A STAKEHOLDER DRIVEN PROCESS TO DEVELOP A MORE EQUITABLE AND SUSTAINABLE WATER RESOURCE MANAGEMENT PLAN

Report to the
WATER RESEARCH COMMISSION

By

DAVID GWAPEDZA[1]

and

Sukhmani Mantel[1], Sakikhaya Mabohlo[1], Stefan Theron[2], Sinetemba Xoxo[1], Bruce Paxton[2], Olivier Barreteau[3], Rodney Tholanah[4], Karen Bradshaw[4], Bruno Bonte[3], Jane Tanner[1]

[1]Institute for Water Research, Rhodes University
[2]Freshwater Research Centre
[3]National Research Institute for Agriculture, Food and Environment (France)
[4]Department of Computer Science, Rhodes University

WRC Report No. 3157/1/24
ISBN 978-0-6392-0638-7

July 2024

Obtainable from
Water Research Commission
Bloukrans Building, Lynnwood Bridge Office Park
4 Daventry Street
Lynnwood Manor
PRETORIA

orders@wrc.org.za or download from www.wrc.org.za

This is the final report for project no. C2020/2021-00607.

EXECUTIVE SUMMARY

BACKGROUND

Water scarcity is an urgent problem throughout South Africa, especially in the Koue Bokkeveld (KBV) in the Western Cape, where average rainfall is too low to provide for the needs of both people and the environment. Regular droughts and the increasing impacts of climate change make the situation worse. Laws, such as the South African National Water Act and Water Services Act, were established for two reasons: to control human water usage, and to protect the environment through Environmental Water Requirements (EWR). However, continuing low rainfall in the KBV region has not produced enough water in rivers and reservoirs; this situation has led to increased competition among water users. Upstream farmers, who have first access to river water, often clash with downstream farmers who are left to use what remains after upstream needs are satisfied. This competition undermines the EWR and threatens the health of river ecosystems and the ecosystem services downstream.

The dam systems constructed in the KBV have made the conflicts in the region worse because the dams decrease the EWR and are a threat to various plant and animal species that depend on river systems. This situation increases inequality, stimulates conflicts, and, if it is unmanaged, it could have negative environmental outcomes, because of the presence of endangered endemic fish species in the rivers. The possible loss of agricultural productivity is also a threat to food security and the livelihoods of farmworkers in the area.

In response to these challenges, this project is developing a shared water management strategy in the KBV region, aimed at achieving fairness in water access and, at the same time, protecting the EWR. The conflicts between upstream and downstream farmers stress the urgency of effective water management. This collaborative approach aims to reduce water conflicts, promote ecosystem health, and prevent biodiversity loss.

AIMS

These are the aims of the project:

1. To develop an Agent-Based Model (ABM) for the KBV with the active participation of local farmers.
2. To assist KBV farmers to establish rules and regulations for sustainable and fair water use, considering environmental water requirements.
3. To evaluate water availability under various climate scenarios using a hydrological model, and to explore adaptive measures through the ABM.

METHODOLOGY

The research in the Koue Bokkeveld (KBV) employs a comprehensive group of models within a framework of engagement with stakeholders in order to address the complexity of the region and to include different stakeholder perspectives. These models, shown in Figure 1, include an Agent-Based Model (ABM), two water-balance models at catchment and farm levels, and established hydrological models such as the Pitman hydrological model and the Soil and Water Assessment Tool (SWAT+). The ABM is linked with the locally developed Water Sharing Tool (WST) to help advance stakeholder engagement in exploring various water management scenarios and establishing a water management plan.

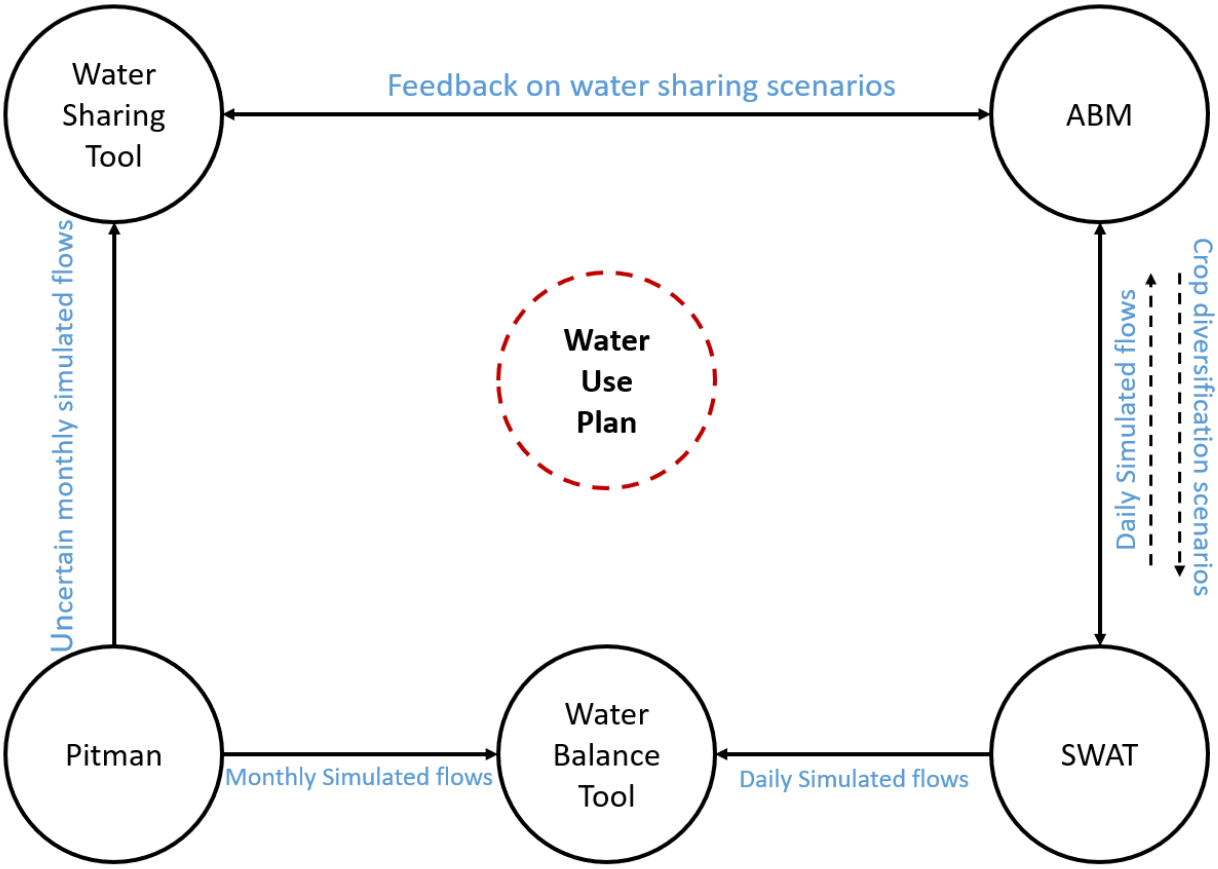


Figure 1. The collection of models used in the KBV to achieve a shared water-use plan.

The Water Balance Tool (WBT) is a simple hydrological model that operates at the farm level and plays a crucial role in implementing the water management plan. Stakeholders participate at every stage of the process and are involved in developing, implementing, and testing these models; the data that stakeholders provide is of key importance. Between November 2021 and November 2023, a series of workshops held to establish collaboration between all the stakeholders.

Workshop 1 introduced the project to the KBV community and stakeholders;

Workshop 2 shared methodologies and gathered baseline data;

Workshop 3 focused on sharing model prototypes, gathering stakeholder feedback, and obtaining additional data to improve the model;

Workshop 4 shared model outputs and laid the foundation for adopting a water use plan.

The workshops provided an important platform for engaging stakeholders in developing the models together and ensuring their perspectives were built into the research. Stakeholder engagement drew on two approaches, a locally developed Adaptive Planning Process (APP) and an internationally developed Actors Resources Dialogue and Interactions (ARDI) approach.

A four-stage development approach was followed, based on the initial engagement with stakeholders. The first stage was to understand the hydrology of the catchment, followed by determining possible ways to share water using models of different systems. In these two stages, the research took a more prominent role and stakeholders collaborated in developing and testing the model for accuracy. In the third stage stakeholders decided on a water-sharing plan based on the scenarios, strategies, and hydrology from stages 1 and 2. The final stage was implementing the plan, where the research team provided a water balance tool to use that farmers can use. The last two stages are clearly led by the WUA with the research team providing technical support and the models providing evidence to support decisions about water sharing.

RESULTS AND DISCUSSION

UNDERSTANDING THE HYDROLOGY

- *Model Calibration and Parameters:* Manual calibration, addressing equifinality concerns, resulted in a well-fitted model for the Twee catchment. Selected parameters, including bulk density, plant uptake compensation factor, and runoff curve number, exhibited calibrated values optimizing model performance.

- *Hydrological Dynamics and Human Impact:* The calibrated model successfully imitated the natural streamflow dynamics, simulating peak flows and wet season low flows. Human development, represented by reservoirs and irrigation on farms, significantly altered catchment flows, reducing the streamflow, particularly during dry years.

- *Water Balance Components:* Accurate simulation of water balance components highlighted the importance of evapotranspiration, accounting for 62% of total water input. Seasonal variations in surface runoff, interflow, and groundwater flow underscored the influence of rainfall on catchment hydrology.

- *Reservoir Dynamics and Impact on Flow:* Reservoir water levels varied, based on water withdrawn for irrigation, with substantial decreases during dry years. Reservoir spillage (overflow) was reduced during irrigation, impacting downstream flow during dry periods, and worsening downstream dryness.

DETERMINING WAYS TO SHARE WATER USING AGENT-BASED MODELLING

- *ABM Implementation and Validation:* Implemented using CORMAS simulation environment, the ABM for KBV catchment was changed many times. Three major versions were defined, focusing on the river network, crop fields, and dams; these versions were continuously checked and tested. Objective validation involved comparing ABM output flows to observed data, while feedback evaluation gauged stakeholder acceptance.

- *Farm-Level Validation:* Simulation assessed the real water demand, revealing a 234,085 m^3 disparity, which was fixed with a correction parameter. Water shortage validation recognised the absence of historical records and relied on workshops and stakeholder discussions. Stakeholders acknowledged realistic outcomes, in spite of the challenges in obtaining precise historical shortage data.

- *Short Term Future Water Use Analysis _ 2025 to 2030:* Scenarios explored moderate and extreme climate change, indicating increased catchment stress and potential water shortages. A scenario including increased dam storage was also explored. In each scenario, model outputs indicated when farms (and the EWR) will be in deficit and for how long. A trend of increasing shortage was noted under climate change and when farmers increased hectarage. Increased dam storage led to significant decline in farm water deficit and increased maintenance of the EWR.

- *Effectively Adapting to Climate:* This scenario, which incorporated a shared dam and increased dam capacity, is effective in mitigating water stress and enhancing resilience in agriculture amid climate change. Increased dam storage and a new dam managed by the Water User Association, significantly reduces catchment stress. A noteworthy decrease in weeks where Environmental Water Requirements are not met is achieved, highlighting the scenario's success in addressing critical water scarcity challenges.

- *Stakeholder Acceptance and Engagement:* Stakeholders positively accepted the model's outputs, acknowledging the realistic challenges. The model's ability to engage stakeholders and obtain their acceptance is crucial for refining accuracy and relevance in water resource management.

DECIDING WAYS TO SHARE WATER USING THE WATER SHARING TOOL

- *User Groups:* Five user groups, including corporate farmers, family farmers, downstream farmers, residents, and a reserve group. Categories were based on workshops and input from key informants to ensure that the groups represented the correct contexts.
- *Community Weighting:* The Analytic Hierarchical Process (AHP) was used to establish a community weighting index for conditions of water shortages. The Community Weighting reflects relative importance of user groups and includes ecological, socio-economic, and legislative factors.
- *Resilience Measurement:* This combines the community weighting index and the impact index to assess how much interruption of the water supply a user can tolerate. User questionnaires were used to ensure the ranking of supply priorities was transparent.
- *Vulnerability Assessment:* Impact curves evaluate effects of water deficits on sectors. Systematic method assesses adaptive capacity, integrating social adaptation and stakeholder input.
- *Water Use Strategies:* Four strategies were introduced: Equal Sharing, Proportional Sharing, Proportional to Community Weighting, and Equalized Impact. These strategies recognise societal and environmental concerns and provide nuanced water allocation approaches.
- *Serious Game (RPG) Approach:* Role-playing game was proposed as an interactive tool for stakeholder engagement. This approach facilitates co-learning, participatory analysis, and collaborative decision-making in water management.
- *Key Risks (Deficit-Impact Analysis):* Impact curves assess environmental (EWR) and socio-economic vulnerabilities. Shifting in-stream requirements from reserve level B to D exposes the environment to medium effects at 15% deficits. Downstream farmers are the most vulnerable to water deficits whereas consortium farmers face the least impacts at 15% and 20% water deficit.
- *Overall Impact from Water Sharing Strategies:* We focus on the Split the Bill scenario, which allocates water equally among all users in a sub-catchment. The Split the Bill water allocation strategy shows minimal annual impacts (1-5%) for the community, individuals, and the environment, but the intensity can be severe (>7). Despite this, it helps reduce disastrous impacts at the community level. Considering its overall minor effects, the strategy is worth exploring further, especially as it is in line with water managers' goals of safeguarding national socio-economic interests like food security and employment.

STAKEHOLDER ENGAGEMENT FEEDBACK AND LEARNINGS

- *Workshop Satisfaction and Impact:* Stakeholders were generally satisfied with communication, which improved in the second workshop. Participants were highly satisfied with the workshop structure and facilitation and emphasized the need for clarity and concise explanations. Most stakeholders found the workshops very valuable, indicating a positive impact on participants.

- *Preparation and Stakeholder Engagement:* The success of stakeholder engagement is attributed to collaborating partners, a professional facilitator, and a transdisciplinary team. Stakeholder mapping and identifying influential champions were crucial in planning and creating well-attended workshops. Challenges, such as the absence of key decision-makers, made it necessary to adapt strategies and continue engagement after workshop sessions.

- *Engaging Stakeholders Using APP and ARDI Approaches:* The 'eliciting concerns' step allowed stakeholders to voice issues that were important to them, so contributing to the development of a shared vision. The process of creating a shared catchment vision demonstrated stakeholder commitment, leading to increased participation in subsequent workshops. The integrated use of engagement approaches facilitated collaboration despite competing interests, built relationships, and motivated stakeholders towards a shared vision.

- *Stakeholder Feedback and Model Co-Development:* Valuable feedback from participants emphasized the need for improved science communication, including active translation during workshops. Stakeholders were eager to interact on a practical level with simulation models, demonstrating confidence in the process. The team remained cautious, ensuring participants understood and confirmed simulation model outcomes before progressing to water management planning.

GENERAL

Aim one was completed by developing and implementing an agent-based model together with KBV stakeholders. Significant progress was made in establishing an engagement platform, finding a shared vision, and creating materials for a water use plan, but the plan will be finalised by the KBV WUA. The models that the research team used provided data, scenarios, and strategies; the next step (Aim two) was for the WUA to select the scenario strategies they prefer and include them in the water use plan. Aim three was successfully achieved: the ABM simulated how much water would be available under climate scenarios and explored strategies for adapting, such as increasing dam storage and adding a shared reservoir, along with the impacts of such strategies. An implementation model (WBT) has been provided for implementing the resultant water use plan.

CONCLUSIONS

The comprehensive understanding of hydrology presented in this study, together with the calibration of the Twee catchment model, explained the complex dynamics of KBV hydrology and its vulnerability to human impact. The agent-based modelling (ABM) approach for the KBV catchment, confirmed through repeated processes and stakeholder engagement, stands out as a powerful tool for examining various water-sharing plans. The Water Sharing Tool (WST), with its inventive water sharing strategies and serious game approach, shows the potential for inclusive and adaptive water resource management. Effective stakeholder involvement is key to engaging competing water users, as shown by the positive feedback, the satisfaction with the workshop, and the co-development of the models. The insights gained from this interdisciplinary study contribute to the scientific understanding of hydrological systems and also provide practical methods of sustainable water resource management as they emphasise the crucial role of collaboration, communication, and stakeholder involvement in dealing with complex water challenges. More investment is needed in longer-term stakeholder engagement actions to build trust and enrich collaboration, data sharing, and science communication to ensure that stakeholders and research teams are on the same page.

RECOMMENDATIONS

- Conduct a more detailed groundwater investigation, as the SWAT did not fully capture the complexities of groundwater and other hydrological dynamics in the conceptual model.
- Extend ABM future scenario simulations beyond the 2025-2030 period for a comprehensive, long-term assessment of water availability.
- Enhance models by obtaining detailed farm water use and yield information through increased engagement with farmers.
- Model current and future evaporation and increase in crop water demand under climate change scenarios.
- Simplify and improve communication of water sharing model strategies to enhance understanding.
- Present the findings to other Western Cape WUAs to encourage broader implementation in various catchments.
- Establish robust WUAs in catchments like KBV to stimulate engagement and adoption of water resource management initiatives, in alignment with growing global concerns about sustainable food production.

ACKNOWLEDGEMENTS

The project team wishes to thank the following people for their contributions to the project.

Reference Group	Affiliation
Dr Eunice Ubomba-Jaswa	Water Research Commission [Research Manager]
Ms Penny Jaca	Water Research Commission
Dr Julia Glenday	NRF SAEON
Dr Nhanha Gwedla	North-West University
Dr Eddie Riddell	SANParks
Dr Victor Munnik	University of the Witwatersrand
Mr Sbongiseni Mazibuko	University of Zululand
Prof Jaqui Goldin	University of the Western Cape
Prof Karen Bradshaw	Rhodes University
Prof Stephanie Midgley	Western Cape Government (DOA)
Mr Rudolph Roscher	Western Cape Government (DOA)
Others	
Koue Bokkeveld Stakeholders	
Ms Virginia Molose	Former research Manager
National Research Foundation (NRF)	Provided supplementary funding for mobility
French Embassy in South Africa	Provided supplementary funding for mobility
Rhodes University _Research Office	Provided Supplementary funding
Oppenheimer Memorial Trust (OMT)	Provided postdoc scholarship for project lead
Ms Shelly Fuller	WWF
Ms Lucy O'Keeffe	Provided workshops facilitation services
Dr Sharon Pollard	AWARD
Mr Hugo Retief	AWARD
Prof Dennis Hughes	Provided advise and modelling support for WST

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

ABM	Agent-Based Model
AHP	Analytic Hierarchical Process
APP	Adaptive Planning Process
ARDI	Actors, Resources, Dynamics, and Interactions
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMA	Catchment Management Agency
ComMod	Companion Modelling
CORMAS	Common-pool Resources and Multi-Agent System
CROPWAT	CROPWAT
DALRAD	Department of Agriculture, Land Reform and Rural development
DEM	Digital Elevation Model
ET	evapotranspiration
EWR	Environmental Water Requirements
FDC	Flow duration curve
HAND	Height above nearest drainage
HRU	Hydrological response units
KBV	Koue Bokkeveld
MAP	Mean Annual Precipitation
NSE Value	Nash-Sutcliffe Efficiency
NWA	National Water Act
QSWAT	QSWAT is a QGIS interface for SWAT
RCP	Representative Concentration Pathways
RDM	Resource Directed Measures
RDRM	Revised Desktop Reserve Model
SAM	Strategic Adaptive Management
SANSA	South African Space Agency
SAWS	South African Weather Service
SWAT	Soil and Water Assessment Tool
SES	Socio-ecological systems
STEEP	Social, Technical, Economic, Environmental and Political
TauDEM	Terrain Analysis Using Digital Elevation Models
WBT	Water Balance Tool
WCDoA	Western Cape Department of Agriculture
WGEN	Weather Generator
WST	Water Sharing Tpp
WUA	Water User Association
WULA	Water Use Licence Application

DEFINITIONS

Term	Explanation
Aleatory	Natural variation
Analytic hierarchical process	A structured technique for organizing and analysing complex decisions, based on mathematics and psychology
Aquifer	Rock or sediment that holds water
Bulk density	The weight of a volume unit of powder; it is usually expressed in g/cm^3, kg/m^3, or g/100 ml.
Calibrated values	Figures adjusted in relation to environmental factors to attain a better match between estimated and observed values.
Calibration	The act or process of determining, checking, or adjusting the settings on a measuring instrument
Catchment	The area of land that catches and collects rainwater, and from which the water flows into rivers and streams
Community weighting index	A numerical score representing how a community category is valued relative to others.
Compensation factor	A unit or value used streamline outputs
Dynamics	Forces that make the processes of a system change
Efficacy values	Values measuring a system and its effectiveness and its ability to do what it is supposed to.
Ensembles	A large number of virtual value combinations (sometimes infinitely many) of a system, considered all at once, each of which represents a possible state that the real system might be in.
Epistemic	Relating to knowledge or to the degree of its validation.
Equifinality	The recognition that there are many different ways to reach the same destination/ conclusion/ point/goal
Evapotranspiration	Water evaporates from land and water surfaces and transpires, or is released, from plants and re-enters the atmosphere – the process is called evapotranspiration.
Groundwater table	The distance between the level of underground water storage and the surface of the soil
Horizon	A layer of rock or soil that indicates a distinctive change in the type of rock or soil
Hydrological model	A simulation tool that represents and estimates hydrological processes
Hydrology	The study of the earth's water, especially how it behaves in relation to the land, the rocks,
Individual-based modelling	Simulate populations or systems of populations as being composed of discrete individual organisms
Monte-Carlo sampling	A broad class of computational algorithms that rely on repeated random sampling to obtain numerical results.
Orographic	Precipitation (rain) which is caused by hills or mountain ranges deflecting the moisture-laden air masses upward, causing them to cool and produce rain.
Panta Rhei initiative	To reach an improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems.
Probabilistic index	The probability that the outcome of a randomly selected subject exceeds the outcome of another randomly selected subject, conditional on the covariate values of both subjects
Protocol	A set of rules for formatting and processing data
Prototypes	An earlier version of a product that is improved to make a newer version
Quartzite	A type of a rock that is composed of quartz materials
Rainfall spatial variability	The spread of rainfall across a geographic area

Runoff curve number	A value used to determine the amount of runoff obtained from the rain received in a particular area
S-curve relationship	A mathematical graph that depicts relevant cumulative data for a project
Shale aquitard	A semi-waterproof shale type geological setup that transmits water more slowly than an aquifer
Socio-ecological systems	Reflect a highly interconnected relationship between society and ecosystems
Stochastic	Having a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely.
Toeslope	The area at the base of a slope
Transpiration	The process of water movement through a plant and its evaporation from aerial parts, such as leaves
Tributaries	Rivers or streams flowing into larger rivers or lakes
Vulnerability assessment window	The testing process used to identify and assign severity levels to as many security defects as possible in a given timeframe

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Water scarcity is a significant problem in South Africa; low average rainfall results in limited water available for human and environmental needs (Department of Water Affairs and Forestry (DWAF, 2013). Drought and the increasing impacts of climate change have increased the problems of water availability (Wolski, 2017). The South African National Water Act (Act 36 of 1998) and the Water Services Act (Act 108 of 1997) were instituted to manage human water uses and protect the environment by establishing Environmental Water Requirements (EWR) or what is locally known as the Ecological Reserve. EWRs stipulate the amount of water needed to ensure that a river system remains functional and sustainable. However, low rainfall in many areas means that water-holding areas (catchments) retain too little water in rivers and reservoirs, and scarcely meet human and environmental needs.

As a result, competition for water resources is increasing and has resulted in water-related conflicts among the various water users in many areas of South Africa. Unfortunately, when competition for water use exists, EWRs are often ignored, and the health of riverine ecosystems and downstream ecosystem services suffer. This project has negotiated a shared water management strategy that achieves equity in water access and respects EWR. While the problem exists in many regions of South Africa, this project focuses on the Koue Bokkeveld (KBV) (Figure 1.1) region, Western Cape, where the problem is prominent. Conflicts are frequent between upstream farmers who have first access to river water and downstream farmers who are forced to use what is left after upstream users have satisfied their needs (Paxton & Walker, 2018). Unfortunately, the dam systems that have been constructed have depleted the EWR and threaten riverine ecosystems and the various plant and animal species that depend on the river systems (Paxton & Walker, 2018).

The present situation strengthens inequality and stimulates conflict; if left unmanaged, it may turn into an environmental problem (e.g. there are several endangered endemic fish species in the rivers) and lead to a breakdown in the farming community. The possible loss in agricultural productivity will also affect food security and the livelihood of farmworkers who work in the area. Therefore, effective water management is essential to ensure fair access to water to encourage shared growth, reduce water conflicts, strengthen ecosystem health, and prevent biodiversity loss. This project aims to assist KBV stakeholders in developing a water resources management strategy together, one that results from a shared understanding of the catchment.

1.2 PROJECT AIMS

Project aim: Our broad aim is to assist Koue Bokkeveld (KBV) stakeholders to co-develop a water resources management strategy that is the result of a shared understanding. The project will be regarded as successful once the collective and common interests in water use and management decisions are adopted by the stakeholders within the KBV region.

The following were the aims of the project:

1. Generate an Agent-Based Model (ABM) for the KBV through the feedback and involvement of the KBV farmers.
2. Assist the farmers in the KBV to institute governance instruments to manage their water use requirements in a sustainable and equitable manner while being aware of the environmental water requirements.
3. Evaluate water availability under scenarios of future climate variability using the hydrological model in order to evaluate different measures that farmers could implement using the ABM.

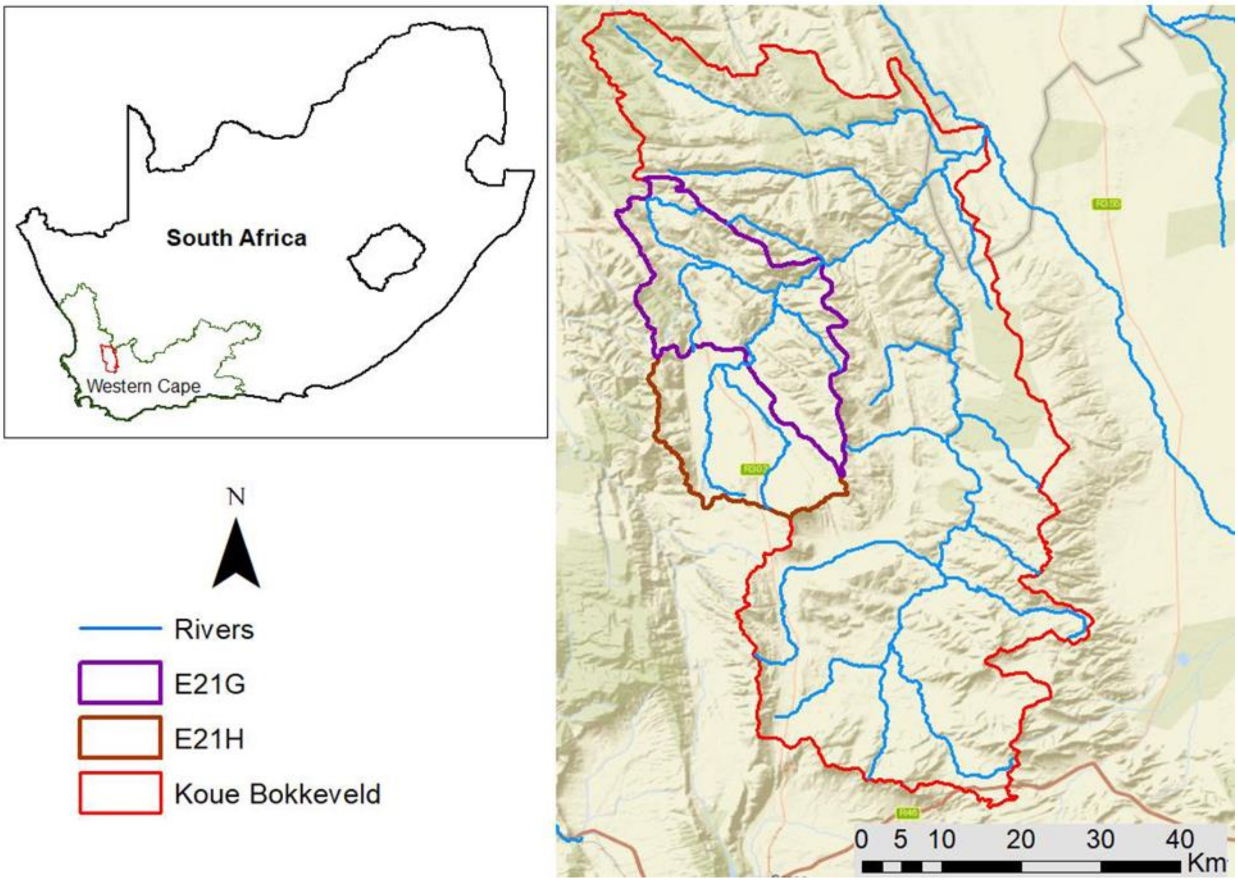


Figure 1.1 The Koue Bokkeveld catchment is located in the Western Cape province, South Africa.

The research uses several models within a stakeholder engagement framework in the KBV. Implementing a group of models is a way to deal with the complexity of KBV to handle the various points of view of stakeholders and meet their expectations. Figure 1.2 illustrates the various models that are implemented in the KBV and how they are linked together. Ad hoc models have been developed within well-known categories an ABM and two water balance models at catchment and farm level. The models developed are associated to classical hydrological models, including the locally developed and widely applied Pitman hydrological model (Hughes, 2013) and the Soil and Water Assessment Tool (SWAT+)(Bieger et al., 2017), were used. Pitman has been widely applied in water resource assessment in southern Africa. Meanwhile, SWAT has been applied globally and previously coupled with an Agent-Based Model (ABM), e.g. by Khan et al. (2017).

Farolfi et al.(2010) have applied agent-based models (Ferber et al., 2004) to water resources management worldwide (Berglund, 2015), including in South Africa. An ABM is used as a tool to support negotiation, together with the locally developed Water Sharing Tool (WST) (Figure 1.2). The ABM and WST simulations are a workable basis stakeholder can use to explore various water management scenarios and to negotiate and set a water management plan. The Water Balance Tool (WBT) is another locally developed tool that operates at the farm level and can thus be used when implementing the water management plan. All the models need stakeholders to participate either in the development, implementation, and/or acceptance of the model. Additionally, model development relies partially on the data provided by stakeholders.

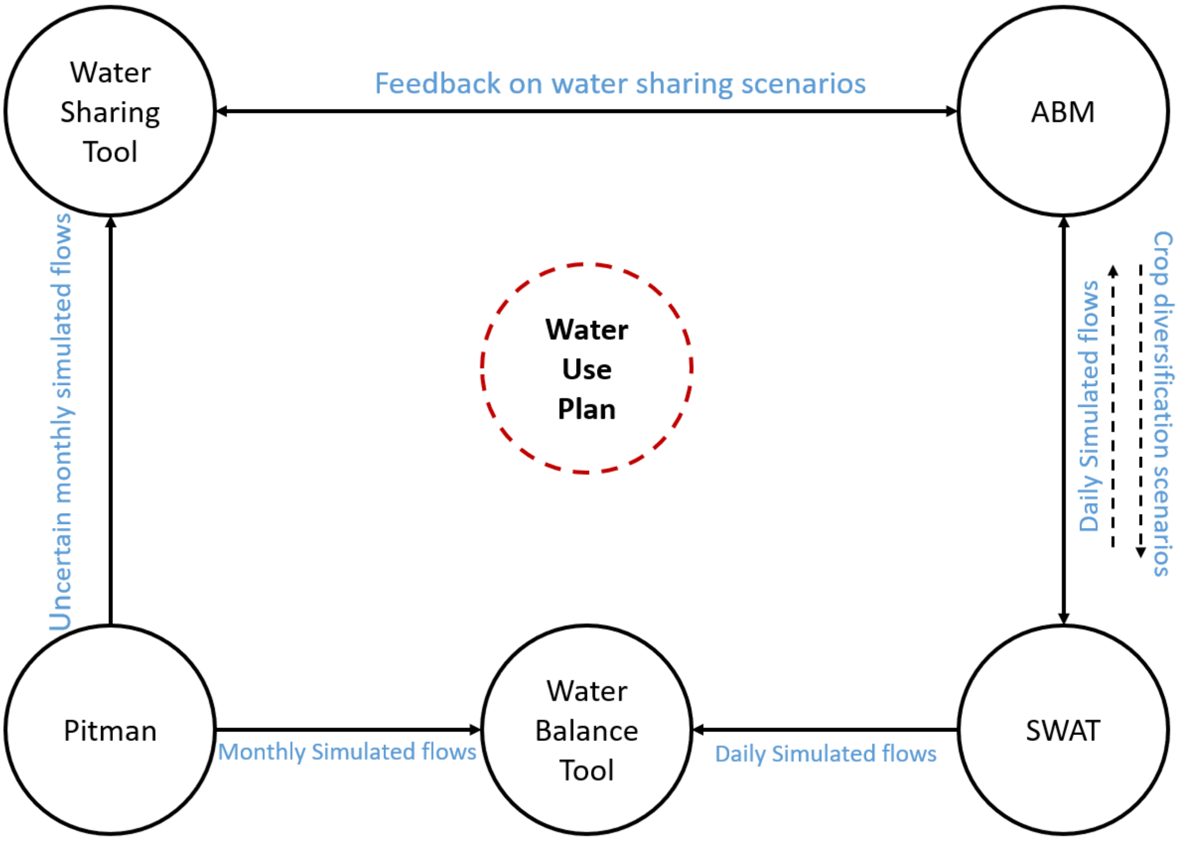


Figure 1.2. The suite of models applied in the KBV towards achieving a shared water use plan.

The backbone of this association of tools and methods is a series of workshops[1] that were implemented to promote the involvement of stakeholders into co-developing the models. Three workshops were held between November 2021 and November 2022: Workshop 1 introduced the project to the KBV community and stakeholders, and Workshop 2 shared the methodologies and gathered some baseline data using APP and ARDI for model development. A key outcome of Workshop 2 was the development of a shared catchment vision that became the focus of collaborative engagement and commitment towards the process of developing a shared water management plan. Workshop 3 was for sharing model prototypes, soliciting stakeholder feedback, and requesting additional data for improving model representations. The last workshop was sharing the model outputs and outlining a way forward in finalising water management plan.

A four-stage development approach (Figure 1.3) was followed as based on the initial engagement with stakeholders. The first stage was to understand the hydrology of the catchment followed by determining possible ways to share water using systems models. In these two stages, the research team took a more prominent role and stakeholders collaborated on the model development and verification.

[1] *The research was granted human research ethics approval by the Rhodes Research Ethics Committee Standards (Rhodes University, 2014) with references: 2022-5386-6678 and 2022-5900-7264.*

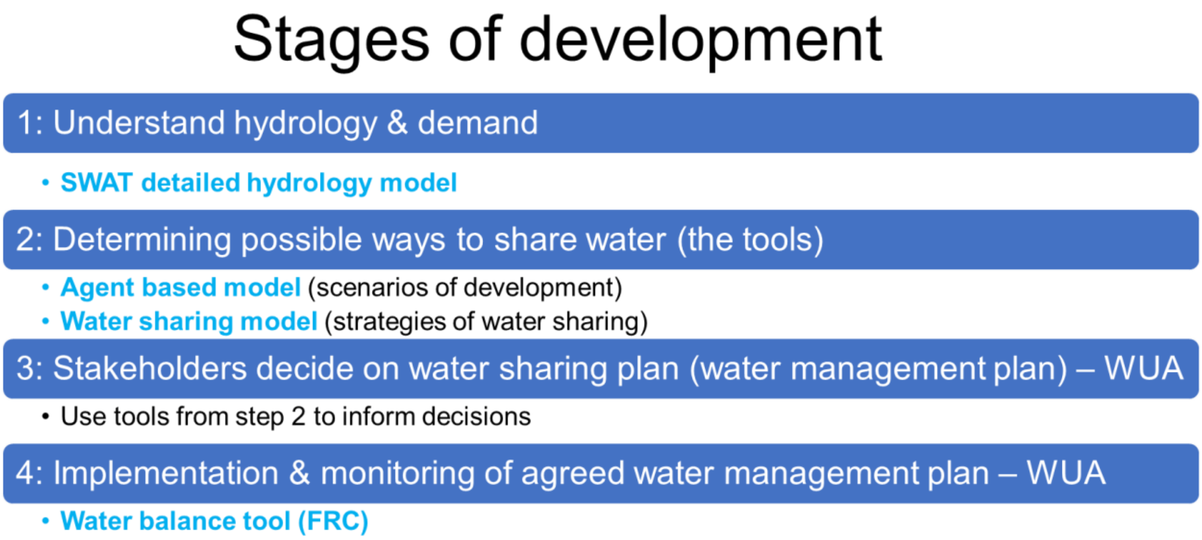


Figure 1.3. Stages of development towards a shared water management plan.

The third stage involves stakeholders deciding on a water sharing plan developed from the scenarios, strategies, and hydrology from steps 1 and 2. The final stage is implementing the plan, where the research team provides a farm-level water balance tool for use. The last two stages are led prominently by the WUA with the research team providing technical support and the models functioning as support systems for the decisions.

1.3 SCOPE AND LIMITATIONS

The scope of the project was to assist the stakeholders develop a water management strategy. We provided a platform for stakeholders to meet and discuss water management in the area. Additionally, we produced information and data that fulfils up to 60% of the water management plan template. Most other information is supplied by the models, but the users have to choose water management scenarios and an implementation plan through a Water User Association (WUA). Unfortunately, the three years of the project, together with Covid-19 and stakeholders' schedules were not long enough to have as many engagement workshops as planned. Although users developed a common vision and interest based on a shared catchment vision, some key players were not involved in the process. Currently, further engagement is ongoing in the KBV WUA to finalise a water use plan. The research team have made themselves available to assist in this process (providing technical support through 2024) beyond the project duration.

