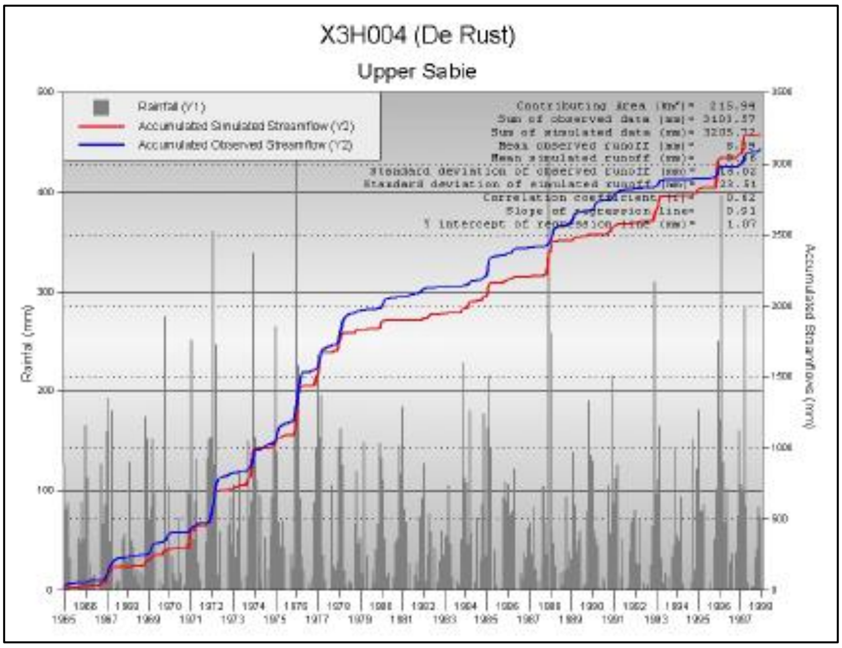

Figure 10.6.6 Accumulated daily simulated and observed streamflows at gauging station X3H004 for the period 1965 to 1997

Table 10.6.1 Verification statistics of the monthly accumulations of daily streamflows on X3H004

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	8.89		Coefficient of Determination R^2	0.38
Mean of Simulated Values	8.66		Slope of Regression Line	0.91
% difference Between Means	-2.59		Y-Intercept of Regression Line	1.07
% Difference Between Std Dev	46.75		Coefficient of Efficiency	-
% Difference between CVs	50.65		Coefficient of Agreement	-

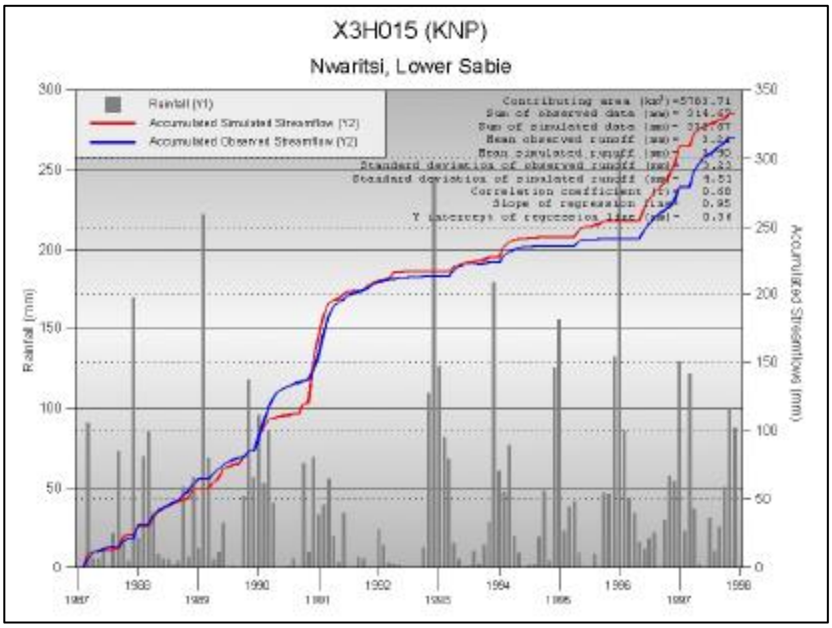

Figure 10.6.7 Accumulated daily simulated and observed streamflows at gauging station X3H015 for the period 1987 to 1997

Table 10.6.2 Verification statistics of the monthly accumulations of daily streamflows on X3H015

Conservation Statistics	Value		Regression Statistics	Value
Mean of Observed Values	3.21		Coefficient of Determination R^2	0.46
Mean of Simulated Values	3.40		Slope of Regression Line	0.95
% difference Between Means	5.92		Y-Intercept of Regression Line	0.36
% Difference Between Std Dev	100.62		Coefficient of Efficiency	-
% Difference between CVs	318.09		Coefficient of Agreement	-

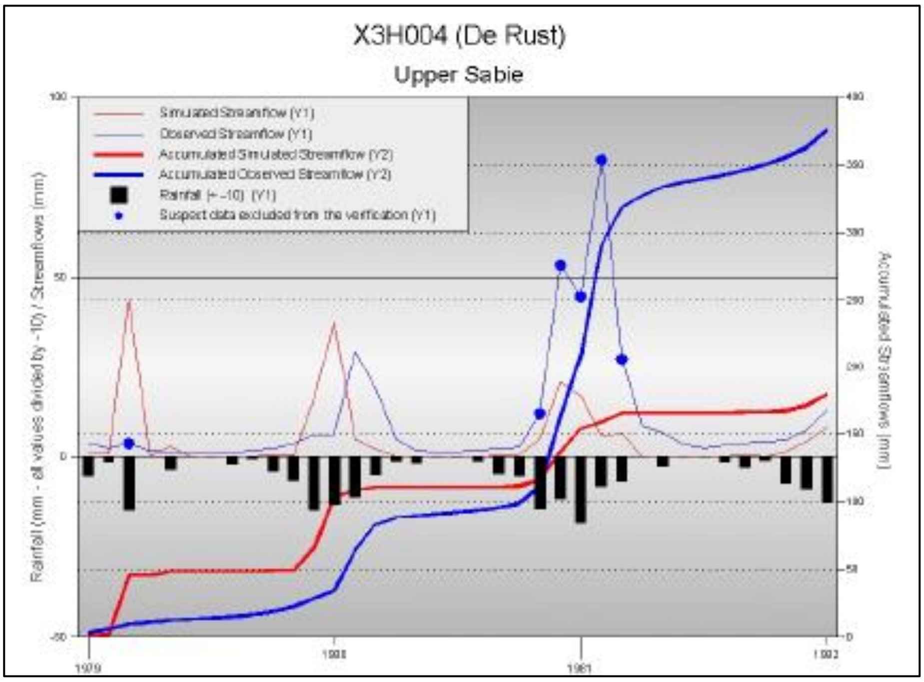

Figure 10.6.8 Diagram showing the suspect daily observed data excluded from the verification at gauging station X3H004, identified by comparing suspect data points with observed rainfall and simulated streamflows (After Pike and Schulze, 2001)

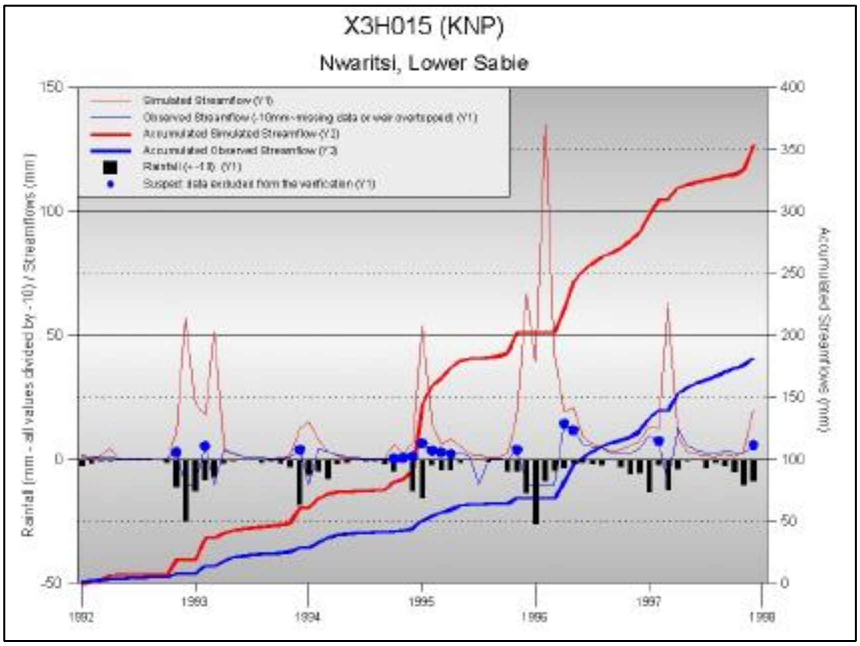

Figure 10.6.9 Diagram showing the suspect daily observed data excluded from the verification at gauging station X3H015, identified by comparing suspect data points with observed rainfall and simulated streamflows (Pike and Schulze, 2001)

Some Concluding Thoughts

Despite *ACRU* not having been developed to simulate explicitly the karst hydrological processes which occur upstream of X3H015, the verification conducted at this gauging station against 11 years of data of acceptable quality serves to show that the model performs adequately in regards to accumulated flows over time at the outlet of this sub-catchment which constitutes 92% of the total Sabie Catchment area for this period.

This study highlighted problems associated model verifications on operational catchments, including problems associated with gauging weir overtopping, non-homogeneity of catchments re. land use changes over time, key local processes (e.g. those related to karst hydrology) not catered for explicitly in the model used, inadequate raingauge networks, and certain verification statistics displaying good fits while other statistics were below expectations. It is the identification of such problems, and attempting to overcome/circumvent them, as much as achieving satisfactory goodness-of-fit statistics, which make verification studies such as these on the Sabi/Sand system valuable learning experiences.

References

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10.7 A Verification Study on Operational Catchments that Provided More Questions than Answers: Can "Overkill" in Hydrological Detail in an Operational Catchment Lead to Sub-Optimal Verification Results? A Case Study from the Blyde Catchment (Researchers: L. Hayes, G.P.W. Jewitt and R.E. Schulze)

Background

The Upper Blyde catchment is situated in the north-east of the RSA in Mpumalanga province (**Figure 10.7.1**) at between 1 500 and 2 400 m above sea level, and it makes an important contribution to the Olifants River system in terms of both water quality and quantity.

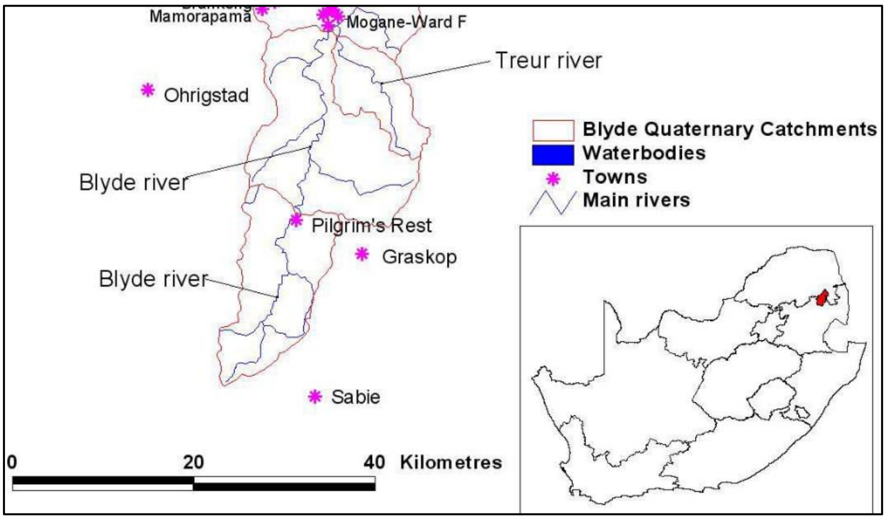


Figure 10.7.1 Location of the Upper Blyde River Catchment in Mpumalanga Province, South Africa

Complexities of Land Uses within the Upper Blyde Catchment

- Within the catchment impacts of plantation afforestation (**Figure 10.7.2** left), including their removal and the rehabilitation plans and practices associated with them, have widespread implications for hydrological responses and environmental resources. Modelling afforestation impacts realistically involves complex hydrological modelling procedures.
- Similarly, Invasive Alien Plants (IAPs; **Figure 10.7.2** right) impact water yield and the conservation and rehabilitation of riparian zones, with
- the riparian zone, delineated as a 30 m buffer around rivers (**Figure 10.7.3** left), estimated to cover nearly 10% of the catchment area, 17% of which is infested by IAPs to varying degrees of density, with the most predominant invasive species in terms of their extent being *Pinus, Lantana, Rubus,* and *Acacia* species*.* These plants are considered a threat to the natural systems and biodiversity in the area, especially in wetlands and riparian zones. As with afforestation, modelling AIP and riparian zone hydrological responses involves complex modelling procedures.

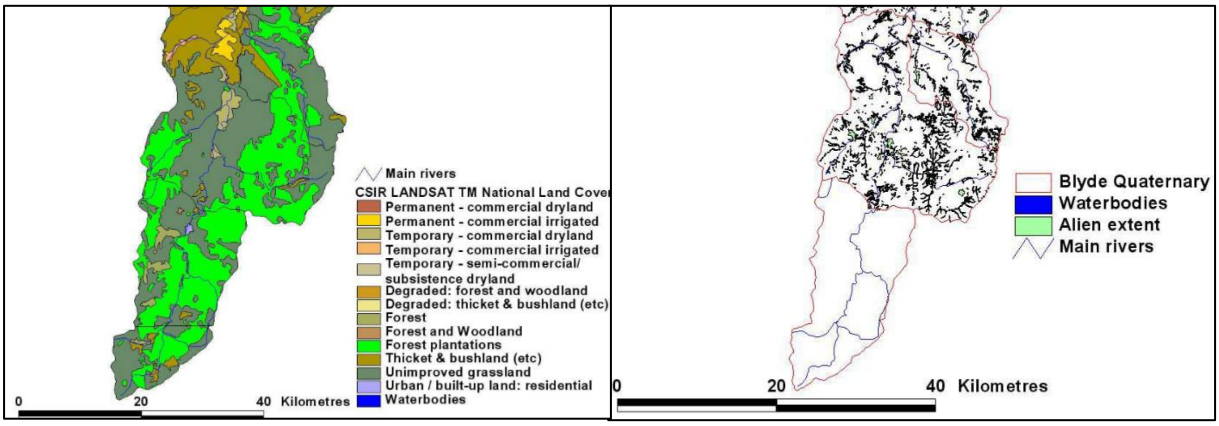


Figure 10.7.2 Land uses in the Upper Blyde catchment (left) with forest plantations in bright green, and (right) the extent of Alien Invasive Plants

- When simulating the hydrological response of the riparian zone, *ACRU* routes all contributing areas' surface flows into the channel (riparian zone) and baseflows are routed from the contributing areas to the riparian zone as subsurface flows. This increases the soil moisture, making more water available to vegetation. When the soil profile becomes saturated to the soil surface, excess water is added to the stormflow contribution of runoff. While the above processes are "hydrologically logical", they do add an element of complexity to modelling which, in real life, may not always be captured realistically.

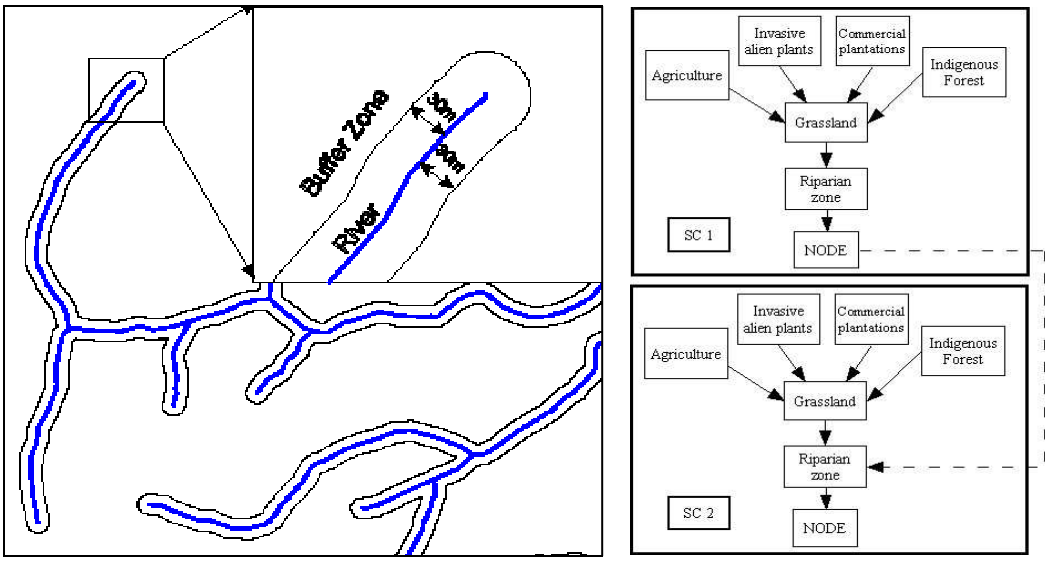


Figure 10.7.3 The 30 m buffer zone generated around rivers depicted on the 1:50 000 topographical map sheets (left) and (right) the configuration of upstream sub-catchment contributions and routing of hydrological response units within sub-catchments

- In this verification study, runoff from all upstream hydrological response units (HRUs) representing different land uses in the catchment were routed to the grassland HRU and then through the riparian zone (**Figure 10.7.3** right). Thus, only the grassland HRU contributed to additional moisture in the riparian zone. In this configuration, the baseflow and stormflow generated by the riparian zone were combined and routed through the channel downstream as streamflow. Again, while "hydrologically logical", this configuration might not capture fully the realities of flows within a catchment.
- Further to modelling the above land use complexities, mining in Pilgrim's Rest abstracts directly from the Upper Blyde River at ~ 193 000 litres per day, i.e. ~ 5 790 m^3 per month.

What Do Verification Results Show when Considering the Complexities of these Land Uses?
Monthly totals of simulated daily streamflow values were compared to observed data from two streamflow gauging stations (**Figure 10.7.4** left), *viz*. B6H001 (511.7 km^2) and B6H003 (94.2 km^2).

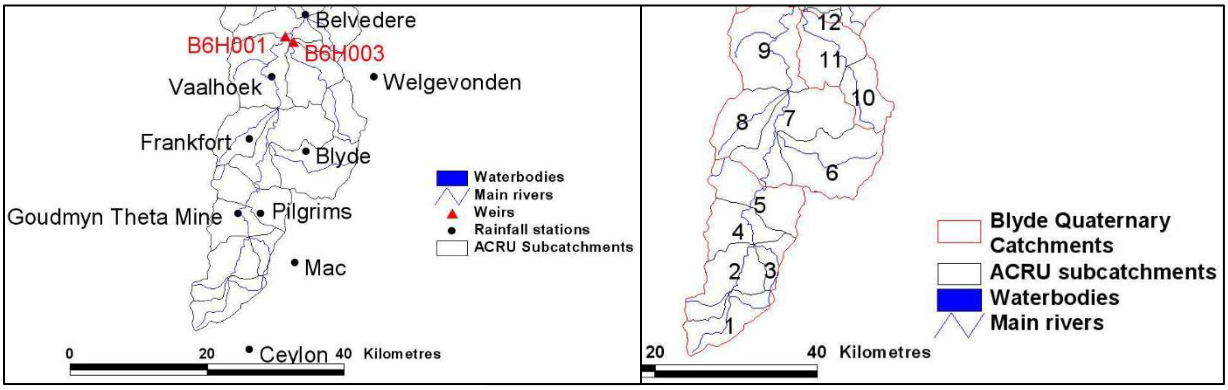


Figure 10.7.4 Rainfall and streamflow gauging stations in the Upper Blyde catchment (left) and (right) sub-catchment delineation

Gauging weir B6H001 lies at the outlet of sub-catchment 9 (**Figure 10.7.4** right), with results for simulated streamflows showing an under-simulation when using *ACRU* model (**Figures 10.7.5** and the table in **Figure 10.7.6**6), especially during periods of peak flows in 1998 to 2000. Seasonal trends are simulated relatively well with over-simulations during winter months. *ACRU* is not generating enough baseflow, but there does not seem to be a substantial phase shift and the general trend is captured well. However, the tabulated results in **Figure 10.7.6** (right) indicate a difference of more than 30%. Is this the result of data of poor quality (rainfall and streamflow)? Or are there just too many complexities and assumptions regarding the parameterization of land uses and their interlinkages? There is, sadly, no way that this can be checked in a complex operational catchment.