CHAPTER 2: UNDERSTANDING THE HYDROLOGY

2.1 INTRODUCTION

Hydrological information is fundamental for water resource planning. The KBV is a complex terrain with large-scale agricultural activities. Human influences on the hydrological systems are extensive and consist of abstractions from surface and groundwater resources. These influences create conflicts during drought; hence, understanding and representing hydrology is critical. Consequently, we first undertook a conceptual modelling of the catchment hydrology, after which we employed the SWAT+ model (Arnold et al., 2018; Bieger et al., 2017) to represent hydrological dynamics. The model is spatially distributed and makes it possible to represent multiple reservoirs and water transfers characteristic of the catchment. In this chapter, we present a detailed exploration of the catchment hydrology for Twee River Catchment (E21G in Figure 1.1) in the KBV.

The work presented here serves three key purposes:

1. Hydrology information is used as evidence of the catchment water resources situation in interactions with water users during stakeholder workshops.
2. Hydrology coupled with an Agent-Based Model for simulating options for sharing water. Hydrology outputs will also influence the Water Sharing Model and the Water Balance Tool.
3. A baseline hydrological model was used to show the impact of climate change on water availability in the catchment.

2.2 CONCEPTUAL UNDERSTANDING OF TWEE (E21H) HYDROLOGICAL PROCESSES

This study developed a conceptual (theoretical) model to understand and describe how water flows through the catchment landscapes. Water flows described in the conceptual model include the surface and subsurface flows and their interaction points. The conceptual model uses diagrams to describe what is known about catchment processes, flows and their connections. It does not refer to any numerical model with a series of equations developed based on understanding catchment processes. The conceptual model for this study was generated from information derived by analysing digital datasets for catchment physical characteristics. These datasets include Stellenbosch University DEM (SU-5M DEM), land use/cover, soils and geology, and rainfall records (Table 2.1). Information from the literature and discussions with farmers about their observations of hydrological processes occurring in the catchment were also included in the development of the conceptual model. Terminologies and approaches used in studies (e.g. Tetzlaff et al., 2007; Hughes, 2010; Schmocker-Fackel et al., 2007; van Tol et al., 2010; Wolock et al., 2004) that explored and described dominant runoff processes across typical catchment landscapes are adopted for the conceptual model of the current study. Geographic Information System (GIS) techniques were used to analyse and visualise the terrain and spatial distribution of the physical characteristics of the study catchment.

2.2.1 Method used to develop a conceptual model

2.2.1.1 Catchment and stream network delineation

To describe surface water flow patterns across the Twee (E21H) quaternary, the catchment area was divided into sub-catchments with major tributaries draining from upper watersheds. The sub-catchments were defined using the 5-metre SU-DEM in ArcGIS 10.8. Detailed surface flow direction and accumulation for each sub-basin feeding into the main channel were also created from the DEM in ArcGIS 10.8. This showed that water in each sub-basin of the catchment flows from upper watersheds through multiple minor tributaries draining from steep-sided rock mountains, and feeds into a major tributary that feeds into the main river channel. The major tributary channels are located at the central valley in each sub-basin, and the main river channel flows in the centre of the valley floor. The floodplain along the main river channel at the centre of the valley was delineated using the TauDEM plugin tools in ArcGIS 10.8.

Table 2.1: Sources of obtained datasets

Data	Data source
DEM	SU & GoeSmart Space
Land cover	DALRRD (https://egis.environment.gov.za/gis_data_downloads, last assessed 29 June 2021) and CFM (https://gis.elsenburg.com/apps/cfm/, last assessed 26 September 2021).
Soil map	ARC & FOA (https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/c3f7cfd5-1f25-4da1-bce9-cdcdd8c1a9a9, last accessed 05 July 2021).
Reservoir	SANSA
Climate	SAWS, FRC, Kunje, De Keur, Du Toit farms
Geology	Map from RU Geography Department website, literature

2.2.1.2 Topographic analysis

The topographic information derived from the DEM was analysed according to the approach used by several hydrology studies that explored the relationship between the topography and hydrological behaviour of a catchment (K. J. Beven & Kirkby, 1979; Savenije, 2010; Winter, 2001; Wolock et al., 2004). These studies defined the topography according to hydrological landscape/topographic units called plateau, hillslope, and wetland. This current study also classified the topography into the plateau, hillslope, and valley floors (wetland) with an extra unit called a toeslope, as they highlight hydrological landscape units with different flow/runoff behaviour (Figure 2.1). The classification of the landscapes is based on the Height Above Nearest Drainage (HAND), calculated using the vertical drop (distance down) tool of TauDEM in ArcGIS 10.8 (Tarboton, 2017; Tarboton et al., 2015). Since the study area is mountainous, hillslopes were defined as the largest proportion (60%) of the catchment area. The valley floors make up 20%, while the plateau and toeslope landscape units share an equal proportion of the remaining 20%.

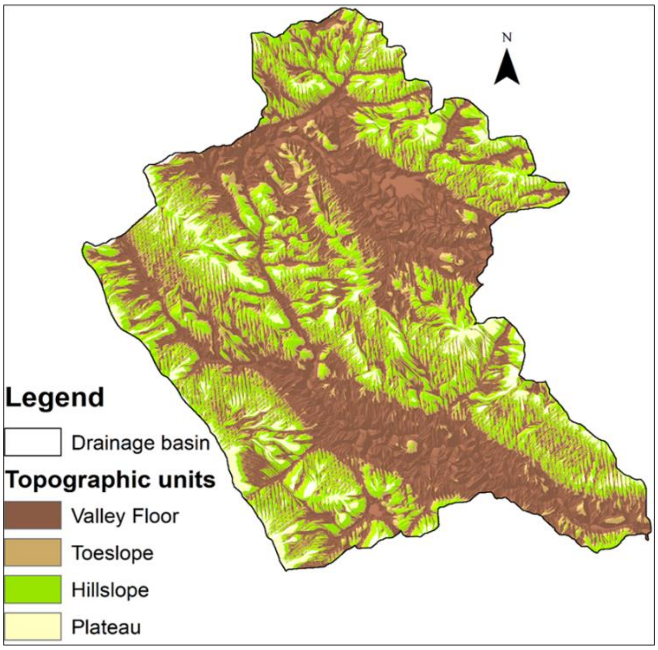


Figure 2.1 An extract of the E21G drainage basin with delineated hydrological landscape units.

2.2.1.3 Landcover/use distribution

The land cover/use digital data show that the catchment area is predominately covered by fynbos shrubs (79%), followed by natural grass (10%) and cultivated areas (10%) (Figure 2.2). Invasive alien plants cover 2% of the catchment area, and 0.5% are outcropping rocks (appears as 0% in the chart). The land cover map was overlaid on the slope map to visualise the spatial distribution of the land cover types across the catchment landscape (Figure 2.2).

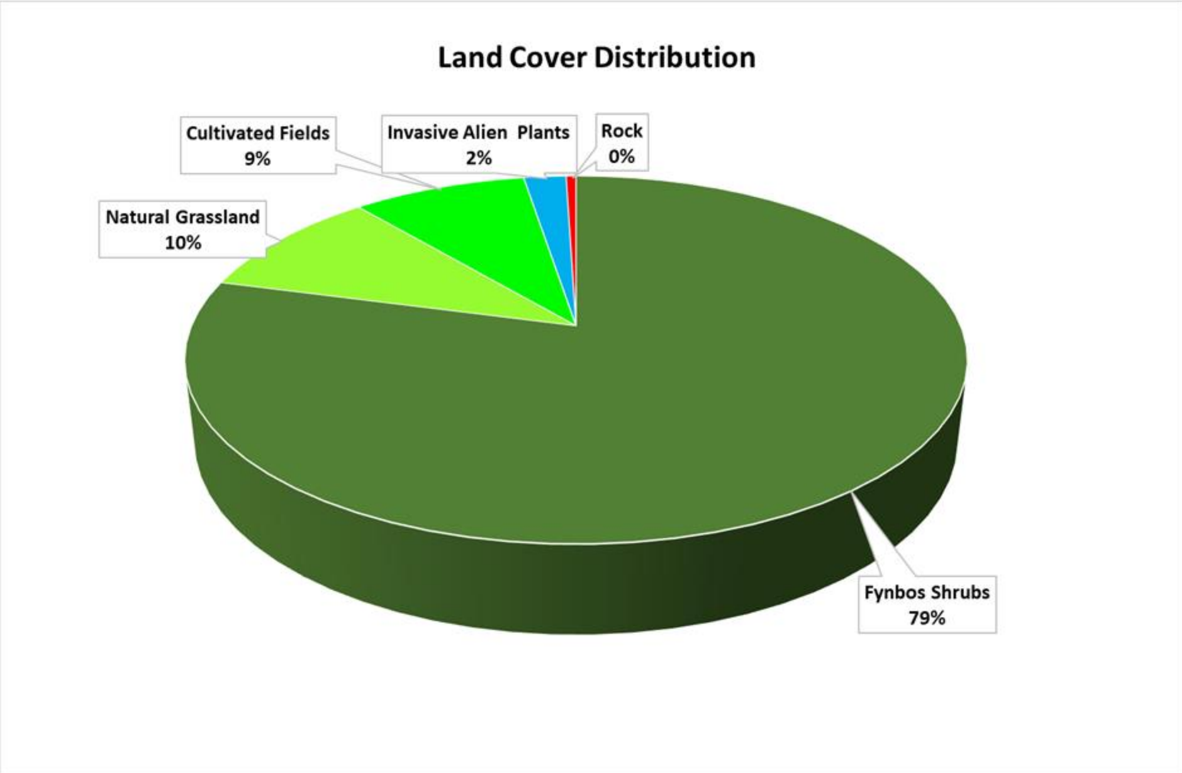


Figure 2.2. The distribution of land cover/use in the study area.

The narrow valley floors of the catchment are almost entirely used for agriculture, and the hillslope areas, which are the largest landscape of the catchment, are covered by fynbos shrubs. The natural grass covers the hilltops and plateaus (Figure 2.3). Fynbos shrubland was made invisible on the map to ensure the visualisation of the catchment's slope. Thus, the area not covered by any land cover type on the map is fynbos shrubland.

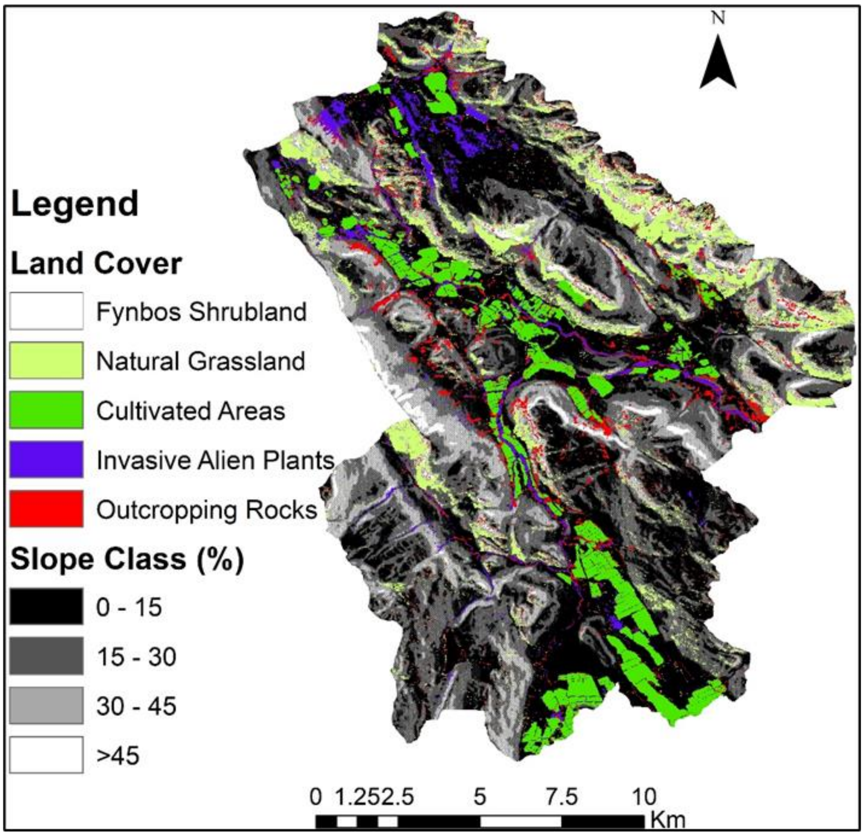


Figure 2.3 Land cover/use spatial distribution across catchment slopes in E21G. Source: Land cover (DFFE, 2020), DEM (Geosmart and Stellenbosch University, 2021).

2.2.1.4 Soil distribution

The soil digital dataset shows that the catchment consists of seven broad land types of soils (Figure 2.4). The dominant land type (Ic) comprises rocky, shallow, sandy soils. This broader land type soil covers the entire area of the steep hillslopes and plateau landscapes and constitutes almost 80% of the catchment area. Since the catchment is mountainous and rocky, even valley floors are covered with loose and shallow soils with no organic matter, overlaying either weathered or solid rock.

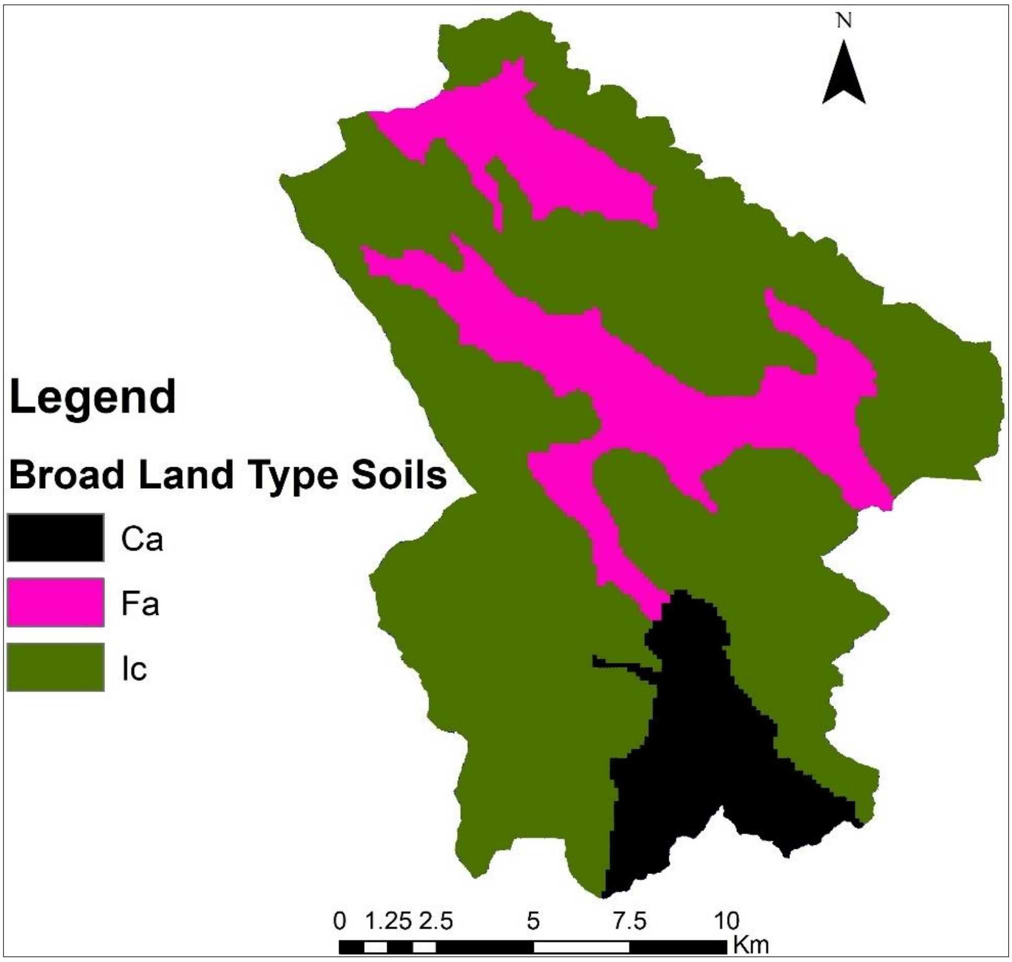


Figure 2.4. The spatial distribution of the broader Land Type Soils. Source: ARC Land Type Survey Staff. (1972-2006).

Detailed information about soil types and forms covering all parts of South Africa is not readily available, so the information in Table 2.2 about land type soils in the catchment was compiled from numerous old and relatively recently conducted studies on soil surveys and analysis (e.g. Land Type Survey Staff, 1972-2006, Soil Classification Working Group, 1991, le Roux et al., 2005; Roux and Preez, 2006; Stolk and van Huyssteen, 2019; van Huyssteen and Ellis, 1997; van Tol et al., 2013).

Table 2.2 Description summary of dominant soils in the study area.

Broader soil code	Soil form/s	Topsoil	Subsoil 1	Subsoil 2	General description
Ca	Longlands	Orthic	Albic	Plinthic	Sandy, overlaying clayey
Fa	Mispah	Orthic	Lithocutanic	Rock	Shallow intact soil overlying weathered rock
Ic	Soil comprises >80% rock	Miscellaneous	Rock	Rock	Shallow and/or rocky soils on steep slopes

*Orthic: A soil horizon that does not qualify as organic/humic topsoil, although it may have been darkened by organic matter. *Miscellaneous: Surface with little or no soil (act as A Horizon). *Albic: E soil horizon mineral soil layer underlying topsoil. *Lithocutanic: B soil horizon underlies topsoil and merges into underlying weathering rock. *Plinthic: B soil horizon formed from sandstone, quartzite, shale and granite, underlying E horizon.

2.2.1.5 Geology

The geology of the Cape Fold Belt, where the study catchment is, is complex (Blewett and Phillips, 2016; Booth and Shone, 2002; Booth, 2020) and to understand the way water flows below the surface requires an understanding of geological formation and structure of the rock. A detailed digital dataset for hydrogeology in the country is currently unavailable, but useful information about geology is available in hard copies. Extensive review of geohydrological studies conducted in the area (DWAF, 2007, 2005, 2003; Brown et al., 2003) led to insights into the structure and arrangement of geological formations underlying the topography of the catchment, followed by hand-drawing a geological cross-section from a hard copy geology map of the study area (Figure 2.5).

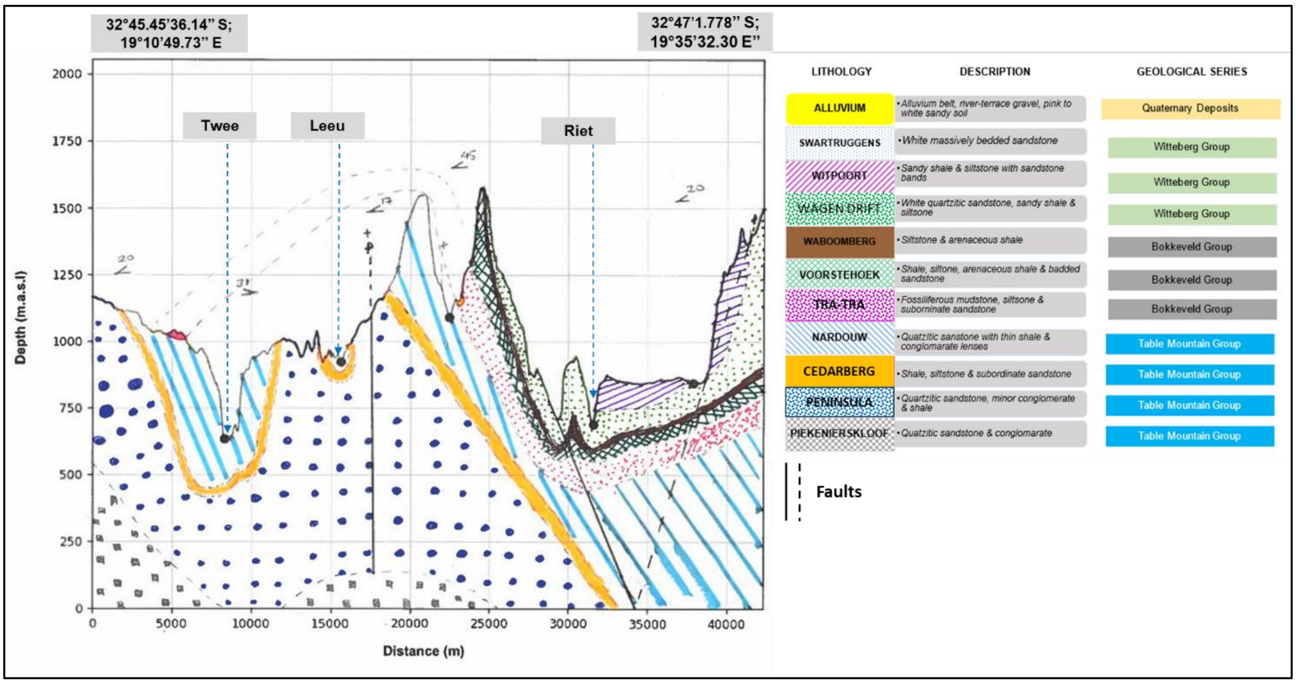


Figure 2.5 Geological cross-section of the Twee and Leeu catchment

The major geological formations of the catchment include fractured quartzitic sandstones and shale aquitard. The quartzite rocks are part of the Peninsula and Nardouw formations, both of them aquifer systems with high water yield (Lin et al., 2014; Xu & Beekman, 2019). A Cedarberg shale aquitard separates these formations. The irregular arrangement of geological formations caused by asymmetrical folds resulted in the Twee and Leeu Rivers establishing on different formations. The cross-section illustrates that underneath the plateau is fractured quartzitic sandstone of the Peninsula formation (blue dotting), which also outcrops in that landscape unit. The steep hillslopes and the Twee River sit on the fractured sandstone of the Nardouw geological formation (blue stripes). The quartzitic sandstone of the Peninsula forms a deep aquifer system.

2.2.1.6 Rainfall distribution

To understand water balance processes in a catchment, it is critical to understand the nature of the rainfall spatial variability. In mountainous catchments rainfall variability tends to be high because of the complex topography and orographic effects. Functional rainfall gauges in the study catchment are sparsely distributed and situated at lower elevations (Figure 2.6) so rainfall that falls at a higher elevation is not captured, making the available rainfall records from these gauges not representative of the catchment-wide rainfall characteristics. Therefore, mathematical interpolation was used to estimate the rainfall amounts of ungauged locations, using the records from the existing rainfall stations (Figure 2.6). Ordinary co-kriging in ArcGIS 10.8.2 geostatistical analysis tool was used for rainfall interpolation. This approach was selected mainly because it allows the inclusion of the DEM in the interpolation process to consider elevation.

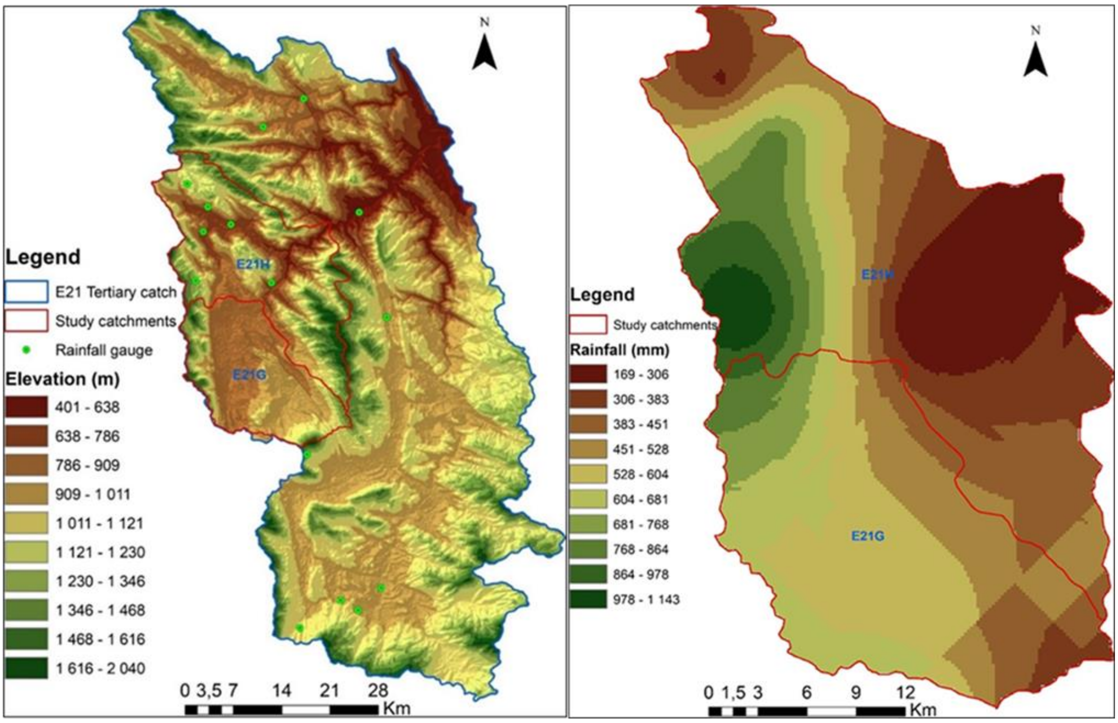


Figure 2.6 Rainfall gauges used to derive rainfall spatial distribution on different elevations. Source: Geosmart and Stellenbosch University (2021).

The method used does not produce the most accurate rainfall interpolation with records from overly sparse gauge networks; however, incorporating elevation information improves the estimation of rainfall (Duethmann et al., 2013; Goovaerts, 2000; Guan et al., 2005; Mair & Fares, 2011; Putthividhya & Tanaka, 2013). Rainfall records from gauges outside the study catchment boundaries were also included in developing the rainfall spatial distribution map (Figure 2.6). This was done to supplement the limited number of gauges within the study catchment, some of which have concise rainfall records (Table 2.3).

Table 2.3 Details of the rainfall gauges used to derive rainfall distribution for the study catchment.

Within study catchment boundaries			
Gauge name	**Record's length**	**Elevation (m)**	**Gauge owner**
Kunje	1990-2016	730	Kunje Farm
Suiker	2021-2022	724	Freshwater Research Centre
Balies	2021-2022	781	Freshwater Research Centre
Zuur	2021-2022	1152	Freshwater Research Centre
Ysterplaat	2003-2021	804	Ysterplaat Farm
Reolofs	Jan-Dec 2022	1247	Stellenbosch University
Outside study catchment boundaries			
Gauge name	**Records length**	**Elevation (m)**	**Gauge owner**
Krommeriver	1990-2021	827	South African Weather Services
Grootriver	2006-2021	501	South African Weather Services
Zonderwater	2006-2021	954	South African Weather Services
Excelsior Ceres	1993-2021	958	South African Weather Services
Bokkeveldkloof	1990-2021	1035	South African Weather Services
Die erf	1994-2021	992	South African Weather Services
Odessa	1990-2021	957	South African Weather Services
Matjiesrivier	1998-2021	739	South African Weather Services
Malabar Farm	1990-2010	979	South African Weather Services

2.2.2 Conceptualisation of flow pattern and pathways

In this study, the landscape units of each sub-basin correspond with three dominant hydrological regimes or flow behaviour: surface runoff, sub-surface flow and deep percolation influenced by surface topography, land use, soils and geology. The Twee River quaternary catchment landscape is characterised by a flat plateau and narrow valley floors separated by a considerably steep hillslope. The plateau areas of the catchment are flat, covered by sparse grass and drain shallow sandy soils with outcropping quarzitic sandstone rocks of Peninsula Formation. These features favour vertical flow (percolation), producing high groundwater storage recharge. High amounts of surface runoff (overland flow) are generated from the steep rocky sides of the mountains of the catchments, given the sparse fynbos shrubs and a thin layer of sandy soil at this landscape unit. Residents and farmers in the catchment have identified several springs (infiltrated/percolated water that re-emerges) at different hillslope elevations, contributing to the surface runoff.

The observers pointed out that the springs vary in size and behaviour; those occurring at higher elevations tend to flow as a tributary to the main river channel. However, some springs form a deep pool of water which spills and flows to the main channel. Various factors including elevation, soils, and geology could cause this process. Much higher up the hillslope of the research catchment, surface re-emergence is assumed to result from the saturation of the shallow sandy soils overlaying the rock at hilltops and plateau area. At the steep side of the hillslope, the identified springs could result from percolating water diverted by lateral aligning major fractures in the aquifer system. This is highly likely to occur in areas with Peninsula and Nardouw aquifer systems since they tend to have a dense fracture network (Lin et al., 2014). The same hydrological process (water re-emergence) resulting from fractures aligning towards the surface has also been observed by Hughes (2010) in Grahamstown, which also lies on the Cape Fold Belt geology, as the study catchment does (Figure 2.7). Water re-emergence caused by saturation of draining soils overlaying an impermeable layer has been observed by van Tol et al. (2010b) at higher elevations of the Bedford catchment.

The groundwater table at the upland areas relative to the plateau landscape unit tends to rise significantly due to high recharge occurring at this point. When this happens in regions with steep slopes, like the study catchment, the groundwater table intersects with the surface, particularly the groundwater table of an unconfined aquifer system, since it follows the topography. Springs form where the groundwater table intersects with the surface (Winter, 2001; Wolock et al., 2004). Based on this knowledge, the possibility of spring formation caused by the intersection of the groundwater table with the land surface is included in the conceptual diagram, as the study catchment has a steep slope and an unconfined aquifer system (Point B in Figure 2.8).

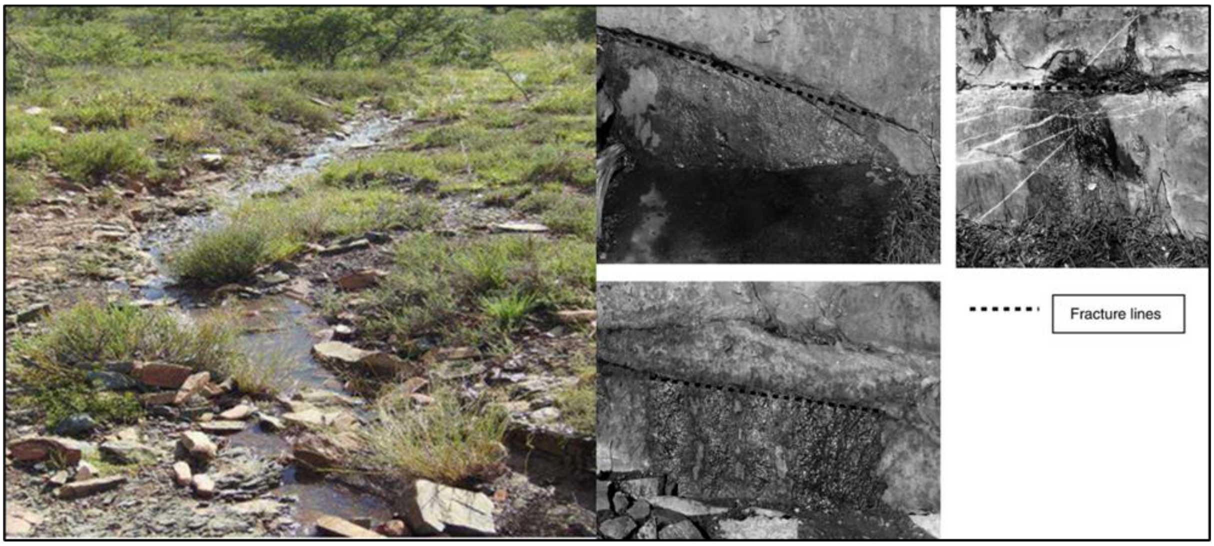


Figure 2.7 Water re-emergence due to saturation of shallow soil overlaying an impermeable layer, observed by van Tol et al. (2010b). Right = Groundwater re-emergence through lateral component, observed by Hughes (2010).

The large proportion of the high surface runoff generated at the hillslope, together with the flow of re-emerging water, is captured by dams located at the toeslope, and a portion soaks into the ground. During the first rainfall events, a considerable amount of hillslope runoff that reaches the valley floors is infiltrated. The high infiltration rate at this landscape would be promoted by cultivation. However, the Orthic A of shallow Mispah soils covering the valley floors of the Twee catchment also favours high infiltration rates. The Orthic A is underlaid by the Lithocutanic B horizon, which overlays a weathered (fractured) rock. This layer serves as a flow path for deep percolation (van Tol et al., 2010b) as it is a young soil formed from unconsolidated materials (Macvicar et al., 1977; Tekle, 2004). Therefore, runoff infiltrated at the valley floors can be assumed to recharge an aquifer beneath these soil horizons. However, when the groundwater table is high enough, interflow occurs. It can also be assumed that there is great seepage from the dams in the area because it is dominated by shallow draining soils sitting on fractured rock.

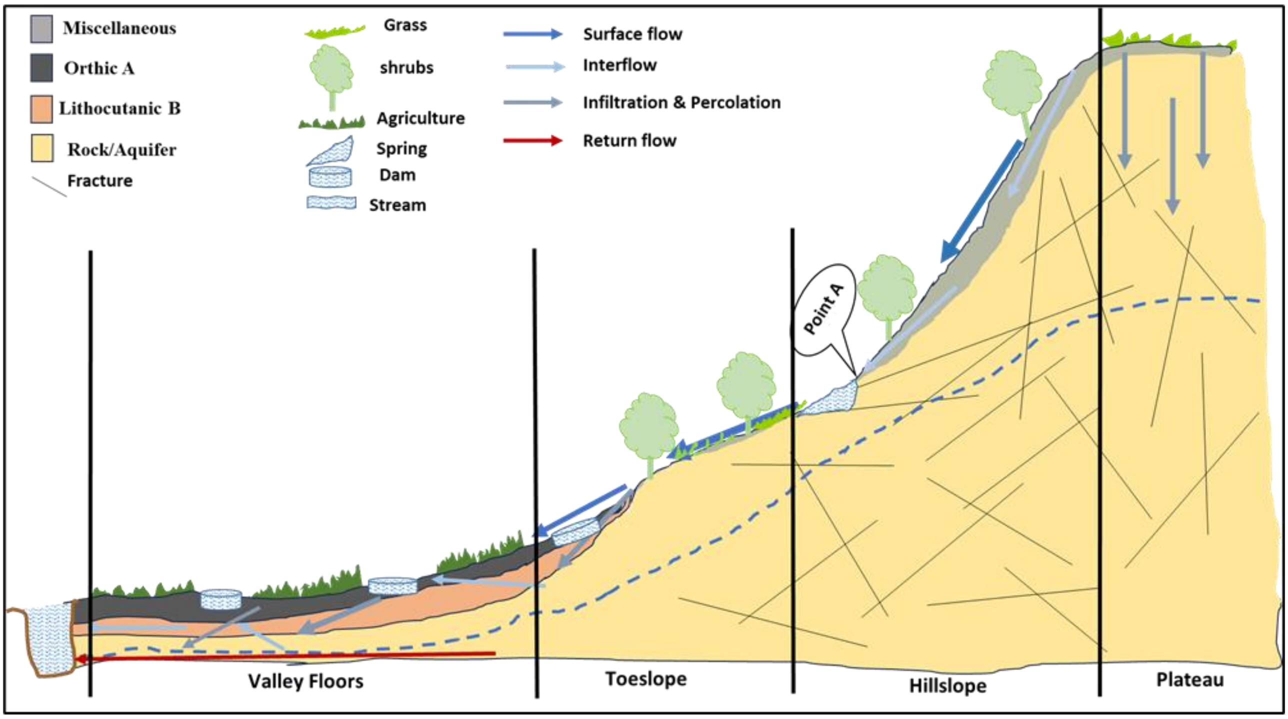


Figure 2.8 Simplified conceptual flow behaviour of the Twee River catchment (E21H). Return flow implies groundwater contribution to the river.

The saturation at the toeslope and high groundwater table along the river channels means that the fynbos shrubs and the riparian vegetation have access to water for a longer time. The presence of fynbos shrubs at the hillslope could indicate that cracks in the weathered rocks serve as water storage for fynbos shrubs. The invasive alien plants (black wattle) dominate along the river channels and access water from saturated soils and groundwater storages since they tend to have a long root system. Despite vegetation having access to the groundwater table, return flows to the river are expected to be high caused by high percolation at recharging areas and the fact that the rivers are sitting on the Nardouw aquifer system. However, this also depends on how much groundwater is abstracted in the area. It is also important to note that groundwater could significantly contribute to the dams, as the dams in the area sit on shallow soils that overlay fractured rocks.

2.3 HYDROLOGICAL MODELLING

A hydrological model was set up to quantitatively represent the hydrological processes described above. The selection of the hydrological model used was guided by a review of models commonly applied in South Africa and an understanding of the catchment processes important to represent. Figure 2.9 demonstrates the steps of the model setup and the type/types of data used at each step.

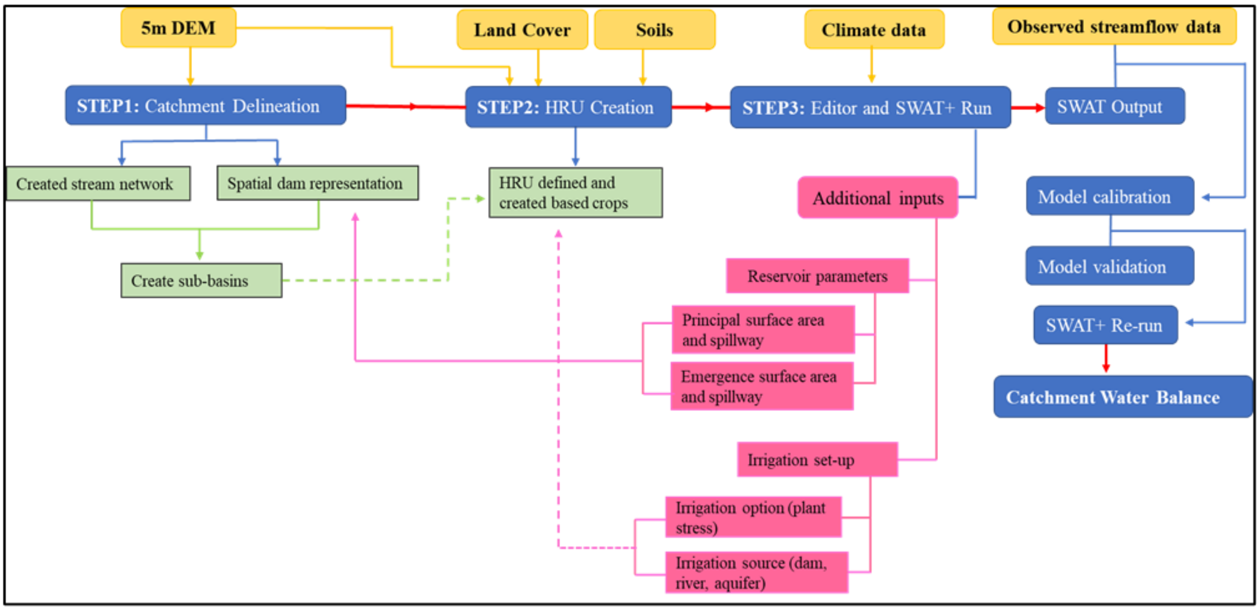


Figure 2.9 SWAT+ model setup (Methodological framework)

SWAT+ was selected for this study because it is flexible enough to represent hydrological structures with extensive spatial distribution and because it is able to represent a complex irrigation process (Arnold et al., 2018; Bieger et al., 2017). Recently, the model was successfully applied in irrigated agricultural catchments (Nkwasa et al., 2020, 2022, 2023; Wu et al., 2020).

2.3.1 SWAT+ Model set-up

The SWAT+ model was set up using the same datasets as those used to develop the conceptual model in Section 2.2 (Table 2.1). The 5-metre DEM was used to create a detailed stream network in QSWAT+. A detailed stream network was required to represent the model setup as realistically as possible since numerous dams built in tributaries exist in the catchment. Existing farm dams were manually placed in the setup as reservoirs on channels, according to their spatial distribution. The DEM was also used for catchment delineation, and this resulted in 33 small sub-basins. The slope of the catchment was divided into four classes in the model setup to make it correspond to the topographic described in Section 2.2. These slope classes were specified as follows: 0-50%; 50-100%; 100-300%, and 300-9999%. Land cover and soil maps were then incorporated into QSWAT+ to create hydrologic response units (HRU). A threshold value of 0% and 20% for land cover and soil types, and slope, respectively, were set to create HRUs. About 2070 HRUs were generated by the model.

2.3.2 Incorporation of human impact in the model setup

The SWAT+ model requires

- the year and month the reservoir became operational,
- the reservoir surface area when the reservoir is filled to the main spillway,
- the volume of water needed to fill the reservoir to the main spillway,
- the reservoir surface area when the reservoir is filled to the emergency spillway, and
- the volume of water needed to fill the reservoir to the emergency spillway.

For this study, the surface area and reservoir capacity were assigned in the model as reservoir surface area when the reservoir is filled to the main spillway, and the volume of water needed to fill the reservoir to the principal spillway, respectively. Reservoir information, such as the surface area when the reservoir is filled to the emergency spillway, and the volume of water needed to fill the reservoir to the emergency spillway, is not available in the dataset obtained from SANSA. To estimate the missing information, SWAT+ default calculations were used, where the principal surface area of the reservoir and the principal spillway were multiplied by 1.15%.

Irrigation in the model set-up for this study was implemented through the SWAT+ auto-irrigation function that is based on crop water stress. This approach was chosen because the data required to setup the irrigation operation manually in the model was not available. The water stress trigger is based on crop water demand (Arnold et al., 2018) and is a function of crop and soil conditions; it considers that crop water uptake is primarily determined by the maximum transpiration, soil layer and root zone depth (Padhiary et al., 2020).

The SWAT+ decision table was used to specify the rules or conditions for auto-irrigation. This includes specifying the water source, the irrigation amount and the water stress threshold. Reservoirs and river channels were defined as the primary source for irrigation, and the aquifer as a backup source. Each HRU was irrigated from the nearest dam, assuming that the dam was on the same farm as the HRU. However, HRUs located on a farm that did not have dams were irrigated from the closest river channel. An aquifer that was in the same sub-basin as the targeted HRUs was used as an irrigation backup.

2.3.3 Climate data for driving the model

For this study, records of observed data for daily rainfall, temperature, relative humidity, and wind speed (for the period of 1990-2021) from South African Weather Services (SAWS) were used to force the SWAT+ model. Since SAWS does not have records for solar radiation, daily values for this weather parameter were simulated using an inbuilt SWAT weather generator (WGEN). However, the records from WGEN end in 2014. Therefore, to fill in missing daily records from 2014 to 2021, the value "-99" was used to inform the model as advised in the SWAT weather data documentation guide (Arnold et al., 2012).

The records from local rainfall stations came in different temporal scales (some daily and others monthly) while SAWS rainfall stations which some have long-term daily records are located outside the boundaries of the study catchment (Figure 2.6;Table 2.3). Therefore, the rainfall time series used to run the SWAT+ model was generated from MAP contained in grid cells of the rainfall spatial distribution map (Figure 2.6). The grid cell with MAP in the centre, between two real rainfall stations close to each other was selected, and a dummy rainfall station was created where the grid cell was selected. Grid cells at higher elevation areas where rainfall is high were selected, as well as at low land areas where rainfall is less. As a result, numerous dummy rainfall stations were created to represent rainfall spatial variation. The records of the real rainfall stations have gaps, and these gaps were filled with rainfall values from CHIRPS.

The procedure (equation) by Nolte et al. (2021) was adopted for this current study to generate a continuous time series for a dummy rainfall station. The equation is an estimation approach, assuming that the rainfall distribution can be defined by values (data) from two nearby rainfall stations and the rainfall intensity by the MAP (Nolte et al., 2021). The equation is expressed as:

$$\sum_{t=1}^{365} P_e = P_{grid} = \sum_{t=1}^{365} (k \cdot w_1 \cdot P_{1,t} + k \cdot w_2 \cdot P_{2,t}) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

Where is P_e is estimated rainfall within the centre of the grid cell; P_{grid} is the value of MAP in a grid cell; $P_{1,t}$ and $P_{2,t}$ represent rainfall at two stations closest to the centre of the grid cell at day t; k is a constant factor; w_1 and w_2 are weighting factors for rainfall stations according to the relative distance to the selected grid cell.

2.3.4 Model run

The model was run for a period of thirty years, from 1 January 1990 to 30 June 2021. Five of the thirty years were used to warm up the model, as suggested by Arnold et al. (2012) and Dile et al. (2022). The model was run for two different scenarios. The first scenario did not include farm reservoirs' irrigation in the model set-up. In the second scenario human impact was included in the model.

2.3.5 Model calibration

The SWAT+ model for this study was manually calibrated. The calibrated parameters were selected based on the understanding of dominant catchment processes acquired from the conceptual model developed in the study. Manually calibrating parameters based on the knowledge of the catchment helps to reduce the problem of equifinality (Beven, 2001; Hughes, 2010). Similarly, manual calibration was preferred in this study as Refsgaard, (1997) and Senarath et al. (2000) suggest that it is the best approach for calibrating complex models as these model types worsen equifinality.

The model for the Twee quaternary catchment was calibrated against observed streamflow data obtained from FRC. The length of the streamflow records is nine years, from 2013 to 2021. However, the streamflow datasets have missing records, as detailed in Table 2.4 below.

Table 2.4 Periods of missing observed streamflow records.

Flow gauge	Years – missing records					
	2015		2019		2020	
FRC (Twee)	Period	No. of days	Period	No. of days	Period	No. of days
	28 Jul-4 Aug	8	13 Jun-31 Dec	202	1 Jan-3 Dec	338

Years that have over 150 days of missing streamflow records, were not considered in the calibration and validation process. This also applied to years where CHIRPS rainfall data was used to fill in gaps in records of existing rainfall gauges. Years with CHIRPS data were not considered as CHIRPS underestimated rainfall amounts which would result in the model under-simulating runoff and that would reflect when comparing rainfall with observed streamflow data (Figure 2.10).

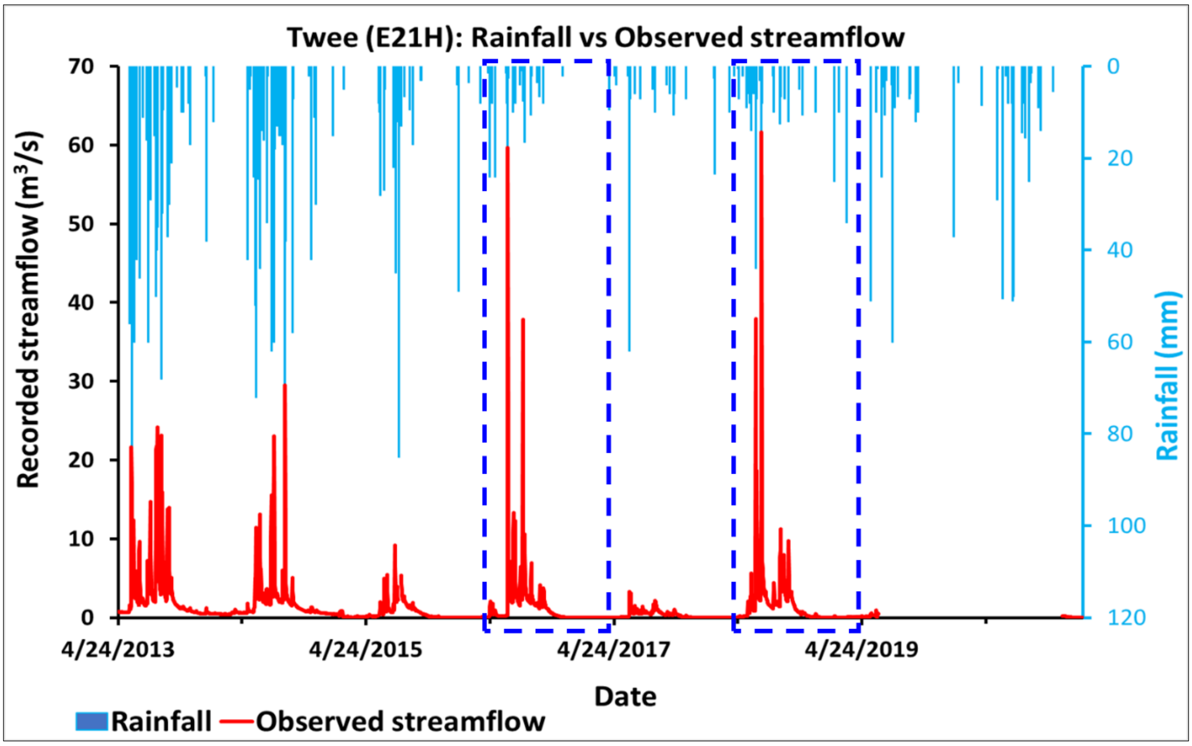


Figure 2.10 Years with CHIRPS rainfall data.

The dashed blue lines in Figure 2.10 highlight the periods with CHIRPS rainfall data. In these periods, streamflow is high, indicating high rainfall in the catchment during these periods as compared to amounts estimated by CHIRPS. For all the reasons outlined above, the model was calibrated for the period between 2013 and 2015 and was not validated. The set of parameters selected, and their calibrated values are listed in Table 2.5.

Table 2.5 A set of selected parameters and their calibrated values.

Parameter	Parameter description	Type of change	Parameter value
bd	Bulk density	Fractional	-0.35
awc	Available water holding capacity	Fractional	-0.45
epco	Plant uptake compensation factor	Absolute	1.00
esco	Soil evaporation compensation factor	Absolute	1.00
revap_min	Threshold depth of water in shallow aquifer for "revap"	Absolute	10
revap_co	Groundwater "revap" coefficient	Absolute	0.05
perco	Percolation	Absolute	0.9
alpha	Baseflow alpha factor	absolute	0.002
Latq_co	Lateral flow	Absolute	0.525
Flow_min	Minimum aquifer storage to allow return flow	absolute	50
bf_max	Baseflow	Absolute	1.2
cn2	SCS runoff curve number	Fractional	-0.15

2.4 HYDROLOGICAL MODELLING RESULTS

2.4.1 Simulated natural streamflow

The streamflow from the natural setup was compared to the observed streamflow to test whether the model captured the flow pattern of the catchment. As shown in Figure 2.11, the model captured catchment flow dynamics very well. However, the model failed to capture low flows, so the aquifer parameters were adjusted in an attempt to improve low flows. As can be seen from the hydrograph, low flows of naturalised flow did not greatly improve.

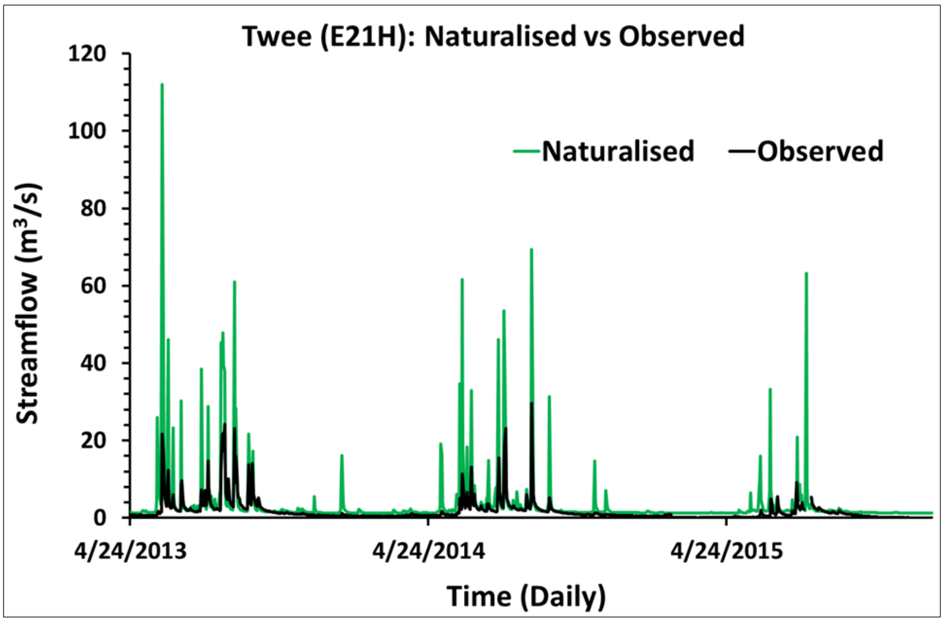


Figure 2.11 Hydrograph of naturalised simulated data and observed flow data.

2.4.2 Calibration results

The calibration of streamflow at Twee gauging station resulted in a good fit of simulated and observed flow. This was confirmed by visually comparing the simulated and observed hydrographs, and by the statistical indicators employed to evaluate the model (Figure 2.12; Table 2.6). As shown by the hydrographs (Figure 2.12) the model captured the timing and magnitude of peak flow and low flow quite well. However, in most times within the calibration period, the model over-simulated the peak flows while reasonably simulating low flows in the wet season. The model slightly under-simulated flows during the dry season, and this is also visible in the flow duration curve (FDC).

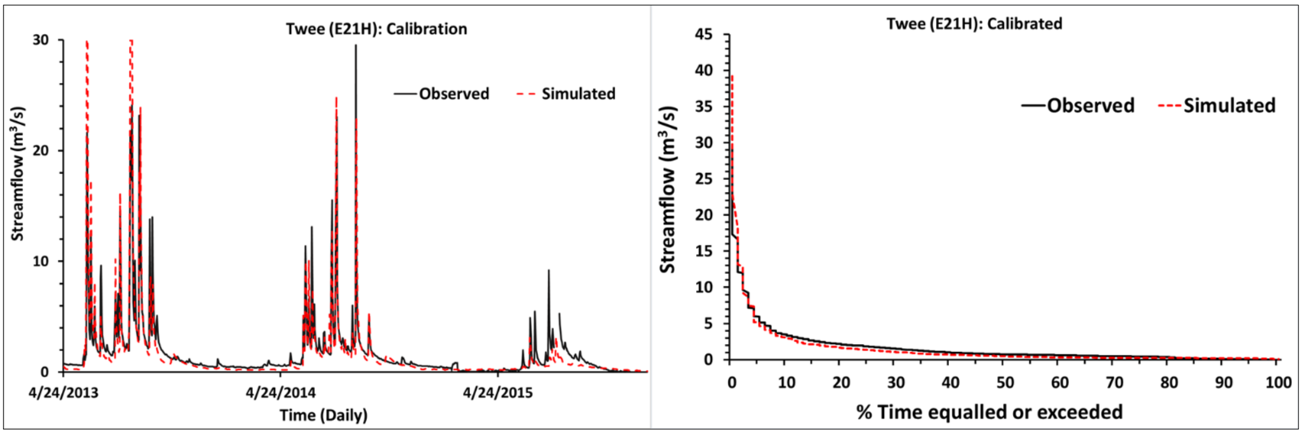


Figure 2.12 Hygrograph and FDC of streamflow from calibrated model against observed flow.

The NSE value 0.67 and R^2 0.79 obtained after calibrating Twee daily streamflow exhibit a good performance of the model according to general performance ratings recommended by Moriasi et al. (2007). These calibration and validation results demonstrate the capability of the SWAT+ model in simulating the hydrology of an agricultural catchment.

Table 2.6 Calibration and validation statistics.

Catchment	Simulation	Warm-up period	Statistic period	R^2	R	NSE
E21H (Twee)	1990-2021	1990-2005 (5yrs)	Calibration: 2013-2015	0.79	0.89	0.67

After calibration, the naturalised streamflow was plotted against the streamflow from a model where there were reservoirs but with no irrigation, and against streamflow from a model set-up where there were reservoirs with irrigation included (Figure 2.13). This was done to observe the extent of the impact of human development on natural hydrology. It was clear that reservoir development and irrigation considerably reduced catchment flows, especially during dry years (2001-2003 and 2015-2018), where the catchment experienced almost zero flow in the dry season. Although human development resulted in reduced flows during the dry season, the catchment still loses a considerable amount of water, even during wet years.

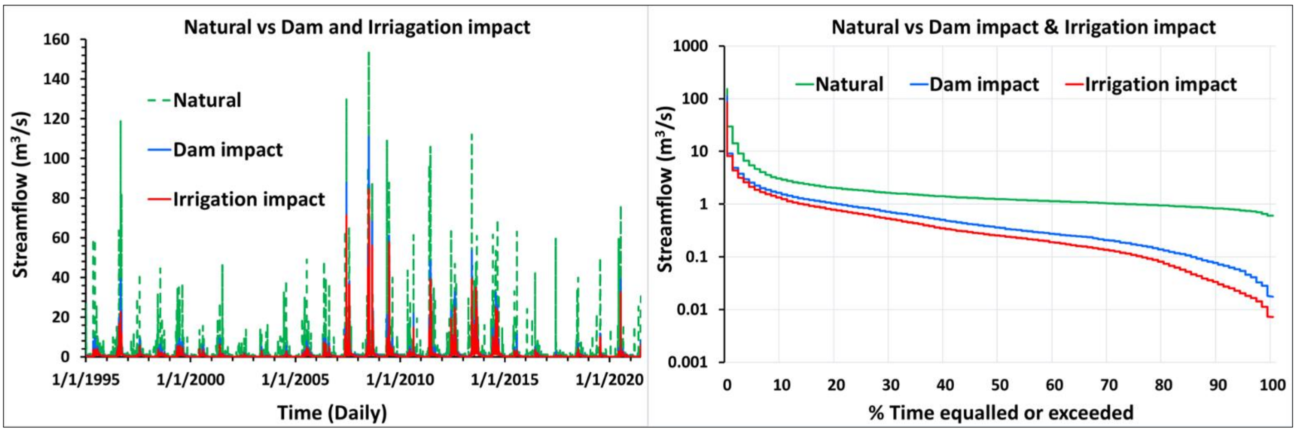


Figure 2.13 Hydrographs of naturalised flows and impacted flows.

2.4.3 Water balance components

Hydrological water balance components of the catchment were assumed to be accurately simulated considering the values of objective functions achieved after calibrating the model. Water balance is based on the principle that the total water inputs in a system must be equal to the total water outputs plus the net change in system storage, for a given period (Chen et al., 2020). The key water balance in a catchment includes evapotranspiration (ET), surface runoff (surq), interflow (latq) and groundwater (gwflow). Change in storage (Δ S) implies that if rainfall is greater than water yield (surface and interflow) and ET, the excess of rain water infiltrates and is stored as soil moisture and groundwater storage of the catchment (Marahatta et al., 2021). Figure 2.14 shows the simulated annual averages and seasonal variation of water balance components of the Twee catchment from 1995 to 2020.

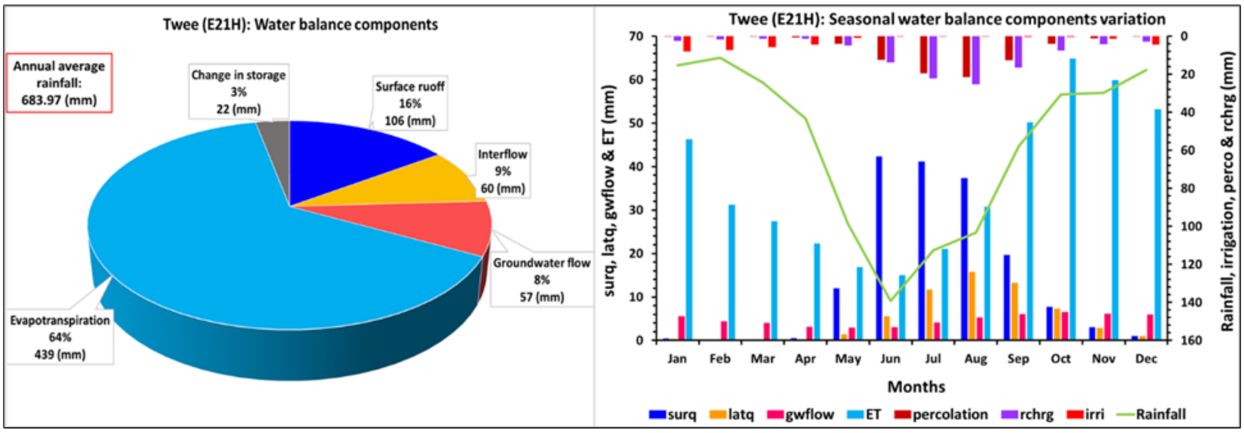


Figure 2.14 Simulated annual averages and seasonal variation of water balance components of the Twee catchment from 1995 to 2020.

Based on the data used to setup and run the model, the results demonstrate that 62% of the total water input into the Twee quaternary catchment is lost through evapotranspiration, while 15% is converted into surface runoff. Interflow and groundwater flow account for 9% and 8% of the catchment water, respectively. The remaining 3% is distributed to soil moisture and groundwater storage of the catchment. It can be seen from the graph of seasonal distribution of water balance components that high surface and subsurface runoff is generated between by high rainfall generally received during the winter period (Figure 2.14). Other hydrological processes such as percolation (perco) and recharge (rchrg) tend to be high during the rainy season, except for evapotranspiration which increases from the beginning of spring to the summer (September to February) period. The ground water flow to the river is fairly consistent throughout the seasons of the year with a slight increase from September to January.

Figure 2.15 shows that rainfall plays a significant role in runoff processes, and it serves as a quantitative representation of the hydrological processes described in the conceptual model. The catchment experienced reduced amounts of rainfall between the years 2000 to 2005, and 2015 to 2020, severely reducing water availability during these years as a result of a considerable decline in all runoff processes. Generally, during wet years, surface runoff dominates the hydrological process, although it occurs for a very short period of time. The outputs also show there are good amounts of vertical runoff processes (percolation/groundwater recharge) in recharging points of the catchment, resulting in high interflow and a consistent groundwater contribution to the stream.

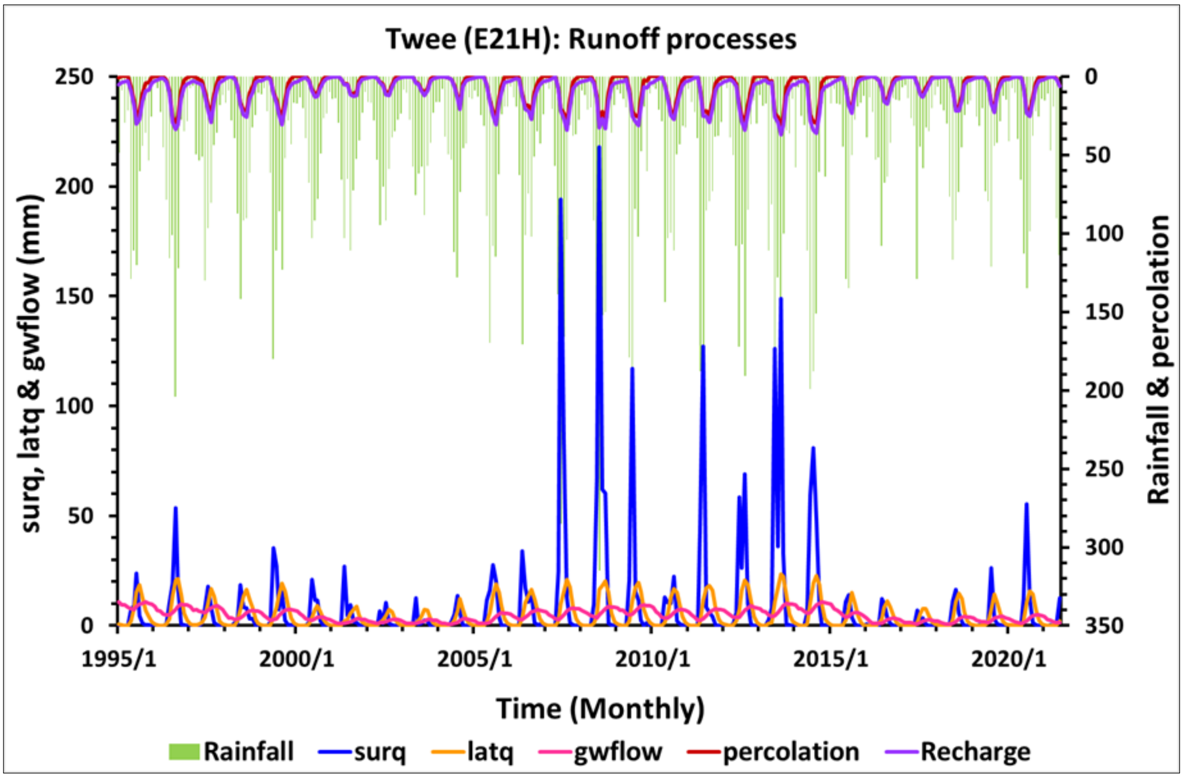


Figure 2.15 Quantitative representation of Twee runoff processes.

2.4.4 Reservoir water balance

The water balance components of a reservoir are made up of inflows which include surface and subsurface flow from upstream and direct rainfall volume, and outflows which include overflow, evaporation, seepage, and water abstraction for irrigation. Inflow into the reservoir, overflow (spillage), and reservoir volumes before and after water abstraction for irrigation are reported in this section. A sample of four reservoirs was selected from the ~50 that were modelled and are numbered for ease of reference (see Figure 2.16). Figure 2.16 illustrates reservoir levels in a scenario when there is no water abstraction and when there is abstraction for irrigation. When there is no water withdrawal, all reservoir water levels generally increase in the wet season and decrease slightly in the dry period. However, overall, water levels remain constantly high. Once there is water withdrawal for irrigation, water levels drop significantly, and reservoirs are almost completely empty in dry years. It is also noticeable that, in wet years, reservoir levels remain high, even during growing seasons when irrigation demands tends to be high.

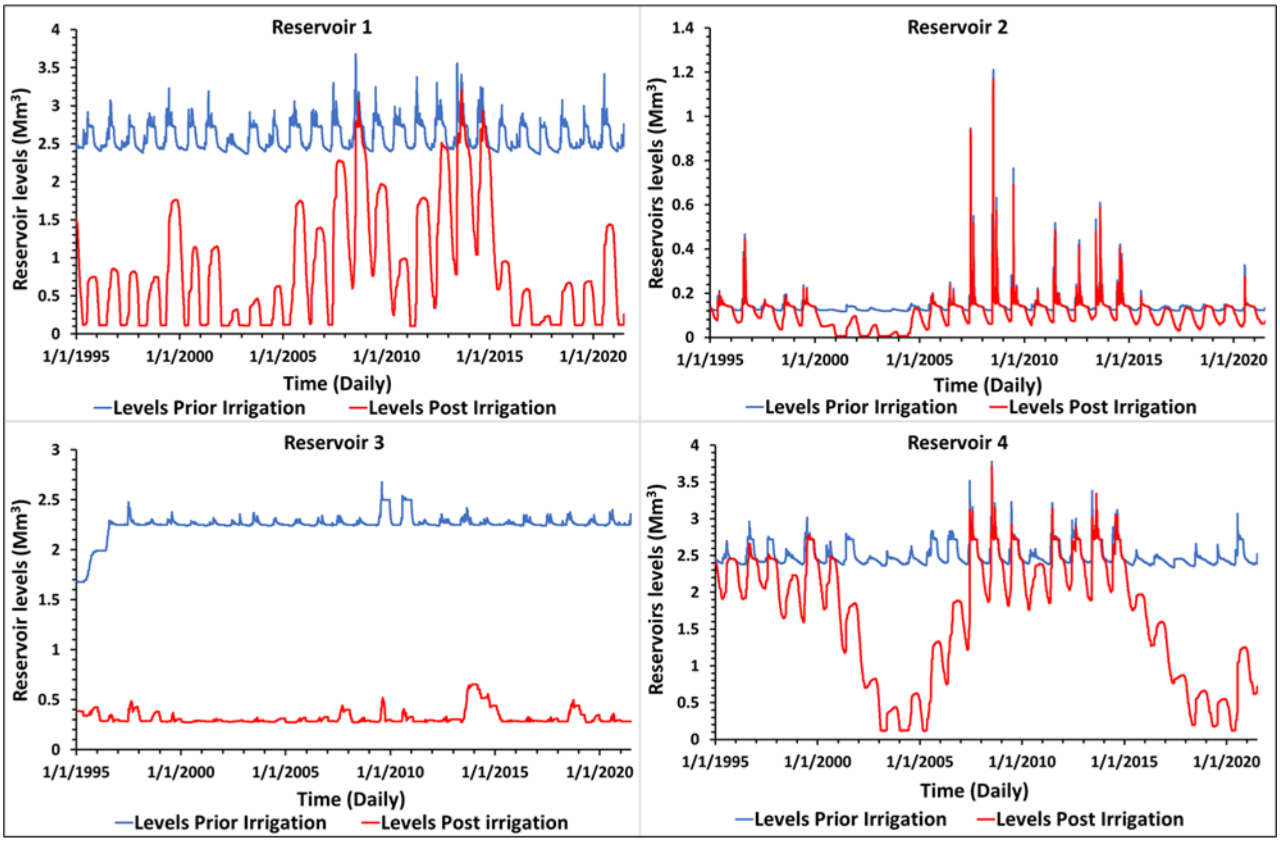


Figure 2.16 Reservoir water level in a scenario where there is no irrigation, and in a scenario where water is withdrawn for crop irrigation.

Figure 2.17 demonstrates the amounts of spillage from reservoirs before and after water withdrawals for irrigation. From the hydrographs and FDC's in Figure 2.17 it is apparent that when there is no water withdrawal there is reasonable spillage from reservoirs which occurs up to about 50% of the time, with the exception of reservoir 3 which only started having some spillage from the year 2010 and spills for 20% of the time under conditions of no withdrawals. Irrigating from the reservoirs considerably reduced overflows and resulted in reservoirs spilling for only 20% of the time. In a case where there was abstraction, reservoir 3 experienced zero spillage 100% of the time.

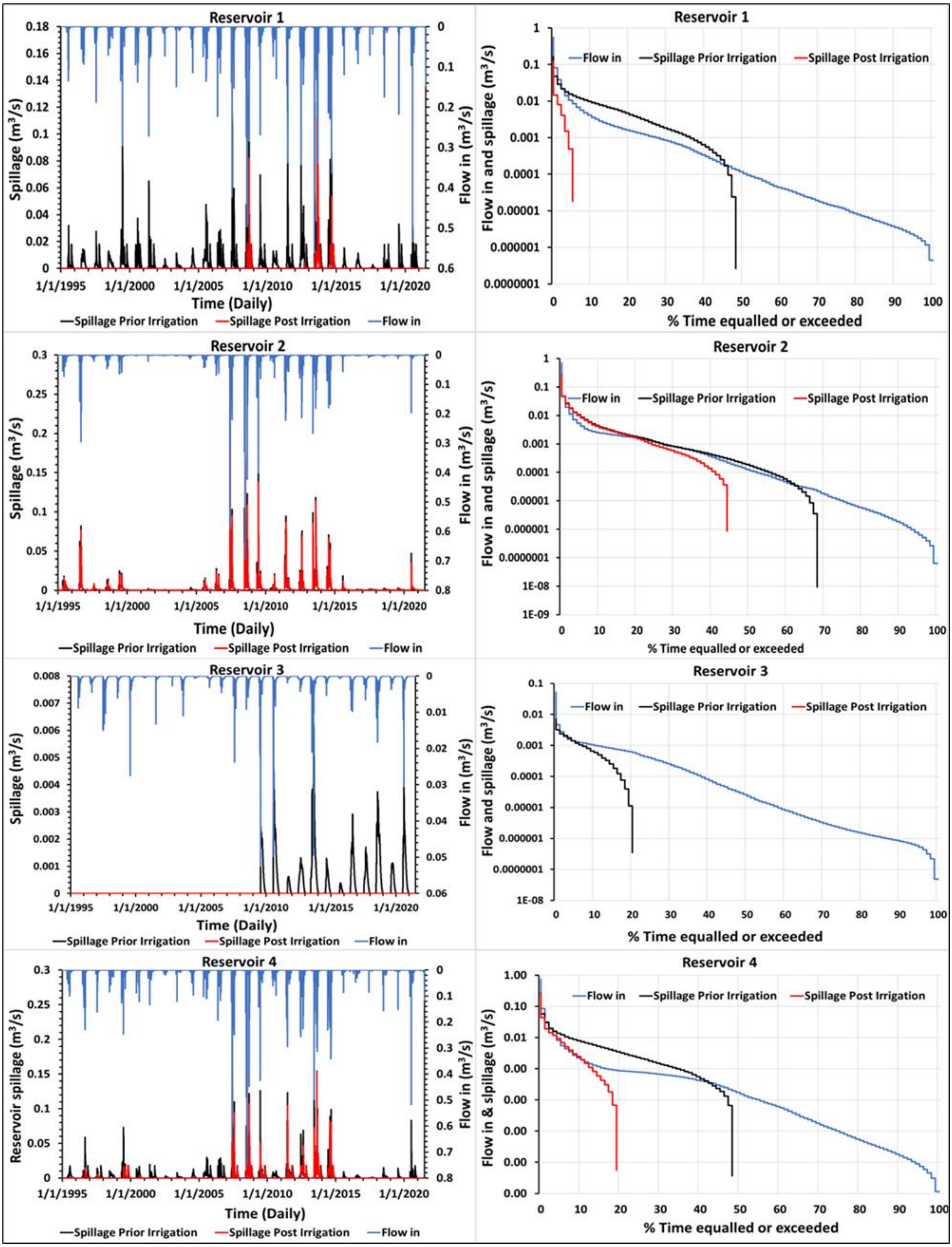


Figure 2.17 Reservoir spillage amounts when there is no water abstraction the irrigation from the reservoir.

2.5 CONCLUSIONS

In conclusion, SWAT+ emerged as a robust tool for accurately capturing the temporal variability of hydrological processes within the Twee catchment. Its ability to align with the qualitative understanding presented in the conceptual model makes it a valuable resource for providing foundational hydrologic data to complement other models.

The simulated hydrology delineates distinct temporally phased hydrological regimes in the Twee catchment, featuring a brief but intense flood-prone period and an extended dry season. The contribution of interflow and baseflow (gwflow) to river flow after rainfall events and during dry spells characterises the catchment as primarily groundwater driven. Furthermore, the hydrological model effectively represents sub-surface flows, portraying water re-emergence leading to spring formation as interflow to the stream.

While the study reveals that reservoirs and water withdrawals significantly diminish river flows, a noteworthy observation is the substantial outflow from the catchment during the short, wet period. This phenomenon is the result of rapid reservoir filling and overflow triggered by intense rainfall events. Consequently, the impacts of reservoirs and water abstractions for irrigation manifest prominently during dry periods characterised by heightened irrigation demand and reduced flows. Acting as water sinks during low-flow periods, reservoirs exacerbate downstream dryness. The findings underscore the significance of SWAT+ in comprehensively depicting the hydrological dynamics of the Twee catchment and provide valuable insights for effective water resource management.

CHAPTER 3: DETERMINING WAYS TO SHARE WATER USING AGENT-BASED MODELLING

3.1 INTRODUCTION

Computer models of complex socio-ecological systems (SES) are widely used to assist stakeholders in these systems to understand the interactions taking place, and also to support decision making. Agent-based modelling (which was derived from individual-based modelling) is a technique that allows mechanistic system models to be created. Autonomous 'players' with built-in behavioural rules interact with other players and the environment in which they exist to mimic the interactions in the 'real world' being modelled.

Schlüter et al. (2019) described agent-based modelling as "a powerful model type to generate a mechanistic and multilevel understanding of SESs", which is why this simulation tool was selected as the basis of generating knowledge to assist the stakeholders in the KBV to share the water available in the catchment fairly.