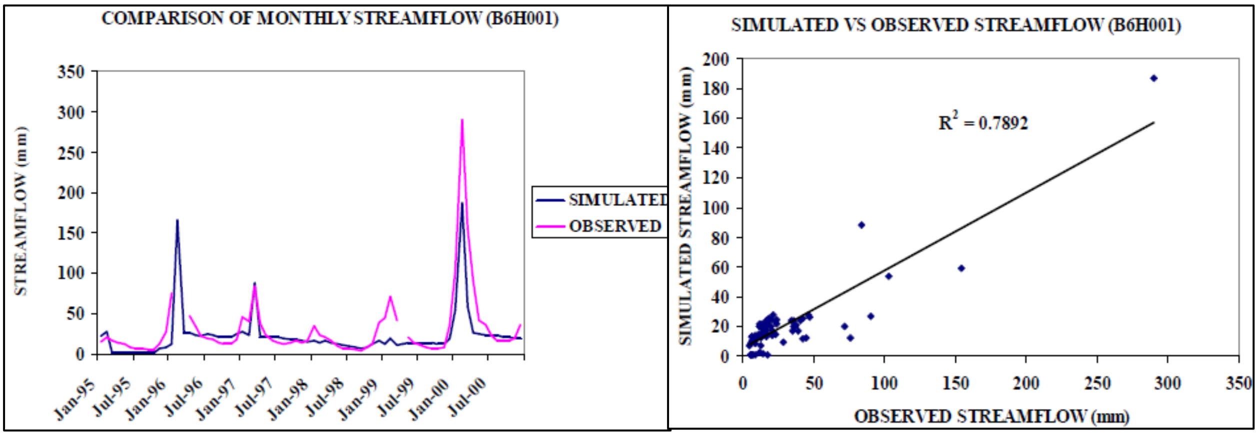
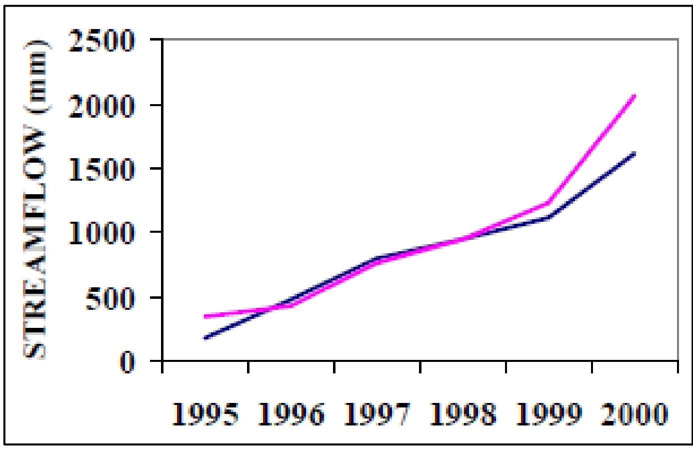


Figure 10.7.5 Comparison of 1995-2000 total monthly streamflows (left) and (right) a scatter plot of simulated versus observed streamflow at gauging weir B6H001



CONSERVATION STATISTICS	
Sum Observed Values	2071.83
Sum Simulated Values	1417.25
Mean Observed	30.03
Mean Simulated	20.54
% Difference Between Means	31.59
% Difference Between Variances	65.02
% Difference Between Standard Deviations	40.86
% Difference Between Coefficients. Of Variation	13.54
% Difference Between Skewness Coefficients	-18.40
REGRESSION STATISTICS	
Correlation Coefficient - Pearson's r	0.89
Regression Coefficient (Slope)	0.53
Regression Intercept	4.77
Coefficient of Determination - R^2	0.79
Coefficient of efficiency	-0.01
Coefficient of agreement	0.94

Figure 10.7.6 Comparison of accumulated streamflows at B6H001, with pink line showing observed and blue line simulated streamflow (left) and (right) statistical analysis of monthly totals of daily observed and simulated streamflows

The second verification in the upper Blyde system was at the 94.2 km^2 catchment at gauging weir B6H003 on the Treur river at the outlet of sub-catchment 11 (**Figure X.4**), with graphical results (**Figures 10.7.7** and **10.7.8**) for simulated streamflows indicating a good simulation and general trend of observed values. The seasonal trends are accurate with no significant phasing effects. Peak flows are consistently under-simulated but fall in phase with observed values. Low flows appear to be slightly over-simulated (baseflow retention too high).

The results obtained for the simulation at B6H003 indicate a difference of 18% (Table in **Figure 10.7.8** right). This is markedly better than the simulation obtained at the much larger B6H001 and can most likely be attributed to the fact that the Treur River catchment is a smaller catchment and therefore more likely to have fewer complexities regarding modelling assumptions made on land uses.

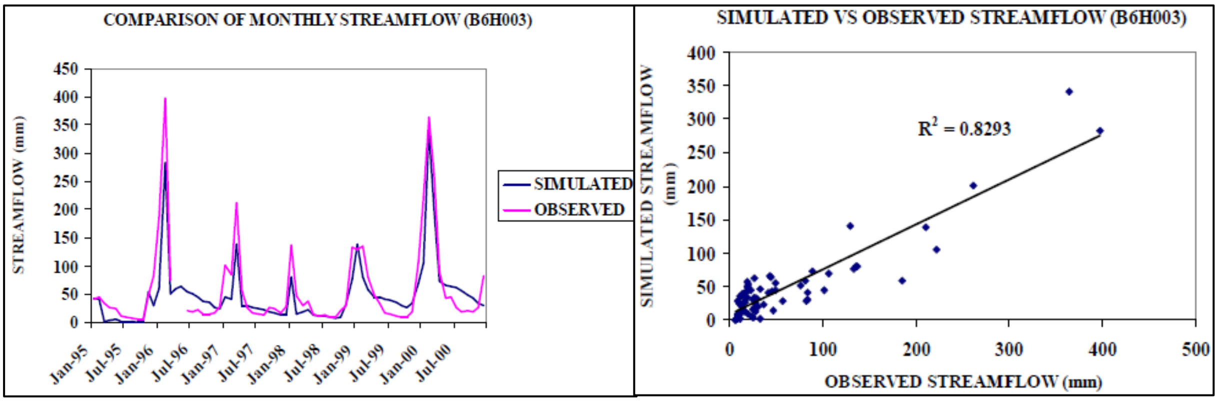
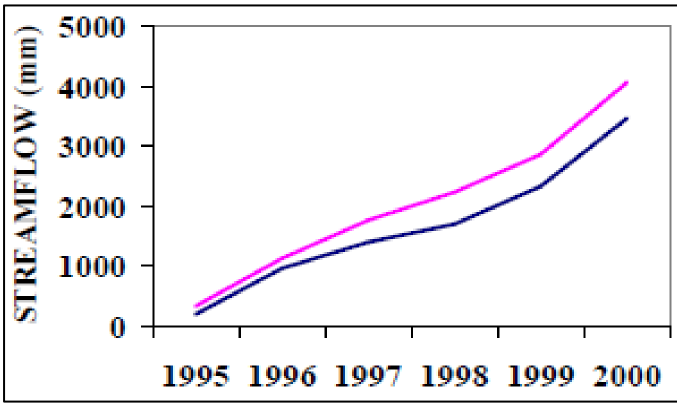


Figure 10.7.7 Comparison of total monthly streamflow (1995-2000) at B6H003 (left) and (right) a scatter plot of simulated vs. observed streamflows



CONSERVATION STATISTICS	
Sum Observed Values	4078.56
Sum Simulated Values	3342.09
Mean Observed	58.27
Mean Simulated	47.74
% Difference Between Means	18.06
% Difference Between Variances	45.76
% Difference Between Standard Deviations	26.35
% Difference Between Coefficients. Of Variation	10.12
% Difference Between Skewness Coefficients	-24.23
REGRESSION STATISTICS	
Correlation Coefficient - Pearson's r	0.91
Regression Coefficient (Slope)	0.67
Regression Intercept	8.67
Coefficient of Determination - R^2	0.83
Coefficient of efficiency	0.60
Coefficient of agreement	0.95

Figure 10.7.8 Comparison of accumulated streamflows at B6H006, with pink line showing observed and blue line simulated streamflow (left) and (right) statistical analysis of monthly totals of daily observed and simulated streamflows

In the Final Analysis: Can "Overkill" in Hydrological Detail in an Operational Catchment Lead to Sub-Optimal Verification Results? What was Shown in the Blyde Catchment, Mpumalanga?

Although the trends of simulated streamflows were well modelled on both the Blyde River (r^2 = 0.79) and the Treur River (r^2 = 0.83), the statistics present substantial differences. Discrepancies such as these are inevitable in operational catchments, and while they can be attributed to several typical verification problems such as:

- Errors in streamflow or rainfall records in operational (vs. research) catchments;
- Rainfall values not being representative of the catchment and sub-catchment; and
- Averaging of soil properties taking place across large sub-catchments;

it could well be the "overkill" in hydrological detail in operational catchments such as B6H001 and B6H003 in regard, for example, to processes and responses of AIPs and the riparian zone processes and assumptions, coupled with the uncertainties around water abstractions, that result in verifications to be less than satisfactory, rather than the process representations in the core water budget of the model *per se*.

Reference

Hays, L.F. 2003. *Estimation of Hydrological Responses to Invasive Alien Plants in the Upper Blyde Catchment.* MSc in Hydrology, School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg. pp 123.

10.8 Benefits of Modelling at Quinary vs Quaternary Scales in the Crocodile Catchment (Original Research: N. Wangusi, G. Kiker, R. Muñoz-Carpena and W. Henson with additions by R.E. Schulze)

Setting the Scene

Most South African catchments are severely water stressed, often as a result of stakeholders such as irrigation, forestry, mining and municipal water users competing for a limited amount of water. To manage water resources under such circumstances, or to forecast streamflows or to guide water allocation decisions, models are often used, where model performance is judged by comparing the simulated values to the corresponding observed data as a benchmark. Any improvements in model performance should, therefore, decrease the uncertainty in management decisions. As technologies and data access have been improved in South Africa, catchment data have been developed at finer spatial resolutions to ostensibly improve the quality and accuracy of simulated results.

The basis for this verification study is the hypothesis that model accuracy is scale dependent. It is assumed that finer spatial and temporal parameterization of the *ACRU* model will result in better simulation outputs. The disparity in simulation accuracy at the different scales of measurement can occur due to spatially variable rainfall patterns, changes in vegetation and soil surface profiles which are often not captured adequately at coarser scales, or are area averaged over the coarser scale in a discipline where responses are non-linear. Given the availability of different scales of catchment data, specific questions occur as to which scale of simulation that will best support the management decisions needed by water resource planners.

Quinary vs. Quaternary Catchments

Up to the present time the most common official spatial water management scale in South Africa has been the fourth level Quaternary Catchment (QC), with South Africa and the imbedded/contiguous countries of Lesotho and Eswatini having been sub-delineated into 1 946 hydrologically interlinked QCs. With over 1 000 of these QCs having been shown to be hydrologically too heterogeneous for meaningful hydrological analyses, each QC was sub-delineated into 3 fifth level Quinary Catchments (QnCs) of unequal size based on breaks in altitude using a GIS procedure known as Jenks' optimisation, thereby attaining a high degree of hydrological homogeneity amongst the 5 838 QnCs in regards to rainfall, temperature and soils (Schulze and Horan, 2010).

Hypothesis

In a study in the Crocodile river catchment in Mpumalanga, South Africa, Wangusi *et al*. (2013) investigated whether and if, to what extent, modelling at Quinary scale would improve model performance in comparison with observed flow data than using the coarser Quaternary scale, also whether an expanded statistical analysis of simulated and observed flows would help highlight both uncertainty in the observed data and the overall model performance, whether Quinary-scale models would have less bias than the Quaternary scale and how models at finer spatial resolution can better inform management decisions of water resources. This analysis was executed at both Quaternary and Quinary scales using the *ACRU* model in selected Crocodile river catchments at which observed streamflow time series existed, with the analysis including discussions on the implications of uncertainty in measurements due to systematic or random errors and on implications of simulation scale for water management decisions and regulatory frameworks.

The Study Area

The Crocodile River study area falls within the Inkomati Water Management Area and covers the entire X2 secondary catchment, with a total area of 10 446 km^2 (**Figure 10.8.1**). The catchment is divided into four tertiary catchments, of which the following three are relevant to this study, *viz*. the Upper Crocodile (X21) covering 3090 km^2, the Middle Crocodile (X22) of 1 573 km^2 and the Kaap (X23) covering 1 640 km^2, with the study catchments shown in Figure GK1.2 and catchment descriptions in **Table 10.8.1**.

Table 10.8.1 Study catchment descriptions (After Wangusi *et al.*, 2013)

Tributary	Quaternary	Quinaries	Flow Station	Area (km^2)	MAP (mm)	MAR (Mm^3/a)	Main Land Use
Upper Crocodile	X21C	X21C1-3	X2H070	311.0	761	121.8	Irrigated Agriculture
	X21H	X21H1-3	X2H034	228.8	1069	51.6	Forest Plantations
Middle Crocodile	X22A	X22A1-3	X2H014	251.4	990	71.5	Forest Plantations
Kaap	X23C	X23C1-3	X2H024	81.3	1134	25.4	Sugarcane
	X23E	X23E1-3	X2H008	180.4	1024	36.7	Forest Plantations

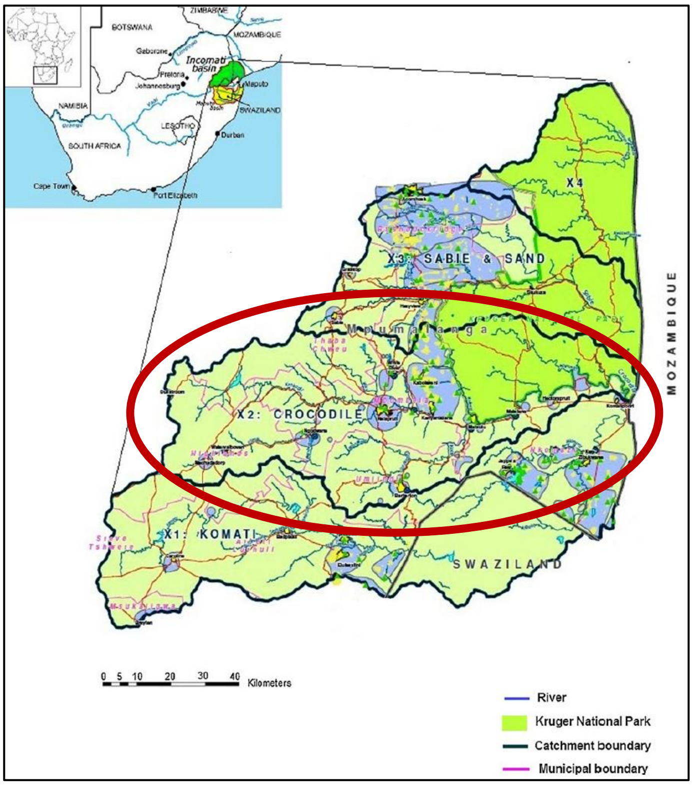


Figure 10.8.1 Location of the Crocodile River catchment within the Inkomati Water Management Area (Inhlakanipho Consultants, 2009)

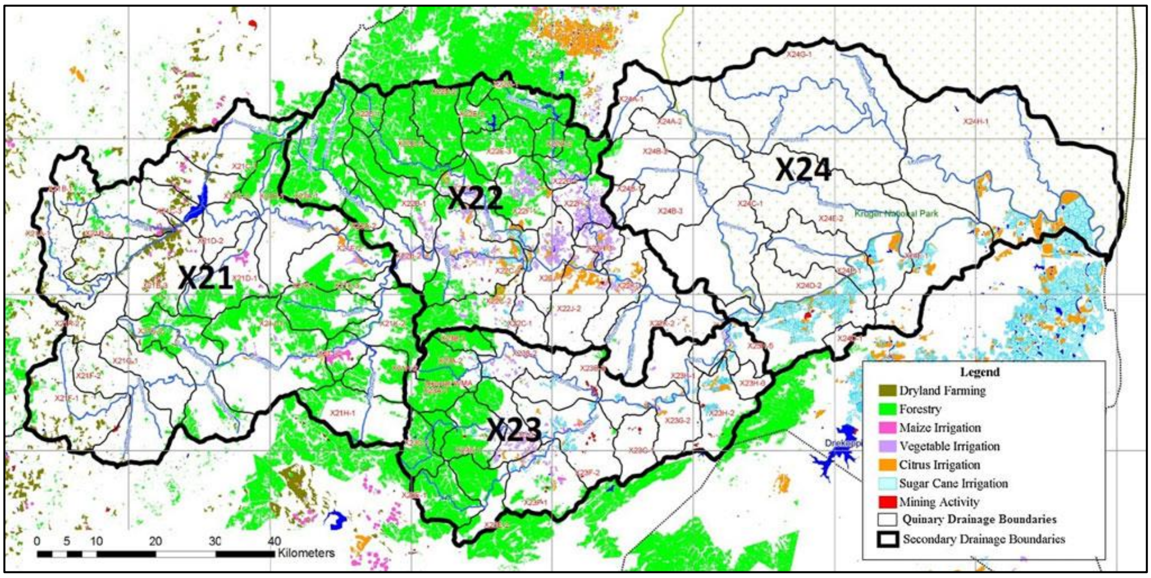


Figure 10.8.2 Major land uses within the Crocodile River catchment (Inhlakanipho Consultants, 2009)

Model Evaluation Indicators and Testing Criteria

Since the major objective of this study was to determine whether the performance of the *ACRU* model was influenced by different spatial resolutions, *viz*. Quaternary and Quinary scales, monthly summations of daily flows from each dual-scale simulation were compared to the observed flow data for the 5 test catchments described in **Table 10.8.1**. The primary differences in the two modelling scales are the resolutions of the parameter values for climate, land use and soil. The model was parameterized to reasonably depict the actual agricultural and other land use characteristics based on historical maps. The simulations for the 5 test Quaternary catchments are run for between 5 to 10 years (**Table 10.8.1**) depending on the observed data availability for different time periods between 1950 and 1993.

Comparison of the simulated and observed results was performed by regression analysis of the simulated and observed data, with conventional ''goodness-of-fit'' and relative error measures used conjunctively to assess the model results as it compares to reality. The conventional two measures that were selected were the coefficient of determination (R^2), which measures the degree of co-linearity between model simulated variates, and the coefficient of efficiency (C_{eff}) which is the ratio of the mean square error to the variance in the observed data subtracted from unity. Additionally, the root mean square error (*RMSE*) of the residuals was calculated for each data set to provide an estimate of the accuracy of model predictions. The *RMSE* expresses the average model-prediction error in the units of the variable of interest. Tests for bias and outliers were also undertaken, where the model bias is explicated as a percentage of the error from the mean and the mean absolute error (MAE) calculated to quantify and explain the presence of outliers in the data.

Comparison of Results at Quaternary and Quinary Scales

Yield modelling in a catchment has an impact on catchment level decisions as the simulated discharges form the basis for assessments of design flows and water use at the outlet of each sub-catchment. The results from the model evaluation of the Quaternary and Quinary scales are presented in **Tables 10.8.2** and **10.8.3**, respectively.

Simulation at Quaternary scale is satisfactory with a R^2 ranging from 0.47 to 0.63 and with a corresponding C_{eff} from 0.05 to 0.61 (**Table 10.8.2**). Statistical evaluation indicates that the C_{eff} may have been influenced by model bias. The *RMSE* values range from 0.87 to 6.61 Mm^3/month.

Table 10.8.2 Comparison of Quaternary scale simulations and observed monthly accumulations of streamflow for 5 selected catchments of the coefficients of determination (R^2), coefficients of efficiency, median annual observed streamflow and the *RMSE*, as well as whether or not there were outliers or there was model bias on the coefficient of efficiency (After Wangusi *et al*., 2013)

Catchment	Period	No. of Observations	R^2	Coefficient of Efficiency	Median Flow (Mm^3/month)	RMSE	Outliers	Model Bias
X21C	1980-1985	67	0.53	0.50	4.19	6.61	No	Yes
X21H	1972-1982	121	0.63	0.61	3.11	2.97	No	No
X22A	1960-1970	141	0.54	0.49	3.66	2.29	No	Yes
X23C	1973-1983	132	0.57	0.48	1.16	0.87	No	Yes
X23E	1965-1975	129	0.47	0.05	0.65	1.87	No	Yes

Results in **Table 10.8.3** at Quinary resolution give R^2 values from 0.49-0.74 (compared with the 0.47-0.63 for corresponding Quaternaries), with a C_{eff} ranging from 0.24-0.73 (compared with the 0.05-0.61 for Quaternaries) and *RMSE*s from 0.73-4.78 Mm^3/month (compared with 0.87-6.61 for Quaternaries).

Table 10.8.3 Comparison of Quinary scale simulations and observed monthly streamflow for 5 selected catchments of the Crocodile River, the coefficients of determination (R^2), coefficients of efficiency, median annual observed streamflow and the *RMSE*, as well as whether or not there were outliers or there was model bias on the coefficient of efficiency (After Wangusi *et al*., 2013)

Catchment	Period	No. of Observations	R^2	Coefficient of Efficiency	Median Flow (Mm^3/month	RMSE	Outliers	Model Bias
X21C	1980-1985	67	0.74	0.73	4.19	4.78	No	Yes
X21H	1972-1982	121	0.67	0.66	3.11	2.78	No	No
X22A	1960-1970	141	0.56	0.54	3.66	2.28	No	Yes
X23C	1973-1983	132	0.67	0.64	1.16	0.73	No	Yes
X23E	1965-1975	129	0.49	0.24	0.65	1.68	No	Yes

For each catchment, therefore, and for each of the 3 statistics quantified in **Tables 10.8.2** and **10.8.3**, Quinary scale simulations displayed improvements over those of Quaternaries. Model efficiency for Quinaries > the 0.5 threshold in 4 of 5 catchments, indicating that the model is a better predictor than the average, whereas for Quaternaries the 0.5 threshold is exceeded only once, indicating that means of observations would have been a better streamflow predictor than the model. Simulation results for Quinaries thus display consistent, sometimes marked, improvements over those of the Quaternaries.

Wangusi *et al*. (2013), however, showed that there were significantly more bias and outlying data effects detected at the Quinary level, which they attributed to the model parameterization at a finer scale providing more information on uncertainty such as information on discharge loss due to unsanctioned irrigation withdrawals and hydrological events such as localized rainfall due to microclimates. Their results also indicated the presence of outliers in the observed data to have a wider range in the Quinary versus the Quaternary simulations, which helps explain the behaviour of the other measures such as the coefficients of determination, which are sensitive to outliers.

The biases found prompted a further evaluation of statistical significance in two case studies on catchments X21H and X23C, shown in **Figures 10.8.3** and **10.8.4**. These catchments were used to demonstrate that while conventional statistical measures show results from Quinaries to be more acceptable than those from Quaternaries, the statistical levels of acceptability of the C_{eff} illustrate how *much more acceptable* they were or were not. This was achieved using the Wangusi *et al*. (2013) levels of acceptability, which check whether the range of the C_{eff} around its 95% Confidence Index is

- *very good* at C_{eff} 0.90 to 1.00;
- *good* at C_{eff} 0.80 to 0.89;
- *acceptable* at C_{eff} 0.65 to 0.79; or
- *unsatisfactory* at C_{eff} < 0.65

They found for two of the sites, at X23C and X21H (**Table 10.8.4**), that levels of acceptability of the C_{eff} were invariably higher at Quinary than at Quaternary scale with, for example, the “good” level for X21H increasing from 7.4% to 16.7% or the “unsatisfactory” category in X23C decreasing from 84.2% to 68.6% for simulations with Quinaries compared to those of Quaternaries.

Table 10.8.4 Comparison of levels of acceptability of the C_{eff} at Quaternary and Quinary scales

Coefficient of Efficiency	Quaternary X23C	Quinaries X23C1-3	Quaternary X21H	Quinaries X21H1-3
Very Good	0.0%	0.0%	0.0%	1.6%
Good	0.1%	0.3%	7.4%	16.7%
Acceptable	15.7%	31.1%	31.7%	29.5%
Unsatisfactory	84.2%	68.6%	60.9%	52.2%

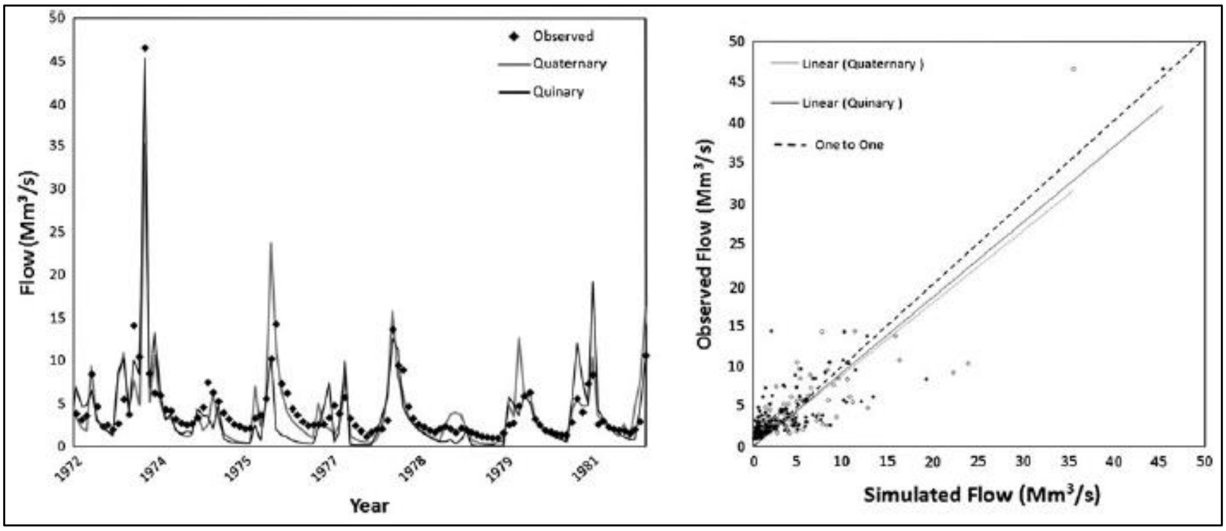


Figure 10.8.3 Observed monthly streamflows for X21H and comparison of simulated vs. observed scatter plot at Quaternary and Quinary simulation scales (After Wangusi *et al*., 2013)

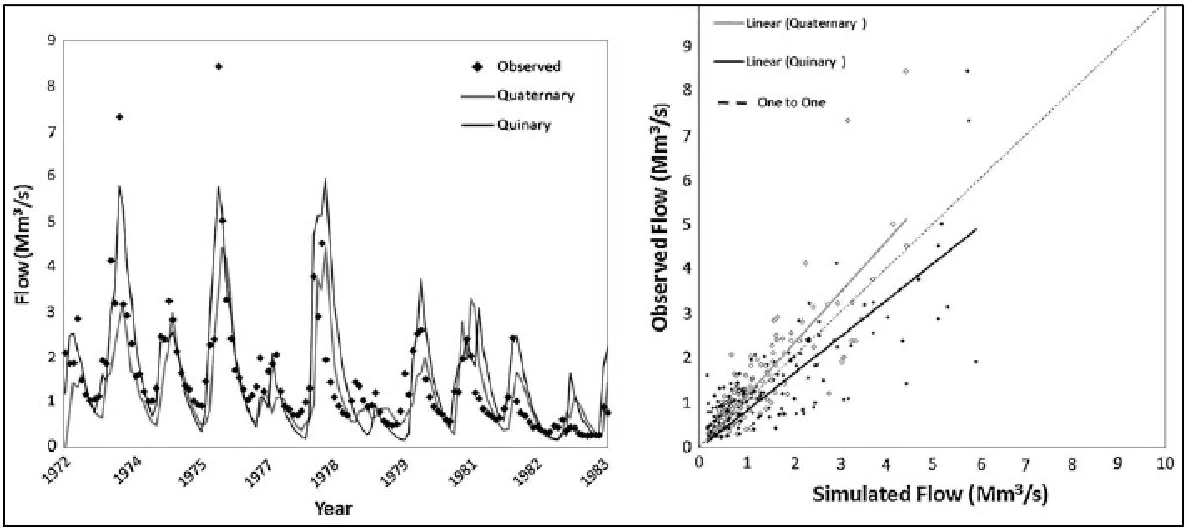


Figure 10.8.4 Observed monthly streamflows for X23C and comparison of simulated vs. observed scatter plot at Quaternary and Quinary simulation scales (After Wangusi *et al*., 2013)

Implications of Model Performance at Quaternary vs. Quinary Scales on River Flow Management

One of the methods under which the Crocodile catchment is currently managed assesses the state of flow in the river using so-called "*worry levels*" of flow by utilizing Thresholds of Potential Concern (TPCs). An example of such *worry levels* is shown in **Figure 10.8.5** at X2H024, with worry levels determined for points in time when management decisions are taken. These are determined as *high worry*, *the reserve* and *inform DWA* (i.e. Department of Water Affairs), as shown in the figure.

Accepting these *worry levels*, a water manager would observe the river flow draw down below the reserve on 1 August when using the Quinary model outputs or observed data. However, this level of draw down would only have been reflected nearly 2 months later at the beginning of October if relying on the Quaternary information. In this case, simulated outputs from this system would benefit greatly by utilizing Quinary as opposed to Quaternary output as it mimics observed data more accurately and hence enables fine-tuning decisions which involve, for example, the timing of water allocations or restriction decisions which in turn influence demand, application rates for irrigation water and ultimately crop yields, to be made with greater confidence in time and space.

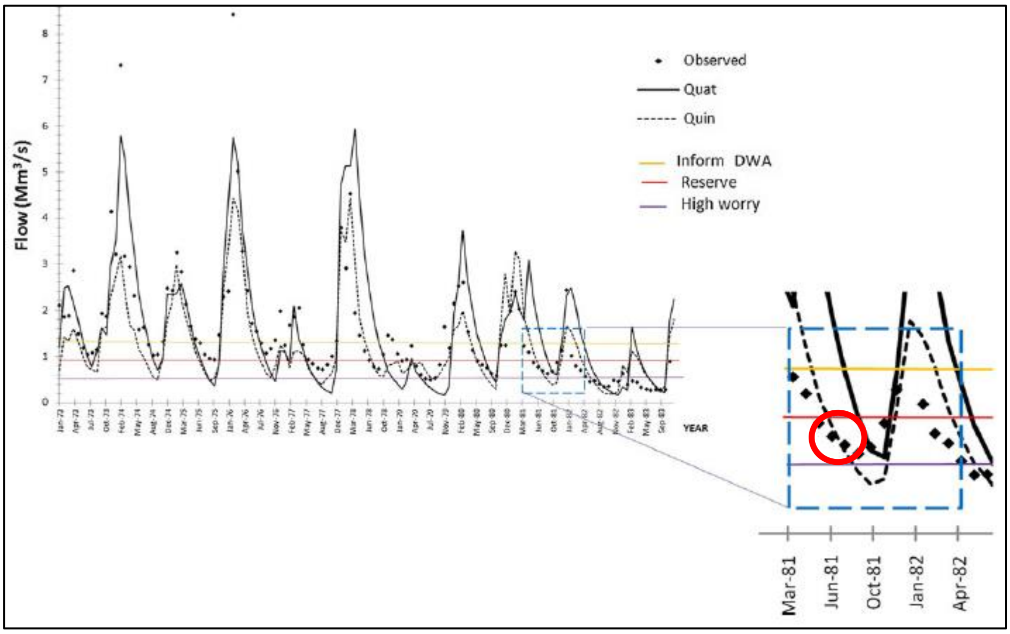


Figure 10.8.5 Flow at X2H024 showing three TPC "worry levels" and the lags in management decisions dependent on Quinary vs. Quaternary simulations (After Wangusi *et al*., 2013)

Conclusions

There were two objectives of this study, *viz*. to demonstrate that *ACRU* model parameterization at a higher spatial resolution produced better simulation results and, secondly, to illustrate that modelling management scenarios could be undertaken at the finer Quinary scale with greater confidence. Results of this study indicate that parameterization of *ACRU* at the Quinary spatial scale can markedly improve statistical outputs when compared to those at a Quaternary scale with, however, the improvements varying across catchments. Furthermore, this verification study by Wangusi *et al*. (2013) has also illustrated the use of Quinary scale simulations to provide greater confidence in the timing of management decisions than if Quaternary catchment outputs were to be used.

Cumming and Norberg (2008) have pointed out that the process by which we learn about the world has two scale-dependent components, *viz*. the actual scale at which patterns and processes occur (e.g. in hydrology) and the scales at which we obtain data about the processes and then use that scale for decision making (e.g. in catchment management). In the interest of catchment level hydrological modelling, these two considerations play an important role in informing the decision making at various scales. Different scales and levels of complexity are required when planning to account for various small-scale processes that might affect management decisions at different resolutions. This is particularly important in the current South African climate with the implementation of the National Water Act of 1998 (NWA, 1998), for example in integrating hydrological with ecological models to estimate impacts of environmental flows. In this regard (and in many others) this verification study by Wangusi *et al*. (2013) has shown that a move from the Quaternary to a Quinary spatial unit should be the way to go in South Africa hydro-ecological decision making.

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11 SELECTION OF VERIFICATION STUDIES ON SPECIALISED VERSIONS OF THE *ACRU* MODEL

11.1 Verification of Snow Hydrological Modelling with *ACRU-SMiM* in the Middle Mountain Range of Germany (Original Researcher: D. Herpertz, Friedrich-Wilhelm University in Jena, Germany; Translation and Additions: R.E. Schulze)

Background

In the past three decades the mid-European region experienced a series of extreme flood events, many in the winter season, which caused serious socio-economic damages. Added to this has been a public and political sensitisation of the flood problem, while simultaneously a strong inter-disciplinary research effort on causal research, risk assessment and adaptation development has taken place. The spectrum of causes of these winter floods is wide-ranging. However, mono-causal explanations such as extreme rainfall events, snowmelt or anthropogenic land use changes by themselves are no longer enough. Rather, the major winter floods reflect an interplay of numerous causes. Key to this is the fact that hydrological winter conditions experience saturated soil conditions, which enhance flooding.

All these mainly snow hydrological issues need to be modelled. Some key model related questions to the above issues on winter flooding include the following:

- What are the principle dynamics of snow related hydrological processes, and more especially in Germany's so-called Mittelgebirge, i.e. Middle Mountain Range (MMR), which is the key area of concern in this study?
- How can the spatial heterogeneity of a selected study area be taken account of in modelling?
- Which model routines and algorithms are suitable and available to capture snow hydrological process dynamics, particularly in the MMR region?
- What is necessary to enable such a simulation tool to be operationally applicable?
- How does one account, for example, for the composition of precipitation into rain, snow and mixed precipitation, or regional aspects of precipitation composition, or systematic point measurement error of snow and mixed precipitation, or the characteristics of the snow cover.

Such a model has, furthermore, to account for the following:

- the composition and structure of a snow cover;
- the snow water equivalent as the hydrologically key storage variable of a snow cover;
- the snow density as the secondary entity, dependent on the water equivalent and on air temperature, with this being especially important for the retentivity of liquid water and for determining snow depth;
- the heat budget and thermal characteristics of the snow cover, which affect all melt and evaporative processes as well as largely controlling the metamorphosis processes;
- hydraulic characteristics, to which belong the retention ability for liquid water and water movement within the snow cover;
- the basics of the mass budget of a snow cover as the foundation for balancing the snow cover development and demise; and
- within catchment areas the possible need for spatial differentiation in the modelling.

In this study an important aim was to develop an independent snow hydrological model structure which could be integrated with a general hydrological model, and in this manner utilise already existing means of catchment discretisation and runoff routines. A further aim of the study was the comparison of snow hydrological regimes at different altitudes, in order to identify differences and commonalities within physiographically heterogeneous catchments, such as those found in the MMR. Further to that was the necessity to assess not only the overall simulation results, but to include also verifications of the efficiency of individual component processes within the complex snow hydrological system.

All these aims were to be implemented and the results then verified in two study areas within Germany.

Study Area 1: The Bröl Catchment

The 216 km^2 Bröl catchment in western Germany (**Figure 11.1.1** top) is located in a temperate climate zone with an annual rainfall of ~ 1 100 mm, distributed almost equally between summer (~ 520 mm) and winter (~ 580 mm). Mean annual temperature is ~ 10.3°C and mean annual potential evaporation by the Penman-Monteith method is ~ 535 mm. The catchment was delineated into 6 sub-catchments (**Figure 11.1.1** left middle), each of which was further discretised into 4 land use determined hydrological response units (HRUs) based on land uses shown in **Figure 11.1.1** (left bottom), giving a total of 24 HRUs (**Figure 11.1.1** right bottom).

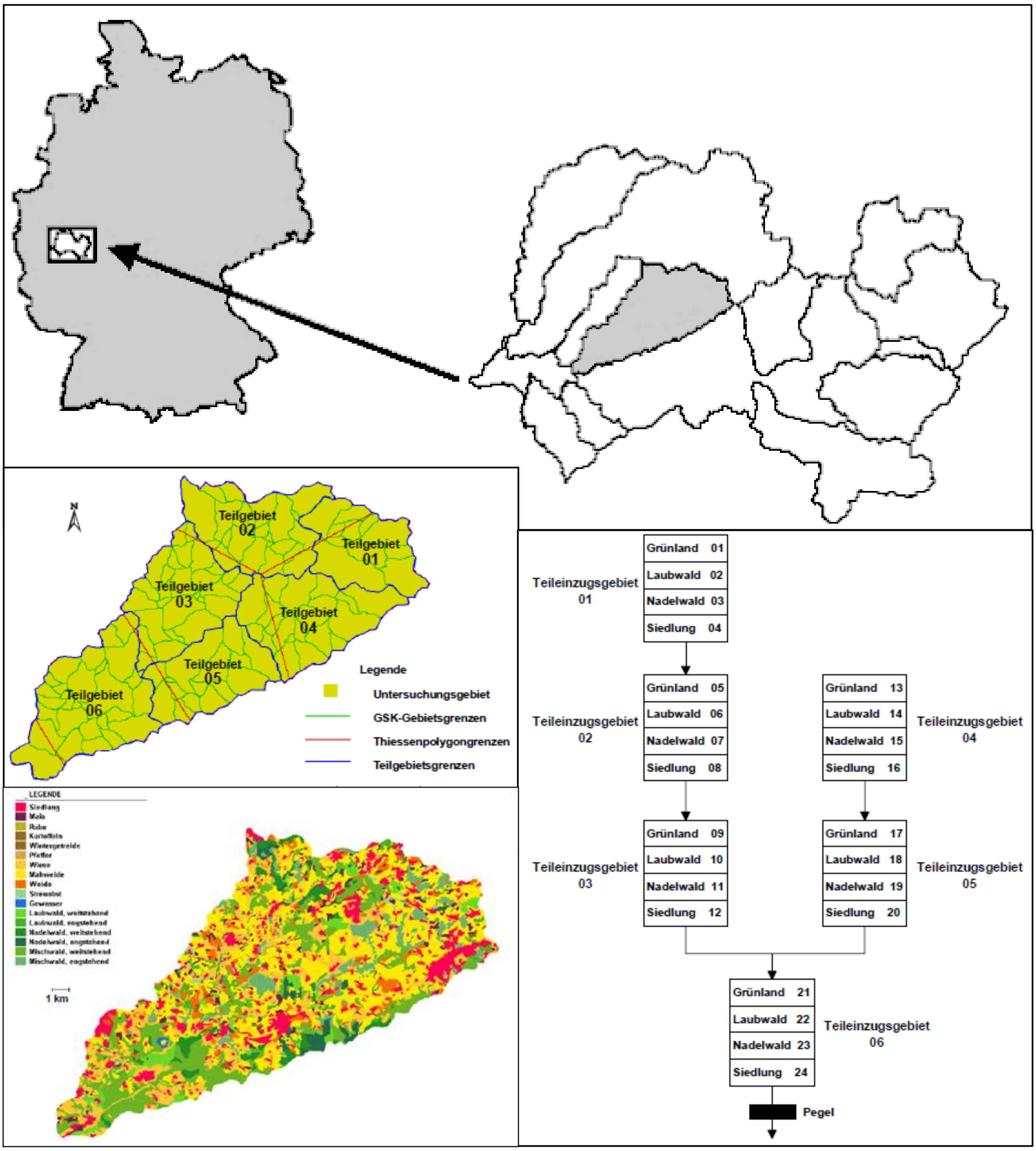

Figure 11.1.1 Location of the Bröl catchment within Germany (top) and its delineation into 6 sub-catchments (left, middle) and (right, bottom) each further into 4 hydrological response units by land use classes derived from the land use map (left, bottom), in which *Grünland* is grasslands/pastures, *Laubwald* is deciduous forest, *Nadelwald* is conifers and *Siedlung* is human settlements (After Herpertz, 2002; from various sources)

Study Area 2: The Schmücke and Steinbach Catchment

Located in east central Germany (**Figure 11.1.2** top), mean annual temperatures in the Schmücke and Steinbach catchment vary from 4.4°C to 5.4°C with a temperature lapse rate of 0.56°C per 100 m. MAP is altitude dependent and ranges from 1 400 mm at higher altitudes to only 500-550 mm at lower altitudes, but in this much colder climate the mean annual potential evaporation is only ~ 265 mm. The catchment was sub-delineated into 4 terrain oriented sub-catchments (*Teilgebiete*) for modelling purposes.