In developing the agent-based model (ABM) of the KBV catchment, we were aware of the barriers (as identified by Macal, 2016) that prevent ABMs being adopted on a wider scale: a lack of credibility, transparency, and ease of use. Some of the opportunities identified for expanding the use of ABMs have also been considered in the design and development process described in this chapter.

Ways of expanding the use of ABMs include:

- Increasing credibility by explaining the value and benefits gained from an ABM application to justify its use. It is vital that the potential users of any developed ABM trust it; this trust can be facilitated by co-developing the ABM with the users, as has been done in this research, using companion modelling and other participatory approaches.
- Increasing transparency, which is hindered by complexity, by describing the ABM in enough detail so that others can copy the work. The Overview, Design Concepts, and Details protocol is a significant step towards standardising documentation and communication of ABMs. This protocol has been adopted in the design of the KBV catchment ABM.
- Expanding knowledge of developing ABMs efficiently, using the models to generate relevant information, and analysing and explaining the model results. Develop an ABM body of knowledge with a common language and definitions. Lack of educational programmes for next-generation researchers is holding the field back. At the start of the project, the stakeholders in the KBV were entirely unfamiliar with computational simulation. However, with the use of high-level "desktop" simulations and detailed descriptions of how an ABM works during the three workshops held in the KBV, the concept of agent-based modelling is no longer an alien one.
- Increasing the ease of use of agent-based modelling tools. The lack of accessible tools and standardised interfaces is a barrier to ABM application. While the Common-pool Resources and Multi-Agent System (CORMAS) development framework is not sufficiently user friendly to allow those without programming knowledge to execute the model, it did facilitate the implementation of the ABM for the KBV catchment enormously, enabling the task to be completed within the timelines of the overall project.

The design (which includes knowledge gathering), implementation, and validation of the KBV catchment ABM is documented in subsequent subsections. Thereafter, the results of executing some future scenarios are presented together with implications for the use of the ABM in defining the equitable sharing of the catchment's resources.

3.2 DESIGN OF THE AGENT-BASED MODEL

3.2.1 Overview of the Design Phase

The development of an ABM is typically conducted as an iterative process that involves multiple stakeholders (Schlüter et al., 2021). In this study, we used Companion Modelling (ComMod), which is an iterative, participatory approach that enables stakeholders to discuss natural resource sharing (Barreteau et al., 2003).

Stakeholder engagement took place mainly through the three workshops that were organised. The Actors, Resources, Dynamics, and Interactions (ARDI) method (Etienne et al., 2011) is used in ComMod to help stakeholders agree on a conceptual model of the system. It was used in the first workshop to obtain more information about the catchment to kick-start the design process.

A conceptual model was then developed using the information obtained from the first workshop, together with additional data obtained from various sources, including Cape Farm Mapper developed by the Western Cape Department of Agriculture (WCDoA, 2023), which provided data on farm boundaries, crop types and cultivation hectarage; the WR90 study on surface water resources of South Africa (Pitman et al., 1998), which provided A-Pan evapotranspiration and crop factor values; and the South African Space Agency (SANSA), a representative of which provided data for calculating dam capacities.

The conceptual model was presented to the stakeholders for feedback at the second workshop. A survey was also conducted at this workshop to obtain additional information regarding farming strategies related to irrigation and cultivation hectarage, amongst others. At the third and final workshop, results from the model were presented to the stakeholders and validation of these results as well as any necessary changes to the model were sought. Water-sharing plans were discussed with the stakeholders and additional future simulation scenarios were also requested.

3.2.2 Conducting the ARDI process

The ARDI methodology was designed to facilitate co-creation of models for natural resource management with various stakeholders. Participatory modelling requires stakeholders to have a shared understanding of their system and thus this approach was followed in the first workshop. However, the participants were split into two groups, one identifying actors and resources and the other discussing the dynamics in the catchment. The research question acted as the anchor in the discussions.

Multiple actors were noted in the identification of the Actors stage. Some of the direct actors were farmers, labourers, and eco-tourism operators. Some indirect stakeholders were the government, retailers, and the Water User Association (WUA). The resources that the stakeholders mentioned included soil, water, and biodiversity. Some of the dynamics that the stakeholders raised were irrigation, job creation, mining, and water abstraction.

The facilitator then asked the stakeholders to provide interactions between identified actors and resources and between two actors. Some of the interactions that came up were the usage of water by crops and other vegetation, pumping of water by farmers from the river into dams, and tilling of the soil by farmers.

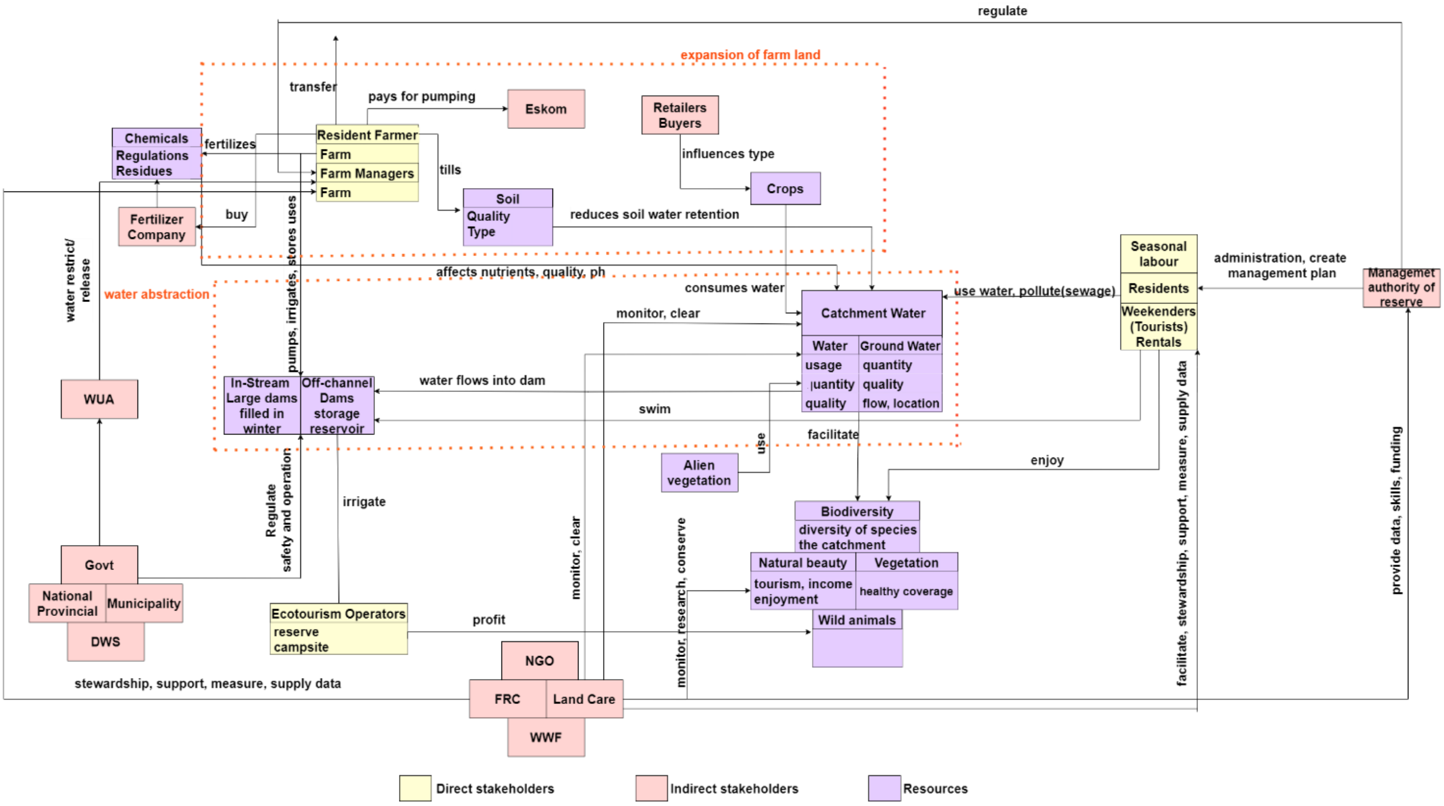


Figure 3.1. Interaction diagram created through ARDI process conducted with KBV catchment stakeholders.

Figure 3.1 shows the interaction diagram created at the end of the ARDI process. The chart shows the actors, resources and interactions the stakeholders raised during the ARDI workshop and shows the high level of complexity in the catchment. Because one of the project objectives is to show how the stakeholders could use water more equitably and sustainably, only the components directly related to this goal were prioritised.

3.2.3 Farming practice questionnaire

This section provides details on the survey conducted during the second workshop to obtain information from the farmers regarding their farming practices. A questionnaire was sent out to the 11 farms in the catchment that use irrigation. Unfortunately, only five responses were received. Information on the farming practices of those farms that did not respond was taken from suitable literature sources.

Ethics approval for this survey was obtained from the Rhodes University Ethics Committee (Ethics Application no. 2022-5900-7264). All data was treated as confidential and not disclosed to anyone outside of the project team. When presenting outputs of the ABM, individual farms were referred to by coded IDs rather than actual farm names.

3.2.3.1 Design of questionnaire

The questionnaire was designed to elicit information in four areas: Water Abstraction, Crop Decisions, Irrigation Strategy and Plans for the Future.

The first section included questions relating to the farmers' usage of surface and groundwater. The information sought in this section was in connection with the location and pumping rates of any water pumps, dam locations and capacities, whether the dam was in-stream or off-stream, as well as the percentage level at which farmers would start topping up the dam. This information was needed to understand the storage capacities of each farm, how the dams were filled, the rate at which the farmers could fill the dams and when they would fill their dams.

The section on crop decisions presented questions on how farmers decide whether to plant a seasonal crop, and the hectarage of each crop cultivated. This information is vital as crop hectarage and type are the main factors determining a farm's water requirements. Knowing the factors considered when determining what seasonal crops and how many hectares to plant is important to ensure that the water usage calculations in the ABM are accurate.

The irrigation strategy questions related to the irrigation infrastructure the farmers used. It also included questions on how they prioritised crops when irrigating during a water shortage, the volume of water used for irrigation during different months, and the water sources. Irrigation equipment determines the efficiency of irrigation and so affects the volume of water used for irrigation. Prioritisation of crops during times of shortage is once again important to ensure the agents in the model behave in a realistic manner; finally, requesting the total volume of water used for irrigation per year ensures the calculation of crop water demand in the KBV ABM is correct.

Questions about the farmers' plans for the future were focused on potential changes the farmers might consider implementing in the future, such as construction new dams, expanding or reducing the irrigated land under cultivation, or cultivating different crops. This information was used to inform the future scenarios that the ABM might explore.

3.2.3.2 Summary of the responses

Although the catchment has multiple farms, not all farms irrigate. Farms that do not irrigate use water from the river for domestic purposes only, and the volume of water used for this purpose is negligible compared to that used for irrigation. For that reason, those farms were not included in the KBV ABM.

Most of the other farms have dams that they use for irrigation. These dams are mostly in-stream dams, with one farm having a storage capacity of 30 000 m^3 and another having 720 000 m^3. One of the farms uses groundwater to fill dams during emergencies.

Multiple crops are cultivated: citrus crops of oranges and lemons, and deciduous crops of apples, peaches, and nectarines. The responses also showed that pastures are cultivated. The hectarage per crop per farm varied from 1.7 ha to 53 ha.

All the farms use micro-spray irrigation and recorded soil moisture to schedule irrigation. The survey showed that the farms supplied different percentages of crop water demand during water shortages, depending on the crop's importance and growth stage. The farms' crop priorities varied, with one farm having oranges as the highest priority and another having apples as its highest priority. The high-priority crops had larger hectarages than the lower priority ones. The farmers agreed that no irrigation takes place during winter (which is typically the wet season). Most responses included plans for new irrigation pipelines and the use of drip irrigation. One of the farmers was planning to build new dams, while another was planning to expand the land under cultivation.

3.2.4 Conceptual model

3.2.4.1 High-level overview of the design

Figure 3.2 gives a high-level overview of the basic model components. Similar to other studies (Farolfi & Bonté, 2005; Khan et al., 2017), streamflow and rainfall values are obtained from a hydrological model, in this case, the Soil and Water Assessment Tool (SWAT) discussed in Chapter 2 of this report. The main players (or agents) in the model are those representing farms, crop fields, river segments and off-stream dams, each of which is discussed in more detail in the next section.

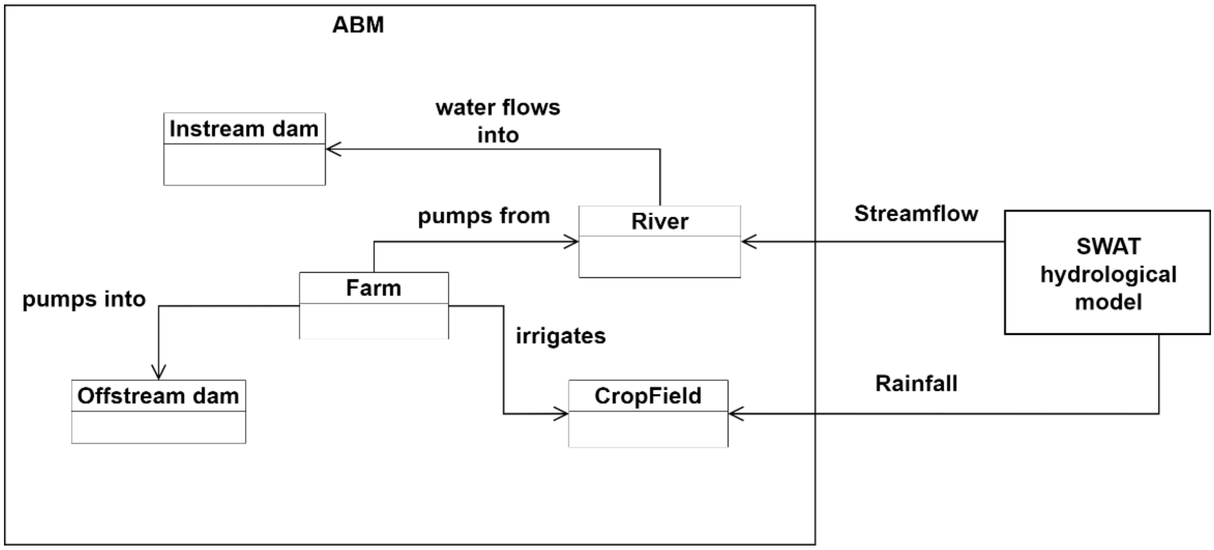


Figure 3.2. KBV ABM showing main agent types and input from the SWAT hydrological model.

Based on discussions with the project team and information gleaned from the literature, the following assumptions and limitations were considered in the ABM design and implementation:

- Only 70% of rainfall is effective and available to crops. This was adopted from the CROPWAT model, which can calculate effective rainfall using a fixed percentage with losses ranging from 10-30% (Smith, 1992).
- All the water supplied during the irrigation of fruit trees can be taken up by the trees because farmers use highly efficient micro-spray irrigation, which has an efficiency of 90% (Eisenhauer et al., 2021).
- Irrigation for pastures and seasonal crops requires 20% more water due to the use of sprinkler irrigation, which is less efficient than micro-spray irrigation (Eisenhauer et al., 2021).
- Evaporation of water from dams is considered to be negligible and is thus not explicitly calculated.
- Farmers are deemed to use only surface water – thus, ground water is excluded in this model.
- Because most farmers use highly efficient irrigation techniques such as micro sprayers, return flows are not represented.
- Water transfers from E21H to E21G are not represented in the conceptual model as no data about these transfers was available.

3.2.4.2 Agent types

Figure 3.3 shows a class diagram of the main agent types as explained in this section. The diagram also shows various attributes or indicators of each agent type, e.g. `damStorageCapacity` which is the capacity of a dam, or `cropType` which gives the crop being cultivated on a particular CropField agent.

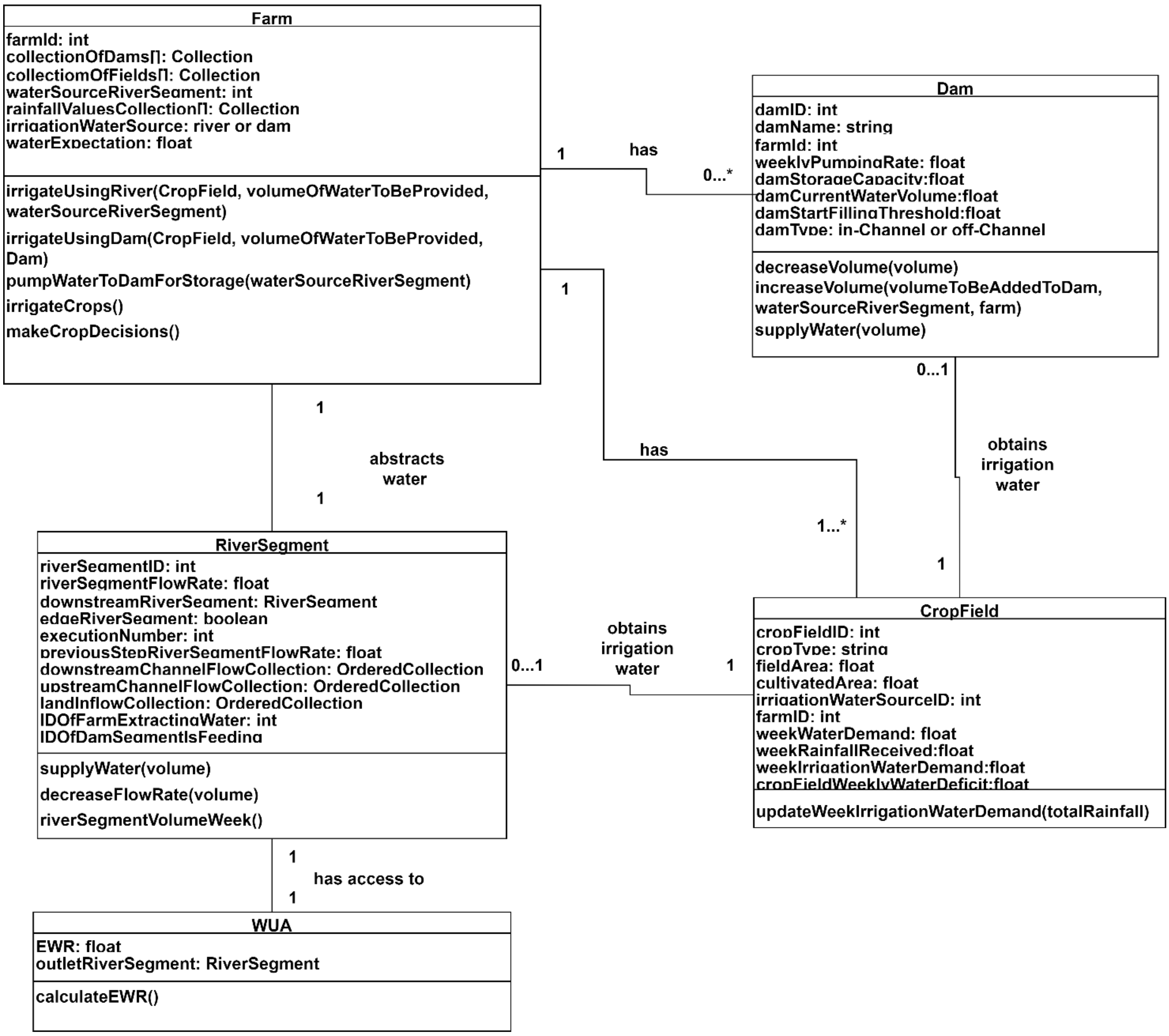


Figure 3.3. Class diagram of basic conceptual model.

RiverSegment agent:

The conceptual model divides the KBV river system into multiple RiverSegment agents. Each RiverSegment receives water from its upstream RiverSegment and sends water to its downstream RiverSegment. If a RiverSegment feeds water into an in-stream dam, the RiverSegment does not allow water to flow to the downstream RiverSegment until the in-stream dam is full and overflowing.

Although the RiverSegment network is a simplified form of the stream network from the hydrological model, all the water is accounted for. In-stream dams and farm boundaries are the main factors that determine where each RiverSegment starts and ends. Figure 3.4 shows a portion of the river catchment. The thin, light blue lines are the river channels defined by the hydrological model whose IDs are the unbolded black numbers; the grey areas represent farms with the large bold letters representing the farm IDs, while the thick lines depict the RiverSegments. Light blue polygons represent dams.

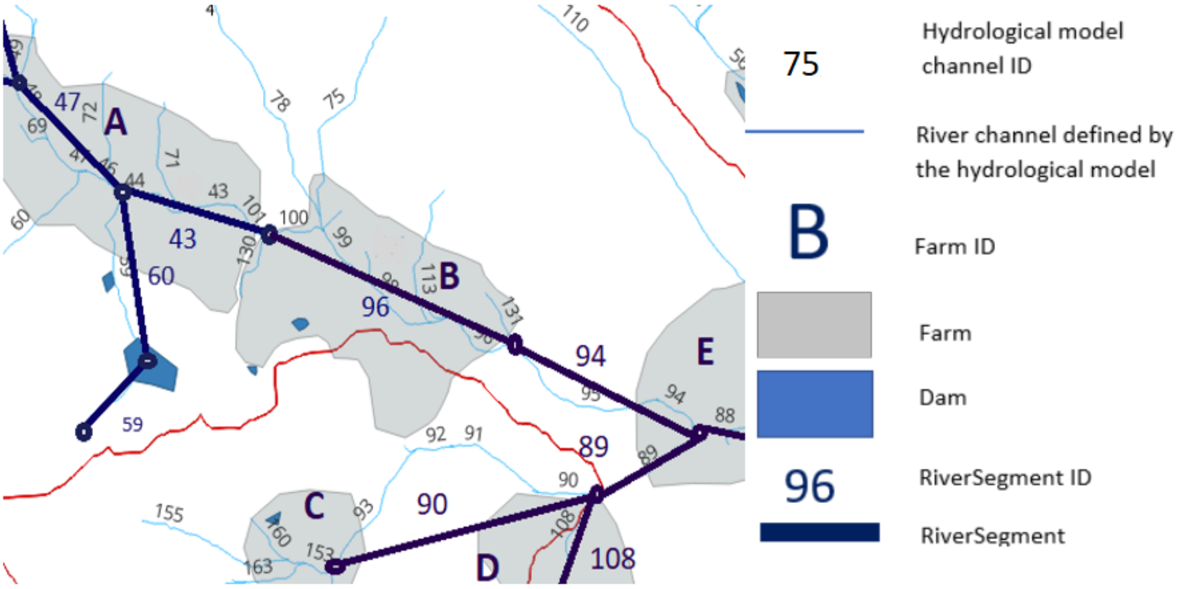


Figure 3.4. Design of the RiverSegment network.

As shown in Figure 3.4, RiverSegment 43 starts where two RiverSegments (47 and 60) end and RiverSegments 59 and 60 are connected to an in-stream dam. The position where RiverSegment 43 ends coincides with the boundaries of Farms A and B.

Farm agent:

The KBV catchment has multiple farms. Each farm has several fields, and farmers cultivate different crops: apples, pears, oranges, and cabbages. Most farms have one or more dams used for irrigation. The conceptual model represents the farm and farmer as a single agent, namely the Farm agent. The Farm agent decides how much irrigation water is supplied to different CropFields, when to pump water to fill dams, and the hectarage of seasonal crops to plant.

Dam agent:

Most farms in the KBV catchment have in-stream or off-stream dams that they use for irrigation. In-stream dams block the flow of water until they are full and overflow. Farmers pump water into dams when they reach a certain threshold. In the conceptual model, we represent both in-stream and off-stream dams using Dam agents. Each in-stream Dam agent is connected to a RiverSegment agent from which it obtains water.

Crop field agent:

The conceptual model represents each farm's crop fields using CropField agents. Each CropField agent has a weekly irrigation water demand that the Farm agent needs to provide. We calculate the crop's irrigation water demand by considering weekly rainfall and the weekly evapotranspiration demand of the CropField agent. The agent also has fieldArea and cultivatedArea attributes. The cultivatedArea for seasonal crops changes from season to season, depending on water availability.

Water User Association agent (WUA):

This agent checks if the flow at the outlet is below the required EWR. This is the only responsibility of the WUA in the base model. However, a separate agent type was created to enable more functionality of the WUA should control over a shared dam be necessary, for example, in a future scenario simulation.

3.2.4.3 Agent behaviour

The fundamental principle in an ABM is that agents act autonomously; in other words, there is no controller agent that dictates what each agent must do at any timestep in the simulation. Thus, in order to achieve autonomous action in computerised agents, the behaviour of each agent type needs to be defined in detail, together with the 'triggers' that might dictate a certain behaviour being chosen. Triggers may be in the form of environmental conditions (e.g. lack of rain that causes farm agents to start irrigating) or an action of another agent (e.g. a RiverSegment might be flowing strongly past a farm, causing the farm agent to start filling an off-stream dam).

The class diagram in Figure 3.3 depicts some of the behaviours of the various agent types; for example, a RiverSegment agent can supply Water, while a Farm agent can make Crop Decisions, irrigate Using Dam or irrigate Using River, amongst others. Attributes for each agent type are used extensively in determining possible agent behaviour at each timestep. Details of some of the behaviours of each agent type are given below.

RiverSegment agent behaviour:
Based on the structure of the ABM, each RiverSegment agent is executed (i.e. allowed to do something) in turn from the most upstream RiverSegment to the last RiverSegment in the catchment (i.e. the one connected to the catchment outlet). Each RiverSegment has an executionNumber attribute, which the model uses in controlling this order of execution of the RiverSegments. During the execution of a RiverSegment, the main behaviour of the agent is to supply water to the next RiverSegment in the ordering.

If a RiverSegment is connected to an in-stream dam, the RiverSegment directs its water to the dam until the dam is full. Once this happens, water is allowed to flow to the next downstream RiverSegment.

If a RiverSegment has an associated Farm (i.e. one that obtains water from that segment), the respective Farm agent is allowed to execute at the same time as the RiverSegment.

WUA agent behaviour:
After all the RiverSegments have executed in a particular timestep of the simulation, the WUA calculates the EWR using the natural flow rate at the catchment outlet (i.e. the flow rate that would have occurred at the outlet if no human activities, like irrigation, had taken place) and compares the EWR with the actual flow rate from the RiverSegment connected to the outlet.

Farm agent behaviour:
The main activities that farmers perform and which are modelled in the KBV ABM are irrigation and filling dams (done weekly), and planting vegetable crops (once each season). At the beginning of each season, the Farm agent makes crop decisions, which involve determining the hectarage of seasonal vegetable crops to cultivate.

Irrigation is the primary water usage in the KBV catchment; hence, the main water usage reflected in the ABM is irrigation. The factors determining the water volume used for irrigation are the crop type, water demand, hectarage of the CropField, and the irrigation schedule. The irrigation scheduling depends on crop water demand, water availability, and crop priority. Each Farm agent has attributes that determine the percentage of water demand that can be provided to a CropField agent when there is a water shortage, while each CropField agent has summerPriority and winterPriority attributes. These attributes are used by the Farm agent in prioritising crops for irrigation.

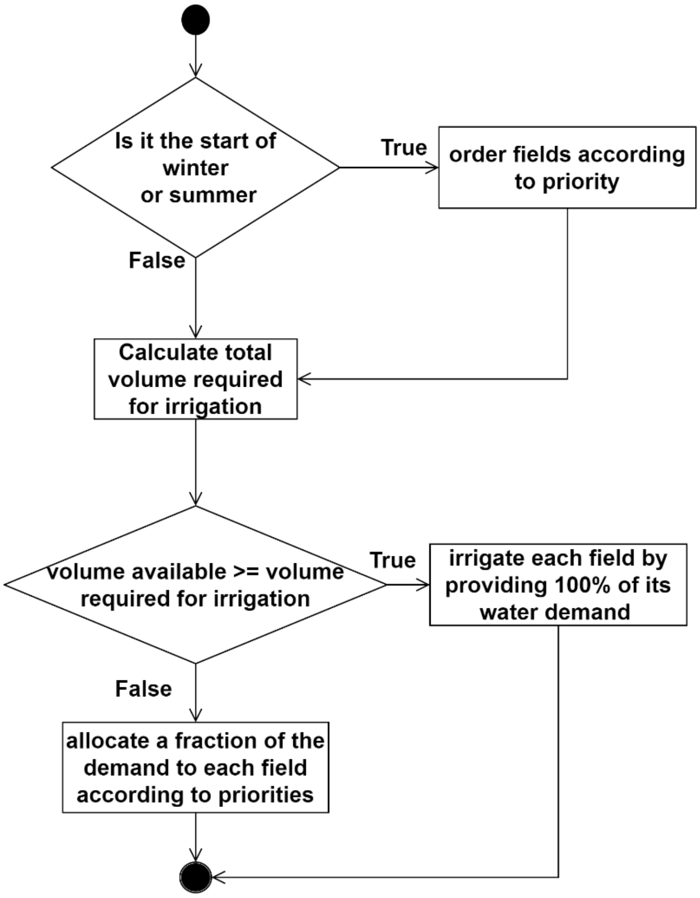


Figure 3.5. Flowchart of Farm agent's behaviour regarding irrigation.

Figure 3.5 shows the Farm agent's decisions and actions regarding irrigation. At the beginning of the season, a Farm agent sorts its CropFields according to crop priorities. The Farm agent then calculates the total irrigation demand of all its CropField agents. The Farm agent compares the total irrigation water demand to the volume of water available according to the attribute `irrigationWaterSource` that specifies these sources, which can either be dams or the river. If the available water equals or exceeds the irrigation water demand, the Farm agent provides the CropFields with 100% of their water demand. However, when the total water demand exceeds the available water volume, the Farm agent will irrigate the CropFields in the order of importance and the volume determined by a CropField's priority.

Some farmers in the catchment cultivate seasonal vegetable crops. They determine the hectarage of these vegetable crops at the beginning of each season using the previous year's rainfall and the volume of water they have in storage. Similar to Becu et al. (2003), who used a water expectation attribute that the Farmer agents used in determining the types of crops they would cultivate, the Farm agents in the KBV ABM use an attribute called waterExpectation in combination with the total volume of water in storage to determine the hectarage of vegetable crops. The waterExpectation attribute keeps track of the previous year's rainfall, which the Farm agents use to predict the following year's rainfall. The ABM has a parameter rainfallThresholdFor-FullVegetableCropCultivation that the Farm agents use in determining the hectarage of the vegetable crops to cultivate.

The calculation of the hectarage of vegetable crops starts at the beginning of a new season, with each Farm agent first checking if the waterExpectation is above the threshold amount required for full vegetable cultivation. If the condition is satisfied, there will be full cultivation of vegetable crops, i.e. each CropField set aside for vegetable cultivation will have a cultivatedArea equal to its fieldArea. If the amount of water expected is less than that required for full cultivation and the Farm agent has no dam storage, the fraction of the field area for vegetable cultivation will be the ratio of the water expected to the required water. If the Farm agent has dam storage, the area cultivated is determined by the ratio of the Farm's total volume of water stored plus expected water to the required water for the vegetable crop.

3.2.4.4 Timestep scheduling in the ABM

When designing an ABM, the temporal scale of the model is important as this defines how the behaviour is described. During a simulation (i.e. an execution of the static ABM) the 'tick' process ensures that each agent is given an opportunity to execute one (or more) of its behaviours defined for each timestep.

For the KBV ABM, the timestep was set to be a calendar week. Justification for this decision is as follows:

- It would be easier to model the system using a weekly timestep because agent actions were consolidated into a weekly scale and the model would run more quickly.
- The stakeholders/farmers did not express an interest in questions relating to day-to-day decision-making at the farm level. Instead, they were more interested in strategic issues.
- It made the questionnaire design easier; although questions remained detailed, they did not require detailing the day-to-day decision-making of the farmers.

However, the drawback of this decision is that river flows may be somewhat less accurate as the SWAT simulation outputs are given on a daily or monthly scale and therefore, a simple flow aggregation is required to derive weekly flow volumes from daily flows.

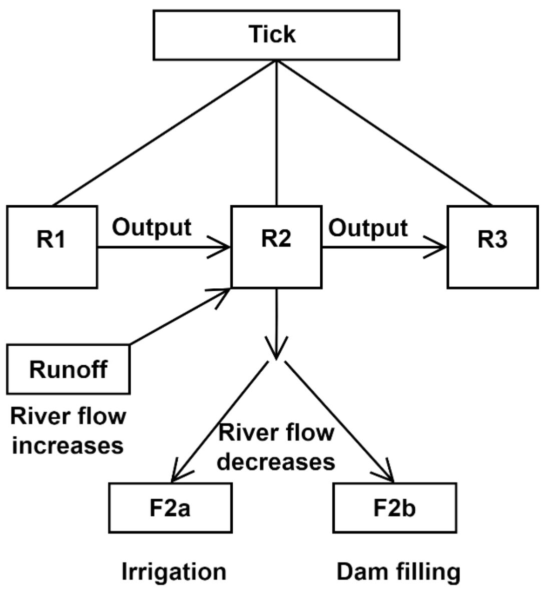


Figure 3.6. Scheduling of agent execution at each timestep. Rx and Fx represent a RiverSegment and Farm, respectively.

Figure 3.6 illustrates the model scheduling at each timestep or model 'tick'. This scheduling is important to ensure that the river flow is calculated in the same way as natural flow, that is, from upstream to downstream river segments.

R1, R2, and R3 are RiverSegment agents. At each tick, water flows from upstream to downstream as shown by the arrows linking the RiverSegments. F2a and F2b are Farm agents obtaining water from R2. F2a uses the water for irrigation while F2b uses it to fill dams. The *output* flow from each RiverSegment is given by:

$$output = input + runoff - use$$

where o*utput* is the water flow exiting a RiverSegment,
input is the water flow entering the RiverSegment,
runoff is additional water flowing into a RiverSegment from the surrounding land, and
use is the water used by farmers for either irrigation or dam filling.

3.3 IMPLEMENTATION AND VALIDATION OF THE ABM

The ABM was implemented using the CORMAS simulation environment (Bousquet et al., 1998). An iterative process was followed because the real-world system being modelled is so complex. Verification was performed continuously to ensure the model was correct, while validation was done after all the model components had been incorporated.

3.3.1 Implementing the ABM

The conceptual model designed for the KBV catchment was extremely complex, so its implementation took place as a series of smaller models. This method ensured that each version of the KBV could be verified for correctness before additional functionality was added. Although functionality was added continuously in small increments followed by thorough testing, for simplicity, here we describe the three main versions of the ABM that defined major achievements in the implementation.

1. Development of the river network. The river network was designed and implemented using RiverSegment agents that were arranged to reflect the flow of water from upstream to downstream. The river network was verified by comparing the flow rate obtained from SWAT with that from the KBV ABM at various points in the catchment to determine if they matched.

2. Addition of crop fields and irrigation. Crops and their irrigation were included in the ABM by adding the CropField agents with attributes and behaviour as explained in Section 3.2.4.3. For this version of the ABM, all irrigation was done directly from the river.

3. Addition of in-stream and off-stream dams. The dams were added as Dam agents, which were associated with the respective Farm agents based on location. Farms agents with dams could now use dams for irrigation. At this point, the water balance was verified, that is, we checked whether the water being input into the model was equal to the sum of water used for irrigation, stored in dams and leaving the catchment. This check was important as it allowed us to determine if the KBV ABM was losing or gaining water through errors in the implementation.

3.3.2 Validation of the model

Both objective and subjective evaluation was done to measure the success of the implemented model, that is, how well it reflected the real world. Objective validation involved measuring the extent to which the output flows from the ABM matched historic observed flows, while subjective evaluation was based on stakeholders' acceptance of the model outputs.

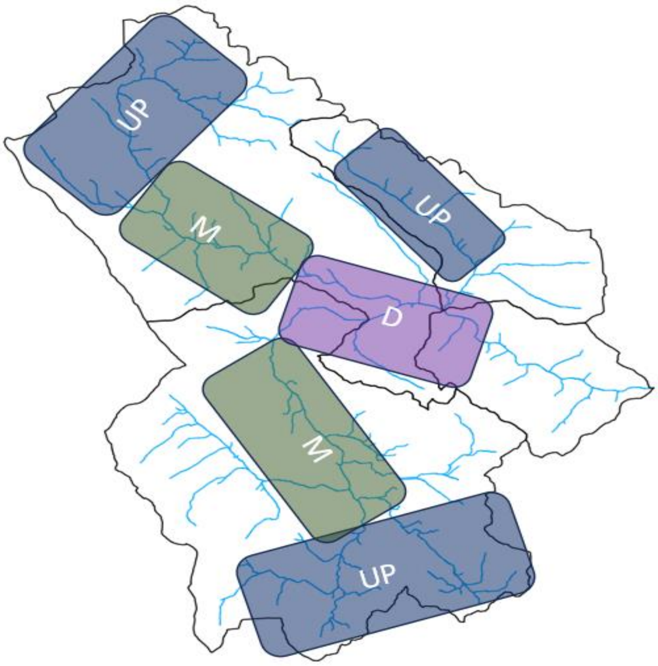


Figure 3.7. Grouping farms based on location.

To adhere to the agreed confidentiality of farmers' strategic data, farm codes were assigned to the farms based on their location in the catchment, such as UP-1 for an upstream farm, M-1 for a midstream farm and D-1 for a downstream farm. Upstream farms are defined as those farms that abstract water upstream; downstream farms are those close to the outlet, while midstream farms are the remaining farms (see Figure 3.7).

3.3.2.1 Validation of water demand at farm level

This simulation aimed to determine if the water demand calculated by the KBV ABM was realistic when compared to the survey data. One of the questions in the questionnaire was about the volume of water farmers use for irrigation per season when water is sufficient. We received responses to this question for three farms, namely UP-2, M-3 and D-1.