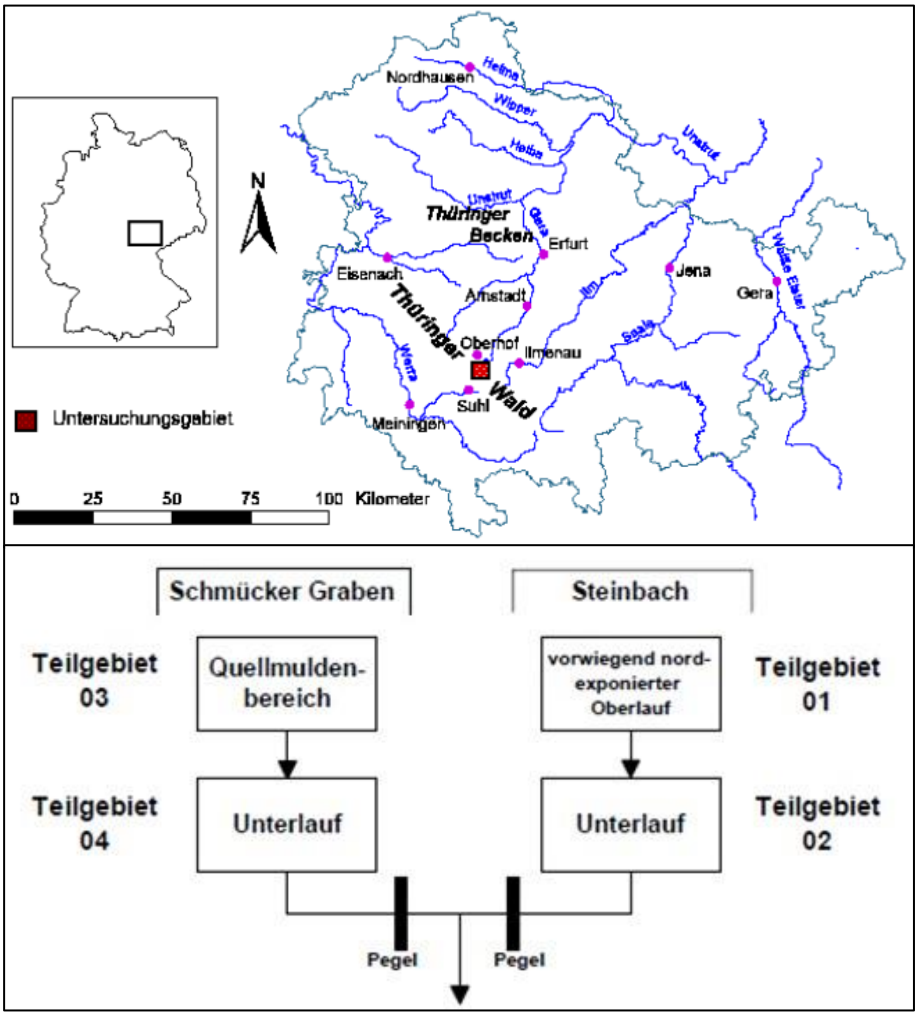

Figure 11.1.2 Location within Germany (top map) of the Schmücke and Steinbach catchment (*Untersuchungsgebiet* is the study area in the red block) and (bottom) its 4 terrain oriented sub-catchments (*Teilgebiete*) for modelling purposes, where *Pegel* denotes a streamflow gauging weir and *nord-orientierter Oberlauf* denotes an upper river reach with a northern (cool) aspect (After Herpertz, 2002, based on various sources)

General Snow Hydrological Model Requirements, Considerations and Limitations

- A scientifically valid model representation of the physical system requires the identification and isolation of relevant component processes (internal state variables), which initially have to be examined separately, but eventually have to be integrated with one another.
- In this regard, from a research perspective, one has to consider/derive/synthesise component processes of snow hydrological systems such as the make-up of the precipitation, relevant snow cover characteristics, snow accumulation, snow densification, evaporation and melt processes in generic terms, but with particular reference to the MMR.
- The desired level of complexity of the model does, however, have to be verifiable in a step-wise manner and should not lead to losing an overview of the system.

- Data availability is a limiting factor for the modelling initiative. However, the data demands for parameterising and running the model will have to match whatever information would be available for most sub-catchments of the study area.
- Processes which cannot be captured by available data need to be simplified or omitted.
- Because point measurements of snow depth, of the water equivalent or of snow density are seldom representative of those of a catchment, the point measurements can only be used as comparative data, and their availability should not be compulsory for the modelling.
- The heterogeneity of the test catchment demands that possibilities/options should be available in the model structure for spatial differentiation of snow hydrological processes to be made.
- Effects of altitude on snow dynamics must be considered via application of air temperature lapse rates.
- In particular at higher altitudes and steep gradients the influence of aspect has to be considered, with separate modules for impacts of aspect on snow accumulation and on snow melt processes.
- Under forest a reduced snow accumulation is expected when compared with that in open areas. Additionally, the water equivalent in open areas increases more strongly with altitude than in forested areas. Consequently, the divergence of snow accumulation between forest and open areas increases in the predominantly forested areas of higher altitudes. Further to that, snow interception on tree tops takes on special significance in the water budget. Hence it becomes important that the modelling algorithms have to distinguish between forest and open areas.
- To capture in detail all the variable snow hydrological relationships, the model needs to operate on short time steps, ideally at hourly intervals, but because of an overall lack of hourly data, at minimum at a daily time step.
- Stand-alone snow melt models can, as a rule, generally not be as spatially disaggregated as snow modules made up of components. However, by integration with a host hydrological model one can fall back on existing well-validated and tested runoff routines. Hence the development of a snow module to be coupled with a suitable hydrological distributed modelling system, with the selected runoff model and the snow module operating on the same time step.
- A qualifying, and hence the selected, hydrological model as the host model is the *ACRU* model – a physical-conceptual and process-based multi-purpose system-oriented daily time step model based on simple structures, on relatively input lean data requirements and which is component modular in structure.

Further, More Specific Snow Hydrological Model Requirements

- In the MMR air temperatures around the critical 0°C threshold occur frequently, rendering it difficult to distinguish between rain, snow and mixed precipitation. Additionally, snow precipitation can fall within a wide range of air temperatures. Hence the application of a simple threshold temperature for the determination of precipitation type is inadequate and a threshold interval/range is required to accommodate the frequently occurring mixed precipitations.
- Additionally, suitable corrections for systematic measurement errors have to be enabled because these errors are distinctly different for the three precipitation types of rain, snow and mixed rain/snow.
- Within a snow cover phase in the MMR with its variable weather types there are often warm air periods in combination with rainfall events. Consequently, the large influence of rainfall events on the snow cover dynamics has to be considered via suitable module algorithms.
- For the choice of an adequate snow melt simulation procedure consideration has to be given to data availability, the regionalisation of point measurements and the simulation time step.
- As a result of limited data availability and the application in catchment areas a temperature-based method of simulating the energy balance is preferred.
- Under consideration of the variable snow hydrological conditions a variable melt factor is preferred which is applicable spatially, temporally and by individual event.
- Similarly, when the melt water contribution to runoff is considered, limited data availability is a consideration.

All of the above considerations were captured in the snow hydrological module called *SMiM*, a schematic overview of the concepts of which is shown in **Figure 11.1.3**.

The regulatory function for the temporal and volumetric determination of liquid water exiting the snow related routines depends on its storage capacity. In more detail, and shown in **Figure 11.1.4**, the *SMiM* snow module captures the following main processes of the snow hydrological system, *viz*:

- Type/make-up of precipitation (rain, snow or mixed),
- Snow evaporation,
- Snow cover accumulation,
- Snow cover development (densification, metamorphosis), and
- Snow melt.

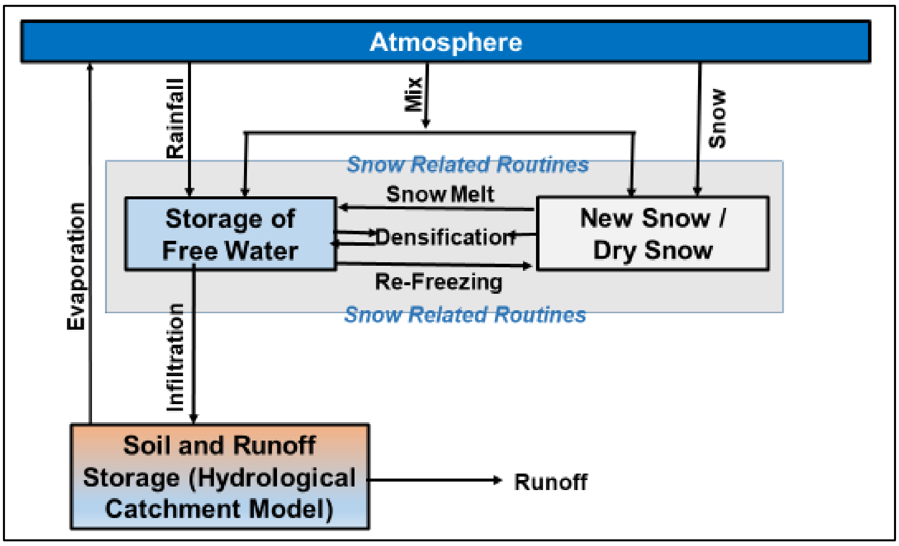

Figure 11.1.3 Schematic representation of the conceptual system through the *SMiM* snow module (Adapted by Schulze from Herpertz, 2002)

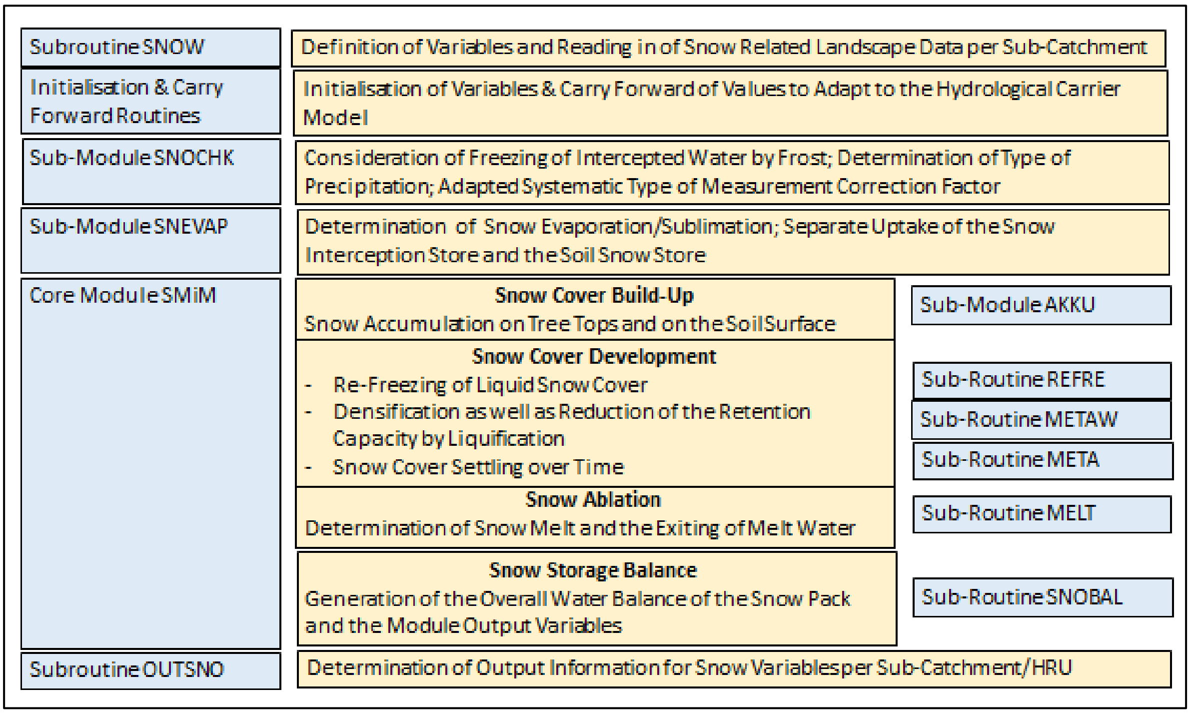

Figure 11.1.4 A more detailed schematic representation of the elements of the snow hydrological simulation *SMiM* module (Adapted by Schulze from Herpertz, 2002)

A schematic depiction of the *SMiM* snow hydrological module imbedded within the *ACRU* model structure is shown in **Figure 11.1.5**, in which

- *Niederschlag* is precipitation,
- *Aggregatzustandsbestimmung* is the determination of the type of precipitation,
- *Regeninterzeption* is rainfall interception,
- *Schneespeicher* is snow storage,
- *Schneeinterzeption* is snow interception,
- *Bodenschneedecke* is snow cover,
- *Schneeverdunstung* is snow evaporation,
- *Verdunstung von Bodenoberfläche und Pflanzen* is evaporation from the soil surface and plants,
- *Streuschicht* is surface cover,
- *Oberbodenspeicher* is the topsoil storage,
- *Unterbodenspeicher* is the subsoil storage,
- *Zwischenspeicher* is the vadose zone storage,
- *Grundwasserspeicher* is the groundwater storage,
- *Schneller Abfluβspeicher* is quickflow storage, and
- *Afluβ* is runoff.

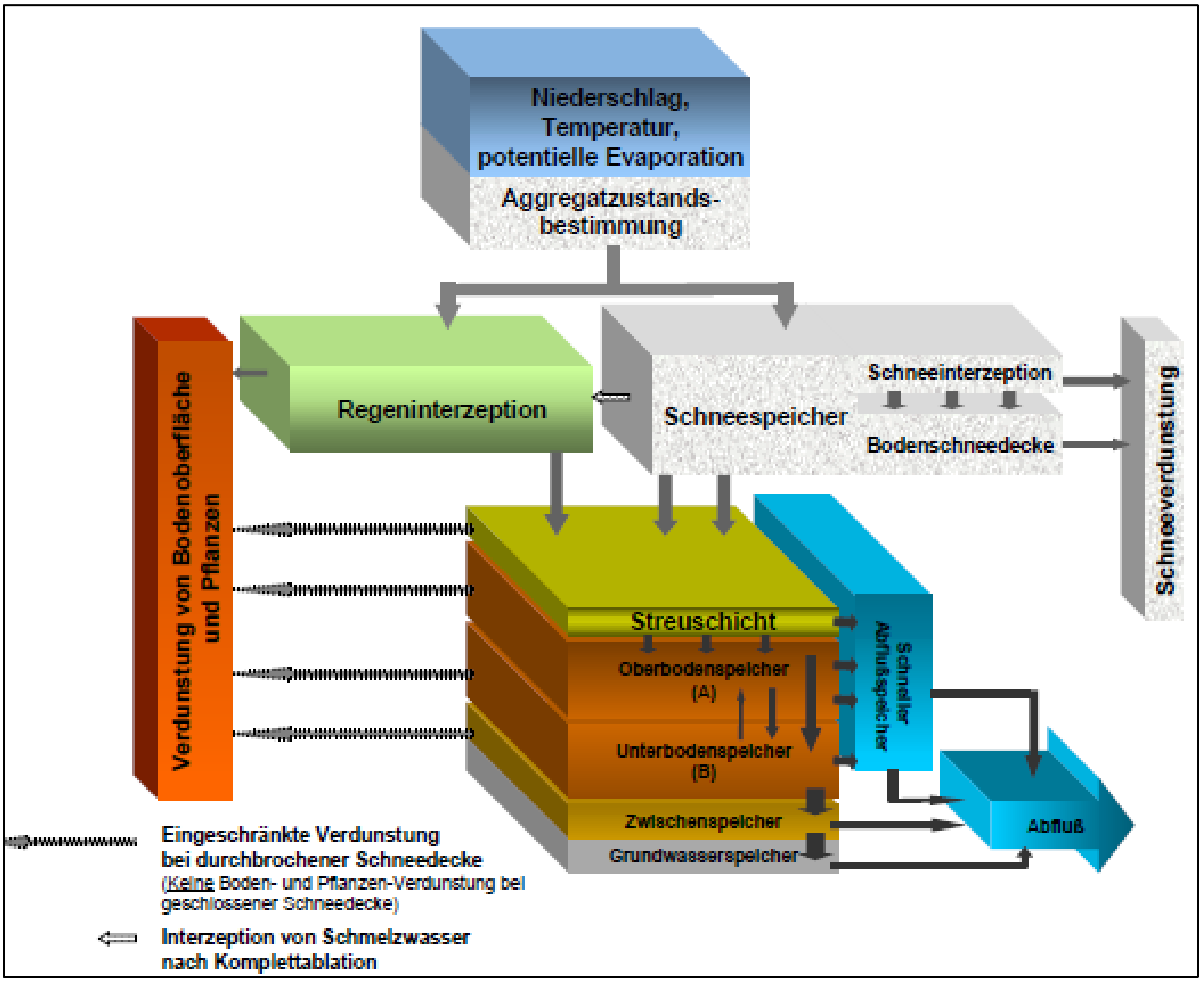

Figure 11.1.5 Snow module *SMiM* imbedded within the structure of the *ACRU* modelling system (After Herpertz, 2002)

Criteria and Steps for the Validation of the Snow Hydrological Module SMiM

For a validation of the *SMiM* snow hydrological module the following criteria and associated steps were undertaken, following Schulze (1992):

- Checks were necessary to ensure that the input variables and parameters used were correct in regard to their physical reality and representativeness, ensuring where possible that the parameters used were comparable to those from empirical research, in order "to get the right answer for the right reason".
- The module's programming had to be validated that it is mathematically and logically correct.
- By comprehensive programming tests with synthetic data before full model application, the functionality and correctness of the computer code needed to be ensured. Additionally, the programming elements as well as model components and their validity were checked and re-checked with simulations in the study areas using long data series.
- The model simulated water balance had to balance.
- The representativeness of coupled *ACRU-SMiM* model was assessed by graphical and statistical methods.
- The modelling effort/attempt had to be seen to be suitable to providing answers to the key questions of the ensuing analysis.
- By thorough testing and analyses of the snow hydrological simulations in the two study areas the suitability/functionality and structure of the snow module was assessed.
- By way of a component analysis of the snow module the efficiency and validity of the modelling effort as well as its adaptability to assess relevant processes were checked.

In the system-oriented modelling which was undertaken in the two test catchments, the following procedures were adopted:

- In preparation for spatially differentiated modelling of the process dynamics the study catchments were discretised into hydrologically homogeneous sub-catchments/HRUs.
- Not only the final runoff output, but also the internal outputs of module components were assessed for their efficiency by graphical and statistical means.
- By way of using selected years as examples, runoff and individual snow related parameters could be compared and analysed with observed data.

Model Input Variables and Parameters

a. *Precipitation and Temperature*

- Daily time series of the externally determined sub-catchment values of daily precipitation as well as maximum and minimum temperatures were read into the host model (*ACRU*). Within *ACRU* any systematic measurement error could be corrected by the monthly correction factor.
- Daily temperatures per sub-catchment were corrected internally in *ACRU* with regional month-by-month lapse rates, separately for maximum and minimum temperatures.
- By utilising air temperature values in the *SMiM* snow module, a distinction could be made between rain, snow and mixed precipitation, and the systematic measurement error of snow and mixed precipitation was applied on a daily basis.

b. *Potential Evaporation*

- Daily values of A-pan equivalent reference potential evaporation per sub-catchment were read directly into *ACRU*.
- To account for evaporation from a snow surface, the monthly varying ESNREL coefficient was applied via the *SMiM* module's database.

c. *Vegetation Related Parameters*

To account for interception, vegetation water use and root distribution, monthly values of these variables were derived externally to the *ACRU* model and then input on a month-by-month basis for each sub-catchment/HRU. Under snow and mixed precipitation conditions, however, the snow module *SMiM* computed the accumulation and decay of the snow cover storage as a temporary areal storage.

d. *Soils Related Inputs*

From the literature and previous soils studies on the study catchments, topsoil and subsoil values of soil water content at saturation, the drained upper limit and the wilting point, as well as saturated drainage rates from the top- to subsoil and from the subsoil into the groundwater store were derived externally for each sub-catchment/HRU before being input into *ACRU*.

Simulation Analysis

This section presents results of the *ACRU-SMiM* snow module in the two selected study catchments. Based on best-available model inputs for *ACRU* the best-available parameters for *SMiM* were checked. While the water balance of an area is a complex system with dynamic feedforwards and feedbacks within and beyond a hydrological year, the focus here was on assessments in the winter months.

Verification of Simulations in the Bröl Catchment

In a comparison of observed versus simulated time series of runoff for selected hydrological years, an assessment was first made of a selected component simulation with the *ACRU-SMiM* modelling system. Following that, a verification study was made in the Bröl catchment of the linked *ACRU-SMiM* system for the winter months from November to April to illustrate improvements to the model outputs.

a. A SMiM Component Verification in the Bröl Catchment

The component selected was *SMiM*'s ability to mimic the thickness of the snow cover. **Figure 11.1.6** shows that for both forested (*Wald*) and open areas (*Freiland*) the simulation of snow cover thickness was good, and while it lagged initially, it was particularly good when the snow cover was in recession.

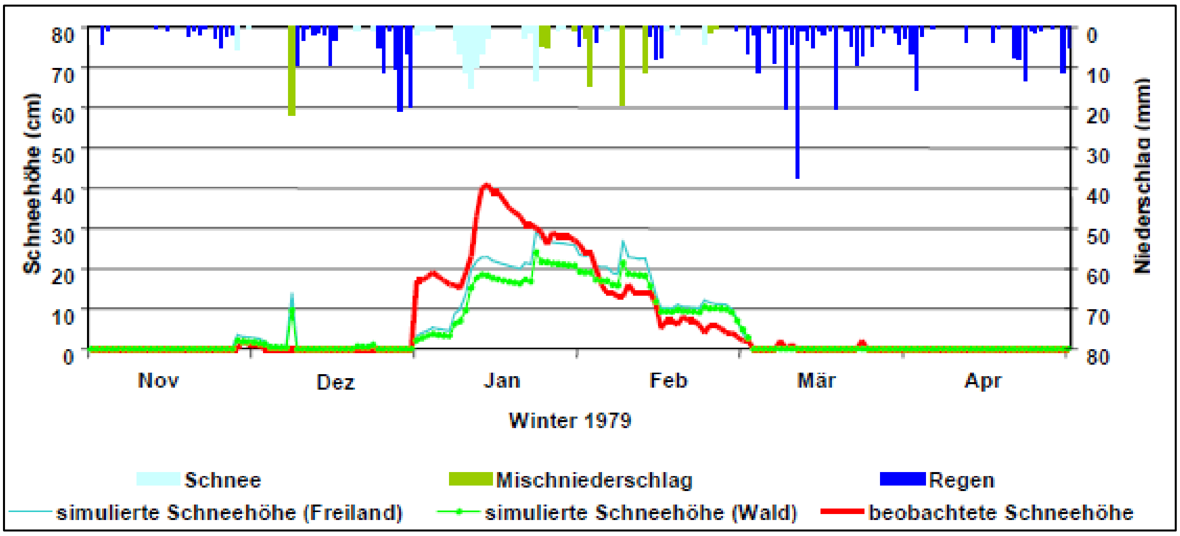

Figure 11.1.6 Comparison of observed snow depths (red line) at the Neunkirchen-Seelscheid-Meisenberg station in the Bröl catchment with simulated snow depths under forests (green line) and open areas (light blue) for the winter months of the hydrological year 1979 for rainfall events (dark blue bars), snowfall (light blue bars) and mixed precipitation (green bars) for the initial model parameterisation (After Herpertz, 2002)

b. An Integrated ACRU-SMiM Verification in the Bröl Catchment

An example of runoff simulation improvements in the Bröl catchment when invoking the *SMiM* module with *ACRU* is illustrated for the winter of 1979-80 in **Figure 11.1.7**. Here catchment precipitation is shown by the blue bars, the observed hydrograph is shaded in grey and simulated hydrographs are shown by the brown line when *SMiM* is not invoked, and by the thin red line when it is included. The results show marked improvements in both magnitudes and timing of the hydrographs with the linked module.

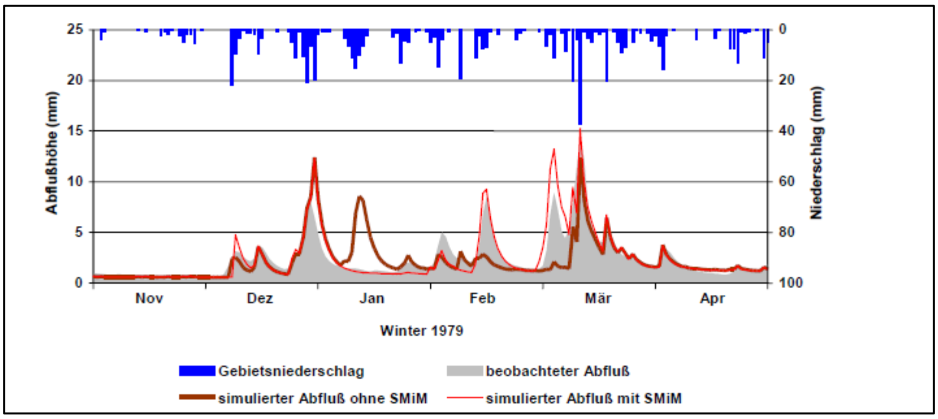

Figure 11.1.7 An example of simulation improvements when invoking the *SMiM* module. In the figure, catchment precipitation is represented by the blue bars, observed hydrographs are in grey shading and simulated hydrographs for the winter of 1979 in the Bröl catchment are shown, both *without* (bold brown line) and *including* (thin red line) the *SMiM* snow module (After Herpertz, 2002)

Verification of Simulations in the Schmücke and Steinbach Catchment

In the first combined *ACRU-SMiM* simulations in the Schmücke and Steinbach catchment, simulation deficiencies were identified which were linked back to an inadequate regional adaptation of the *ACRU* host model. The result was responses which were too early, an over-simulation of peaks, a baseflow recession that was too linear and a stormflow recession that was too steep. Furthermore, total runoff volumes were under-simulated. These simulation deficits were particularly acute in the Steinbach catchment which has unique storage dynamics. Once those problems had been resolved, an assessment was first made of a selected component simulation with the *ACRU-SMiM* modelling system. Following that, two verification studies were made in the Schmücke and Steinbach catchment of the linked *ACRU-SMiM* system for the winter months from November to April.

a. A SMiM Component Verification in the Schmücke and Steinbach Catchment

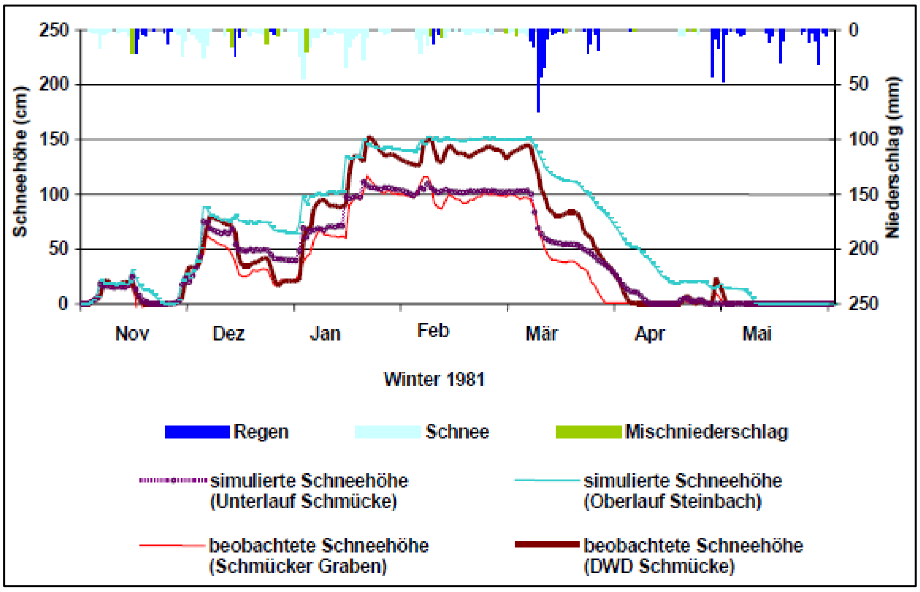

Figure 11.1.8 Observed snow depths at the Schmückergraben (red line) and at the DWD Schmücke (brown line) stations in the Schmücke and Steinbach catchmenti in relation to simulated snow depths in the upper Steinbach (light blue line) and in the lower Schmücke (purple line) areas for different simulated precipitation types with rain in dark blue bars, snow in light blue bars and mixed precipitation in green bars (After Herpertz, 2002)

It is seen from **Figure 11.1.8** that the *SMiM* module simulated the snow depths in the Schmücke and Steinbach catchment exceptionally well at both the Schmücker Graben observation station representing the lower (*Unterlauf*) Schmücke sub-catchment and at the DWD Schmücke observation station representing the upper (*Oberlauf*) Steinbach sub-catchment. This component verification (also termed an internal state variable verification), together with the other verified components given in Herpertz (2002), is an indicator of the improvements made by coupling the *SMiM* snow hydrological module with the core *ACRU* modelling system.

b. An Integrated ACRU-SMiM Verifications in the Schmücke and Steinbach Catchment

Mindful of the complicated terrain and low temperatures of the Schmücke and Steinbach catchment, both the top and bottom simulation outcomes shown in **Figure 11.1.9** illustrate that the coupled *ACRU-SMiM* model has captured the snow related process dynamics very well when the red line of simulated runoff (*simulierter Abfluß mit SMiM*) is compared with the grey shading representing the observed hydrograph (*Beobachteter Abfluß*). The improvement in the verification may be gauged when the thin red line of *ACRU-SMiM* is compared with the bolder brown line when *SMiM* was not invoked.

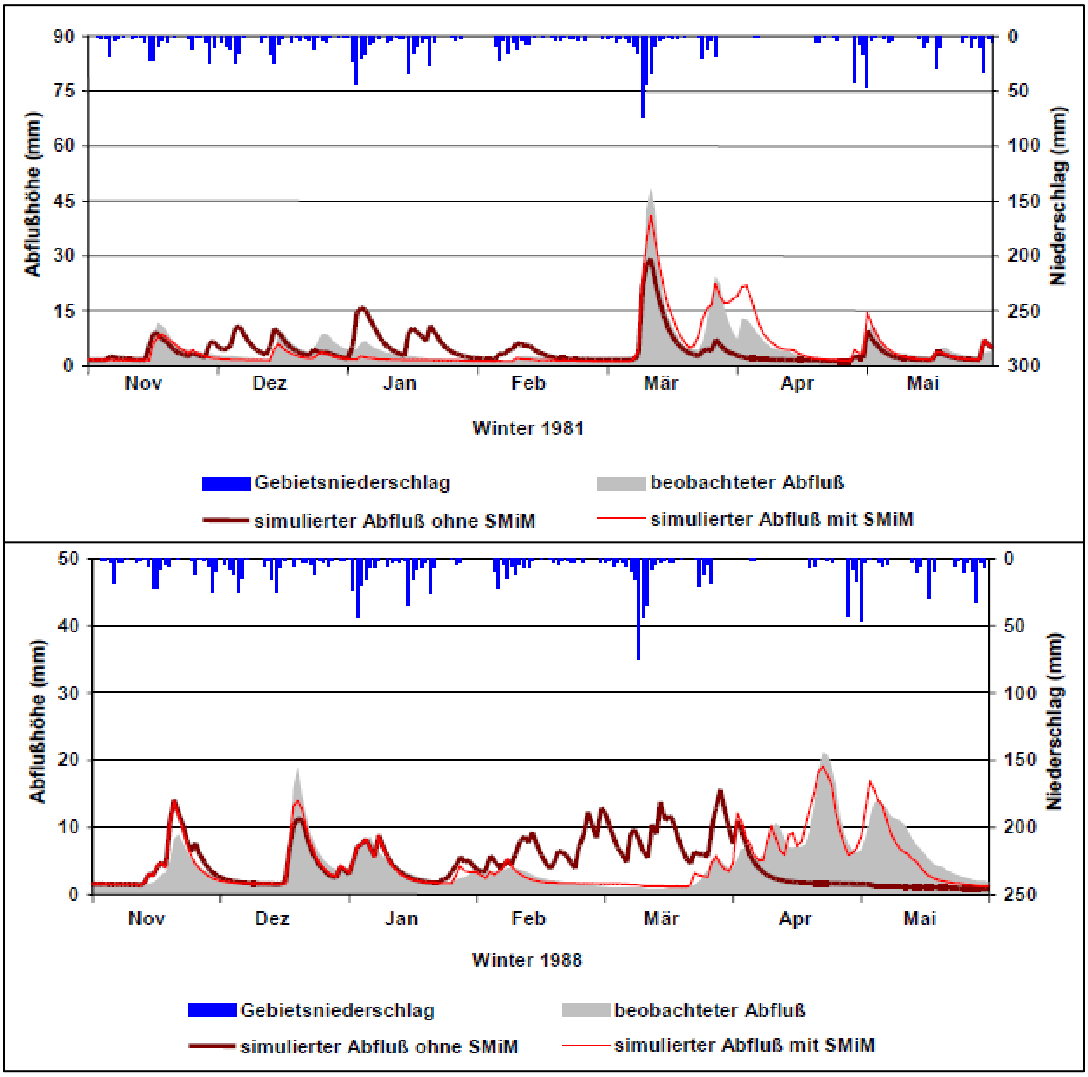

Figure 11.1.9 Examples of simulation improvements when invoking the *SMiM* module. In the figure, catchment precipitation is represented by the blue bars, observed hydrographs are in grey shading and simulated hydrographs for the winters of 1981 (top) and 1988 (bottom) in the Schmücke and Steinbach catchment are shown, both *without* (bold brown line) and *including* (thin red line) the *SMiM* snow module (After Herpertz, 2002)

An Overall Assessment of Results from the SMiM Component Analysis

The following assessment results, discussed in detail in Herpertz (2002), were deemed to be important:

- In both study catchments the snow module enhanced the simulations, especially in the case of the Schmücke and Steinbach in which the winter runoff dynamics are strongly affected by snow hydrology and where the inclusion of the *SMiM* module significantly enhanced correlations between simulated and observed runoff.
- It was confirmed that the *SMiM* module could mimic snow melt processes and melt water runoff under moist as well as dry conditions.
- Consideration of the effects of forest cover with the *SMiM* displayed a meaningful adaptation of the dynamics of the considerable snow covers in the Schmücke and Steinbach catchment. In the Bröl catchment, however, where snow cover is much less, the forest component could have been omitted.
- In the Schmücke and Steinbach catchment the explicit consideration of the cooler north aspects in the upper Steinbach within *SMiM* improved simulations. The simplified modelling of reduced solar radiation on north (cool) facing slopes by way of a month-by-month reduction in temperatures is therefore viewed as an efficient attempt to confirm conditions in that catchment.
- Consideration of the relatively low values of evaporation from the snow cover in *SMiM* through the SNEVAP routine only made small and insignificant improvements to the overall simulation results. For the physical system representation of the module it nevertheless is imperative that this component be kept.
- In both study catchments the temporal representation of the hydrograph is improved by the *SMiM* module. Module component META may therefore be assessed as being an efficient structural element of the *SMiM* snow module.
- The *SMiM* option for a differentiated melt factor dependent on physical and temporal considerations of the snow cover was assessed as an important model adaptation for snow hydrological simulations in topographically complex areas such as the MMR.

Overall the above assessments show that runoff analyses without snow hydrological considerations are inadequate. This is confirmed by way of statistical analyses to complement diagrammatic displays of the functionality and validity of the *SMiM* snow module. Also, on the basis of the options to vary the inputs of the different components of *SMiM*, the module adaptability under heterogeneous snow hydrological conditions was confirmed.

Summary Assessment of the Modelling with ACRU-SMiM

A statistical summary assessment of the combined *ACRU-SMiM* modelling system in the Bröl as well as in the Schmücke and Steinbach study catchments is given in **Table 11.1.1**.

Table 11.1.1 Comparative statistics of the runoff simulations in the Bröl as well as the Schmücke and Steinbach catchments across the respective periods of analysis

Statistic		Bröl	Schmücke/Steinbach
Sum of Runoff over the Time Period (mm)	Observed	12 039	15 073
	Simulated	12 078	14 533
Correlation Coeff, Observed vs Simulated Runoff		0.93	0.88
Coefficient of Determination, r^2		0.87	0.78
Y-Axis Intercept of the Regression		0.01	0.39
Median Values of the Runoff Time Series	Observed	1.65	2.95
	Simulated	1.65	2.84
Standard Deviations of the Runoff Time Series	Observed	2.01	3.48
	Simulated	2.14	3.29
Variances of the Runoff Time Series	Observed	4.03	12.11
	Simulated	4.48	10.82

The table shows very close totals of runoff for the years assessed for both catchments, high correlation coefficients, a y-axis intercept near zero and similar variances between simulated and observed runoff time series.

Overall Conclusions from the Model Applications and Verifications

Through the statistical and graphical assessments, the overall simulation with the linked *ACRU-SMiM* model may be confirmed as having been successful in the two study areas. In particular in the high lying Schmücke and Steinbach catchment with its near sub-alpine process dynamics in winter any hydrological modelling without considering snow would have been shown up as being inadequate. Also, in the Bröl catchment, with its typically sporadic snow cover phases, the introduction of the *SMiM* snow module improved simulations markedly and captured relevant snow related dynamics well.

The following conclusions may be drawn from results emanating from the study catchments:

- *Bröl Catchment*: Here the categorisation of the precipitation type around the 0°C threshold was critical for simulations, especially in regards to snow cover accumulation and reduction. As a rule, snow melt situations were accompanied by specific precipitation types, which resulted in rapid total melt. These were simulated well with the *ACRU-SMiM* model.
- *Schmücke und Steinbach Catchment:* Here the precipitation type was less important in simulations than the quantification of the mixed precipitation component, especially in regards to the duration of partial ablation phases which are dependent on rain and mixed precipitation. With only rainfall, the melt rates are under-estimated.
- *In Both Study Areas* the correct determination of precipitation type was found to be highly important for successful simulations. Best simulation results were attained with the snow module in the snow accumulation and reduction phases during periods when there were no rainfall influences.

The snow hydrological *SMiM* module may, in summary, thus be assessed as follows:

- In particular for daily time step modelling, highly satisfactory adaptations to the weather conditions in the two study catchments were achieved.
- Within certain constraints, the problem of identifying the correct precipitation type was solved well, as shown in the model verifications.
- The snow cover water equivalent, snow depth, and snow density could be determined adequately by the *SMiM* module.
- The number of snow cover phases and days with snow cover, as well as the respective durations of snow cover, were well quantified and presented by the *SMiM* snow hydrological module.

The addition of the *SMiM* module, when imbedded in the *ACRU* hydrological modelling system, has thus proved highly successful in verifications on two catchments with markedly different snow hydrological regimes.

Reference

Herpertz, D. 2002. *Schneehydrologische Modellierung im Mittelgebirgsraum*. Dr rer nat Thesis, Friedrich-Schiller-Universität Jena, Germany. pp 273.

11.2 Verification of the ACRU-Salinity Hydro-Salinity Module of ACRU (Researchers: A.T. Teweldebrhan under Supervision of S.A. Lorentz and R.E. Schulze)

Setting the Scene

Salinity, i.e. the total dissolved solutes in water, is influenced by a combination of several soil-water-salt-plant related processes. In order to develop optimum management schemes for environmental control it is important to identify and understand the processes affecting salinity to enable modelling thereof. The *ACRU* agro-hydrological modelling system, with its physically-conceptually based characteristics and its ability to operate both as a lumped and distributed model, was found to be suitable for hydro-salinity modelling at a catchment scale through the incorporation of an appropriate hydro salinity module. In this Chapter a hydro-salinity module developed for the *ACRU* model is verified against observed salinity measurements. This module involves the interaction of the hydrological processes represented in *ACRU* and salinity related processes – hence *ACRU-Salinity.*

The processes in *ACRU-Salinity* revolve around six packages, *viz*.

- the initial salt load determination in sub-surface components and a reservoir
- the determination of wet atmospheric deposition and salt input from irrigation water
- a sub-surface salt balance, salt generation and salt movement
- a surface flow salt balance and salt movement
- reservoir salt budgeting and salt routing, and
- channel-reach salt balancing

and, in the case of distributed hydro-salinity modelling, salt transfers between sub-catchments.