The simulation ran for 52 timesteps and made use of the current land-use and hectarage data, as well as rainfall and streamflow generated by the SWAT model from October 2019 to September 2020. The structure of the underlying model was the same as that described by the iterative steps in Section 3.3.1, i.e. the baseline model.

Results of this simulation showed that the three farms had a total water demand of 1 212 305 m^3. However, data from the survey showed that the farms would have a water demand of 1 446 390 m^3. This means the ABM's water demand is lower than that from the survey by 234 085 m^3. To correct this problem, a parameter was added to the model and its value was set to 1.2 (based on imperative testing). The calculation of a crop field's water demand was changed to include multiplying the water demand obtained from the table holding crop water demands by this correction factor.

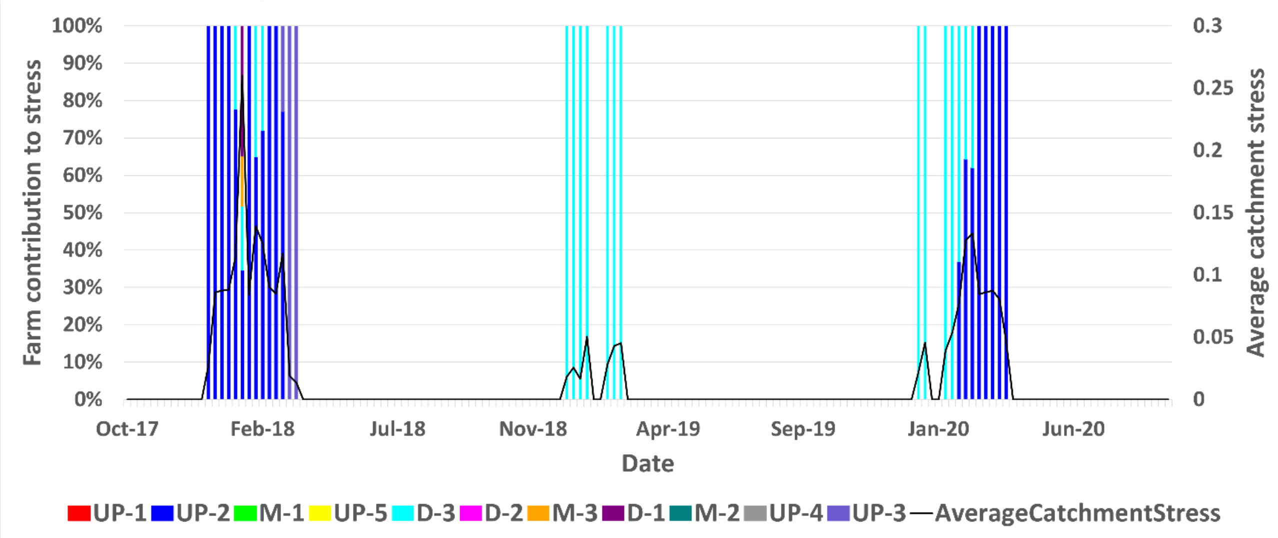


Figure 3.8. Farm contribution to the average catchment stress (= ratio of water deficit to water demand) for the period October 2017 to September 2020.

3.3.2.2 Validation of water shortages experienced at farm level

A new simulation was executed to determine whether the water shortages experienced by farms were realistic. Obtaining exact water shortage values for each farm was impossible because there are no historical records. Therefore, we relied on workshops with farmers and discussion with the KBV Catchment Coordinator to ascertain how realistic the model is.

The simulation used the current land-use and hectarage data, as well as rainfall and streamflow generated by the SWAT model from October 2017 to September 2020. This simulation was executed on the baseline ABM including the correction parameter incorporated after the first validation (described in the previous subsection).

Figure 3.8 shows the average catchment water stress and the percentage each farm contributes to the catchment water stress. The water stress is the ratio of water deficit to water demand, meaning if water stress is zero, enough water is available, and if it is one, there is no water. The average catchment water stress is the average water stress of all the farms in the catchment. Given that the farms' water requirements differ, water stress was chosen to show some of the model's outputs because this indicator allows a simpler comparison of water availability for different farms than using water volumes directly.

Figure 3.8 shows that for each year, there was a higher water shortage during the summer months (December to March) than at other periods because the KBV receives most of its rainfall during winter and very little rainfall in summer. In addition, there is high water demand during this period. These two factors resulted in lower water availability during these months than in the other months.

Another aspect to note is the relatively high-water stress in the catchment and the higher number of farms experiencing water shortage in the summer of 2018. This can be attributed to the drought experienced in the Western Cape from 2015 to 2018 (Archer et al., 2019). There was lower-than average rainfall, so there was not enough water for irrigation.

Figure 3.8 also shows that two farms, D-3 and UP-2, have relatively higher water stress. Farm D-3 has no storage, while farm UP-2 has a small dam and obtains water from a seasonal river.

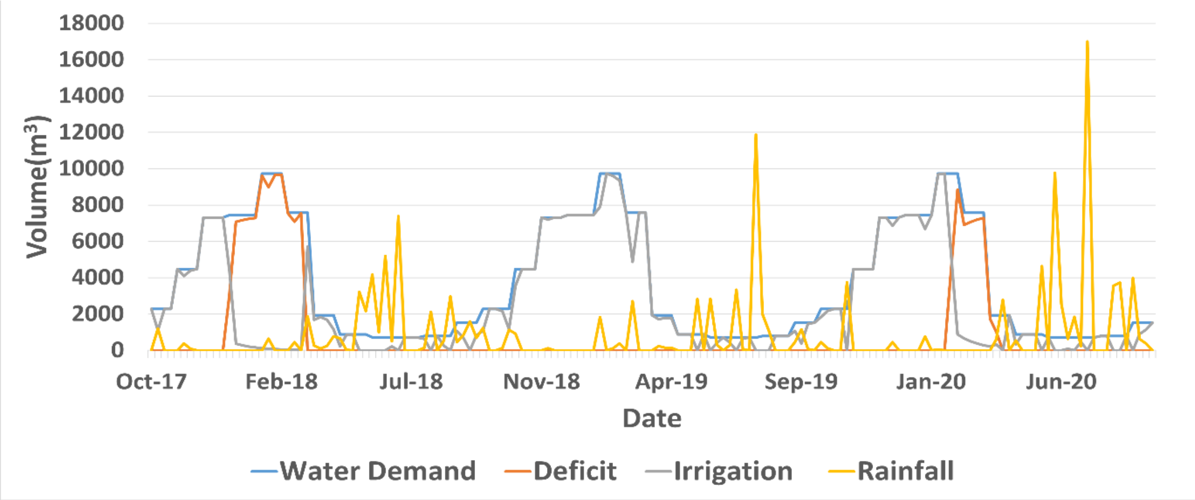


Figure 3.9. Water demand, deficit, irrigation and rainfall for farm UP-2 from October 2017 to September 2020.

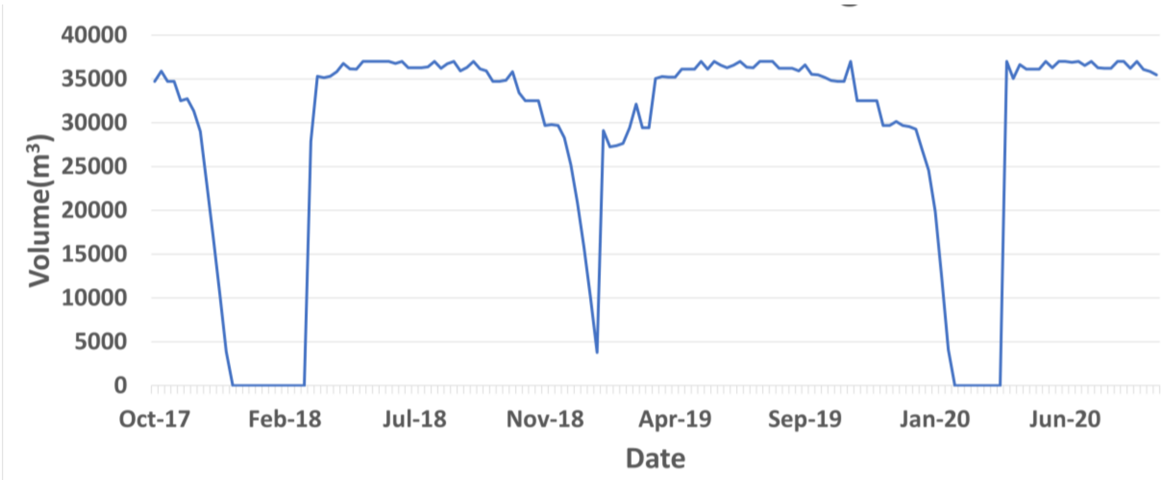


Figure 3.10. Volume of water in storage for farm UP-2 from October 2017 to September 2020.

The KBV ABM can provide indicators at the farm level, as shown in Figures 3.9, 3.10 and 3.11 for farm UP-2.

Figure 3.9 shows the water demand, deficit, irrigation, and rainfall for farm UP-2 from October 2017 to September 2020. Figure 3.10 shows the farm's water storage volume, while Figure 3.11 shows the average farm water stress. The graphs are consistent. The periods with high water stress coincide with periods with little rainfall and a low volume of water in storage. For example, Figure 3.10 shows that during February 2018, there was no water in storage. Figure 3.11 shows little rainfall, high water demand and a high-water deficit for the same period. It also shows that the water stress was close to 1 during this period.

These indicators give a comprehensive depiction of the model dynamics. As stated in Section 3.2.4.1, the KBV ABM only considers the use of surface water. Some farms, e.g. farm UP-2, mentioned that they used groundwater during emergencies. Therefore, the real-life water shortage might not have been as high as that shown by the model's outputs.

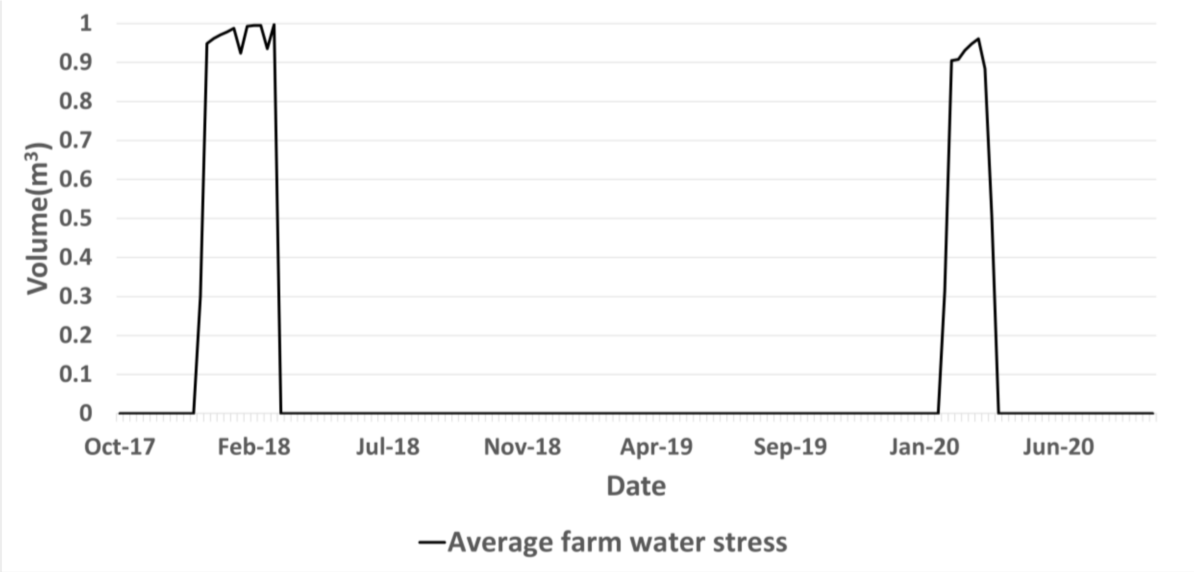


Figure 3.11. Average farm stress for farm UP-2 from October 2017 to September 2020.

3.3.2.3 Stakeholder acceptance of the model outputs

We shared the validation outputs with the Catchment Coordinator, who confirmed that the results were realistic, but since there is no historical data on shortages, it was not possible to quantitatively confirm the exact water shortage volumes. The Catchment Coordinator confirmed that the farms shown in the model outputs as having shortages were those that did indeed have these but mentioned that farm D-2 also had shortages. The KBV ABM did not show any water shortage for farm D-2 because farm D-2 responded to the questionnaire with updated land use and hectarage values, which are the ones used in the model. The responses to the questionnaire showed that this farm had reduced its cultivation, which could explain the differences observed in the model results.

We shared the model results with the stakeholders at the third workshop as a way of obtaining stakeholder acceptance of the model. A single slide from this presentation is shown in Figure 3.12. On the whole, the stakeholders agreed with the results shown.

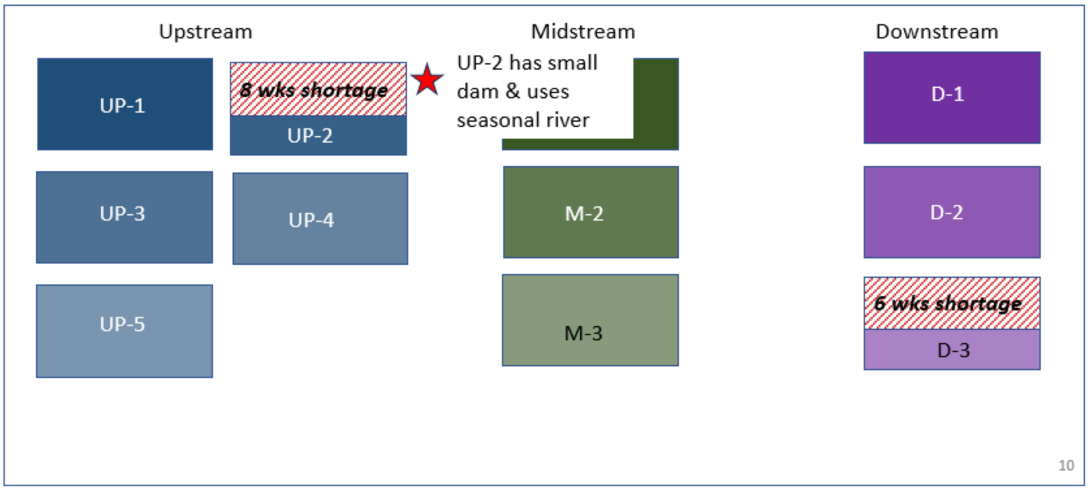


Figure 3.12. Model output showing farm-level water shortages during 2019/2020.

3.4 PREDICTING FUTURE WATER USE USING THE ABM

For the validation simulations, the baseline ABM was executed using historic climate and rainfall data. However, in order to predict future scenarios, we used projected climate data taken from the predicted rainfall and temperature values from ten Global Climatic Models (GCMs) using Representative Concentration Pathways (RCP) 4.5 and 8.5, together with other relevant farm-level changes, such as increased crop hectarage or greater dam storage capacity, as given in the scenario description. The RCP values are a measure of carbon emissions, with 4.5 being the lowest and 8.5 the highest future emission scenario. The Intergovernmental Panel on Climate Change (IPCC) defines RCP 4.5 as a carbon emission scenario where carbon emissions peak in 2040 (referred to in this chapter as the moderate climate change scenario), while RCP 8.5 is a scenario where carbon emissions peak in 2100 (referred to as the extreme climate change scenario) (Pachauri et al., 2014).

For each of the future scenarios executed, the simulation was run for five years (representing the period October 2025 to September 2030). However, the output graphs displayed in this section, show only small portions of the results for the sake of clarity.

3.4.1 Predicted water availability based on moderate climate change scenario

As climate change is a given, it is important to ascertain how this change may affect the KBV region. This scenario uses RCP 4.5 to explore the effects of moderate climate change on the water availability in the catchment. The scenario uses current land-use data. The rainfall and streamflow are obtained from the SWAT model, which was run for the period October 2025 to September 2030 using RCP 4.5 predicted rainfall and temperature.

Figure 3.13 shows the predicted results for this scenario, where, for the period October 2028 to September 2030, six farms have water shortages. The image shows a maximum average water stress of 0.25 which is similar to that of the validation scenario discussed in Section 3.3.2.1. However, if all the five years (October 2025 to September 2030) are considered, the highest average catchment stress was 0.4, and it occurred in January 2028. This is a 38% increase compared to the peak catchment water stress of 0.25 shown in this scenario.

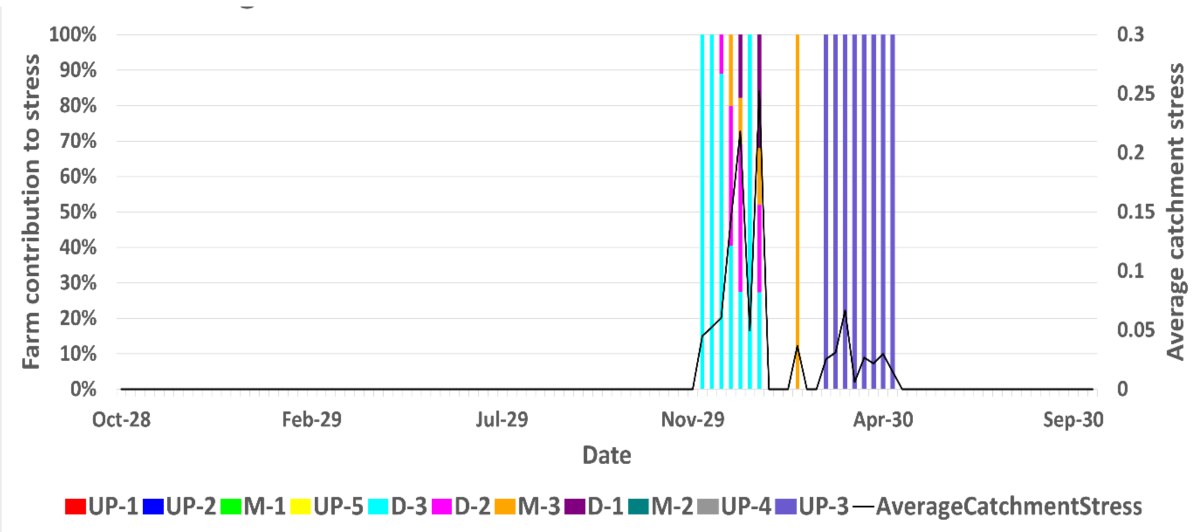


Figure 3.13. Predicted farm contribution to average catchment stress for October 2028 to September 2029 under moderate climate change.

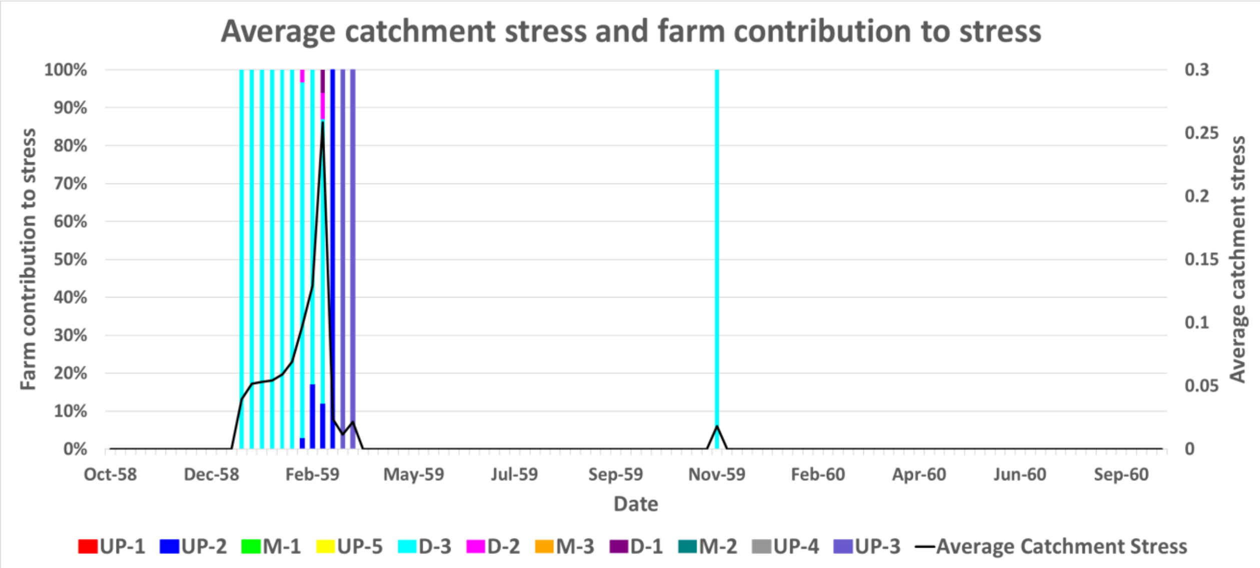


Figure 3.14. Predicted farm contribution to average catchment stress for October 2058 to September 2060 under moderate climate change.

Given that RCP 4.5 predictions are worse in terms of rainfall for the near future (i.e. 2025-2030) than the RCP 8.5 predictions (presented in Section 3.4.2), we reran this simulation to predict water availability in the catchment in the far future under moderate climate change.

Rainfall and streamflow were obtained from the SWAT model from October 2055 to September 2060, using RCP 4.5 predicted rainfall and temperature. Figure 3.14 shows the average catchment stress and each farm's contribution to the stress under moderate climate change from October 2055 to September 2060. This figure also shows maximum average catchment stress of 0.25, with six farms suffering from water stress.

3.4.2 Predicted water availability based on extreme climate change scenario

This scenario was run to explore the impacts of extreme climate change on the catchment. The scenario uses current land-use data with the rainfall and streamflow values obtained from the SWAT model, which was run from October 2025 to September 2030, using RCP 8.5 predicted rainfall and temperature.

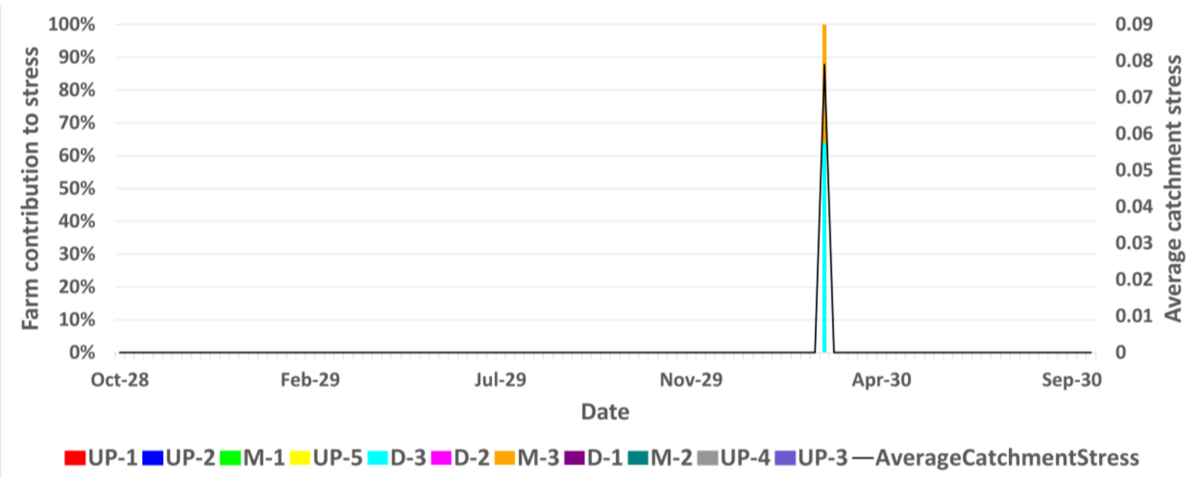


Figure 3.15. Predicted farm contribution to average catchment stress for October 2028 to September 2030 under extreme climate change.

Figure 3.15 shows the average catchment stress and each farm's percentage contribution to the stress between October 2028 and September 2030. Surprisingly, the water availability for this scenario is higher than that experienced in the moderate climate change scenario. This is because, for the 2025 to 2030 period, the RCP 4.5 data has a higher average temperature and lower average rainfall than the RCP 8.5 data. However, from 2030 to 2060, RCP 8.5 data has a higher average temperature and lower rainfall than RCP 4.5.

The results of this simulation show that the maximum average stress is 0.25, which is 37.5% lower than the maximum catchment stress in the moderate climate change scenario. In addition, fewer farms suffer water stress, and those that do have water stress for a shorter period than in the moderate climate change scenario.

Similar to what was done for the scenario discussed in Section 3.4.1, we reran this scenario simulation from 2055 to 2060. Figure 3.16 shows the average catchment stress and each farm's contribution to the stress under extreme climate change from October 2055 to September 2060. It shows a maximum catchment stress of 0.35 with seven farms having water shortages, while Figure 3.15 shows a maximum average catchment stress of 0.25, with six farms suffering from water stress. This shows that the extreme climate change scenario has lower water availability for this period than the moderate climate change scenario, similar to the trends reported by Tanner et al. (2022)

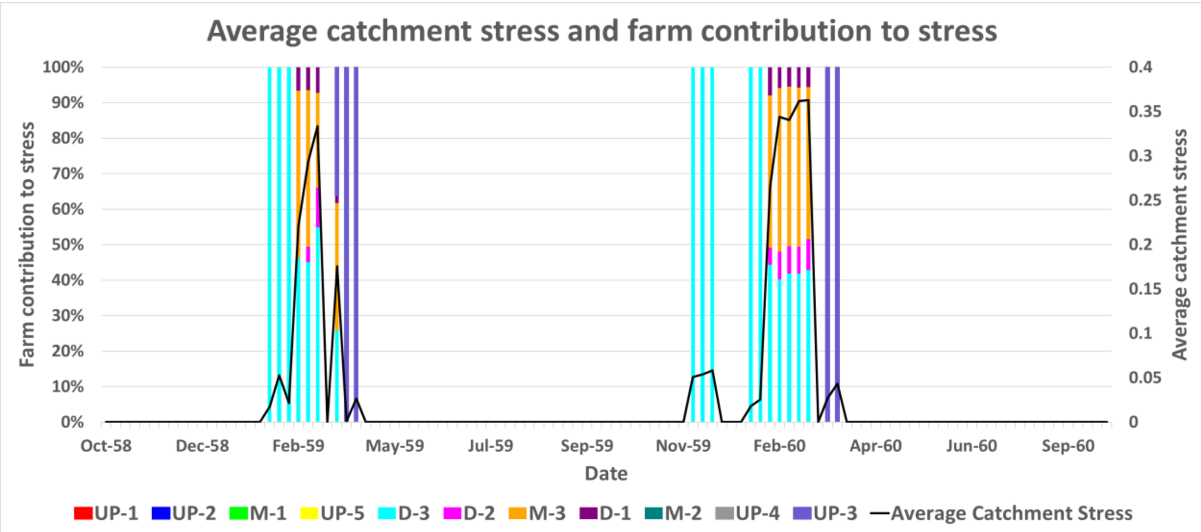


Figure 3.16. Predicted farm contribution to average catchment stress for October 2058 to September 2060 under extreme climate change.

3.4.3 Predicted water availability under moderate climate change and increased crop hectarage for upstream farms

The survey responses showed that some farmers planned to expand their land under cultivation. We ran this scenario to explore the impacts that cultivation expansion might have in the catchment and increased the hectarage of the main crops of upstream farms by 20%. The rainfall and streamflow values were obtained from the SWAT model, which was run from October 2028 to September 2030 using RCP 4.5 predicted rainfall.

Figure 3.17 shows the average catchment stress and each farm's contribution to this stress from October 2028 to September 2030. The diagram shows that for this scenario, there is a slight decrease in water availability when compared with the moderate climate change scenario discussed in Section 3.4.1. The maximum average water stress for this scenario is 0.45, which is an increase of 12.5% compared to the maximum average water stress shown in the moderate climate change scenario.

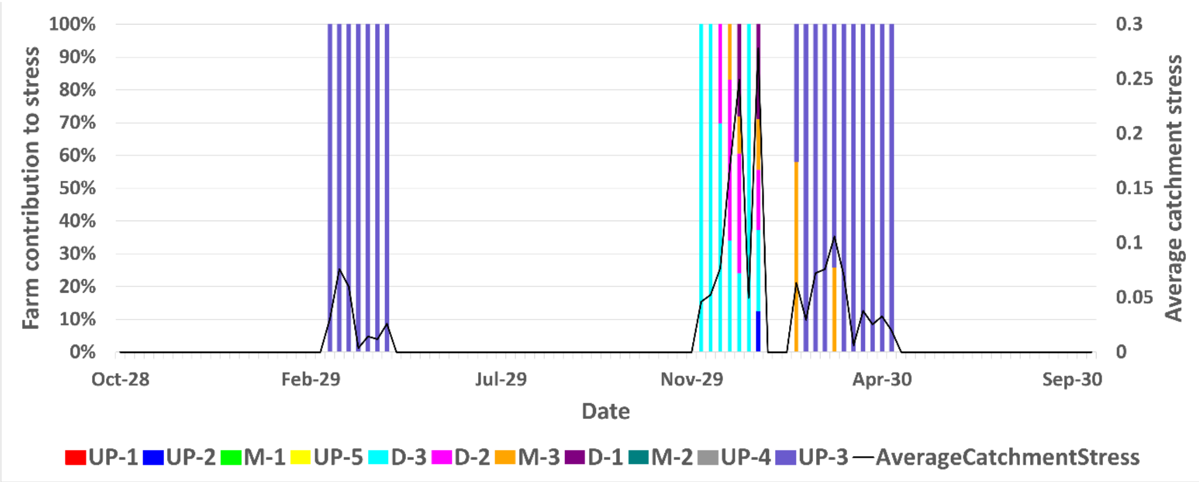


Figure 3.17. Predicted farm contribution to average catchment stress for October 2028 to September 2030 under moderate climate change with an increase in hectarage of main crops by upstream farms.

3.4.4 Impact of future scenarios on EWR

Each of the scenarios discussed has an impact on river flow. It is evident from Figure 3.18 that the extreme climate change scenario has the least number of weeks when the EWR is not met because for the period modelled (October 2028 to September 2030), RCP 4.5 has lower rainfall and higher temperatures compared with RCP 8.5. Note that the red line in Figure 3.16 representing moderate climate change is completely obscured by the green line due to the similarities in the data and the scale of the graph.

The impacts of the moderate climate change and moderate climate change with increased hectarage scenarios are quite similar. As seen in Figure 3.13 and Figure 3.17, the effect of both scenarios on water availability is similar, most likely because a 20% increase in the hectarage of the most important crops by upstream farmers does not cause a significant increase in aggregate water demand for the catchment.

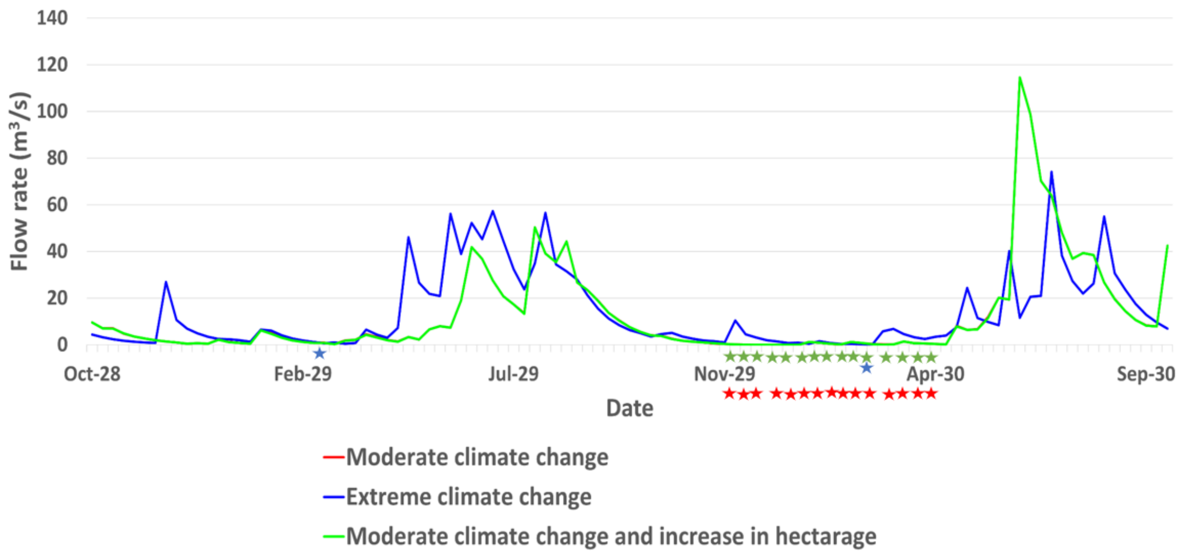


Figure 3.18. River flow rate at the catchment outlet under the different scenarios – stars indicate weeks when EWR is not met.

3.4.5 Climate adaptation scenario: introducing a shared dam and increase in dam capacities.

The survey showed that some farmers were planning to construct new dams. Howard (2010) explored the viability of building new dams at various locations in the KBV (both E21G and E21H), and one of the sites the author considered was the Hex River located in E21H. Thus, we explored a scenario where farms increased their storage capacities, and a shared dam on the Hex River was added. We increased the storages of all Farms that are not located downstream. A shared dam was added at the Hex River and had a capacity of 1 094 627, which is 10% of the total initial dam capacities. The rainfall and streamflow were obtained from the SWAT model, which was run from October 2025 to September 2030, using RCP 4.5 predicted rainfall.

The WUA is the shared dam controller and the Farm agents with access to the shared dam make water requests to the WUA agent. Various modifications were made to the model to explore this scenario.

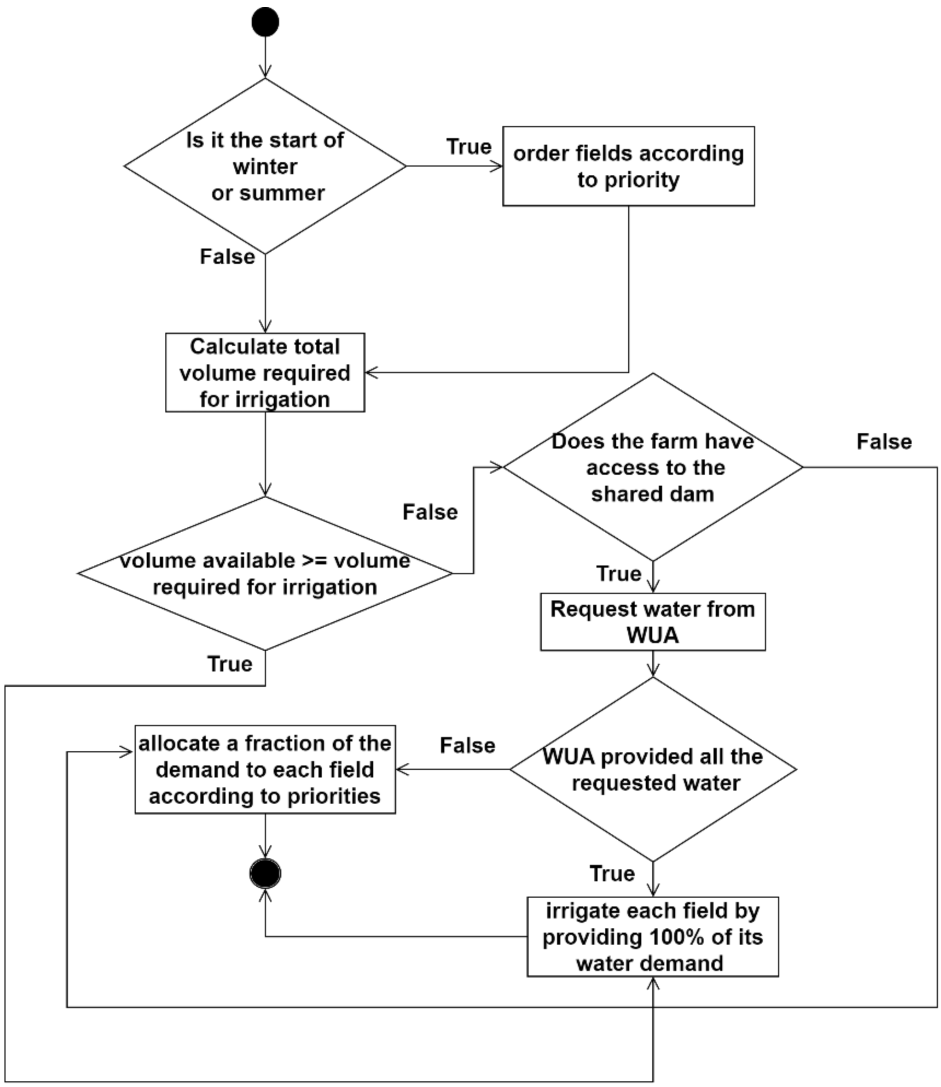


Figure 3.19. Modification to the irrigation process of Farms.

Figure 3.19 shows the modification to the irrigation behaviour of the Farm. The difference in the irrigation process occurs when a Farm agent does not have enough water for irrigation. Figure 3.19 shows that when a

Farm does not have enough water, it checks if it has access to the shared dam. Only downstream Farms can access the shared dam in this scenario. If a Farm has access to the shared dam, it makes a water request to the WUA agent. The Farm agent checks if the WUA agent provided all the requested water. If all the water was provided, the Farm agent irrigates each CropField with 100% of its irrigation water demand. If not all the water is provided, the Farm agent uses crop priorities in determining the volume of irrigation water demand to provide to each CropField.

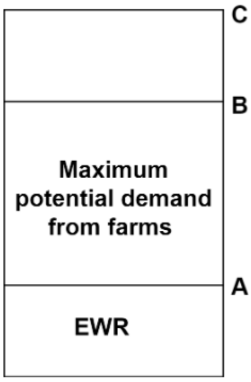


Figure 3.20. Shared dam thresholds.