The verification of the module was through comparison of simulated streamflow salinity against observed values as recorded at gauging weir UIH005 which drains the Upper Mkomazi Catchment at Camden in Kwa-Zulu-Natal, South Africa.

Background to Sources of Hydro-Salinity, Controlling Factors and Modelling Approaches

Sources of hydro-salinity may be grouped into those that are natural and those of anthropogenic making. The factors that control hydro-salinity include those related to soil and to geological formations, hydrological and climatic factors, to rainfall, irrigation water, total evaporation, runoff volume and other flow components, land use and land cover, topographic characteristics and the effect of time. There are a number of types of hydro-salinity models, including calibration and parameter optimizing models, parametric models, stochastic models, more deterministic and physical conceptually based models, mechanistic models and functional models. Modelling hydro-salinity is complex, and in the mechanistic modelling approach of salt balance and movement in soils, for example, consideration is given to processes related to diffusion, mechanical dispersion, convection and combined convective-diffusion transport, to miscible displacement and anion exclusion. Within the more simplified modelling approaches to the soil salt balance and movement are empirical and simplified functional approaches. One approach in this regard is soil water and TDS (i.e. total dissolved solids) balance modelling, including the modelling of salt generation and combined salt generation and mixing models.

Development of the Hydro-Salinity Module

The modelling approach in *ACRU-Salinity* revolved around

- Sub-surface TDS balance and baseflow salinity by considering
  - total evaporation and the soil water balance as conceptualised in the *ACRU* model
  - rainfall and irrigation water salt input
  - subsurface salt movement, both downward and upward
  - salt generation and the
  - effect of total evaporation on subsurface TDS balance;
- Determination of surface flow salt balance by considering
  - stormflow generation mechanisms in *ACRU,* including the concept of delayed stormflow
  - stormflow and quick flow salinity
  - the effect of delayed stormflow on TDS balance determination and
  - runoff salinity and salt load;
- Salt distribution to reservoir and channel reaches, by considering
  - runoff distribution in *ACRU*
  - salt distribution from non-irrigated lands
  - salt distribution from irrigated lands, and
  - salt distribution from impervious areas including hydrological responses of impervious areas as conceptualised in the *ACRU* model and the determination and allocation of runoff salt load from impervious areas;

- Reservoir salt budget and salt routing by considering
  - reservoir water budgeting in *ACRU*, including gains to the system, losses from the system and surface area to storage relationships and
  - determination of TDS concentration of reservoir storage and outflows; and
- Channel salt movement and distributed hydro-salinity modelling.

The Upper Mkomazi as the ACRU-Salinity Verification Catchment

The Upper Mkomazi Catchment of 1 744 km^2 in the province of KwaZulu-Natal in South Africa rises in the foothills of the Drakensberg Mountains and constitutes the upstream part of the Mkomazi Catchment, draining to the UIH005 streamflow gauging weir at Camden (**Figure 11.2.1** top). As shown in the figure, the catchment has been delineated into 18 relatively homogeneous hydrological response zones which range in altitude from 2 165 m in the north western part of the catchment (sub-catchment 5) to 1 339 m in the south eastern part of the catchment (sub-catchment 14). More information on the sub-catchments' flow directions (and hence salt transport routes) is shown in **Figure 11.2.1** (bottom) and details on the physiography are given in **Table 11.2.1**. Although salinity is not a threat to this catchment (**Figure 11.2.2**), some of the criteria considered when selecting the catchment were that

- the entire catchment had been previously configured for the *ACRU* model by Taylor (2001) and
- that this catchment has good streamflow TDS concentration data.

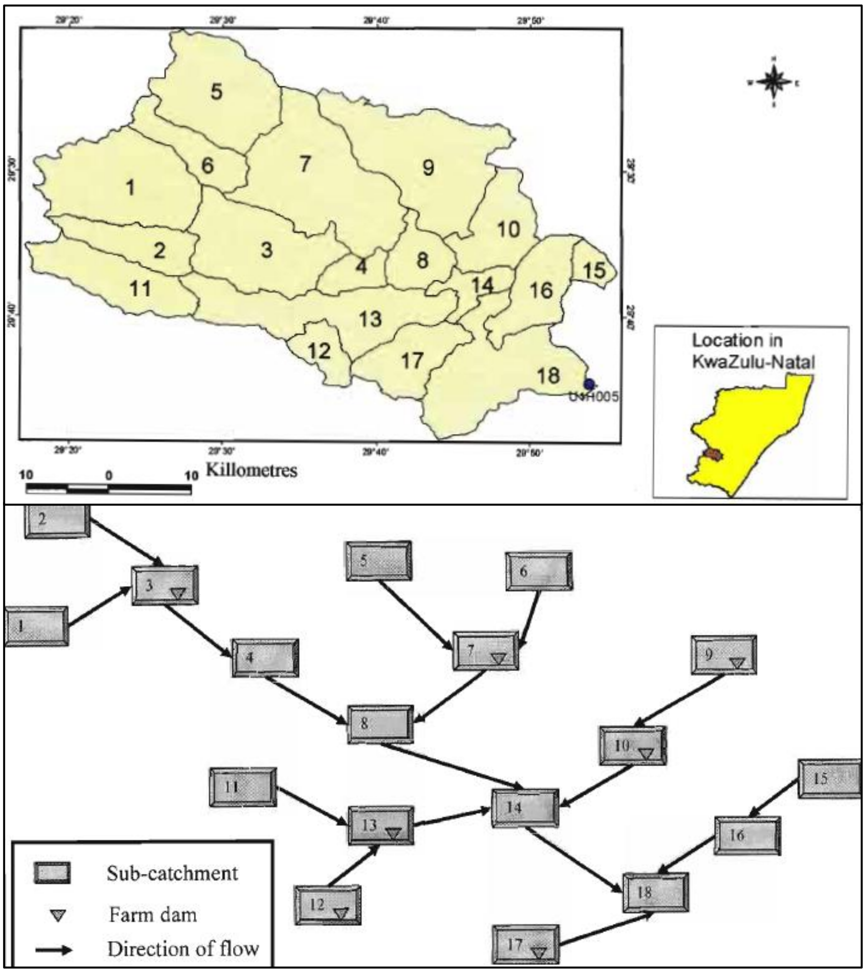

Figure 11.2.1 The Upper Mkomazi catchment and (top) its delineation into sub-catchments with (bottom) flow directions, and thus salt transport routes, between sub-catchments (After Taylor, 2001)

Climatically the Upper Mkomazi Catchment is in a humid zone, with a Mean Annual Precipitation (MAP) in the upstream parts of the catchment ranging from ~1 000 to 1 300 mm and mean monthly A-pan equivalent evaporation ranging from ~ 60 mm for June to 150 mm for December. The Upper Mkomazi Catchment is dominated by unimproved grassland, but with a significant proportion of the area being degraded due to overgrazing on the steep gradients of the landscape. A few forest plantations and subsistence dryland agriculture are other land uses in the catchment.

Each of the 18 sub-catchments of the Upper Mkomazi is composed of nine hydrological response units (land use categories), giving a total of 162 units each with its own input files (18 x 9).

Table 11.2.1 Physiographic information on the sub-catchments making up the Upper Mkomazi Catchment (After Taylor, 2001)

Sub-catchment No	Longitude (degree, decimal)	Latitude (degree, decimal)	Area (km^2)	Mean Altitude (m)
1	29.38	29.51	162.91	2124
2	29.39	29.59	63.32	1959
3	29.54	29.58	141.69	1533
4	29.64	29.61	29.22	1373
5	29.49	29.41	142.97	2165
6	29.46	29.47	57.76	2088
7	29.60	29.50	208.01	1639
8	29.71	29.59	47.09	1410
9	29.71	29.49	189.23	1851
10	29.79	29.56	77.44	1643
11	29.38	29.62	93.12	2104
12	29.60	29.71	32.87	1685
13	29.60	29.69	148.15	1568
14	29.79	29.64	29.97	1339
15	29.90	29.60	18.87	1680
16	29.84	29.64	70.94	1492
17	29.71	29.72	69.99	1678
18	29.81	29.72	158.55	1310

Current Salinity Levels in the Catchment

Current levels of salinity in the Upper Mkomazi Catchment are not a threat for most uses/users of the water in the catchment. Natural and human-induced salinity in the catchment result from point and non-point sources, with the natural sources generally originating from the weathering and dissolution of underlying rocks or from soils overlying the rocks. The Upper Mkomazi Catchment is nevertheless still influenced to some extent by human activities, with agricultural land use constituting a substantial part of the catchment. Department of Water and Sanitation (DWS) salinity data from 1985 to 1995 from weir UIH005 were assessed to identify seasonal fluctuations and any general long-term trend. The EC results in **Figure 11.2.2** do not display any significant increases over time. Seasonal fluctuations in EC are, however, evident mainly as a result of seasonal changes in natural processes. During the rainy season, TDS concentrations drop due to the dilution effect of rain falling on the area, whereas during the dry season salt concentration starts to increase due to the "evapo-concentration" processes.

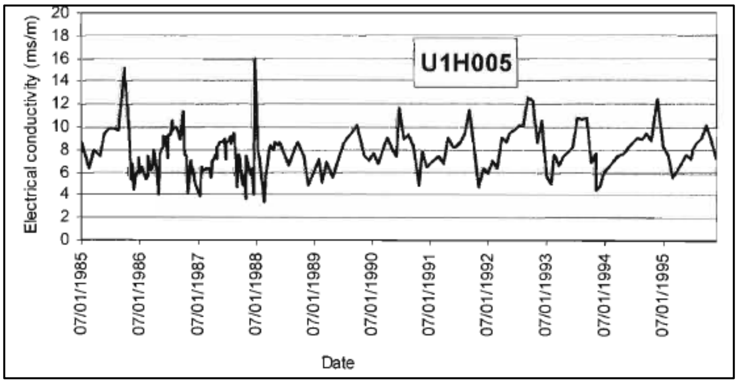

Figure 11.2.2 Intra- and inter-annual trends of streamflow salinity in the Upper Mkomazi catchment at gauging weir U1H005 (After DWS and Teweldebrhan, 2003)

Validating the Hydro-Salinity Module: Overall Approach

The approach employed in validating the hydro-salinity module of *ACRU* involved salt balance computations for different components to ensure that the algorithms underlying the various hydro-salinity processes in terms of mass conservation were correct. This step is not intended for generating outputs to be used for comparison against the observed data, and hence some of the salinity related inputs to the model were hypothetical values. The following algorithms were validated for correctness of the computer code:

- subsurface salt movement processes,
- surface salt movement processes,
- reservoir salt budgeting processes, and
- channel salt movement and distributed hydro-salinity modelling processes.

Basic Data Input Requirements, More Detail on Validation/Data Preparation for ACRU-Salinity

For verifications which compare output with measured data in order to prove that the model realistically represents field processes, model input variables and parameters must be known and field data to compare with model outputs must also be available. Thus, the first step towards *ACUSalinity*'s verification phase was to obtain the required raw data inputs and subsequently prepare these data in a way that can be used by the model. Data relating to the hydrological aspect were already available. However, data that were specific to the *Salinity* module still needed to be input, and these requirements are listed below, with details on their derivation discussed by Teweldebrhan (2003). These data and inputs were obtained from various sources, and included

- rainfall and irrigation water TDS concentrations,
- initial TDS concentrations of subsurface and reservoir water storage, and
- salt uptake rate and equilibrium values.

Data requirements of this last-named process include, *inter alia*, the equilibrium value (saturation value) and the rate constant, which can only be determined if daily soil salinity data are available for the area. However, no such time series records are found for the Mkomazi Catchment. Therefore, the rate constant (k) and equilibrium values (C_e) had to be derived by calibration against observed TDS values and then fitting a regression equation to those observed data. This was achieved by changing the k and C_e values to optimise the module predictions of the streamflow salinity against the observed data. From the various calibration trials undertaken to obtain a representative uptake rate constant *(k)* and an equilibrium (C_e) values for the Upper Mkomazi Catchment, the best fit was attained at a k value of 4.5E-5 and C_e value of 3 000 mg/l. During the calibration trials constant values of k and C_e parameters were used in all sub-catchments.

On each sub-catchment the sources of salt input to a channel reach are:

- salt load associated with runoff water from adjunct impervious areas,
- salt load associated with runoff water from non-irrigated lands,
- salt load associated with runoff water from irrigated lands, and
- salt load transported from upstream reaches, in the case of distributed hydro salinity modelling,

with no channel reach salt storage assumed in *ACRU-Salinity.*

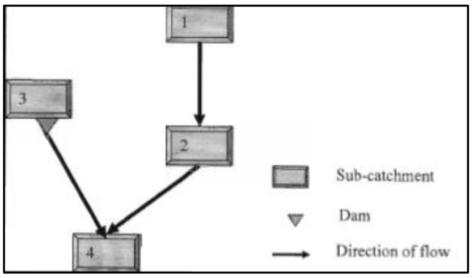

Figure 11.2.3 Layout and direction of salt transport for the catchment used in code validation of channel and distributed modelling processes

Therefore, on a particular day, the total salt load that enters the channel reach is transported to a destination reach on the same day. Thus, when using the configuration of **Figure 11.2.3** as an example, the total salt load at the river (channel) reach of Sub-catchment 2 (River 2) is calculated as the sum total of:

- streamflow salt load from River Reach 1 (River 1),
- runoff salt load from adjunct impervious area in Sub-catchment 2,
- runoff salt load from irrigated land in Sub-catchment 2, and
  runoff salt load from non-irrigated land in Sub-catchment 2.

Based on configuration of the four sub-catchments used as an example for this purpose (**Figure 11.2.3**), the salt load from River 2 is transported to River 4. Similarly, the salt load associated with the total outflow from the external reservoir of Sub-catchment 3 (Dam 3) is allocated to River 4. Therefore, the calculated total salt load at River 4 would be computed from the sum total of:

- salt load from River 2,
- salt load from Dam 3,
- salt load associated with runoff water from adjunct impervious area of Sub-catchment 4
- salt load associated with runoff water from irrigated lands of Sub-catchment 4, and
- salt load associated with runoff water from non-irrigated land of Sub-catchment 4.

The calculated total salt load at all river reaches were compared against the simulated values on these reaches and were found to be error free, thus confirming the validation procedures.

Verification against Observed Data 1: Preparing the Data

The approach to verify the model's output involved use of hydrological and salinity related data specific to the Upper Mkomazi Catchment, with the model outputs then graphically and statistically analysed against observed data. First, however, the data for the verification had to be obtained and checked. Observed data from the Upper Mkomazi Catchment were daily streamflow data for the UIH005 gauging weir obtained from the DWS and streamflow salinity data for this station obtained from the CSIR (2002). Streamflow TDS concentration grab samples collected on a weekly basis from January 1986 to December 1987 were used for calibration (1986) and verification (1987) purposes, with this period being chosen because it has relatively few missing records compared to data of the remaining years.

The weekly grab samples of salinity data, in mg/l, had to be converted to daily values so as to be used for comparison with the daily model output. Therefore, infilling of missing values and subsequent conversion to daily data are done in two steps. The first step involved the infilling of missing TDS values from the EC record, if the EC value was available for the given day. This was done with a regression equation established using observed TDS and EC values at gauge UIH005 is plotted in **Figure 11.2.4**. The linear regression analysis yielded the following relationship with a R^2) of 0.79:

$$TDS = 6.388 * EC + 8.256$$

The second step involved data patching using the TDSGEN program developed by Ninham Shand Consulting Engineers, by infilled missing data based on locally recorded flow-TDS relationships.

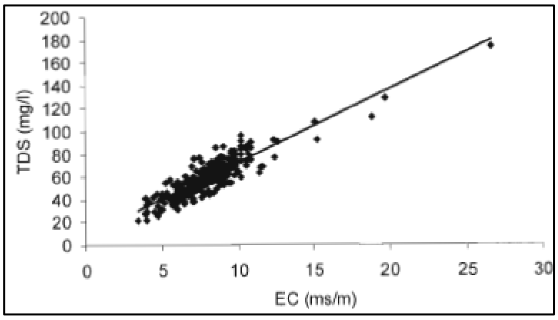

Figure 11.2.4 TDS versus EC relationship as recorded at UIH005 (Camden)

Verification against Observed Data 2: Graphical Results and Discussion
The uptake rate constant *(k)* and the equilibrium values as determined from the calibration result were used as input in simulating streamflow TDS concentration for the verification period (January to December, 1987). Both graphical and statistical methods were then used to evaluate the module performance using the same criteria as considered for calibration.

The daily simulated TDS concentration values and the observed values from the weekly samples were plotted in the same graph, **Figure 11.2.5**, from which it can be seen that the simulated values follow the observed seasonal fluctuations remarkably well.

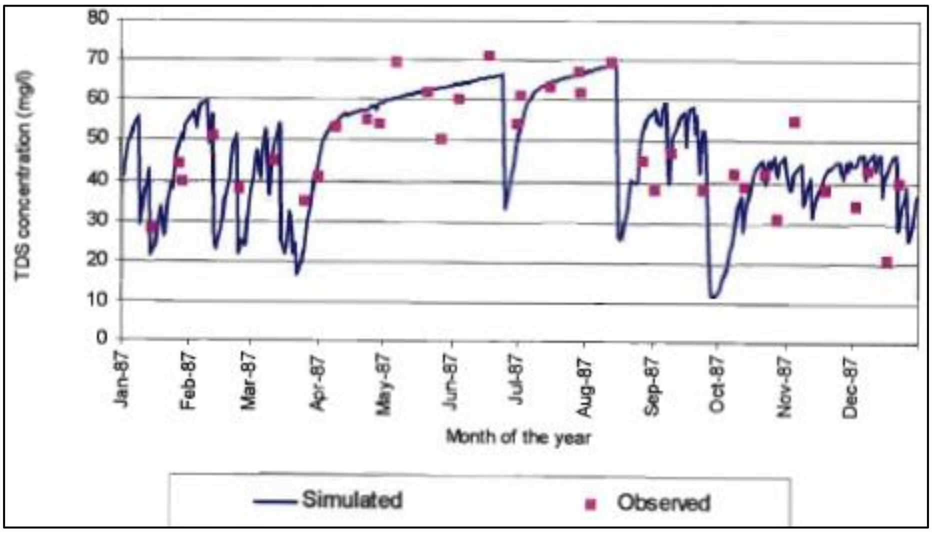

Figure 11.2.5 Observed values of weekly grab samples and daily simulated streamflow TDS concentrations at the Camden sample site U1H005 (After Teweldebrhan, 2003)

Similarly, the monthly means of daily observed TDS concentrations which were infilled from the weekly grab samples were plotted in the same graph with the simulated values as shown in **Figure 11.2.6**. From **Figure 11.2.6** it can be seen that the simulated TDS concentration follow the observed seasonal fluctuations remarkably well. However, the monthly mean of daily simulated TDS concentration values, especially in the dry period from April to August of the verification year (1987), have slightly exceeded the observed streamflow salinity values, while on the other hand, the simulated streamflow TDS concentration values for the wetting up period of October to December have shown very good fits with the observed values (**Figure 11.2.6**).

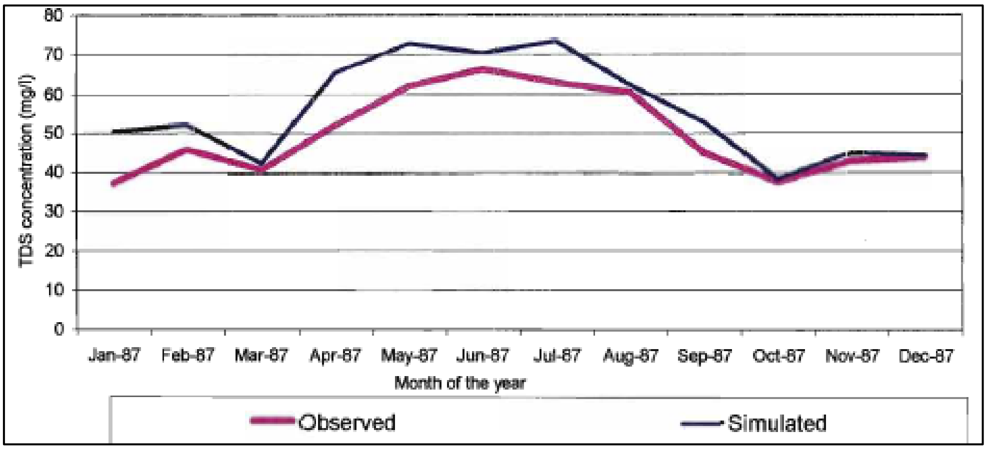

Figure 11.2.6 Monthly means of daily observed (infilled wit TDSGEN) and simulated streamflow TDS concentration values at the Camden sampling site U1H005 for the verification period (After Teweldebrhan, 2003)

Figure 11.2.7 shows observed and simulated percentile curves of the daily streamflow TDS concentration at Camden for the verification period. In general, the percentile curve for simulated values has followed the trend of observed streamflow TDS concentration curve very well. However, the graph shows an overall slight over-simulation of streamflow TDS concentrations, especially for those with relatively higher values (values that would be exceeded in less than 50% of the time).