The WUA is responsible for responding to water requests from Farm agents and releasing water into the river for EWR. Figure 3.20 shows some of the thresholds used in controlling how the WUA responds to Farm water requests. A represents the fraction of the dam capacity (C) reserved for EWR. If the dam volume is below this threshold, the WUA will not provide water to Farms. The threshold was set to 30% of the shared dam capacity. Because the model executes according to the order of execution of the RiverSegments, the WUA cannot receive the demands of all the Farms simultaneously. Therefore, we introduced threshold B, the total maximum water demand of the Farms with access to the shared dam. The WUA shares the water equally amongst the Farms. The volume of water available for sharing between farms is the difference between A and B. Each Farm agent would get a maximum volume given by:

$$\frac{1}{number\ of\ farms\ accessing\ shared\ dam} \times\ (shared\ dam\ volume - A)$$

However, if a Farm makes a water request and the shared dam's volume exceeds B, the Farm will receive all the water it has requested.

The WUA releases water for EWR each week. The volume of water released was set to 5% of the shared dam capacity. The WUA doubles the volume it releases for EWR if the EWR was not met in the previous timestep.

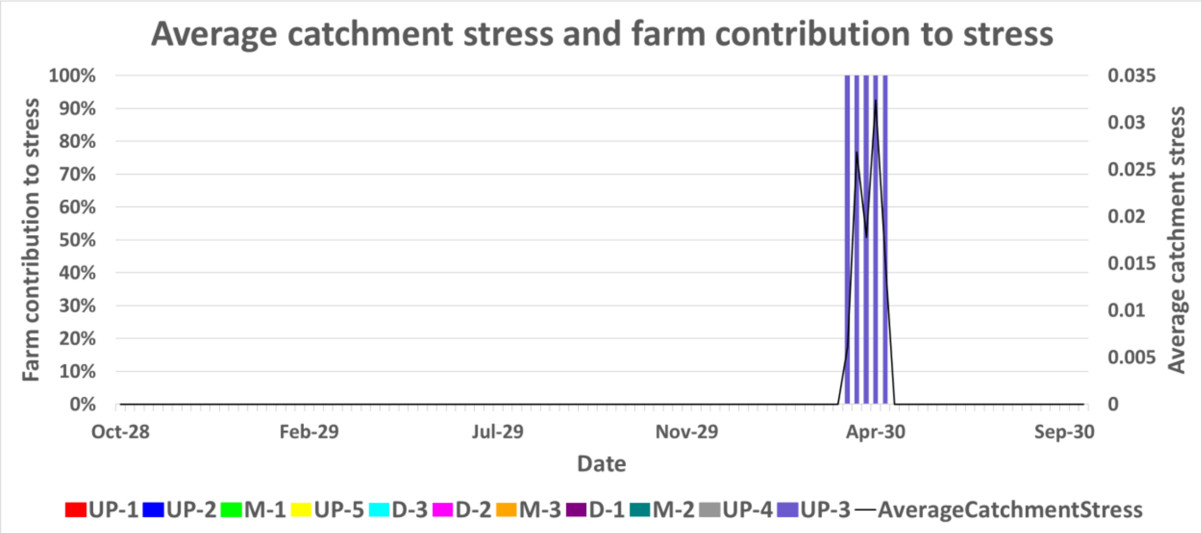


Figure 3.21. Catchment stress for the period October 2028 to September 2029 under moderate climate change, shared dam, and increased dam capacities.

Figure 3.21 shows the average catchment stress and each farm's contribution to the stress from October 2028 to September 2030. The maximum average water stress experienced in the catchment was 0.14. This is much lower than the maximum average water stress experienced in the catchment in the moderate climate change scenario. Additionally, D-3, UP-2 and UP-3 were the only farms that suffered water stress, which was an improvement compared to the number of farms that had had water shortages in the moderate climate change scenario.

The shared dam scenario had a total of 23 weeks where EWR was not met which is much lower than the 33 weeks where EWR was not met in the moderate climate change scenario. This reduction was due to the weekly EWR releases that were made by the WUA agent using the shared dam.

3.5 CONCLUSION

In summary, the Agent-Based Model (ABM) implemented in the CORMAS simulation environment underwent a meticulous and iterative process to accurately represent the complexities of the KBV catchment. The implementation involved breaking down the conceptual model into three main versions, each contributing to major achievements. The first version focused on developing the river network, ensuring its accuracy by comparing flow rates with SWAT data at various points in the catchment. The second version incorporated crop fields and irrigation, introducing CropField agents with defined attributes. In the third version, in-stream and off-stream dams were added as Dam agents, with a meticulous water balance verification process to ensure model accuracy.

Validation of the model encompassed both objective and subjective evaluations. Objective validation involved comparing ABM output flows with historically observed flows, while subjective evaluation relied on stakeholders' acceptance of model outputs. Farm codes were assigned based on catchment location to maintain confidentiality. Validation simulations were conducted to assess water demand and shortages at the farm level. The ABM's water demand, initially lower than survey data, was rectified through the introduction of a correction factor. Results demonstrated the model's ability to simulate farm-level water stress, shortage, and storage dynamics.

Stakeholder acceptance, confirmed by the Catchment Coordinator and workshop participants, emphasized the model's realistic portrayal of water shortages. Moving forward, the ABM was used to predict future water use under different scenarios. For moderate climate change during the 2025 to 2030 period, the model predicted increased water stress, while the extreme climate change scenario indicated higher water availability. This is due to the fact that carbon emissions in RCP 4.5 peak in 2040, whereas those in RCP 8.5 only peak in 2100. Thus, the actual effects of the extreme climate change only become noticeable in the far distant future. This is confirmed in the predictions from simulating both the moderate and extreme climate change scenarios for the period 2055 to 2060, where the extreme climate change scenario showed much higher water stress than the moderate climate change one. Additionally, a scenario involving increased crop hectarage by upstream farms indicated a slight decrease in water availability.

The impact of these scenarios on Environmental Water Requirements (EWR) was also assessed using the ABM. The strategic augmentation dam storage, governed by shared dam thresholds and responsive management by the Water User Association, led to a substantial reduction in weeks where Environmental Water Requirements were not met. The collaborative approach showcased in this scenario, particularly the shared dam's impact on decreasing catchment stress, highlights the potential for coordinated water resource management to enhance resilience in agriculture amidst changing climatic conditions. Some uncertainty exists in that groundwater withdrawals are not included in the ABM; this could have led to an underestimation of impact on the reserve as groundwater withdrawals impact river flows. On the contrary, farmers do not use groundwater a lot because of high pumping costs.

In conclusion, the ABM has proved to be an effective tool in comprehensively capturing the complexities of the KBV catchment. Its ability to provide valuable insights for sustainable water resource management was validated through stakeholder acceptance, solidifying its role as a reliable decision-support system. Moreover, stakeholders expressed interest in expanding the model to include additional scenarios, showcasing the model's adaptability. Looking ahead, the ABM is poised to play a pivotal role in the KBV catchment's water management strategies. The model, now embraced by stakeholders, will be a key instrument for informed decision-making. By simulating various scenarios, the ABM will empower KBV stakeholders to proactively explore and evaluate water management options, fostering a resilient approach to the dynamic challenges of water resource management in the catchment.

CHAPTER 4: DETERMINING WAYS TO SHARE WATER USING THE WATER SHARING TOOL

4.1 INTRODUCTION TO THE WATER SHARING TOOL

The Water Sharing Tool (WST) aims to provide a platform to encourage a shared understanding of water resource management decisions and their impacts on the user and the larger ecosystem. The model responds to the need for methods that can account for ecosystem functions, and for differences in the way in which beneficial use within different water sectors is measured. While there are many water resources allocation models available, the WST includes key variables, such as the inclusion of uncertainty, Environmental Reserve requirements and the incorporation of socio-economic factors associated with water use (Figure 4.1). In particular, the model assesses allocation options using more than purely economic considerations. Prof. Denis Hughes of the Institute for Water Research at Rhodes University developed the WST in response to the Panta Rhei initiative, and the overall objective was to use uncertain input data to generate outputs for a range of plausible scenarios that could support a decision-making process. The tool promotes water sharing at a community level by different water users/user groups, and it encourages deliberation to identify an optimal water sharing strategy by communicating frequency distributions of assurance shortfall risk (what deficits are probable and how probable they are). The tool explicitly considers epistemic (data) uncertainty and aleatory (natural variation) uncertainty; the water users' value for environmental water requirements; and considers social heterogeneity using socio-economic factors that may influence the way people make water-use decisions.

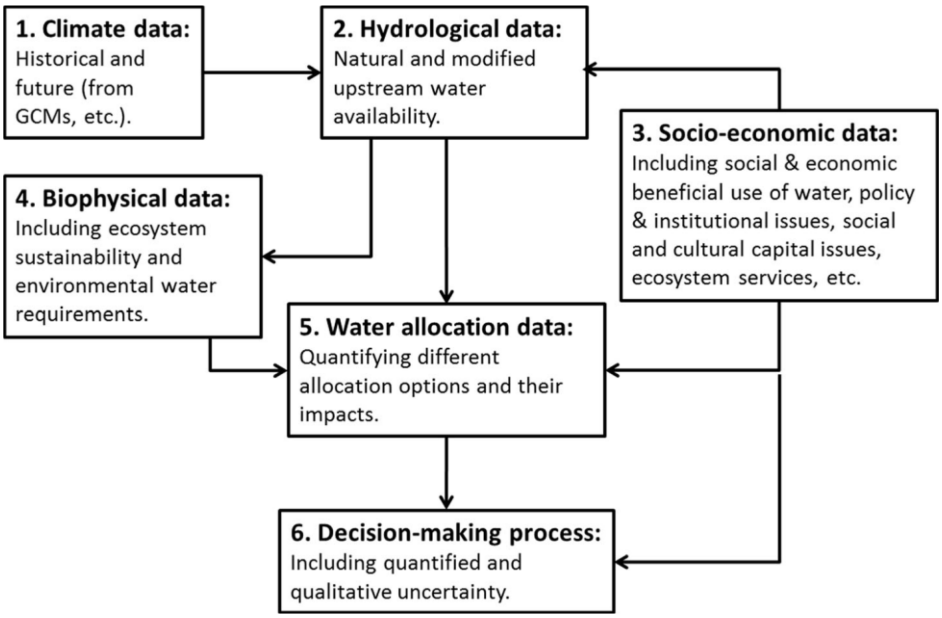


Figure 4.1 Overview of the key variables used in the Water Sharing Model.

The model can include run-of-river abstractions (no storage in the catchment) or can assume reservoir storage and abstraction. Another notable feature is that there is significant flexibility with how the socio-economic data are used. Details of the model can be found in Pienaar and Hughes (2017), but it was never used or tested prior to this project. Some minor modifications were made during the testing process. This chapter details the particular methods used in the project but also suggests alternative ways to incorporate the socio-economic data.

4.2 STRUCTURAL OVERVIEW OF THE VARIOUS MODEL COMPONENTS

Figure 4.2 outlines a detailed schematic overview of the WST components, indicating that the model requires outputs from two models: a hydrological model (Box 1 in Figure 4.2), and an Environmental Water Requirements (EWR) model (Box 3 in Figure 4.2). Socio-economic data is incorporated into the model as an ‘impact curve’ per user as well as a ‘community weighting’ per user (Box 2 in Figure 4.2).

These data are then used to estimate impacts and deficits for each user/user group depending on which water sharing strategy is selected (Box 5 in Figure 4.2). The model provides visualisations that can guide decision-making depending on the costs/benefits of the four plausible sharing strategies (graphs at the bottom in Figure 4.2).

The Water Sharing Tool is appropriate for use in gauged and ungauged catchments owing to the inclusion of uncertainty in the simulation (both the hydrological model and WST). The Water Sharing Tool provides uncertainty frequency distributions of impact levels given a water shortage scenario (Box 5 in Figure 4.2). The tool’s approach can be valuable in negotiating increasing water crises among very different users/user groups.

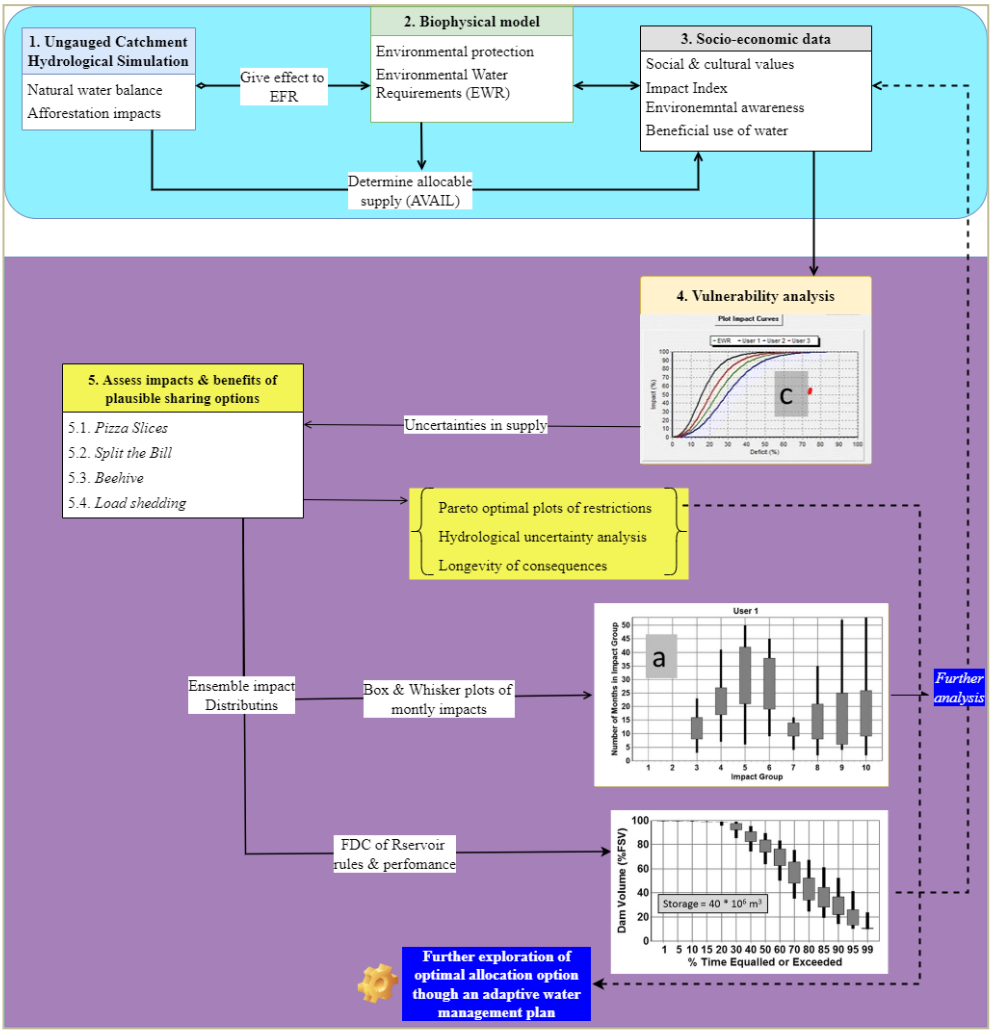


Figure 4.2. Overview of the structure of the Water Sharing Model.

4.3 DETAILS OF THE VARIOUS COMPONENTS OF THE WATER SHARING MODEL FRAMEWORK

4.3.1 Sub-catchments used in the water sharing tool

The Pitman model was set up slightly differently to the SWAT and ABM models, both of which targeted farm level. The WST lumped farmers by user group (described below) around each tributary, to maintain decision-making similarity. In the end, there were six sub-basins: Upper Suurvlei, Suurvlei, Upper Middledeur, Middledeur, Sandfontein, and the Twee River.

4.3.2 The hydrological model and the uncertainty framework

4.3.2.1 The Pitman Model

The modified Pitman monthly rainfall-runoff model (Pitman Model; Hughes, 2013), which is conceptually semi-distributed and operates at monthly time-steps, was employed in this investigation even though any hydrological model capable of producing stochastic streamflow estimates can be used (Pienaar & Hughes, 2017). The locally developed Pitman Model boasts nearly 50 years of existence within the southern African rainfall-runoff estimation territory (Hughes, 2013). Ongoing developments of the modified Pitman rainfall-runoff model are mainly targeted towards practice (Hughes, 2013), but the modelling package is well represented in water resources literature, thereby aiding understanding of southern African natural hydrology, and associated anthropogenic and climate impacts (e.g. Tumbo & Hughes, 2015; Ndzabandzaba & Hughes, 2017). See Figure 4.3 for the structural overview of the model.

Two model functions contribute most to runoff generation at surface and subsurface levels. The first is a distribution of catchment absorption function that is triangular and is characterised by the parameters ZMIN, ZAVE, and ZMAX. The second function establishes the primary moisture storage's drainage rate (S, with a capacity of ST, mm). Evapotranspiration (ET), interflow (FT), and groundwater recharge (GW) all reduce its store. At lower levels of moisture storage, two power functions (parameters POW and GPOW) dictate the maximum FT and GW rates (in mm/month), which occur at ST (S, mm). A groundwater storage function that routes recharge takes into consideration ET loss. The model also has features to simulate man-made influences on the availability of water resources, such as forestry plantations, small farm dams, and substantial reservoirs (Hughes & Mantel, 2010).

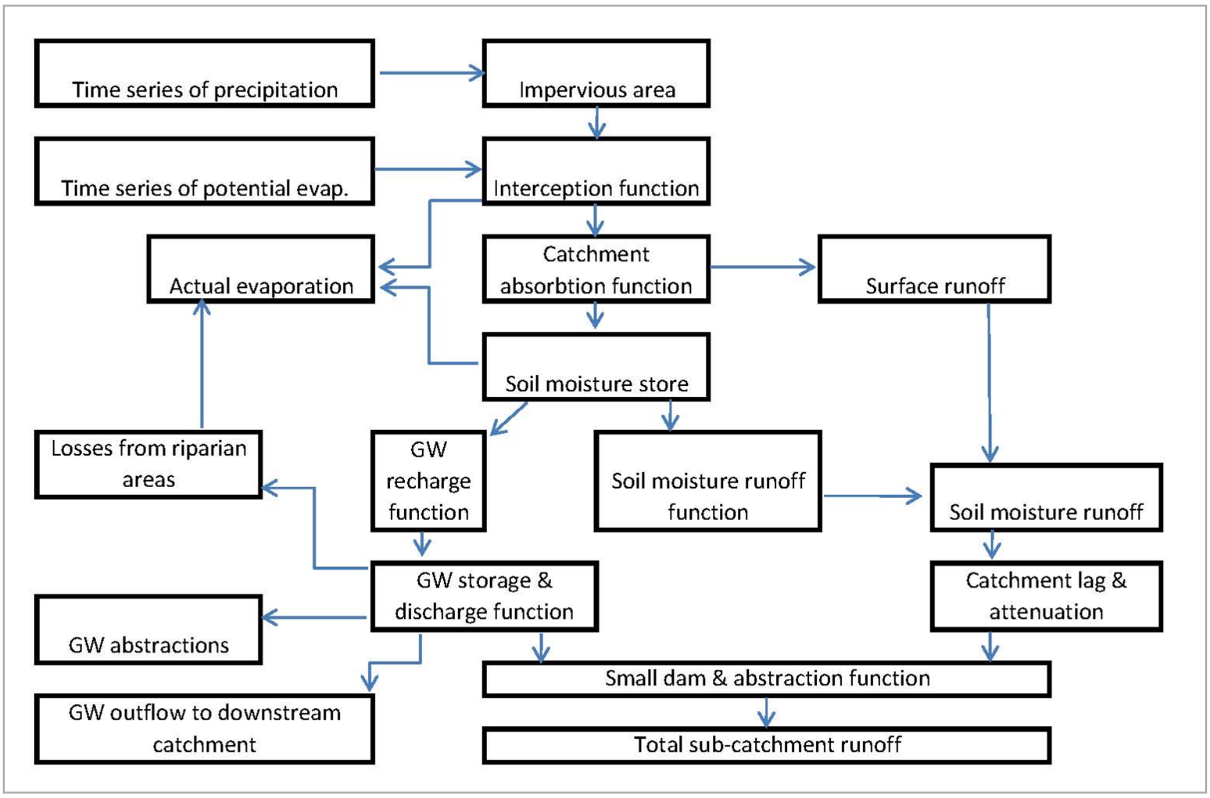


Figure 4.3 Overview of Pitman Model structure

The model uses 41 parameters (Table 4.1) to simulate the main storages and fluxes at a quaternary or sub-catchment scale. Pitman rainfall-runoff model parameters cover interception, soil moisture and groundwater storage, including runoff-generating features: infiltration, saturation excess and direct surface runoff, interflow, and groundwater baseflow. Data required to run the Pitman rainfall-runoff model include the catchment area, hydroclimatic time-series data, and parameter estimates.

Table 4.1 Parameter ranges used in the Twee-Wyk hydrological simulation. Parameters shown are for the Twee River (outlet) and differ from the upstream sub-catchments. Uncertain parameters are denoted with distribution Type 3.

Array Parameter	Mean	Dist.Type	Min Value	Max Value
1 Rain Distribution Factor	1.28	0	0	0
2 Proportion of impervious area AI	0	0	0	0
3 Summer intercept cap.(Veg1) PI1s	1.5	0	1.2	2
4 Winter intercept cap.(Veg1) PI1w	1.5	0	1.2	2
5 Summer intercept cap.(Veg2) PI2s	4	0	3	4
6 Winter intercept cap.(Veg2) PI2w	4	0	3	4
7 % Area of Veg2 AFOR	0	0	0	0
8 Veg2/Veg1 Pot. Evap. Ratio FF	1.4	0	0	0
9 ST fraction for sat. excess runoff	1	3	0.8	1
10 Annual Pan Evaporation (mm) PEVAP	1692	3	1667	1802
11 Summer min.abs.rate (mm/mth) ZMINs	1.1	3	0	10
12 Winter min.abs.rate (mm/mth) ZMINw	1.1	3	0	10
13 Mean fract. (ZAVE*(ZMAX-ZMIN)+ZMIN)	0.733	3	0.5	0.8

Array Parameter	Mean	Dist.Type	Min Value	Max Value
14 Maximum abs.rate (mm/mth) ZMAX	350	3	250	350
15 Maximum storage capacity ST	293	3	235	345
16 No recharge below storage SL	0	0	0	0
17 Power: storage-runoff curve POW	2	3	1.5	2.5
18 Runoff rate at ST (mm/mth) FT	22	3	15	23
19 Max. Recharge rate (mm/month) GW	5.2	3	5.5	10
20 Evaporation-storage coefficient R	0.65	3	0.55	0.65
21 Sub-area Routing Coeff. (mnths) TL	0.225	0	0	0
22 Channel Routing Coeff (mnths). CL	0	0	0	0
23 Irrig.area (km^2) AIRR	0	0	0	0
24 Irrig. return flow fraction IWR	0	0	0	0
25 Effective Rainfall fraction	0	0	0	0
26 Non-Irrig. Direct Demand (Ml/year)	0	0	0	0
27 Maximum dam storage (Ml)	0	0	0	0
28 % Catchment area above dams	0	0	0	0
29 A in area volume relationship	0	0	0	0
30 B in area volume relationship	0	0	0	0
31 Irrig. Area from Dams (km^2)	0	0	0	0
32 Channel Loss TLGMax(mm)	2	0	0	0
33 Power: Storage-Recharge curve GPOW	2.6	3	2.5	3.5
34 Drainage density	0.4	0	0.4	0
35 Transmissivity (m^2/day)	20.7	0	15	30
36 Storativity	0.001	0	0	0
37 Initial GW drainage slope	0.011	0	0	0
38 Rest water level (m below surface)	75	3	25	75
39 Riparian Strip Factor	0.1	0	0.001	0.2
40 GW Abstraction (Upper slopes-Ml/year	0	0	0	0
41 GW Abstraction (Lower slopes-Ml/year	0	0	0	0

4.3.2.2 The uncertainty framework

Natural hydrological processes are complex and interact with other environmental and human processes leading to large uncertainties (Kapangaziwiri et al., 2012) that are difficult to communicate to decision makers. The explicit inclusion of uncertainty is still not common practice among water resources managers (Pappenberger & Beven 2006), but it is evident that new approaches are needed to take uncertainty into account when making water allocation decisions (Matrosov et al., 2013). The complex nature of water resource systems suggests that they are seldom at equilibrium due to variability, and this variability must be considered in decision-support systems to promote less risky decisions (Matrosov et al., 2013). Therefore, using uncertain flows as a first step to enable adaptation to water shortfalls while promoting distributional equity in this research is essential, given the complex nature of water resource systems and input data uncertainty.

Recognising the unfolding water management crisis due to uncertainty in available water supply, the Pitman rainfall-runoff model has been developed to offer a harmonised approach for estimating water availability using an uncertainty framework (Kapangaziwiri & Hughes, 2008; Kapangaziwiri et al., 2012). The model can run with up to a maximum of 500 rainfall time series (input data uncertainty), as well as uncertain parameters (parameter uncertainty). The framework has been successfully applied in Tanzania (Tumbo & Hughes, 2015), and Swaziland (Ndzabandzaba & Hughes, 2017), amongst others.

The Pitman uncertainty run is a two-step approach focusing on the incremental contribution of each modelled sub-catchment (step 1), and the cumulative streamflow volumes, including wetland and water use impacts (step 2). In the first step, six streamflow signature constraints (min/max ranges) are identified based on observed flows or other pre-existing simulation data, which indicate possible natural hydrological behaviour (Kapangaziwiri et al., 2012; Tumbo & Hughes, 2015; Ndzabandzaba & Hughes, 2017). The six constraints are: mean monthly runoff (MMQ), mean monthly local recharge (MMR), fraction of flow duration curve points to MMQ at 10th, 50th and 90th percentile (Q10, Q50, Q90), and expected periods of no flow (%Zero). Since the Koue Bokkeveld region is poorly gauged, the initial model parameters and hydrological constraints (signatures) were based on the WR90 and WR2012 regional studies (https://waterresourceswr2012.co.za/). Observed hydrological flow data were obtained from the Department of Water and Sanitation (https://www.dws.gov.za/Hydrology/Verified/hymain.aspx). See Table 4.2 for a list of the constraints used in the hydrological simulation.

Table 4.2 Hydrological constraints used to identify behavioural ensembles in the simulation.

Sub-catchment	Monthly runoff	Monthly recharge	FDC10	FDC50	FDC90	%Zero
Upper Suurvlei	0.318 to 0.516	0.000 to 2.2074	1.815 to 2.949	0.553 to 0.899	0.077 to 0.250	0
Upper Middledeur	0.627 to 0.980	0.744 to 2.067	1.747 to 2.729	0.463 to 0.723	0.067 to 0.104	0
Sandfontein	0.109 to 0.190	0.744 to 5.000	1.820 to 3.155	0.385 to 0.621	0.022 to 0.038	0
Suurvlei	0.129 to 0.223	0.744 to 2.067	2.086 to 3.615	0.293 to 0.508	0.405 to 0.708	0
Middledeur	2.154 to 3.734	0.744 to 2.067	0.091 to 0.158	0.026 to 0.045	0.003 to 0.005	0
Twee	0.235 to 0.352	0.744 to 2.067	2.003 to 3.005	0.440 to 0.660	0.023 to 0.034	0

The uncertainty framework is underlined by the premise that all incremental flow inputs are known to be behavioural (Figure 4.4-Stage 1) and that the downstream outputs are just various combinations of the upstream behavioural inflows (Figure 4.4-Stage 2). In the model, the incremental hydrological response of any sub-basin is derived from constraining a streamflow signature set that represents the natural hydrology, in this case, naturalised streamflow from the WR90 and WR2012 datasets. Once constraint ranges are identified, and uncertain parameters specified, the first stage of the model is run. Model outputs include the best 1000 successful parameter combinations out of 10 000 parameter sets. The behavioural parameter combinations were often found after running 47% of the 10 000 parameter sets, thereby increasing confidence of the hydrological outputs per catchment (incremental). The model uses random Monte-Carlo sampling to achieve this. Secondly, water use is incorporated into the model before the model is run again, to produce 100 000 ensembles representative of the cumulative streamflow in the catchments.

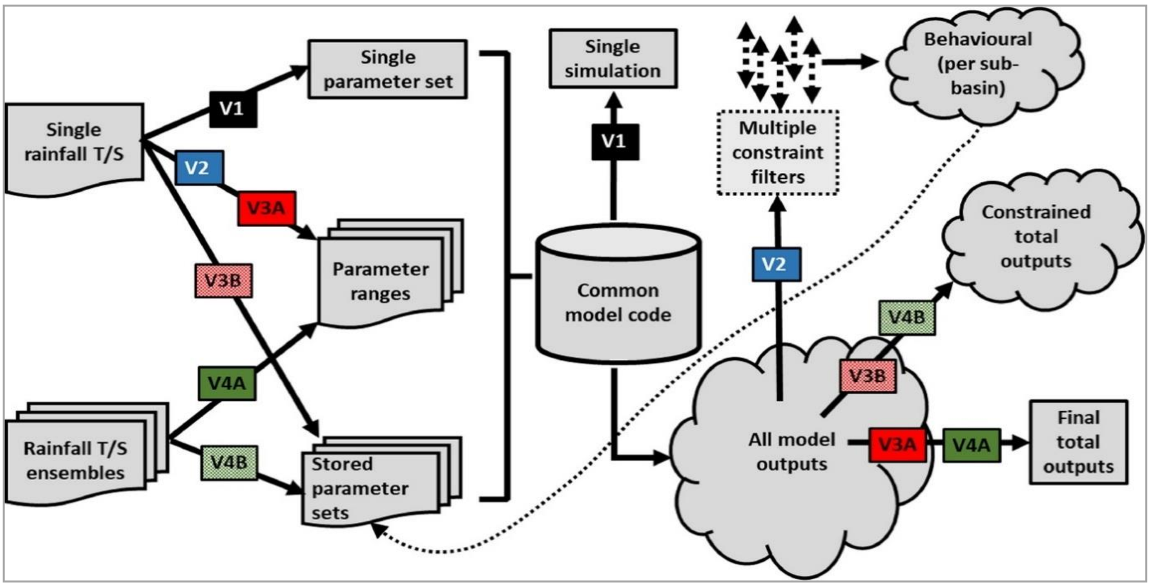


Figure 4.4 Flow diagram showing the four Pitman visions for hydrological simulation. The uncertain versions are represented by V2-3B, showing the 2-Stage simulation approach followed by the Pitman uncertainty model (Kabuya et al., 2022).

4.3.2.3 Hydrological model outputs

Figure 4.5 displays the results of the surface water simulation (10 000 simulations) for the Twee Wyk, covering a 30-year period. The results were simulated based on the physical understanding of the sub-catchment, owing to flow data scarcity. The 5th and 95th mean monthly river flow percentiles for the Twee Wyk were estimated to range between 2.256 and 2.697, representing a 24% uncertainty range.

The streamflow divergence from the mean for the 50th (median) ensemble is shown in Figure 4.6. The standardised streamflow index is a drought indicator showing monthly deviation of streamflow compared to the previous year, and it varies over the assessment period in the Twee River. Streamflow anomalies over the 30 years are characterised by six drought events and four wet spells that give way to each other over time. Both spells have a similar intensity (mild to moderate) but different durations.

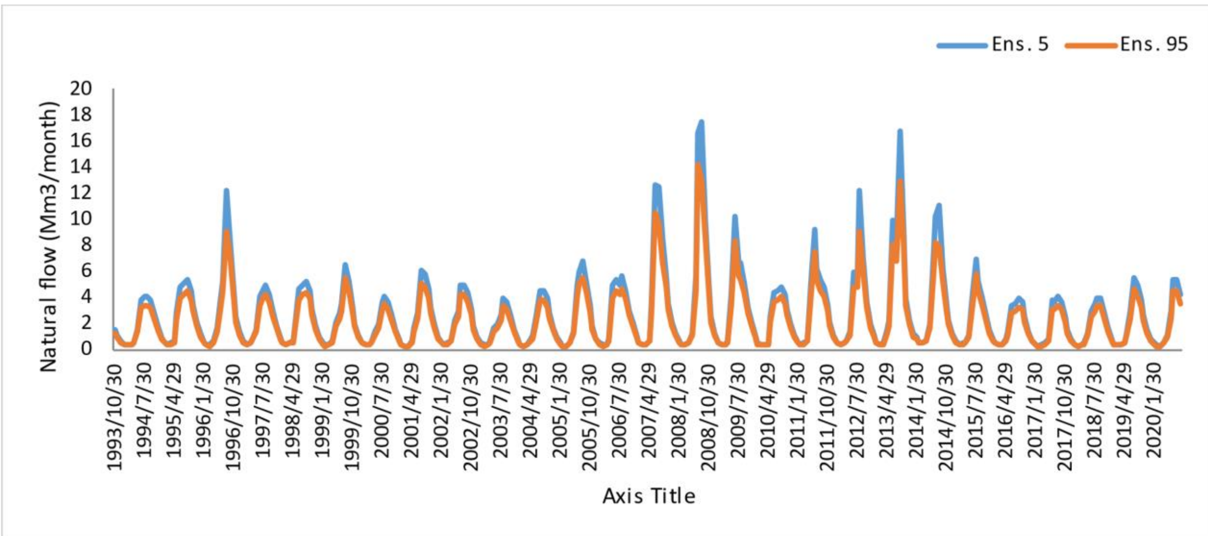


Figure 4.5 Naturalised streamflow for the Twee Wyk covering the period Oct 1993 to September 2020. 2021.

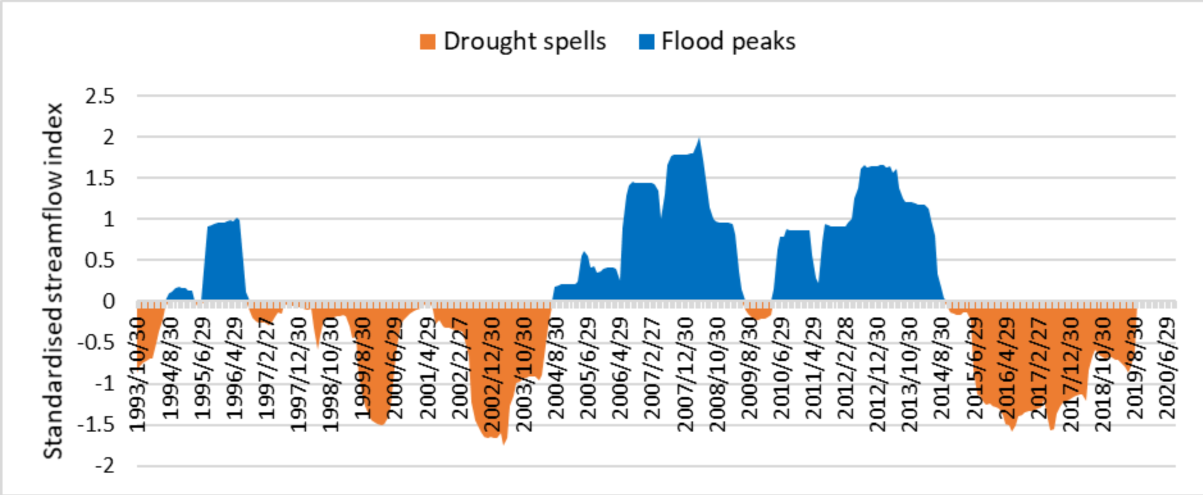


Figure 4.6 Streamflow anomalies, generated with the Standardised Streamflow index for the Twee River for 30 years, showing dry and wet spells.

4.3.3 The Environmental Reserve

The Water Sharing Tool is set up to use environmental flow outputs from the Hughes et al. (2014) Revised Desktop Reserve Model (RDRM). The ecological reserve requirements in the RDRM are estimated based on hydrological information, channel hydraulics and ecological characteristics. The ecological status for the Twee Wyk and its nearest EWR survey point "EWR Site 6" are gazetted category B and B/C – near natural flow requirements. Although EWR Site 6 is the most upstream in the Olifants/Doorn and was intended to monitor farm dam impacts on streamflow, it monitors cumulative flows for three quaternary catchments with a 750 km^2 cumulative area and an annual runoff of 137.86-169.69 MCM. This makes EWR Site 6 outputs a larger scale than the upstream Twee Wyk for the Koue Bokkeveld. Therefore, the RDRM (Hughes et al., 2014) outputs for EWR Site 6 that were computed by Tanner et al. (2022) to understand climate change impacts on EWR, were downscaled to the Twee Wyk using the 50th ensemble of natural flows estimated in this study. Since there are no large reservoirs in the sub-catchment whose operation rules can be adjusted, the water management focus is on low flow requirements for EWR.

Consistent with the risk assessment requirements, the downscaling was done for EWR categories B, B/C and D. As shown in Figure 4.7**,** the total low flow EWR for the Twee River averages 6.173 m^3/s for the B category and 3.495 m^3/s for the D category, with a percentage difference of 4.34%. This percentage difference represents the vulnerability of the environment. The lowest EWR (April) for the Twee River is 0.926 and 0.579 m^3/s for the B and D categories. The maximum (August) is 23.1 and 13.5 m^3/s for the two categories.