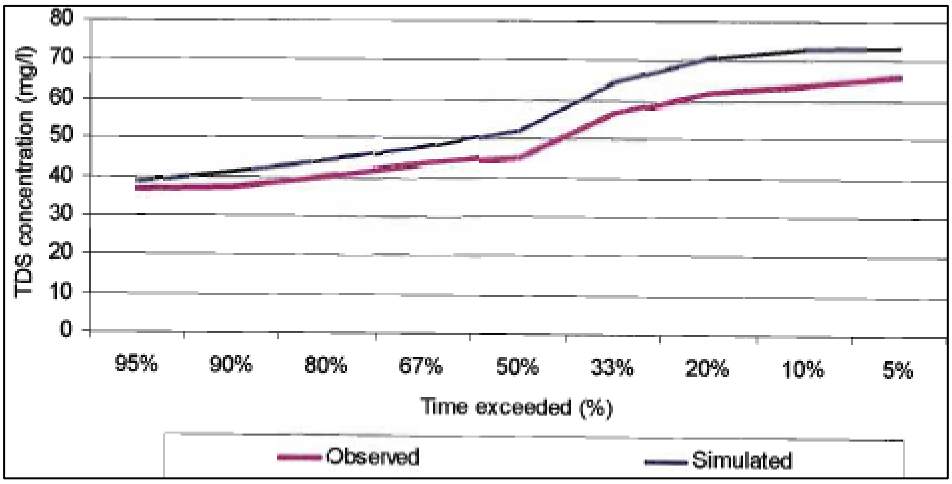

Figure 11.2.7 Percentile curves of observed (infilled with TDSGEN) and simulated TDS concentration values at the Camden sampling site U1H005 for the verification period (After Teweldebrhan, 2003)

Verification against Observed Data 3: Statistical Results and Discussion

Both conservation and regression statistics were used to compare the simulated and observed streamflow TDS concentrations. Results from the statistical analysis are shown in **Tables 11.2.2** and **11.2.3**. In both tables the "Daily" Column refers to value of the statistical parameter determined using daily simulated values and daily observed values which had been infilled using the TDSGEN program from the weekly grab samples, whereas the "Weekly" Column refers to value of the statistical parameter calculated using only the weekly grab samples and the simulated values for the particular day. In general, the conservation and regression statistics show a fair ability of the hydro-salinity processes encoded in *ACRU-Salinity* to mimic the natural processes taking place in the catchment.

The conservation statistics in **Table 11.2.2**, save for the skewness coefficient, do not indicate high divergence between observed and simulated values. The high difference observed between the skewness coefficients, however, reveals a considerable difference in the symmetry of the observed and simulated salinity distributions. The regression statistics in **Table 11.2.3** show a very good fit with the slope showing a slight over-simulation of the model, the Y-intercept having a value close to 0, showing a slight over-simulation, and the correlation coefficient and coefficient of determination showing a high degree of association between observed and simulated values.

-

Table 11.2.2 Conservation statistics of streamflow TDS concentration at Camden U1H005

Statistical parameter	Observed		Simulated		Difference %	
	Daily	Weekly	Daily	Weekly	Daily	Weekly
Mean (mg/l)	49.81	48.12	55.82	48.33	12.07	0.44
Standard deviation	10.57	10.18	12.57	12.49	18.92	22.69
Skewness Coefficient	0.45	0.42	0.21	-0.31	-53.33	173.81

Table 11.2.3 Regression statistics of streamflow TDS concentration at Camden U1H005

Statistical parameter	Value	
	Daily	Weekly
Slope	1.11	0.97
Base constant (y-intercept)	0.33	1.52
Correlation coefficient	0.92	0.79
Coefficient of determination	0.87	0.63

Overall Conclusions

The verification undertaken to evaluate how *ACRU-Salinity* performs under field conditions through comparison of model simulation against observed data yielded good result when considering the data limitations for some of the hydro-salinity input parameters for the Upper Mkomazi Catchment, and considering the complex nature of actual hydro-salinity processes, as they involve geochemical processes in addition to all of the other processes influencing water quantity.

In general, results from the model evaluation have indicated that *ACRU-Salinity* can be used with confidence to provide a reasonable first order approximation in various hydro-salinity studies.

References

CSIR. 2002. Water quality on disc: Water quality data from the hydrological information system. Version 1. CSIR, Pretoria, RSA.

Taylor, V. 2001. Hydrological modelling applications for water resources management in the Mkomazi catchment. MSc Dissertation. School of Bioresources Engineering and Environmental Hydrology. University of Natal, Pietermaritzburg, RSA.

Teweldebrhan, A.T. 2003. The Hydro-Salinity Module of the *ACRU* Agrohydrological Modelling System, *ACRUSalinity*: Module Development and Evaluation. MSc Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, RSA. pp 190.

11.3 Modelling Nutrient and Sediment Dynamics at the Catchment Scale with the *ACRU-NPS* Model Using a Calibration-Validation Approach (Original Researchers: S.A. Lorentz and J. Kollongei; edited/collated by R.E. Schulze)

Background

Agriculture has been recognised, both locally and internationally, as a significant contributor to non-point source (NPS) pollution of water resources. For this reason, progressively more attention has been given to identifying NPS sources and to quantifying the extent of the NPS pollution problems, so that appropriate steps might be taken to reverse, halt, or minimise their environmental impacts. Such steps might include biophysical control measures at field- or farm-scale, or statutory and policy instruments, with biophysical control measures yielding benefits to the water environment.

Development of the ACRU-NPS Model

The *ACRU-NPS* model was originally developed to represent dominant NPS pollution dynamics and processes observed and modelled at the field scale in a range of local and international studies, with the process-based *ACRU a*gro-hydrological model already including algorithms that simulate daily discharge and peak runoff from daily rainfall as well as sediment yield per unit land area based on the Modified Universal Soil Loss Equation (*MUSLE*), in which the energy for sediment entrainment and transport is derived from the event discharge volume and peak flow rate and empirical soil erodibility, vegetative cover, slope and practice factors determine the sediment yield.

Inclusion of nutrient mass balance algorithms in *ACRU* enabled simulation of N and P losses in surface runoff, sediment, and leaching; N and P cycling in the soil-water-plant-animal system; and N and P mass balances in the catchment system. The resultant *ACRU-NPS* includes rainfall, irrigation, fertilisers, plants and animal wastes as potential nutrient sources and simulates pollution management impacts on N and P transformations and transport. New components and processes added to *ACRU* were a plant residue layer, a soil surface layer, plant matter removed, soil temperature, ammonification, nitrification, N plant uptake and fixation, volatilisation, denitrification, N adsorption and extraction, ammonium partitioning, immobilization, P mineralisation, P plant uptake, P adsorption and extraction, labile P partitioning, harvest, tillage surface and evaporation transport, subsurface transport and crop stress recovery after moisture or nitrogen shortfalls.

The Mkabela Catchment on Which ACRU-NPS was Validated

After consultation with the local Mgeni Water Supply Board, the 40 km^2 Mkabela experimental catchment was established in the sugarcane growing region of the KwaZulu-Natal Midlands, 1 km east of the town of Wartburg (30°41' East, 29°22' West), as indicated in **Figure 11.3.1**. While sugarcane covered the larger part of the catchment, vegetables, pastures and forestry covered much of the remainder of the catchment. With the topography of the Mkabela catchment being a major determinant in the movement and behaviour of NPS pollution, a Digital Elevation Model (DEM) allowed for catchment boundary delineation, using pixel sizes of approximately 21 m x 21 m from 5 m contour intervals obtained from 1:10 000 maps. The land use data derived from existing aerial photographs was supplemented *by in situ* ground-truthing surveys. Key weather data for the research period are shown in **Figure 11.3.2**.

Point observations comprised weather data, overland flow at two runoff plots, sediment and nutrient yield and, additionally, soil water tensions in transects to waterways, soil nitrate profiling and groundwater sampling. Field-scale observations at two flumes in field-draining waterways included runoff and concentrations of suspended solids and nutrients. Catchment-scale observations comprised discharge at multiple scales as well as concentrations of suspended solids and nutrients.

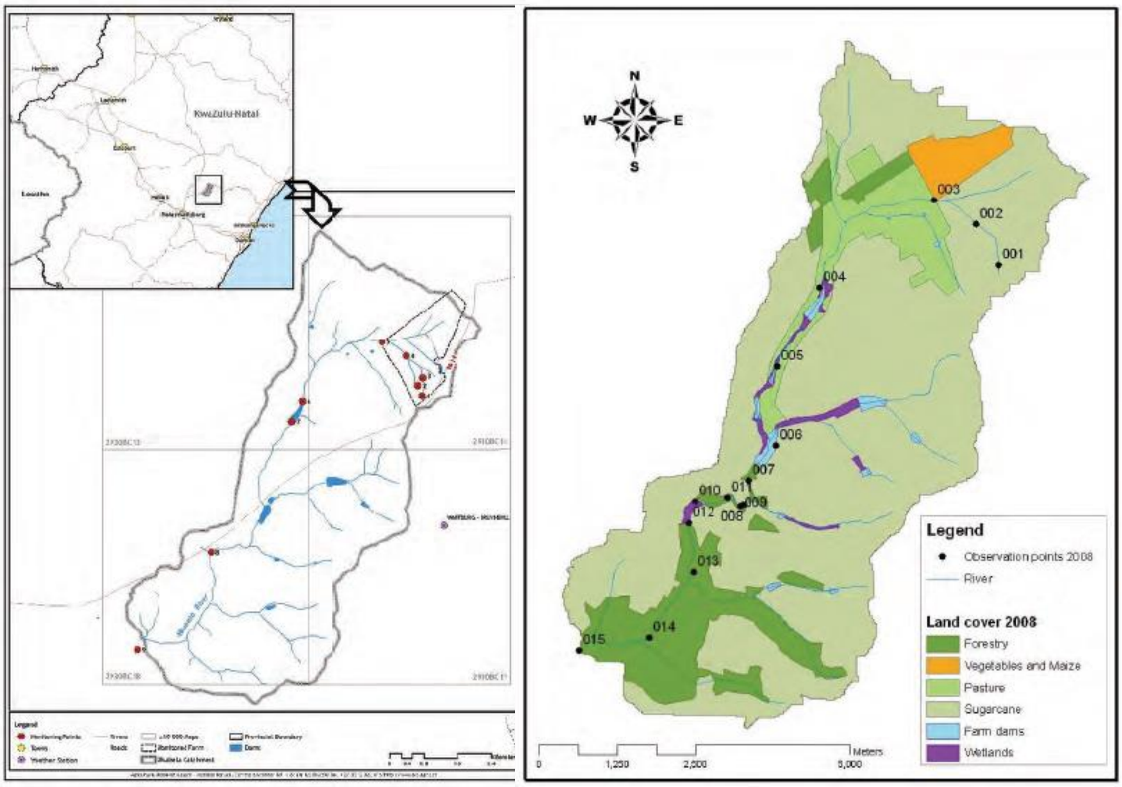

Figure 11.3.1 The Mkabela catchment showing nested sampling positions (left) and land uses (Lorentz *et al*., 2012)

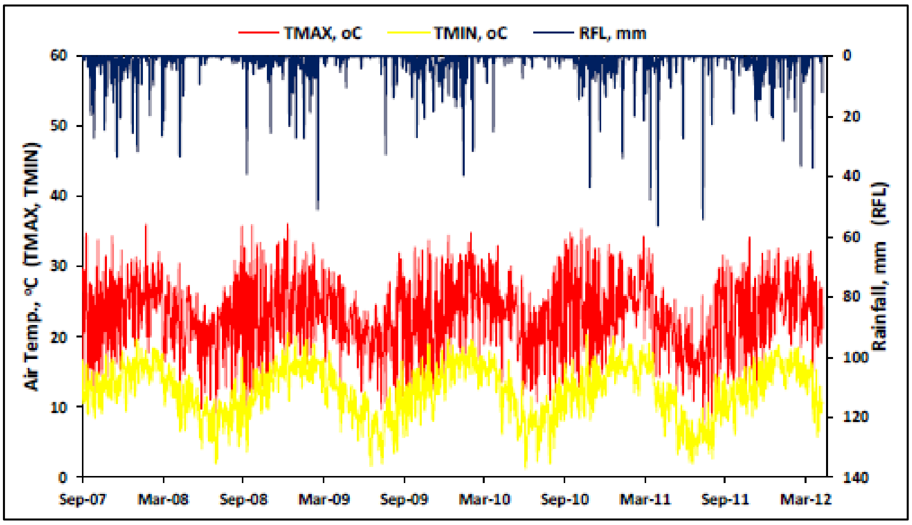

Figure 11.3.2 Daily weather station data for the Mkabela catchment for the period September 2007 to April 2012 (Lorentz *et al*., 2012)

Calibration and Validation Procedures

Following a period of calibration between October 2007 and March 2008 from 6 rainfall events within this period, *ACRU-NPS* was then validated for the period January 2009 to March 2012 against the observations at the lower flume at the small catchment scale. Calibration was restricted to runoff, nutrients and sediment measurements from the ISCO sampler and H-flume at the outlet of what was defined as Flume 2.

Calibration of the *ACRU-NPS* model focused mainly on the hydrological component of the model by adjusting the most sensitive parameters. The *hydrological component* was calibrated by adjusting both the *QFRESP* (stormflow response coefficient) and *COFRU* (baseflow response coefficient), where *QFRESP* represents the fraction of total storm flow that will run off from the catchment on the same day as rainfall event, and this was found to be 0.6 during calibration. *COFRU* represents the fraction of the intermediate groundwater store that becomes streamflow on a given day, with this found to be 0.0012 after calibration. The *erosion component* was calibrated by adjusting the *MUSLE* soil erodibility and support management practices. The *MUSLE* equation allows the prediction of sediment yields for an individual event directly without using a sediment delivery ratio.

The *ACRU-NPS nutrient components* that were found to be sensitive to the simulated nutrient loads were plant rooting depth, leaf area index, fresh organic matter and the rainfall NO_3-N concentration, while fresh organic nitrogen in crop residue was represented as 20% mineralizable soil-N and 80% NO_3-N. The model performance was tested by subjecting the data to statistical tests.

Calibration and Validation Results

The measured daily runoff, nutrient and sediment yield from 6 rainfall events from the catchment from October 2007 to March 2008 were used for model calibration (**Figure 11.3.3**), whereas measured NPS pollutant loads from 12 rainfall events during 2009-2012 were used to evaluate the model performance.

a. Calibration of Runoff

The measured and simulated daily runoff shown in **Figure 11.3.3** indicate that the simulated runoff follows a similar trend as that of measured runoff. From the graphical comparisons (**Figures 11.3.3 and 11.3.4**) it can be inferred that the calibrated parameters for the studied catchment realistically represent the nature and behaviour of runoff from the catchment. Marginal differences may have resulted from inaccuracies associated with input data to the model, specifically, subtle differences in channel, soil and subsurface properties. The results of the statistical tests outlined in **Table 11.3.1** showed that the values of R^2 at 0.94 and NS_E at 0.87 also indicated agreement between the measured and simulated runoff.

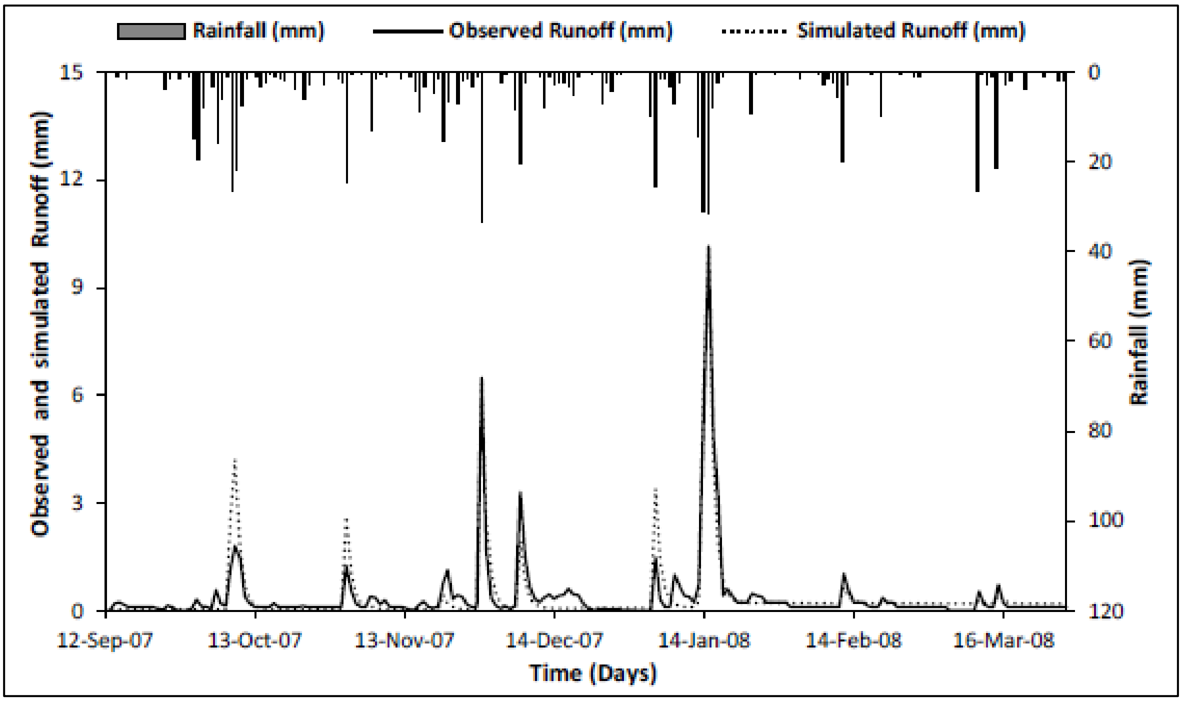

Figure 11.3.3 Hydrological calibration of the *ACRU-NPS* model for daily runoff for the period October 2007 and March 2008 (Kollongei, 2012)

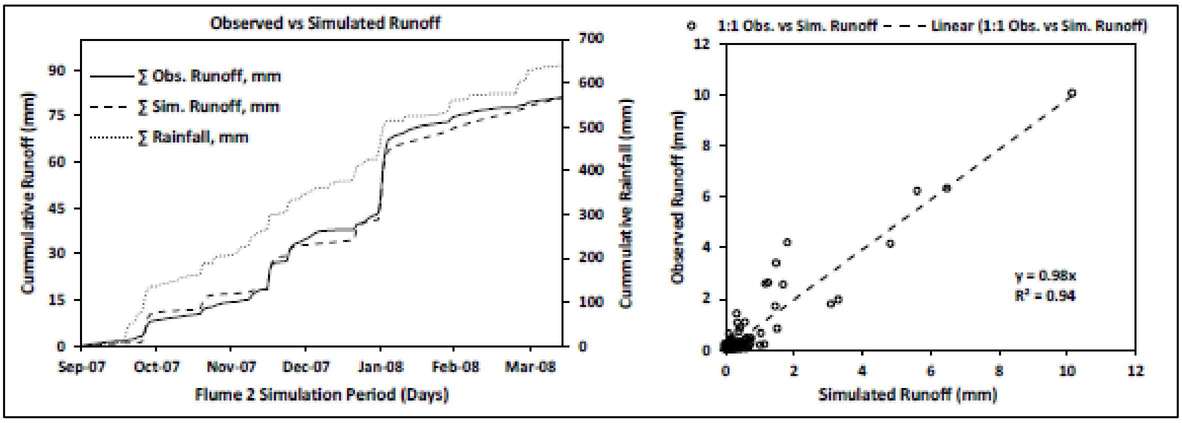

Figure 11.3.4 Cumulative runoff for observed and simulated runoff (left) and 1:1 comparison between observed and simulated runoff (right) during the calibration period (Kollongei, 2012)

Table 11.3.1 Statistical *ACRU-NPS* model performance for the calibration period (Kollongei, 2012)

Criteria	Runoff (mm)	NO_3 (kg/ha)	P (kg/ha)	Sediment (kg/ha)
Coefficient of determination (R^2)	0.94	0.98	0.95	0.98
Nash and Sutcliffe coefficient of efficiency (NS_E)	0.87	0.96	0.90	0.95
Overall % deviation (Dv)	0.01%	3.82%	6.21%	0.66%

b. Calibration and Validation of Nitrate (NO_3) Loads

The model results were compared with the measured NO_3 loads at the outlet of Flume 2 on different events during the simulation period. The simulated events shown in **Figure 11.3.5** indicate that the NO_3 loads (kg/ha) in the runoff were, in general, reasonably well predicted by *ACRU-NPS* for most events, with loads for a few events being under-estimated.

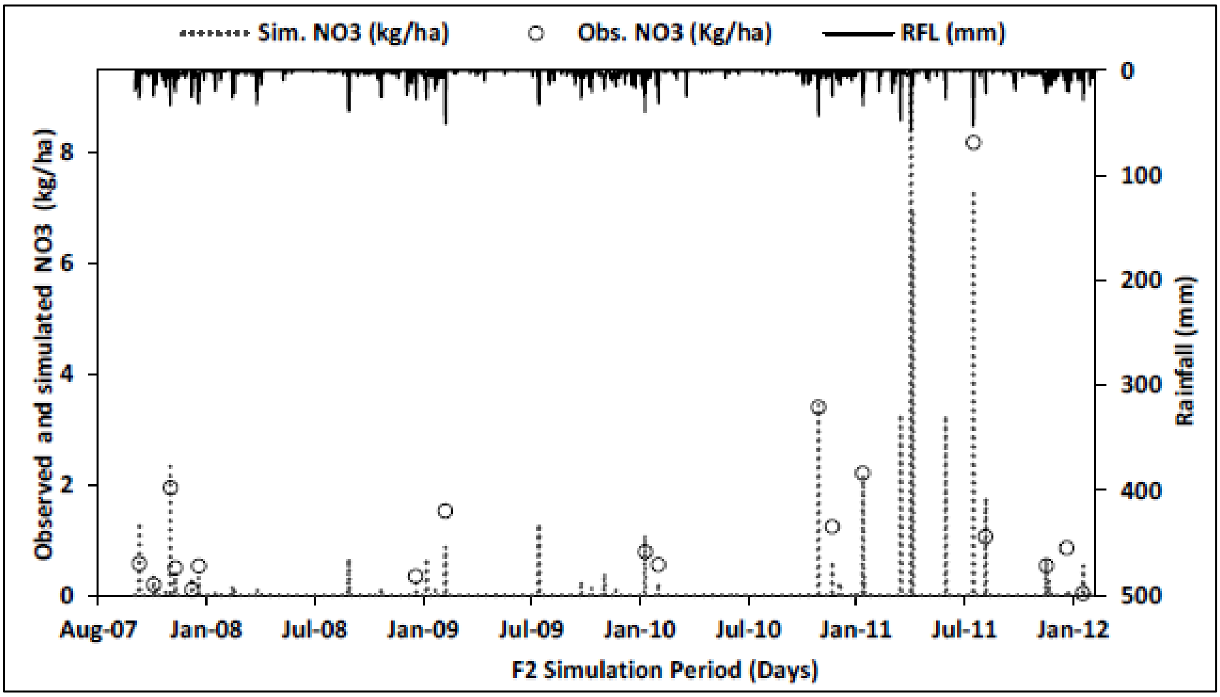

Figure 11.3.5 Hydrological calibration of the *ACRU-NPS* model for daily NO_3 yield (kg/ha) for the period October 2007 and March 2008 and validation for the period January 2009 and March 2012 (Kollongei, 2012)

The statistical test evaluation of the measured and simulated NO_3 loads (**Table 11.3.1**) revealed a close agreement with the R^2 at 0.98 and the Nash-Sutcliffe simulation efficiencies at 0.96, while the percentage deviation of 3.82% indicated a slight under-prediction. The scatter comparison between measured and simulated NO_3 loads for the rainfall events studied show slight under-prediction for at least some observations. However, the statistical analyses suggest that the predictions were within acceptable accuracies. **Figure 11.3.6** (left) shows some rainfall events from which much more prominent high loads were generated than from rainfall events of almost similar magnitudes. One such event occurred on August 2011 (in the low flow winter season) and this may be attributed to a high concentration of nitrates in the baseflow which could probably have had its source from the summer events of the previous season that had percolated as groundwater.

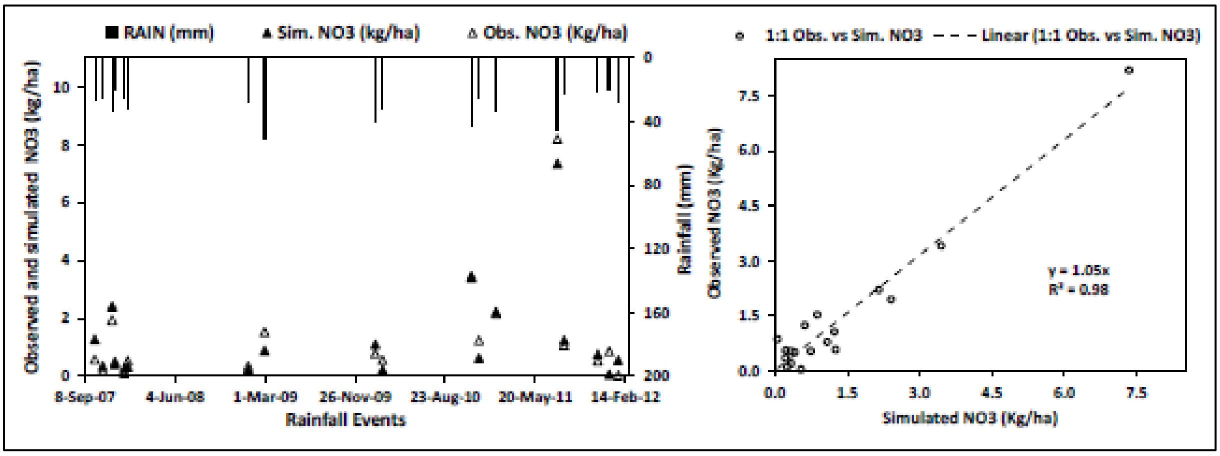

Figure 11.3.6 Comparison of observed and simulated NO_3 yield (kg/ha; left) and their scatter comparison (right) generated by the *ACRU-NPS* model for events occurring in both the calibration and the validation periods between September 2007 and February 2012 (Kollongei, 2012)

c. Calibration and Validation of Phosphorous (Soluble-P) Loads

The comparisons between the measured and simulated values of water soluble-P loads for selected periods during the calibration and validation period between 2007 and 2012 are presented in **Figure 11.3.7**. The scattergram comparison of the same are presented in **Figure 11.3.8**. The simulated results, shown in **Figure 11.3.7**, reveals that soluble-P is under-predicted by the model for at least for some of the observation dates. However, the results of statistical tests performed on the measured and simulated soluble-P showed that the values were not significantly different at the 95% confidence level.

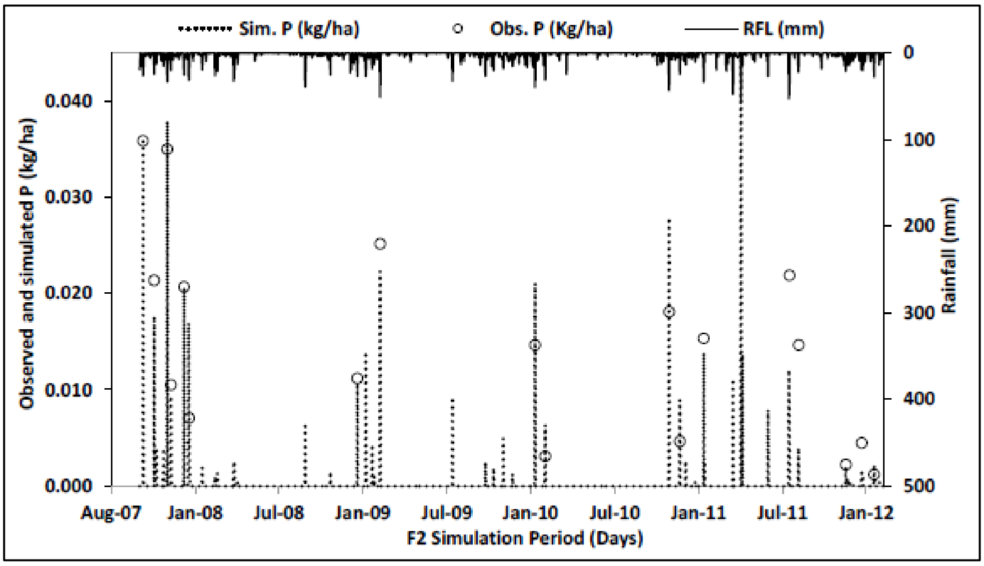

Figure 11.3.7 Hydrological calibration of *ACRU-NPS* model for daily P yields (kg/ha) for the period October 2007 to March 2008 and validation for the period January 2009 to March 2012 (Kollongei, 2012)

The R^2 and NS_E for the simulated soluble-P at the 95% confidence level were 0.95 and 0.90, respectively (**Table 11.3.1**). This indicated a close agreement between the measured and simulated values. The Dv value indicates that soluble-P was under-predicted by 6.21%, which was lower than the general level of acceptance of 20%. Thus, performance of the P-component model was thus found to be well within acceptance levels.

The scattergram between the measured and simulated soluble-P loads for the rainfall events studied show under-prediction for some of the observations (**Figure 11.3.8**). Some of the observed values were on the upper side of the 1:1 line, indicating higher observed soluble-P values than simulated during some peaks. The two outliers of 26th July 2011 shown in **Figure 11.3.8** (right) illustrate higher values for observed soluble-P than simulated.

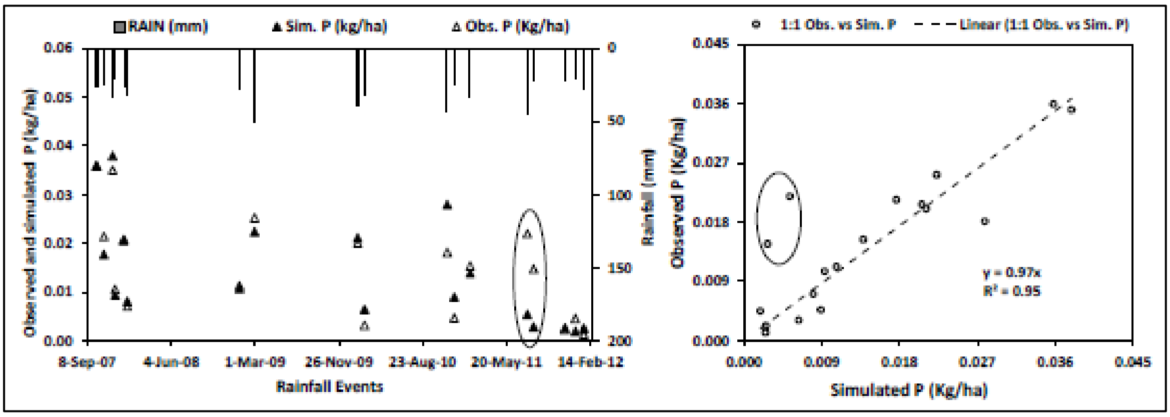

Figure 11.3.8 Comparison of observed and simulated P yield (kg/ha) (left) and their scatter comparison (right) for the *ACRU-NPS* model (Kollongei, 2012)

It is surmised that much of the P transport in contributing hillslopes in the Mkabela catchment is in the dissolved phase and is likely to occur in the sub-surface during recession and low flow sequences in winter. The *ACRU-NPS* model should be improved to capture this important contribution mechanism for nutrients in the landscape in the subsurface, where lateral discharge occurs in the intermediate layer between the sandy soil and bedrock. This could be the reason for the higher observed value compared to simulated soluble-P values.

d. Calibration and Validation of Sediment Yields

The daily measured and simulated values of sediment yields are presented and compared graphically in **Figure 11.3.9**.

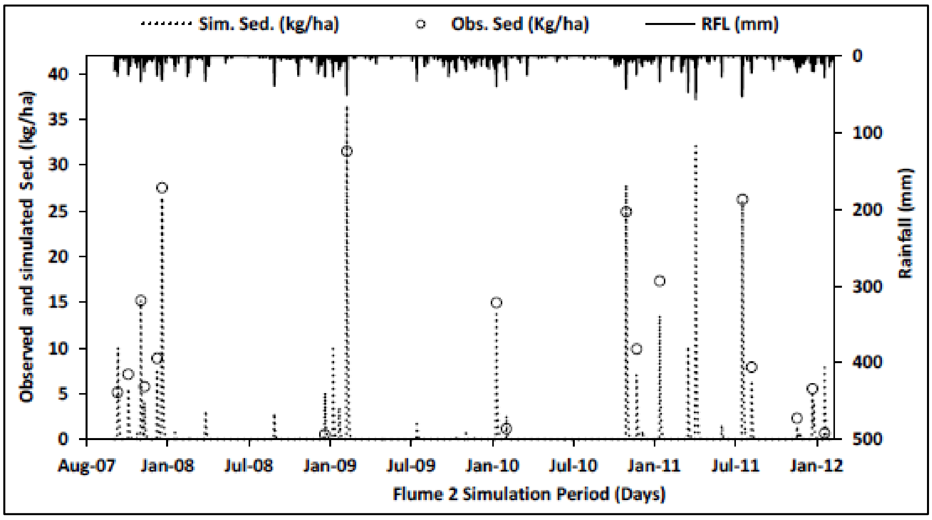

Figure 11.3.9 Hydrological calibration of *ACRU-NPS* model for daily sediment yields (kg/ha) for the period October 2007 and March 2008 and validation results for the period January 2009 and March 2012 (Kollongei, 2012)

The predicted daily values match well with the trend of the measured sediment yield throughout the calibration period. However, the model under-estimates the daily sediment peaks in some instances and over-estimates them for other events. One reason for this is that a high intensity summer rainfall event could generate more measured sediment yield compared with the simulated counterpart, which is estimated on the basis of total quantity of rainfall in a day. Because of this, some peaks of simulated sediment yield were not well matched with their measured counterparts. Nevertheless, the overall prediction of the daily sediment yield during the calibration period showed close agreement with its measured counterpart.

Figure 11.3.10 shows the simulated yields to have been distributed along the 1:1 line for both low and high values of the measured sediment. However, some of the values were on the lower side of the 1:1 line, indicating higher simulated sediment than observed, particularly during low peaks.

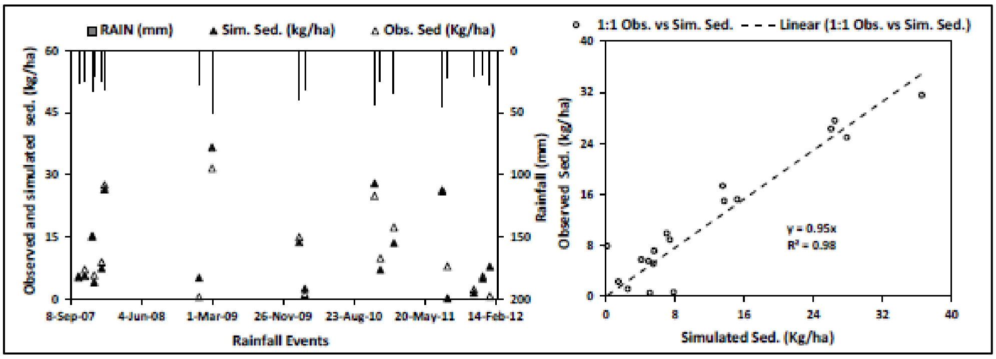

Figure 11.3.10 Comparison of observed and simulated sediment yield (kg/ha) (left) and their scatter comparison (right) for the *ACRU-NPS* model (Kollongei, 2012)

The results of the statistical analyses performed to compare the simulated daily sediment yield with their measured counterparts are presented in **Table 11.3.1**. High values of R^2 (0.98) and NS_E (0.95) showed that the simulated sediment yields were in close agreement with their measured counterparts. Dv of 0.66% further indicated that the model predictions were within the acceptable level of accuracy.

Overall Conclusions

While observed nitrate loads were simulated successfully with *ACRU-NPS*, phosphorus loads were slightly under-simulated and sediment loads slightly over-simulated. The results of simulations nevertheless reveal that the *ACRU-NPS* model can be successfully utilized in characterising the stream runoff, sediment yield and associated NPS pollution of water, and thus can serve as a decision management tool in helping solve water quantity and quality problems. The results can be used as a decision support tool by stakeholders for designing an appropriate management strategy to control runoff and sediment from an area. It can also be used in water and fertilizer management in agricultural fields to minimize the NPS pollution losses hence improving nutrient use efficiency of rain fed crops.

Key References

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Lorentz, S.A., Kollongei, J., Snyman, N., Berry, S.R., Jackson, W., Ngaleka, K., Pretorius, J.J., Clark, D., Thornton-Dibb, S. and Görgens, A.H.M. 2012. *Modelling Nutrient and Sediment Dynamics at the Catchment Scale*. WRC Report No. 1516/3/12, Water Research Commission, Pretoria, RSA.

12 SYNOPSIS AND A WAY FORWARD

R.E. Schulze

12.1 Synopsis

Following some background in Chapter 1 on the concepts around verification of model output considering processes, scales and different hydro-climatic locations, both nationally and internationally, and then in Chapter 2 identifying that verification studies are fraught with problems and require certain pre-conditions to be met, Chapter 3 presents a brief synopsis of statistics that are useful in agro-hydrological model verifications. Thereafter, in Chapter 4, an outline is presented on the *ACRU* agro-hydrological model, followed in Chapter 5 by a brief background on verification studies previously undertaken with the *ACRU* model. This a prelude to a series of verification studies in Chapter 6 of internal state variables in *ACRU*, including verifications of the model's soil water content under both dryland (i.e. rainfed) and irrigated conditions, of actual evapotranspiration and of canopy interception of rainfall. Chapter 7 then presents verification results on biomass related yields with *ACRU* – of maize, of winter wheat, sugarcane and of timber yields, followed in Chapter 8 by results from land use and land management impacts on runoff by assessing the *ACRU* model's performance when simulating changes in land cover over time, of impacts of afforestation, of a wildfire on streamflow responses and of *ACRU*'s flow routing module. In Chapter 9 the focus shifts to international verification studies using the *ACRU* model, with results illustrated from New Zealand, Eritrea, eSwatini (formerly Eswatini), Zimbabwe and Canada, before spatial scale and other issues in hydrological verifications with the model are highlighted in Chapter 10. In that Chapter a general introduction to the problem of scale is followed by a series of verification results, first from small research catchments in the USA and the RSA, then from a number of medium-sized operational catchments across South Africa, followed by verifications from larger operational catchments across different hydro-climatic regions of the RSA, including a verification study that provided more questions than answers, and then a section on the benefits of modelling at Quinary catchments rather than Quaternary catchments. In the last verification chapter, *viz*. Chapter 11, a selection of verification studies on specialised versions of the model is presented, with a verification of snow hydrology responses when using *ACRU-SMiM* in Germany, of the hydro-salinity version of the model called *ACRU-Salinity* and of a non-point source pollution version of *ACRU* named *ACRU-NPS*, all with highly satisfactory results.

12.2 A Way Forward

The *ACRU* model, while already highly versatile and multi-faceted, should be seen as a "living" agro-hydrological modelling system for which it is foreseen that improvements as well as additions (and also at times simplifications) to process representations, should still be made. Once the code and thought processes of those additions have been validated, these all than need to be verified against observed data. In a South African context, for example, additions to the model would include

- improvements to modelling hillslope processes,
- modelling of hydrological responses of ephemeral (i.e. seasonally flowing) streams,
- modelling of hydrological responses of episodic (i.e. only after a significant rainfall event) streams,
- modelling of hydrological responses of endorheic (i.e. internally drained) areas which make up ~ 15% of South Africa,
- improvements to the shallow and deeper groundwater routines,
- the ability to cascade sediment yields through downstream catchments and through dams, and/or
- modelling water temperatures, which have wide-ranging implications to river health, especially under conditions of projected climate change,

again, with verification studies needed in each case.

Finally, the verification of outputs from the *ACRU* model which have been presented in this document, be they of internal state variables (i.e. process representations) or of standard agro-hydrological outputs, while relatively comprehensive, is not an exhaustive compendium of all the model verifications on *ACRU* undertaken to date and in time more examples will be added to this Report. This report should thus also be viewed as a "living" document.