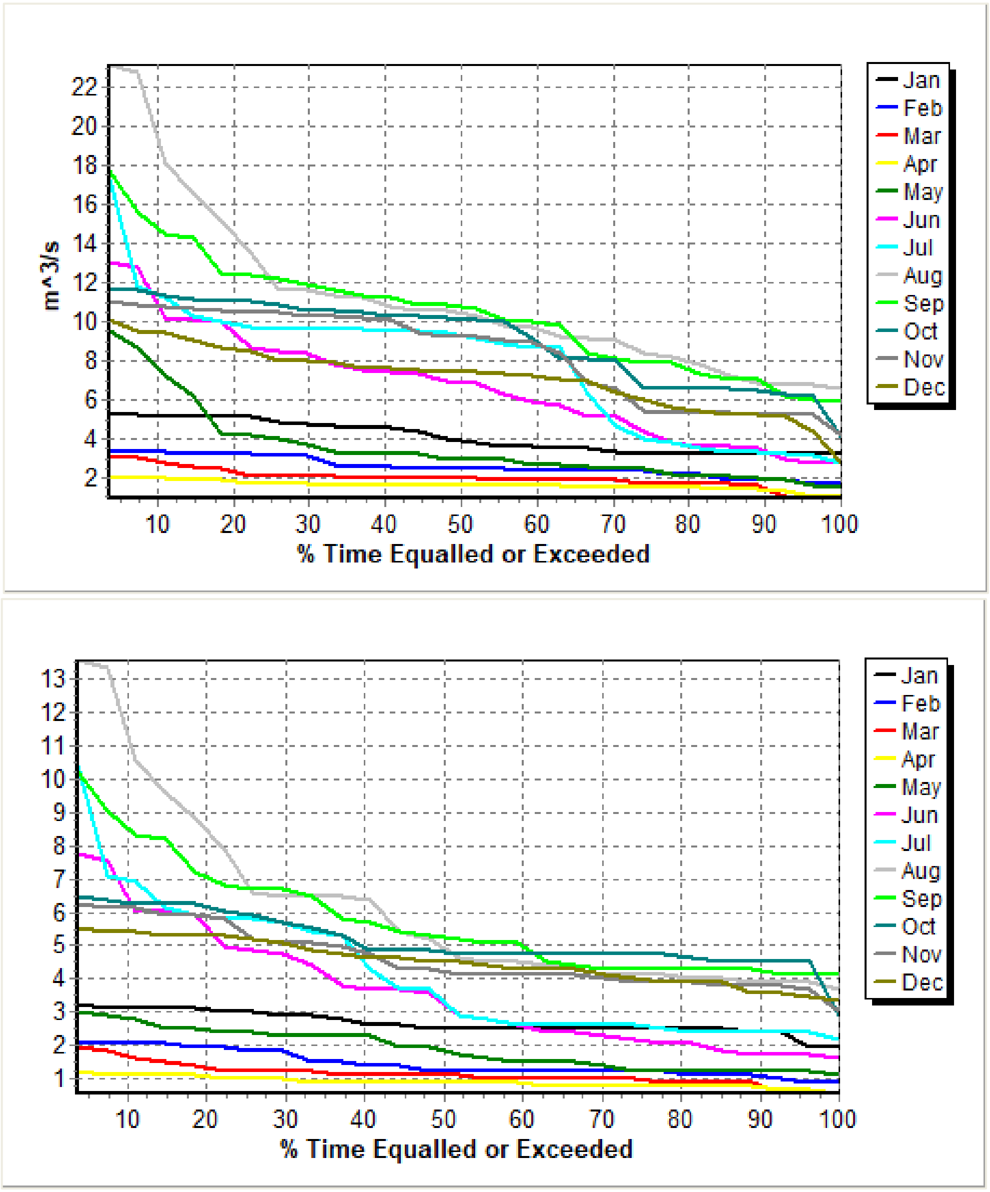


Figure 4.7 Monthly Environmental Water Requirements (m^3/s) for streamflow at the Twee River, showing current requirements (EWR category B – top) and EWR category D (bottom)

4.3.4 User groups

The model allows for a maximum of five user groups, one of which is the Reserve (which. although is treated as a user in the model, can be disabled). The organization of users in a catchment into four groups will depend on the context of the application, and the scale at which the model is being applied. For the Koue Bokkeveld, the users were organised into:

- Consortium farmers (corporate owned or User 1),
- Family farmers (family owned, well-resourced, commercial farms or User 2)
- Downstream farmers (smaller, less-resourced farms or User 3)
- Residents (individuals who live in the catchment, but do not farm, User 4).

Other combinations of users one could consider would be communities, industry, emerging farmers, etc. For the Koue Bokkeveld, the small scale at which the model was applied, as well as the lack of diversity of water users in the catchment, resulted in a particularly specific categorization of users. This classification was achieved through information gathered in the workshops, and with the help of key-informant practitioners (farmers themselves and residents in the catchment) who are familiar with the catchment. Corporate commercial farms are typically located in the upper reaches, whereas the lesser economically advantaged farmers are found downstream. Consistent with human research ethics requirements (Reference: 2022-5386-6678), the actual property names corresponding to water use are concealed, and only code names are used to refer to the users.

4.3.5 Community Weighting

The community weighting score represents supply priority and the relative importance of the user groups to the community, determined through engagements between all stakeholders. While this is a flexible aspect of the model in terms of how one assigns a community weighting, this section details how we determined prioritisation of water supply in the Koue Bokkeveld. The community weighting value ranks users according to a priority of supply and is used in one of the four water sharing strategies.

In this project an Analytic Hierarchical Process (AHP) was used to establish an equity-based allocation criterion (the community weighting index) for deficit conditions. Preference for water supply during low-flow conditions in the Twee area supports the principle of proportionality and for multipurpose use. High endemism of fish species in the rivers draining the Twee sub-catchment, the socio-economic importance of farmers, the constitutional protection of the domestic water user, and the tourism sector’s importance ranking all justify the established index and revealed acceptance of proportionality. Using the AHP for community weighting can facilitate cooperative and inclusive water management decision-making while mitigating ongoing conflicts and ensuring community understanding.

The level of tolerance by different users to water supply disruptions (resilience) (Rockström et al., 2014) can be calculated by combining the community weighting index and an estimated measure of compound impacts on water users. Here, the community weighting index results from a pairwise ranking of water users, representing a community's derived equity index, important or vulnerable users in the community, and attitude towards the environment.

Further details on ranking users for supply priority (Community weights) using the AHP method can be found at Xoxo et al. (2023).

Users in the catchment were asked (in a questionnaire) to rank priority of supply for the user groups, and the following table (Table 4.3) was the outcome. All farmer user groups were set at the same priority, just below the priority level of the Reserve, and higher than the small water users (the lifestyle and weekender residents).

The combination of the impact index (next section) and the community weighting scores are designed to capture the values and tolerances of the users (individually and collectively) to deficits in water supply. The EFR impact index might reflect the sensitivity of the ecological functioning of the river to reductions in flow, while the EFR community weight should reflect the broad community (including national legislation issues) attitude towards ecosystem services and environmental sustainability.

Table 4. 3 User groups and their specified supply priorities (as chosen by the users themselves). Users simply fill in one side of the matrix using Saaty's 1-9 scale when utilising the analytic hierarchical procedure, and the inverse side (grey cells) is auto filled as reciprocals. The diagonals (orange cells) compare the same water user and hence have the same significance (which is expressed by 1 on the Saaty scale)

Water users	EWR	Farmers	Lifestyle	Weekender
EWR	1	1 1/8	1 5/6	2 2/3
Farmers	8/9	1	1 4/5	3
Lifestyle	5/9	5/9	1	1 1/3
Weekender	3/8	1/3	3/4	1
Community weight	35.09	34.12	18.11	12.68

4.3.6 Impact curves/maximum annual vulnerabilities to water deficits

Besides the hazards, poor societal response to better cope with the extremes is the primary driver of adverse climate impacts (IPCC, 2012; Birkmann et al., 2013). Therefore, an important part of mainstreaming fairness in the allocation of water restrictions is understanding the impact of rules that shape the restrictions and how these impacts emerge (Hughes & Mallory, 2009). The Water Sharing Tool has a built-in vulnerability assessment window to assess impact which takes into account the fact that different sectors will be impacted differently if complete assurance of supply is not obtained. The assessment of vulnerability (of deficit impacts) combined (1) water deficits based on a 100% assurance level together with (2) vulnerability severity values for all users (Hughes & Mallory, 2009). The built-in vulnerability assessment produces normalised impact distributions that reflect a probabilistic index of expected consequences of a deficit on different sectors/user groups-distribution of impacts (Hughes & Mallory, 2009). The impacts range from zero (no impact) to 100% (disastrous impact). The impact curves are intended to help the decision-maker understand the temporal changes in water assurance and the potential impact of such deficits on different sectors or user groups.

Different approaches can be used to obtain the vulnerability severity values, and the simplest would be to create a questionnaire asking individual users "*What effects (expressed as a percentage) would it have on your operations if you lost x amount of water?*" In this case study, an alternative method that systematically assesses the adaptive capacity of water users was developed because of observed stakeholder participation concerns, and is an important consideration in recognising fairness. Social adaptation was therefore selected as a starting point for the vulnerability assessment. Table 4.4 lists the seven parameters that describe water users' capacity to cope with water deficits. Since there is no available data on drought adaptation at the local level, a key informant who lives in the catchment and has experience as a catchment coordinator assisted with this assessment. To produce comparative response efficacy values, each user was given a five-point Likert scale, with the options being none (0), low (1), moderate (2), high (3), and very high (4). Vulnerability severity is defined as the anticipated impact a user would experience once all adaptive remedies have been used. This concept is consistently translated using Table 4.5 and is expressed as a percentage impact. This assessment was later presented to the water users in a plenary discussion to receive feedback.

Table 4. 4 Criteria for determining impact rating

Scope	Response strategy	Benefit	Cost
Social and Technical	Access to supplementary water sources (e.g. groundwater or cooperation agreements)	Water security from alternative arrangements	Unmet contractual agreements; increased scarcity in the donor catchment; high operation costs
Technical	Water storage facilities and water-saving systems	Water security from alternative arrangements and reduced waste	High initial investment costs
Technical and Environmental	Access to local and expert knowledge (e.g. improved seeds/varieties or ecosystem restoration)	Capacity to anticipate hazards; improve resilience measures; information access to aid vulnerability intervention	Time commitment to knowledge exchange and travelling costs
Economic	Livelihood diversification	Cope better with variability	High input and equipment costs for the annual crops; soil disturbance
Economic	Insurance	Financial resources to smooth out the losses	High and variable buy-in costs
Economic	Access to formal credit		High and variable repayment rates
Political	Governance and policy support	Risk governance based on institutional capacity	User commitment to water solidarity

The impact criteria for the EWR are conceptualised based on the consequences of not satisfying in-stream flow requirements at the gazetted ecological status (i.e. if we drop from an EWR category of B to B/C or lower, what does that mean in terms of the EWR assessment?). In the study by Tanner et al. (2022), the low flow category B and B/C levels for EWR Site 6 differ by 11%, with the B-Level EWR requiring 29.528 MCM (or 18.4% of mean annual runoff) and the B/C level requiring 16.249 MCM (or 16.3% of mean annual runoff). In comparison, EWR categories B and D differ by approximately 43.4%.

Table 4.5 Level of risk prioritisation.

Response efficacy value	Impact level	Impact level (%)	Description/ Interpretation of impacts
≥30	Very low	0-14.9	High response efficacy results in insignificant risks that cause little to no harm.
20-30	Low	15-34.9	High response efficacy dramatically reduces vulnerability (i.e. there is a low likelihood that hydrological variability will impair the user's socio-economic functions because a user has developed a high tolerance to water scarcity; user-user and user-environment conflicts are less likely to occur).
10-20	Medium	35-44.9	Adequate response efficacy, but still somewhat vulnerable (i.e. a user has developed some tolerance for water scarcity, but the user's socio-economic functions will continue in a modified form; user-user and user-environment conflicts could occur).
5-10	High	55-74.9	Severe vulnerability due to low to no response efficacy (i.e. environmental, and socio-economic functions will be severely impacted because a user has a limited ability to adapt, possibly to the point of temporary or permanent cessation of productive activities; user-user and user-environment conflicts are highly likely to occur).
≤5	Disastrous	≥75	Limited response efficacy results in disastrous impacts (i.e. environmental, and socio-economic functions may shift to a new state, with very high costs and limited recovery; conflicts over water use will occur).

4.3.6.1 Deficit-impact index.

The deficit impact for socio-economic use in the Twee Wyk is shown in Table 4.6, with variable levels of vulnerability to water shortage across users (low and high). The in-stream environment is expected to experience low to moderate impacts if the B-level category is not met. The lack of an active Water Users' Association results in a decentralised and poorly controlled socio-hydrological system because there is no coordinated strategy from a local entity. Insufficient water storage, combined with the high costs of reservoir construction and limited access to additional water resources, result in uneven supply management, leaving the less economically privileged users exposed to deficit-risk. Insurance and pre-existing knowledge to cope with water scarcity were assumed to be the major contributors to the low impact index for socio-economic activities. Finally, location in the catchment indicates a clear difference in vulnerability with those farmers in the upstream water-rich parts of the catchments significantly less vulnerable than the downstream farmers who rely on upstream farmers for water releases much of the time.

Table 4.6 Coping strategies in place to alleviate the risk of water shortages in the Twee Wyk and the vulnerability severity faced by water users

Response strategy	EWR	User 1	User 2	User 3	User 4	User 4
Water storage facilities		4	2	2	1	1
Access to supplementary water sources		4	2	0	3	3
Livelihood diversification		4	2	2	1	1
Access to local and expert knowledge		4	3	2	3	3
Governance and policy support		0	0	0	0	0
Insurance		4	4	2	3	3
Access to formal credit		4	4	2	4	4
Monitoring technology		3	2	2	2	2
Location in catchment		4	3	1	1	1
Total response efficacy		31	22	13	18	18
Vulnerability severity (Level & %)	Medium 43%	Very low 14%	Medium 39%	High 64%	Medium 50%	Medium 50%

4.3.7 The four water use strategies

The first restriction option – Equal Sharing (*Pizza Slices*) follows the notion of equality and treats everyone the same by allowing everyone to take similar proportions until their demand is met or the available supply runs out. Inevitably, *Pizza Slices* distributes the shortfall to the larger user, presuming they can bear the repercussions (Birkmann et al., 2013), and safeguards lower users (such as domestic customers in rural areas and hydropower operators) who would suffer catastrophic consequences in the event of even a slight curtailment. This strategy works well in areas where the "best interests of the society" are social and environmental safeguards.

By restricting water according to a specific element (in this case, total demand), the Proportional Sharing option (*Split the Bill*) guarantees that everyone gets a proportional share of the drought-year supply. Their proportional share remains the same, only total catchment water supply is reduced. This choice is characterised by a blanket proportion of water allocated across users in the same user group (e.g. farmers in the Western Cape experienced up to 85% restrictions during the 2015/19 drought, and outdoor water-use was banned for domestic users). By allocating an equal proportion of water cuts across users, this strategy prioritises the larger users who often play a significant role in meeting social and economic objectives. In other words, this strategy works well in areas where the "best interests of the society" are socio-economic targets such as employment and economic growth.

Similar to *Split the Bill*, Proportional to Community Weighting (*Beehive*) protects socially valued users based on a stated equity index (the community weighting index), as described by Xoxo et al. (2023). In this case, the least essential customers in the catchment are responsible for paying the bill. This strategy works well in areas where the society recognises proportionality and multi-dimensional nature of water values and objectives.

In an Equalised Impact option (*Share the Pain*), each user would receive a deficit that generates roughly the same impact or effort to recover. For instance, if maintaining or losing orchards has more socio-economic consequences than other activities, the user who plants orchards may be protected compared to a user who grows fodder – an annual crop. As a result, regardless of how differently each user uses water for beneficial purposes, all users experience the impact/recovery effort in the same way. This strategy allows all users to play a part in ensuring the rivers do not run dry or in reducing the duration of zero flows, based on the users coping ability when faced with water deficits.

4.4 DEVELOPMENT AND USE OF THE SERIOUS GAME

This work builds on four quantitative water distribution strategies for dry periods (Hughes & Mallory, 2009; Pienaar & Hughes, 2017). The strategies aim to advance equity/fairness in water use during deficit periods. Here, a role-playing game is used to communicate the proposed water allocation strategies and test their feasibility with a multi-stakeholder group.

The role-playing game (RPG) technique is chosen as an integrated assessment tool (Martin et al., 2011) to develop awareness and test the robustness of the water-sharing strategies. The RPG technique aims to improve the ability of Water User Associations and stakeholders to develop demand management plans that do not threaten ecological and socio-economic welfare. *Ad hoc* decisions in each round of play are prompted by surprise cards containing information about the external and internal drivers of the socio-hydrological closure relationships (Elshafei et al., 2014). Socio-hydrological closure relationships are quantitative proxy values used to abstract the coupled human-water interactions.

4.4.1 Rationale for adopting the RPG approach in equitable water management planning

The RPG approach is a powerful, engaging, and interactive platform for co-learning and participatory analysis towards optimal decisions (Kelly et al., 2013; Boyle et al., 2016). Local adaptation plans must consider how water users view and deal with socio-economic challenges and water scarcity at individual and community levels to cope with climate impact on water security (Kumar et al., 2020). Local stakeholder and expert involvement are central to the integrated evaluation, as they play an indispensable role in local knowledge contribution and quantitative evaluation of synthetic or empirical data. With an emphasis on participatory modelling, the RPG approach has demonstrated its usefulness in making stakeholders work together towards an unknown future (Barreteau et al., 2001; Martin et al., 2011; Lamarque et al., 2013).

Historical legacies, domestic and international demand for local agricultural products, and other reasons have contributed to a lack of equal access to water in many parts of South Africa. Consequently, previously privileged operators continue to have the most access to water supply; meanwhile, the state is lagging in oversight function. The issue is further complicated by influential water users' reluctance to participate publicly in the governance process and to uphold agreed resolutions (Adom & Simatele, 2022). Since the project aims to support the co-design of a local water management policy, decision-making is focused on the local level.

4.4.2 Methods: Role-Playing Game Components

4.4.2.1 Design concepts

The game was developed in an iterative process over two years, anchored in the socio-hydrology framework (Sivapalan et al., 2012; Elshafei et al., 2014). Local realities and user needs were integrated into the game with local stakeholder guidance. A systematic and inclusive process of understanding the social and environmental values/objective was followed, starting with defining the shared catchment vision for 2050 using the Adaptive Planning Process (APP; Palmer et al., 2013). The ARDI (Actors, Resources, Dynamics, and Interactions) process permitted a communal articulation of the catchment's main features relating to sustainable water usage.

The ARDI mapping exercise revealed agricultural production and tourism as the two major economic activities in the catchment (see Chapter 3). This is evident in the Koue Bokkeveld in how agricultural output has changed through time, moving from sheep husbandry in the 1700s to commercial fruit cultivation for the EU, USA, and BRICS markets in the present. Foreign fish introduction to improve recreational activities by leveraging clean and high-quality natural water pools distinguishes the tourism industry in the catchment.

4.4.2.2 Entities, state variables and scales

The game board comprises 50 hexagonal tiles (Figure 4.8), 40 of which represents a quantum of arable land per water user and are green in colour, and 10 (brown) represent the riverbank. The RPG interface is built to represent the shape of the sub-catchment of implementation as a way of mimicking reality. In addition to game tiles, a number of tokens represent the primary economic activities in the catchment and water sourced from run-of-river which are also partitioned to match the actual user characteristics (Table 4.7).

There are three main economic activities in the Wyk*:* fruit and vegetable production and tourism. Fruit production in the game situation represented citrus and deciduous fruits, field crops represented onions and potatoes. Potatoes have the largest irrigation needs of the different crop types (760 mm/a), followed by citrus (700 mm/a), deciduous fruit (426 mm/a), and onions (426 mm/a). These projections are based on crop coefficients and WR90 A-Pan evapotranspiration data for the Koue Bokkeveld catchment (River E21). For the game situation, which lumped the different crop types for ease of game navigation, fruits were assumed to use half the demand of field crops (Table 4.8).

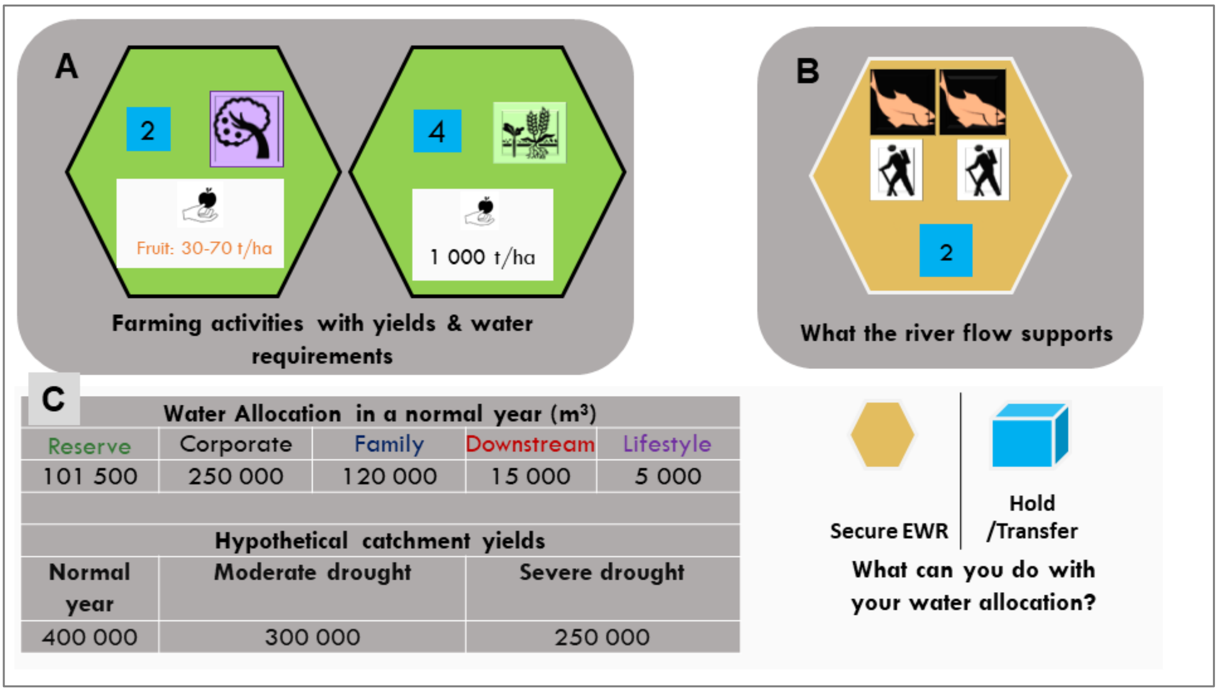


Figure 4.8 Role-playing game tiles showing the smallest unit [arable land per player (A) or riverbank (B)] as hexagonal polygons. The tokens shown in farming activity tiles highlight the relative water demand for each activity, such that each tile can be occupied by three icons at any given time. The blue rectangles show annual water requirements for each crop category. Support services emanate from meeting EWR targets, and these can be traced by the sensitive fish species, and recreational activities from high pool levels. C) Water allocation, its administration by individual users, and catchment yields.

Table 4.7 Input indicator data used to allocate economic activities and run-of-river water requirements to the corresponding players. The actual activities show a lumped hectarage for each player. The three main economic activities were fruit (representing citrus and deciduous fruits), field crops represented by vegetables, and accommodation reflecting tourism.

Land use information						
Player (farmer)	**Actual activities**			**Corresponding game tiles (N°)**		
	Fruit (ha)	**Field crops (ha)**	**Accommo-dation**	**Fruit**	**Field crops**	**Accommodation**
Corporate	160	100	0	13	8	0
Commercial family	141	20	5	12	2	3
Downstream	55	10	10	5	1	5
Lifestyle	0	5	5	0	1	3
Total	356	135.5	20	30	12	10
Riverbank					10	
Water demand (m^3)						
Corporate	90,106.8	50,377.5	0	26	32	-
Commercial family	79,406.6	10,309.9	18	24	8	-
Downstream	30,974.2	5,037.7	36	10	4	-
Lifestyle	0.0	2,518.9	18	0	4	-
Total	200,487.6	68,244.1	72	60	48	
Riverbank		29% of MMQ			20	
Economic indicators						
Yield (ton/ha)	30-70	~1,000	2 people/ unit			
Income (R/ton)	5,020.4 –	~3,500	1,000 pp			

Each game session had six players. At least three farmers take on the role of agricultural water use in their various operations; one manages a consortium commercial farmer (User 1), another runs a legacy commercial family farm (User 2), and the third is a downstream farmer with limited resources (User 3). Resident and lifestyle farmers (User 4) may participate in tourism-related activities, subject to EWR approval and the number of tourists in the catchment.

Water restrictions are introduced by the Water Users Association chair (Player 5), who is also responsible for understanding their impacts, and who plays the moderator role in the game. These impacts are monitored and reported to the Water Users Association by a technical support officer (Player 6).

Other workshop attendees were allocated observer roles.

Farmers who wish to diversify their activities may also host visitors in the catchment. One of the research team members or a stakeholder from an interest group (WWF-SA or Western Cape Government) plays the role of environmental water user (or the riverine environment) that sustains endemic fish species and leisure activities. This player aims to maintain in-stream environmental functioning, subject to agricultural compliance with EWR, based on the most vulnerable indigenous fish species.

Table 4.8 Characterisation of water user groups in the sub-basin.

Player	**User characteristics**				**Possible actions**
	Economic activities	**Water sources**	**Objective**	**Regional importance**	
Commercial farmer (corporate, family and under-resourced) (Agricultural production)	Fruit production activities at different scales, mostly for the export market	Diverts water for off-stream storage to use for irrigation activities	The main economic objective for corporate farmers is to maintain or increase productivity for profit generation.	Invests in water infrastructure	Choose crops Implement adaptive strategies for water gap Add, reduce or substitute crops Negotiate implemen-tation of water policies Request water from neighbours and outside the catchment Trade water Refuse to comply with release requirements Host tourists React to decisions by other users or ignore those If upstream plays first
	Cash cropping activities by all farmers, but popular with small to medium-scale farmers	Those whose financial resources are too limited to afford to build reservoirs pump directly from the river		Food security Economic development	
	Animal fodder production for the domestic livestock market	May abstract groundwater water for irrigation in the dry season, but farmers do not favour this option May transfer water authorisation to another user Arranges for water import through local gentlemen's agreements (mostly undocumented)		Employment creation	
Riverine ecosystem (Environmental use)	None	Relies on surface water	Serves as a reference for environmen-tal	River inhabited by endemic fish species such	Enable tourism activities downstream

Player	User characteristics				Possible actions
	Economic activities	Water sources	Objective	Regional importance	
		releases during winter	sustainability / fairness to the environment.	as the Twee Red Fin and Clanwilliam fish.	
		Relies on baseflows during summer and droughts (indirect groundwater use)	Sustains environmental functioning (e.g. protection of endemic fish species)	Supports tourism activities through natural water pools.	
				Replenishes the Doring estuary, providing 20% of estuarine inflow.	
		Receives artificial flash floods from small farm dam releases before heavy rains		If met, it allows for downstream water-related activities.	
Resident/Life-style (Hedonistic user)	May participate in tourism operations	Relies on spring water for domestic use Often uses water pools for non-commercial recreational activities.	Guaranteed water right under human basic needs (25l/day), (6000 l/household/ day), but pays water tariffs for additional use.	Advocate for EWR satisfaction.	Implements adaptive strategies to water gap Negotiates implementation of water policies
Weekender (Hedonistic user)	Camping, ecotourism, self-catering	Spring water for domestic use (direct groundwater use)	Guaranteed water right for human needs (50l/day or 6 000l/ household), but pays water tariffs for additional use	Advocate for EWR satisfaction. Contributes to municipal tourism development targets	Second to incur costs after EWR

Player	User characteristics				Possible actions
	Economic activities	Water sources	Objective	Regional importance	
		Natural rivers for commercial, recreational activities	Requires general authorisation in case of water use for recreational activities	Advocate for EWR satisfaction.	

4.4.2.3 Gameplay

Two concurrent game sessions were conducted with similar stakeholder groups. The main goal of the game was to familiarise water users with the proposed water sharing options for managing demand during droughts, fair sharing of the costs and benefits of protecting the scarce resource, and to jointly analyse the potential socio-economic and environmental impact of each strategy in a fun and collaborative way. This objective was made clear during a plenary session through a PowerPoint presentation during the workshop on 2 November 2022. English-Afrikaans translations were often required to make the game accessible to non-English speaking players, following the recommendations of the Rhodes University Human Research Ethics Committee (Ref: 2022-5386-6678).

Before providing the water-sharing alternatives as narratives, the game developer reminded the participants of their 2050 Vision (set in May 2022), to which they decide based on; their stated equity index (Xoxo et al., 2023); and the vulnerability assessment (work in progress under Mr Xoxo's thesis, which is not included here). This introductory presentation was an essential building block for the game sessions, and it generated a long discussion of its own.

The process of defining restrictions or a water sharing strategy for a catchment involves four steps (Pienaar & Hughes, 2017). Briefly, water user representatives provide information on environmental water requirements, monthly water demands for all sectors or user groups, and expected impact level on the environment or socio-economic operations. The research team drafted the surprise cards based on synthetic outputs by Pienaar and Hughes (2017). These outputs were based on a hypothetical 'case study'.

Players had to react to a narrative by indicating areas that would be affected by imposed restrictions. Next, the game board and icons were introduced to all players (Figure 4.8). Farmers had to indicate drought damage generated by a water-sharing option by iteratively redesigning their water consumption activities for economic gain while considering the 2050 Catchment vision (or maintaining social reputation).

In the hypothetical case study, the catchment had a normal annual runoff yield of 400 000 m^3/annum, compared to a socio-economic demand of 39 000 m^3/annum. It was assumed that there were no in-stream dams, to maintain consistency with the Twee Wyk. The hypothetical low flow EWR for categories B and D was 29% and 19% of mean annual runoff, respectively. The relationship between deficit and impact (residual impact from adaptive strategies) ranged between tolerable and moderate for the players, with the under-resourced farmer facing the highest risk. Farmers with limited resources were not permitted to extract water because it was assumed that they lacked the financial means to do so.

The research team tested three game prototypes between May 2022 and November 2023, and two sessions were played in the catchment by two stakeholder groups on 2 November 2023, in Kunje Guest Farm. Each session consisted of the six players described in the briefing section above. All the players had first-hand knowledge of farming activities in the catchment. Game instructions had to be made flexible to allow some evolution of the game to match player needs. Players were also allowed up to 5 minutes of discussion in play time.

Each table played four rounds representing two sharing options (either *Split the Bill* and *Share the Pain,* or *Pizza Slices* and *Share the Pain* at EWR level D then at level B), all introduced by the moderators as narratives to promote long-term risk appraisal (Table 4.9). Facilitators introduced themselves as the newly elected Water User Association chairs and indicated that they would hold the role for the next five years. Facilitators then gave a brief overview of the game, its objectives, timesteps and possible decisions. Players were allowed to pose questions to deal with language differences. Beginning each round with a D-level EWR at category D was intended to raise awareness of the rationale behind the gazetted EWR being raised from lower levels to near-natural flows (EWR category B) (DWS, 2017).

Table 4.9 Details of the proposed water sharing options on supplied water to five water users with a monthly demand of 390 000 m³ compared to a catchment yield of 400 000 m³, assuming environmental water requirements are met at level B.

Water users		Reserve	Corporate	Family	Downstream	Lifestyle
Normal year demand (x10^{-3} m³)		116.0	250.0	120.0	15.0	5.0
Community weighting		34.00	21.00	20.00	25.00	10.00
Adaptive capacity (Vulnerability severity)		Med (43%)	V. low (14%)	Med (39%)	High (64%)	Med (50%)
Water sharing options/ equitable allocation of water restrictions						
Pizza Slices	Drought assurance	60.9	64.6	64.6	15.0	5.0
	Supply (% of demand)	100	26	54	100	100
	Deficit (%)	0.0	74	46	0	0
	Impact (%)	0	88	71	0	0
Split the bill	Drought assurance	60.9	95.6	45.9	5.7	1.9
	Supply (% of demand)	29	46	22	3	1
	Deficit (%)	0	62	62	62	62
	Impact (%)	0	80	98	98	98
Beehive	Drought assurance	60.9	97.0	44.3	6.9	0.9
	Supply (% of demand)	100	39	37	46	18
	Deficit (%)	0.0	61	63	54	82
	Impact (%)	0	57	92	99	93
Share the Pain	Drought assurance	60.9	95.6	45.9	5.7	1.9
	Supply (% of demand)	100.0	56.2	27.0	3.4	1.1
	Deficit (%)	0	48	22	13	16
	Impact (%)	0	70	70	70	70

4.4.2.4 Data collection and debriefing

We observed how water users responded to proposed restrictions and how their decisions affected the situation. We analysed their choices of water use, water transfer, crop planting, and environmental protection by logging player reactions to the water-sharing options into an automated operator spreadsheet. The costs of each scenario were compared using the percentage of supply shortfall for economic and environmental use under each scenario. We checked the impact on vulnerable users vs. the rest of society to report on the impact of the strategies on equity. We also tracked the in-game level of EWR satisfaction or violation to report on environmental impacts of the proposed strategies, and which users picked up the environmental costs. All these indicators were summarised into the operator spreadsheet to give a comparative analysis of the water-sharing options. The final indicators were displayed on a projected screen during the debriefing plenary session.

Phase three of the game – debriefing – was allocated 20-30 minutes. At this stage, players reflected on the connections between the simplified representation of behaviours and real-world outcomes. The RPG outcomes were evaluated through a plenary discussion guided by questions focusing on attitude changes (Matthews et al., 2011). The attitudes were specifically targeted to the catchment's collective future vision. This process was guided by an experienced facilitator who had a good understanding of both English and Afrikaans.

4.4.3 Outcomes of playing the game with farmers

The game was played with stakeholders at the workshop on 2 November 2023. Initially the stakeholders were perplexed when asked to play the game, but the relationships that we had built over the past three years, meant that they humoured the project team and fully embraced the game. It is worth noting that no corporate or consortium stakeholders attended the workshop, so the atmosphere was relaxed.

It seemed the farmers enjoyed the game but were critical of certain components that they said did not reflect reality. It also became apparent that the game could be improved in terms of more clearly demonstrating the difference between the water-sharing strategies. Aspects of the game that were abstract (such as removing a crop token to represent reduced allocation of water) were difficult to understand and a key learning was that stakeholders, and particularly farmers, need the specifics to reflect reality and accuracy. Improvements such as the introduction of icons/cards of dams and boreholes so players have access to resources to supplement their strategies are being looked at, as well as improvements to recording the information and movement of tokens.

There were, however, some interesting dynamics and outcomes that emerged, such as the lifestyle farmers clearly prioritising tourism above their farming activities. Downstream farmers prioritised upstream farmers' water supply to ensure consistent employment levels (and prevent instability). Players did seem to be keeping the potential real impacts in mind when they were playing the game, and the interactions the various actions prompted were valuable. Ultimately, the stakeholders enjoyed playing the game, and had fun with it. One feedback comment was that the players gained a lot in terms of conceptually understanding the bigger picture of water sharing in a catchment where there is not enough water for all (the term 'conceptual breakthrough' was used). The conclusion is that, with some modifications, the game could be a useful tool for stakeholders in water-scarce agricultural catchments who need to collectively determine how they are going to share the resource, in particular, demonstrating the finite nature of the resource, and allowing the different ways of sharing the water to be explored.

4.5 WATER SHARING TOOL OUTPUTS

The final setup of the WST is still being finalised, so we have included only a brief summary of the results of the simulation below.

To reiterate and summarise the process (detailed in previous sections):

The water user inputs include the calendar month distribution of the water demands (in m^3 $x10^6$), an index value representing the relationship between water deficits (shortfalls in supply) and impact, and a community weighting score, representing supply priority. The deficit-impact index (Hughes & Mallory, 2009) is used to generate an S-curve relationship between the level of deficit and the impact on the individual user group. The impacts for each user are reduced to a common scale between 0% (no impact) and 100% (disastrous impact) and only represent relatively short-term impacts, rather than any effects of sustained or cumulative deficits over long periods. These latter effects are assessed through the summary output information (shown in Figure 4.8 below) (Pienaar & Hughes, 2017).

Although only one of the water sharing strategies (equalised impact option, *Share the Pain*) uses the deficit-impact index to calculate the volume of water allocated in a deficit period, all the strategies report on the impact level of each user according to their deficit in relation to their water needs.

4.5.1 Key risks across farmers vs the environment.

The rapid vulnerability analysis for environmental (EWR) and socio-economic uses (users 1 to 4) in the Twee Wyk is shown as impact curves in Figure 4.9.

- It is anticipated that shifting the in-stream requirements from category B to D will expose the environment to medium effects at about 15% deficit, but serious effects (>75% impact) can be expected at 20% low flow deficit.
- A similar deficit-impact can be observed for the family commercial farms, non-agricultural users, and downstream farmers, with downstream farmers being most vulnerable to water deficits.
- At 15% and 20% water deficit, consortium farmers were estimated to face the least impacts (<10% impact), reflecting high coping ability.

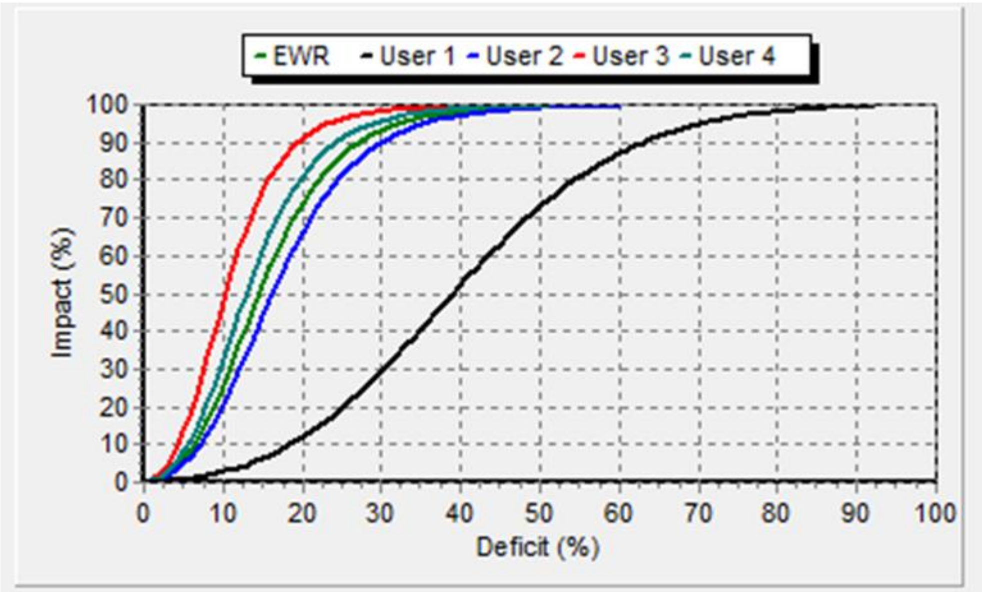


Figure 4.9 Likely environmental (EWR) and socio-economic impacts from reduced blue water assurance in the Twee. User 1 represents commercial corporate farmers, User 2 represents commercial family farms, User 3 represents under-resourced farmers, and User 4 represents lifestyle and holiday farmers.

4.5.2 Overall impact from proposed water sharing strategies: Tolerance of water users to water deficits.

One of the first model outputs is a summary of frequency and variability of impacts due to seasonal streamflow variations, lack of knowledge, decisions about reservoir storage and priorities for allocating water restrictions. This information is combined into six histograms showing maximum annual impacts for 10 impact groups. An application of *Split the Bill,* a water-sharing option that equalises the restriction across users, thereby protecting larger water consumers in the Middledeur, is shown in Figure 4.10. The duration of overall annual impacts from allocating water restrictions using *Split the Bill* are negligible (frequency of impacts ranges between 1% and 5%) for the community, individual users, and the environment. However, their intensity can be disastrous (impact level >7). In contrast, at a community level, high to disastrous impacts are smoothed out. The negligible impacts generated by the water-sharing strategy make the option worthy of further exploration, since this is a popular strategy for water managers, as it protects national socio-economic interests (e.g. food security and employment).

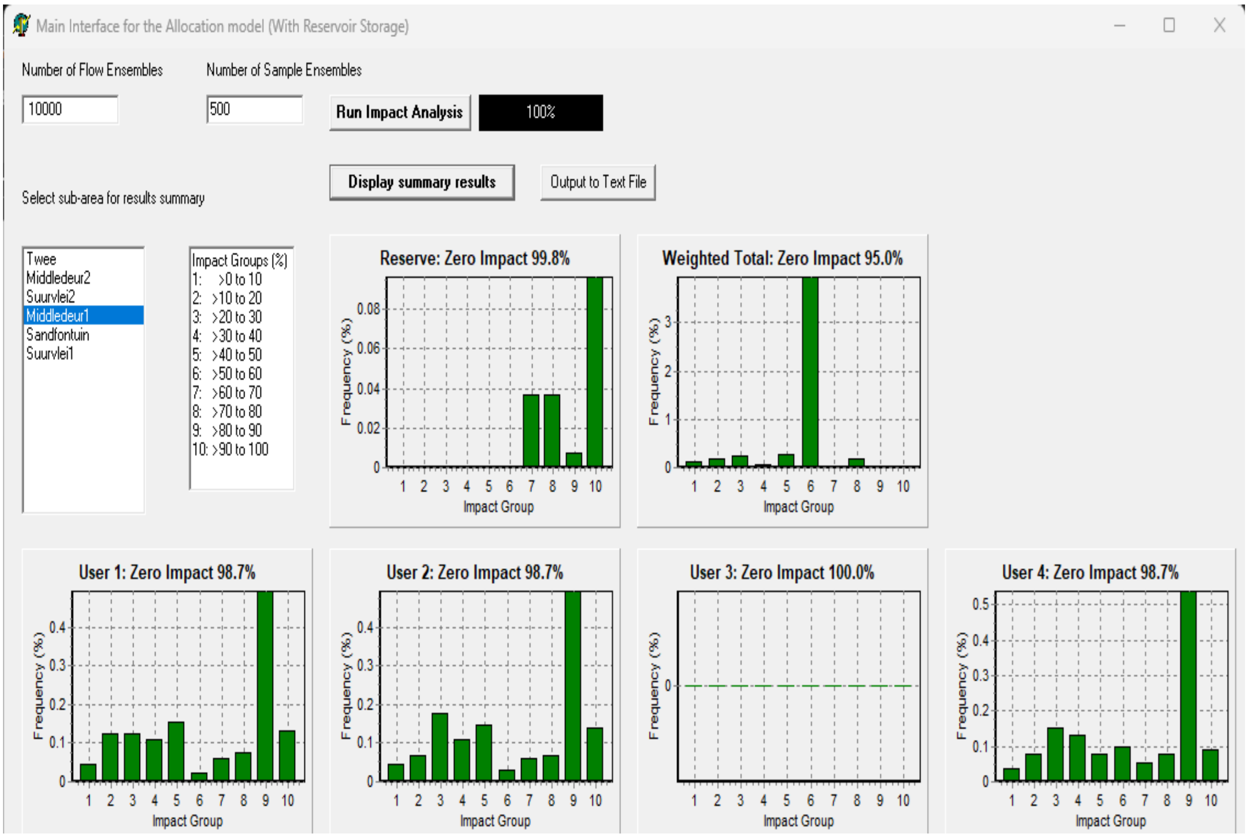


Figure 4.10 Impact analysis showing the lowest detail of risk for *Split the Bill*. Example of maximum annual impacts for the 500 streamflow ensemble samples for the Upper Middledeur

The Water Sharing Tool allows the modeller to export these overall impacts as tables, for ease of comparison as shown in Table 4.10. Therefore, we recommend focusing on environmental impacts and the combined socio-economic impacts (grouped community impacts) of each strategy, to help the decision maker determine if it is worth pursuing the strategy further.

Table 4.10 (1) Community weighted impact distribution and (2) environmental impacts expected for the upper Middledeur and the Twee River sub-catchments. The Upper Middledeur River example offers a look into a situation with small dam storage, and the Twee River example is a run-of-river situation. Shaded cells show frequency of impacts from zero (none) to 100 (disastrous) for each impact category. High risk impacts are those that are found in the impact category range 70-100.

Community Weighted Impact Distribution						
Impact group	**Upper Middledeur River**			**Twee River**		
	Pizza Slices	**Split the Bill**	**Share the Pain**	**Pizza Slices**	**Split the Bill**	**Share the Pain**
0-10	0	0.17	0.18	0	0.00	0
10-20	53.79	0.27	0.27	0	0.00	0
20-30	28.47	0.28	0.24	0	0.00	0
30-40	17.74	0.19	0.13	0	0.00	0
40-50	0	0.21	0.3	0.33	7.44	0.27
50-60	0	4.1	4.06	0.56	0.00	0.6
60-70	0	0	0	11.81	0.00	12.01
70-80	0	0.14	0.25	0	0.00	0
80-90	0	0	0	0	0.00	0
90-100	0	0	0	0	0.00	0
EWR impact distribution						
0-10	0	0.17	0	0	0.00	0
10-20	0	0.27	0	0	0.00	0
20-30	0	0.28	0	0.06	0.00	0.07
30-40	0	0.19	0	0.25	0.00	0.19
40-50	0	0.21	0	0.06	0.00	0.06
50-60	0	4.1	0.01	0.07	0.00	0.03
60-70	0	0	0.07	0.24	0.00	0.33
70-80	0	0.14	0.01	0.24	0.00	0.2
80-90	0	0	0.04	0.08	0.00	0.11
90-100	0	0	0.13	0.01	0.00	0.03

4.5.3 Examining aleatory and epistemic uncertainty in *Split the Bill* for upstream and at the outlet

The Water Sharing Tool allows decision-makers to explore the effects of streamflow uncertainty on different water-sharing scenarios. This is a crucial step to inspire informed decision-making under uncertainty, as the preference for a scenario may change depending on the hydrological variability. Here we focus on the *Split the Bill* scenario, which allocates water equally among all users in a sub-catchment. Figure 4.11 shows how the *Split the Bill* scenario performs under different levels of streamflow uncertainty, and how it affects the available water and the impact levels for each user group. This links to the distribution of streamflow uncertainty for each sub-catchment, based on historical data and climate projections.

The results indicate that the *Split the Bill* scenario is more favourable for the users in the Twee River sub-catchment than for those in the Upper Middledeur sub-catchment. As shown in Figure 4.11, none of the users in the Twee River sub-catchment is expected to experience large deficits or high impact levels, even under the worst-case scenario within streamflow uncertainty because the Twee River sub-catchment has a relatively high and stable streamflow, as shown in Figure 4.5.

On the other hand, the users in the Upper Middledeur sub-catchment are more vulnerable to variability in streamflow, especially the consortium and commercial family farms. As shown in Figure 4.11, these user groups could face low to medium impact levels, depending on the level of streamflow uncertainty. This is because the Upper Middledeur sub-catchment has a relatively low and variable streamflow, as shown in Figure 4.5. This uncertainly is exacerbated by these user groups having high water demand, which makes them more sensitive to water shortages.

These findings suggest that the *Split the Bill* scenario may not be the best option for the Upper Middledeur sub-catchment, as it does not account for the differences in water availability and water use among the user groups. A more adaptive and flexible water sharing scenario may be needed to cope with the streamflow uncertainty and ensure water security for all users.

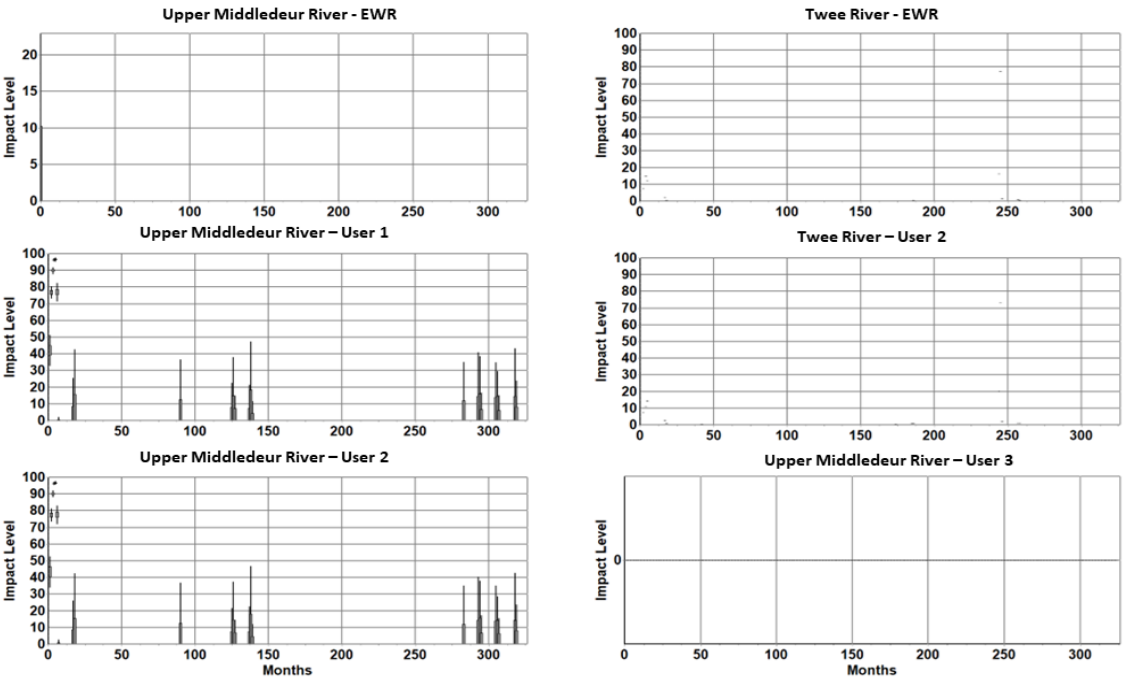


Figure 4.11 Time series variations of impacts across the 500 selected ensembles for the Upper Middledeur and Twee Rivers when the environmental water requirements are always met at level B.

One key adaptation the larger more well-resourced farms have undertaken is to set up transfer systems between dams. For example, user 1 in the Upper Middledeur has such a system. This system also transfers water out of the Upper Middledeur catchment thereby exacerbating the impacts on user 2 and downstream users. Owing to the inability of the model structure to represent this, as well as little information on where these networks are, and how much water is being moved around, means this process is not represented in the simulation.

4.6 CONCLUSION

During the workshop on 2 November 2023, the model and water-sharing strategies were presented to the stakeholders. The stakeholders were interested in the different strategies but needed more time to fully understand them and their implications. A guideline document is planned for distribution to the stakeholders in 2024. However, some of the key feedback listed below reflects a lack of understanding in many cases, which was useful for us in terms of needing to improve our communication of the model components, options and outputs. Some specific feedback included:

- The model is complex, and the explanation needs to be simplified.
- Concerns about the equalised Impact option (*Share the Pain*) scenario favouring less efficient and productive farms.
- Issues with how we had specified the user groups (we need to communicate better the flexibility in this regard).
- Community weights could be focused on aspects such as crop type. For example, someone with an orchard is more vulnerable to water deficits than someone with an annual crop. You could prioritise the user with the orchard (as being more vulnerable), or you could prioritise the user with the annual crop (as they have placed less risk on the system as a whole).
- A user stated that they did not need any of the water sharing strategies, as they didn't want to feel monitored. They would rather work under an umbrella of trust within the farming community and communicate amongst themselves when they need upstream water released (an informal *ad hoc* arrangement).

Overall, the stakeholders did not appreciate the flexible aspects of the model (user group designation, impact curves, and community weighting). Although we explained that we had worked them out a certain way, and that this could be changed to suit contexts and needs, much of the discussion focused on their particular issues with how we had worked out those flexible components. This clearly needs to be communicated better.

However, in closing, a representative from the Western Cape Department of Agriculture requested that the models be presented at a meeting of Water User Association Chairmen. This suggests that the model could be valuable for the increasingly strained agricultural water management of water-scarce catchments.

The next steps are to finalise the model setup for the case study catchment, and then prepare a clear communication documentation for Water User Associations and agricultural stakeholders.

CHAPTER 5: IMPLEMENTATION AND MONITORING THE WATER MANAGEMENT PLAN USING THE WATER BALANCE TOOL

5.1 INTRODUCTION

A multitude of tools are available for supporting water resource planning, management, and decision-making, ranging from foundational hydrological models to more complex models that integrate social arrangements between water users and user groups, such as the Water Sharing Model (Pienaar & Hughes, 2017) and Agent-based models (Pouladi et al., 2019; Schlüter et al., 2021) described elsewhere in this report. These models not only contribute to a more comprehensive understanding of water resource dynamics, but also guide strategic planning and decision-making among water users.

However, the challenges faced by South African water management institutions, particularly at the local level, significantly impact the broader uptake and regular use of these types of models for water resource management. The limited capacity of these institutions to adopt such models is compounded by broader issues within the country's water governance structure. In South Africa, local water governance operates through Catchment Management Agencies (CMAs) responsible for overseeing Water Management Areas (WMAs). The establishment of CMAs, as initially outlined in the National Water Act (NWA) to cover 19 WMAs, has only been realized in a few catchments. Furthermore, the consolidation of WMAs into nine larger areas has imposed additional responsibilities on CMAs, necessitating the management of significantly expanded geographical extents. This has led to concerns about further staffing, capacity, budget constraints, and the efficacy of water resource monitoring within these agencies. The amplified responsibilities and limited resources at the regional level compound the challenges faced by local institutions, impeding the effective management of water resources across the country.

Typically, in rural agricultural regions, the responsibility for managing water resources rests with individuals engaged in the daily operation of water infrastructure, especially farmers. The task also falls on WUAs, which, alongside CMAs, bear the responsibility of overseeing and protecting the resource at local scales. However, like CMAs, WUAs encounter considerable limitations in their capacity to perform these roles. Many of these associations have not undergone transformation from their previous structures as Irrigation Boards, and they lack the technical skills to run complex hydrological or water resources allocation models which would aid decision-making.

In response to these challenges, the Water Balance Tool (WBT) was developed alongside the Agent-Based Model (ABM) and Water Sharing Model described in this report to assist in implementing the water management strategies in the Twee catchment. It is intended to aid in the practical implementation of water management procedures, targeting users who possess a moderate level of technical knowledge but who may lack specialised hydrological or modelling expertise. The tool's design is focused on providing accessibility and user-friendliness and for managing water in agricultural catchments in which there are multiple users and a widely dispersed water resource infrastructure with numerous small privately owned farm dams – as is typical of agricultural catchments in South Africa.

The WBT is also able to assess the degree of compliance with the Ecological Reserve. This function assists farmers in adopting more sustainable water management practices by using the Reserve as a benchmark against which to assess sustainability targets.

5.2 DESCRIPTION OF THE WATER BALANCE TOOL (WBT)

The WBT is a network-based spreadsheet model designed to allow for modifications or adjustments to accommodate any agricultural catchment of interest. Users can easily add or remove farm or sub-catchment units, dams, or abstraction points, adapting the model to suit the requirements of different catchment configurations. It effectively maintains a mass balance of all inflows, abstractions, dam storages, spills, and return flows within the catchment, providing a comprehensive overview of water dynamics within the system (Figure 5.1).

The model is driven by natural hydrology, offering the flexibility of generating flows either within the tool, using a simple daily user-calibrated rainfall-runoff function which can be customised to the catchment of interest, or more dependable simulated flows generated by an external hydrological model if available. The built-in algorithm option is beneficial in situations where modelling expertise is scarce or unavailable. Choosing to use flows generated from a hydrological model is preferable in cases where higher certainty is necessary, particularly for data which may need to be generated for assisting with WULAs or for strategic planning purposes. River inflow estimations are initially derived from calibrated Pitman modelled flows until April 2019. After this period, the estimations rely on a rainfall-runoff relationship described above.

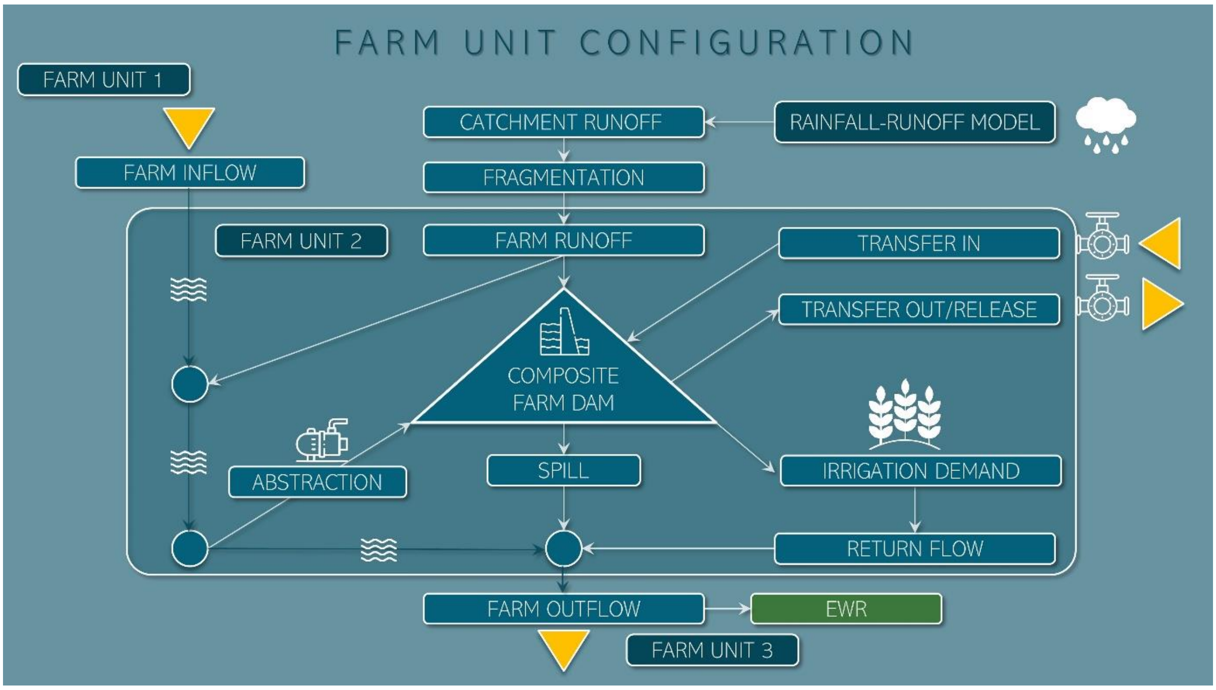


Figure 5.1 WBT farm unit configuration showing inflow to Farm Unit 2 from Farm Unit 1, storage, abstractions, irrigation demands, transfers in and out of the unit and outflows to Farm Unit 3.

The tool operates on a daily basis, involving ten farm sub-catchments representing water users within the project area. Daily natural flows derived either from an externally run hydrological model or the built-in rainfall-runoff function are routed through the catchment on a farm sub-catchment unit basis (Figure 5.1). Water which is not used in each sub-catchment is passed on via the outlet to the next unit. Figure 5.2 shows the configuration for the Twee catchment (E21G) including natural reserves, existing dams and transfers, as well as gauged monitoring sites.

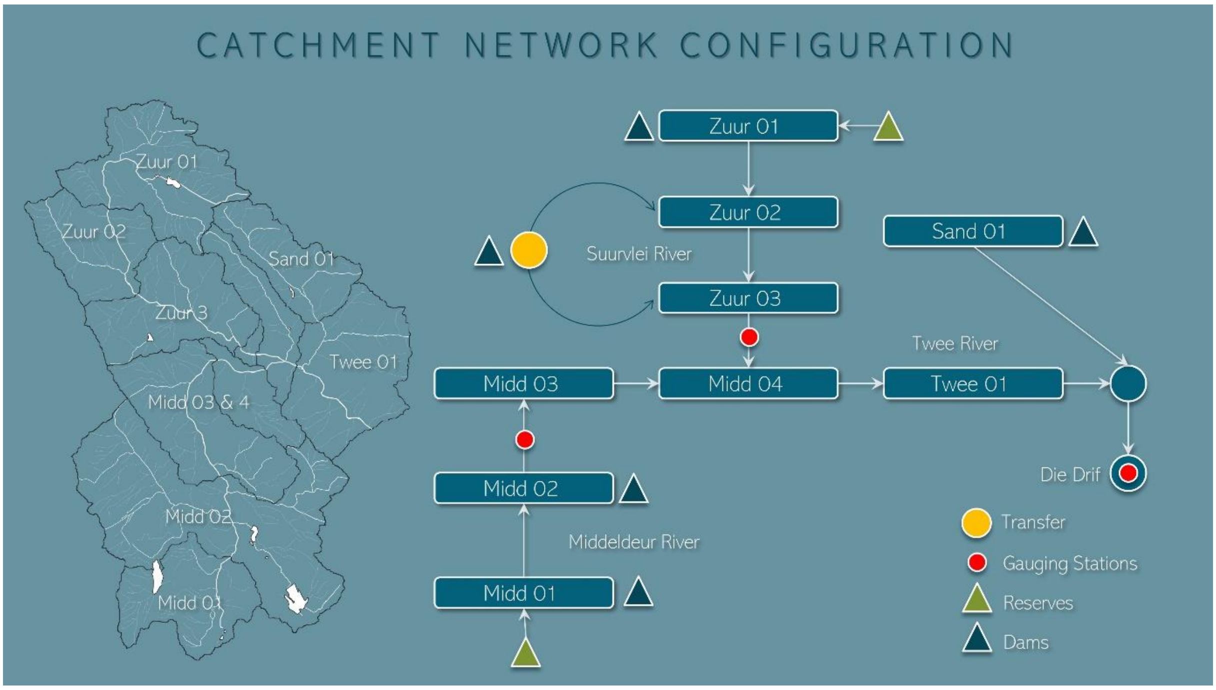


Figure 5.2 Catchment network configuration for the Twee River (E21G) showing farm units, dams, water transfers, natural reserves and monitoring (gauging stations).

Crop requirements for each farm are estimated from the irrigated crop areas and crop types which, for the Twee catchment, were extracted from the Western Cape Crop Census 2018 (Cape Farm Mapper). Net irrigation demands in each unit are calculated using crop factors, evaporation, and effective rainfall. Each farm unit allows for abstractions, storage in a composite dam, spills, transfers in and out of the catchment and return flows. Time-varying input data, such as changes in irrigation areas, crop types, and dam storage capacities, are also accommodated.

The tool includes dams registered by the Dam Safety Office. The identification and capacity assessment for farm dams not included in the registered database were carried out using Google Earth. The capacity was assumed to be the difference between the registered dam capacity and the total crop requirement.

Abstractions from rivers to dams are limited to the winter months (May-September), while irrigation is supplied from storage for the rest of the year. There are no constraints on abstractions from rivers to dams. If a particular dam is full, there is no further abstraction from the river.

5.3 WATER BALANCE TOOL (WBT) OUTPUTS

This tool is capable of generating daily flows at specific locations within a catchment allowing for analysis of inflows and outflows. It provides graphical outputs such as time series data on a daily, weekly and monthly basis, together with the Ecological Water Requirements (EWR) enhancing the visualization and interpretation of the modelled data (Figure 5.3).

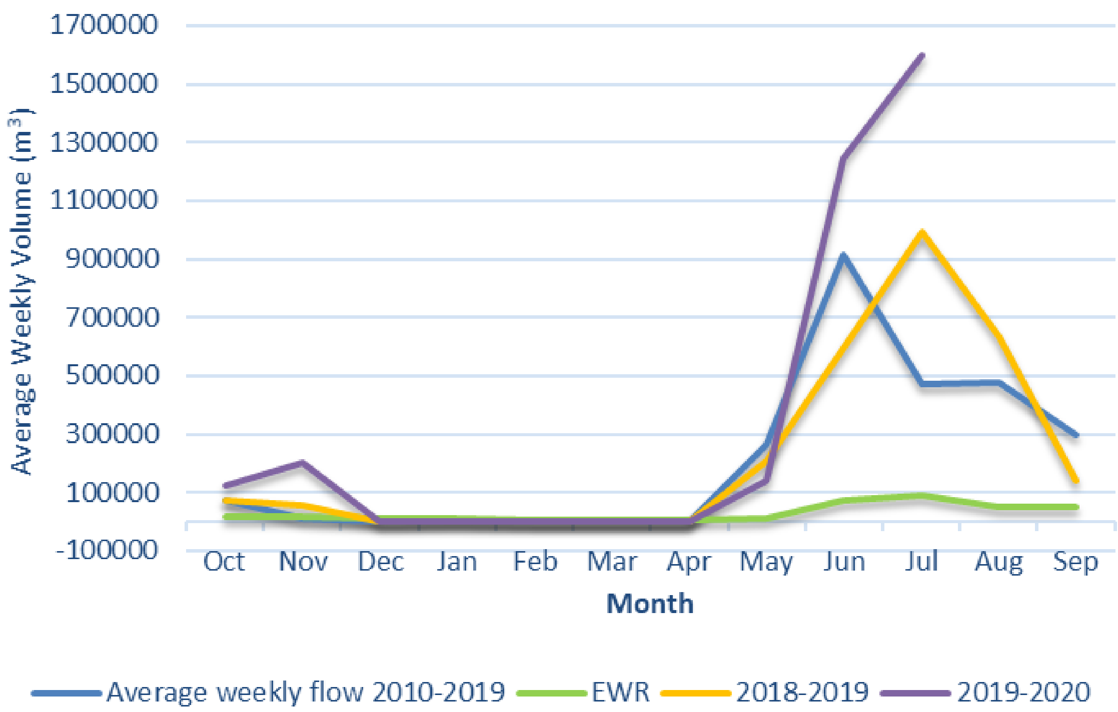


Figure 5.3 The average weekly at the outflow (m^3) at Zuur-01 for the years 2010-19, 2018-2019 and 2019-2020 as well as the EWR.

Various user roles are available within the Water Balance Tool, allowing control over configuration, data input, and reporting functionalities, making it accessible and manageable for diverse users with different levels of authority or expertise. It is envisaged that the model output will be accessible to all interested parties, including farmers and Water User Associations, as well as regulators such as the Department of Water and Sanitation and the Department of Agriculture.

To aid in the management of water during periods of high-water stress, such as droughts, the Water Balance Tool incorporates a 'sharing the pain' module. This module, included in the operational outputs of the tool, functions by calculating the amount of water supplied from upstream to each farm, determining the farm's water demand, and identifying any deficit (Table 5.1). Typically, upstream farmers tend to prioritize water consumption, often exceeding their rightful share. The WBT addresses this issue by equitably distributing deficits among farms, ensuring that each receives an appropriate allocation based on its water needs and rights, thereby optimizing curtailment efficiency and ensuring that the downstream EWRs are met (Table 5.1)

Table 5.1 Calculating deficits in water supply for 'Sharing the Pain'.

	Avg Demand	Avg Deficit	Supply	% Percentage Supply
Farm 1	4800	480	4320	90%
Farm 2	3700	740	2960	80%
Farm 3	6700	2680	4020	60%

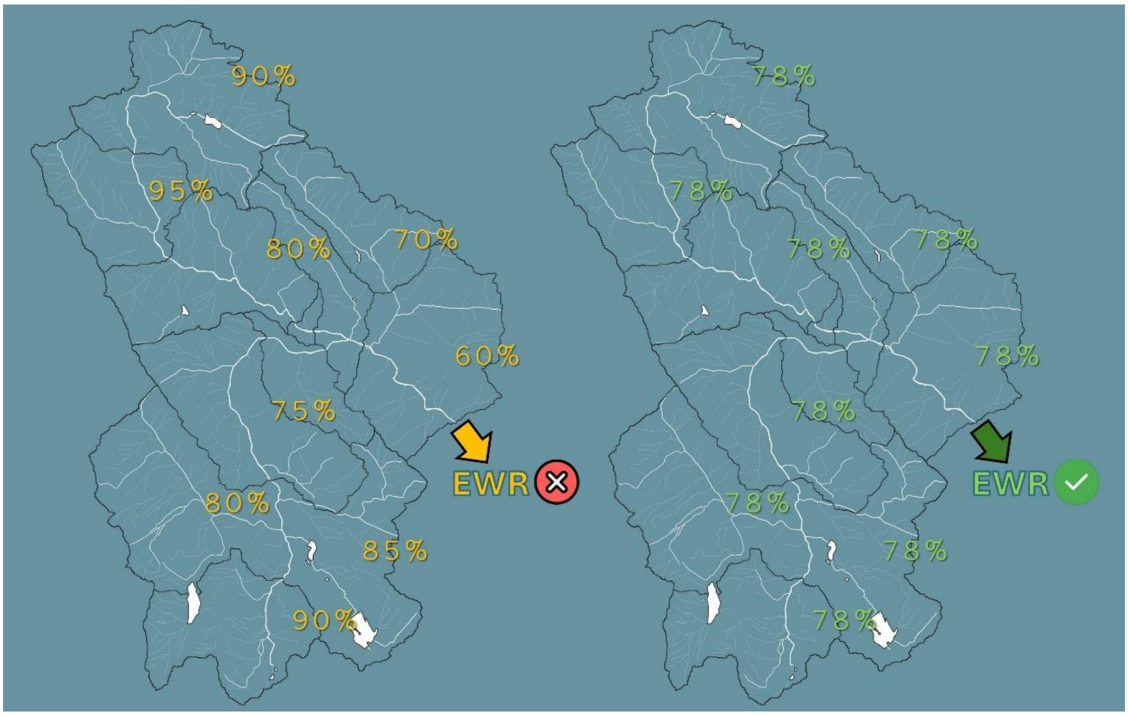


Figure 5.4 'Sharing the Pain' – re-allocating deficits equally among farms during periods of high-water stress.

The Water Balance Tool can generate sustainability indices, indicating the extent to which the Environmental Water Requirement (EWR) is fulfilled on a monthly or yearly basis. These indices are computed by comparing observed or simulated flows at key locations within the catchment, and they are presented as measures of compliance, considering both the magnitude and the duration of fulfillment (Figure 5.5). Targets can be set and annual sustainability performances can be assessed.

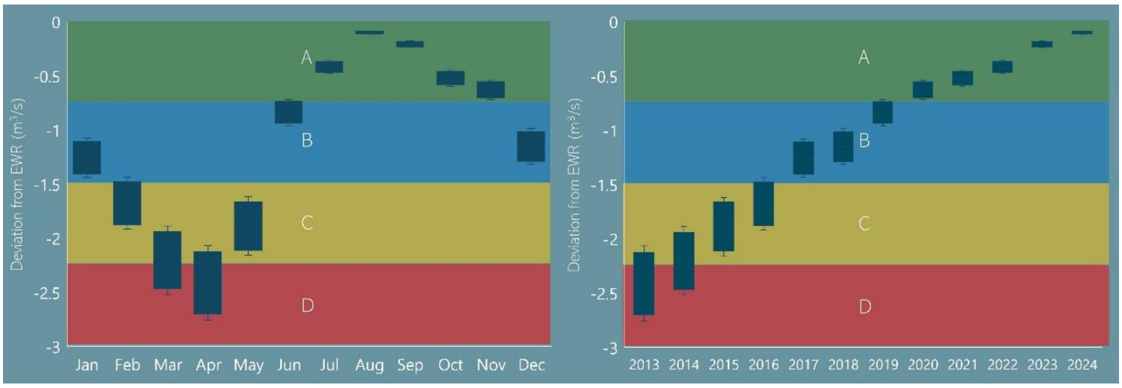


Figure 5.5 Calculating sustainability indicators based on deviation from the EWR.

5.4 CONCLUSION

In summary, the Water Balance Tool (WBT) plays a pivotal role in overcoming challenges faced by South African water management institutions. Tailored for local users, particularly farmers, the WBT provides a user-friendly solution for managing dispersed water infrastructure in agricultural catchments. Addressing the limitations of Catchment Management Agencies and Water User Associations, the WBT offers practical implementation and assesses compliance with the Ecological Reserve. Its adaptable spreadsheet model maintains a comprehensive mass balance of water dynamics within the system.

Utilizing natural hydrology on a daily basis, the WBT accommodates both user-calibrated functions and simulated flows, enhancing the analysis of inflows and outflows. Graphical outputs, including time series data and Ecological Water Requirements (EWR), aid in visualization and interpretation. Accessible to diverse stakeholders, the WBT supports informed decision-making and sustainable water resource management in South Africa's agricultural landscapes, emphasizing simplicity and effectiveness in water planning and allocation.

CHAPTER 6: STAKEHOLDER ENGAGEMENT, FEEDBACK AND LEARNINGS

6.1 INTRODUCTION

The Strategic Adaptive Management (SAM) approach was adopted for the initial engagement workshops. Together with ARDI, SAM became the foundational engagement tool, laying the framework for all future engagements. Instituted in the Kruger National Park, South Africa (Rogers & Biggs, 1999), SAM emphasises consensus as a basis for designing a better future regarding biodiversity conservation. The SAM approach is vital for bringing together stakeholders to identify shared values and goals and can be used to respond to contested water management spaces. The SAM approach employs the Adaptive Planning Process (APP) as a foundational ground for stakeholder mapping. The APP specifies a set of actions that stakeholders engage in to discover common ground and develop an agreement (Palmer et al., 2023).

The project team implemented the Adaptive Planning Process (APP), which is a forward-looking process vital for adaptive management (Palmer et al., 2023). The first phase of the APP involves stakeholders sharing their concerns regarding their space and the project. After concerns are recorded, stakeholders are facilitated to imagine a desired future, followed by collective crafting of a vision of their context with their concerns addressed. The concerns and elements of a desired future were categorised into Social, Technical, Economic, Environmental and Political (STEEP) categories (Pollard et al., 2014). Participants were asked to imagine their ideal future vision for the catchment in approximately 2050. The questions posed were:

> *In 2050, if we were able to work together to contribute to addressing some of the concerns you have raised, what would the ideal future look like for you? What would some specific indicators of success be?*

Or, as phrased differently by one participant, '*What kind of catchment do you want to leave to your children*?'. The vision became the guiding aim of the engagement process, and both the project team and stakeholders resolved to work towards achieving components of the collective vision. The shared vision established through SAM/APP the outcomes process that provided input to frame the scenarios that were subsequently simulated by models.

KBV Catchment Vision:

- *The Stakeholders working together to manage water resources sustainably and equitably with transparency and accountability in ways that balance social, economic, and environmental needs.*
- *Agriculture producing social and economic value through efficient, data-driven, scientific management practices and the adoption of technological and ecosystem-based solutions.*
- *A healthy, resilient ecological system with clean water flowing, even in summer.*

Once the vision was agreed on, stakeholders identified values and actions that contribute to attaining the vision. The values thus define a way of working together to underpin all engagements. This approach is meant to ensure that stakeholders participate in the co-development of a water management plan, having a mutual understanding of the issues and a shared vision of the outcomes, and to open their eyes to what the models will be about. More importantly, the values set the "rules of engagement" in a process that will likely be fraught with conflicts as stakeholders negotiate a workable plan for managing the scarce but shared resource.

6.2 FEEDBACK AND REFLECTIONS FROM THE KOUE BOKKEVELD WATER WORKSHOP SERIES

The Koue Bokkeveld water workshop series is the project design's primary community engagement and knowledge-dissemination process. The posters disseminating the workshop are shared in Appendix A of this report. In this workshop, we engaged stakeholders in the study area, including water users, water managers and other sectors interested in water and environmental resources. So far, we have had three stakeholder workshops, the outcomes of which have been reported in previous deliverables. However, here we report a stakeholder reflection process that enabled us to gauge the effectiveness and impact of our engagement efforts. A template of the stakeholder feedback appears as Appendix B of this report, but we analysed the stakeholder reflections across two workshops. Figures 6.1 and 6.2 illustrate the reflection responses given by stakeholders during the first and second workshops. The responses in the figures pertain to the following questions:

Q1. *How satisfied were you with the communication you received about the purpose and content of the workshop?*
Q2. *How satisfied were you with the information you received before the session about logistical arrangements?*
Q3. *How satisfied are you with the workshop structure and facilitation? (e.g. Was it engaging? Were there sufficient breaks? Was the pace good? etc.)*
Q4. *How valuable did you find the workshop today?*

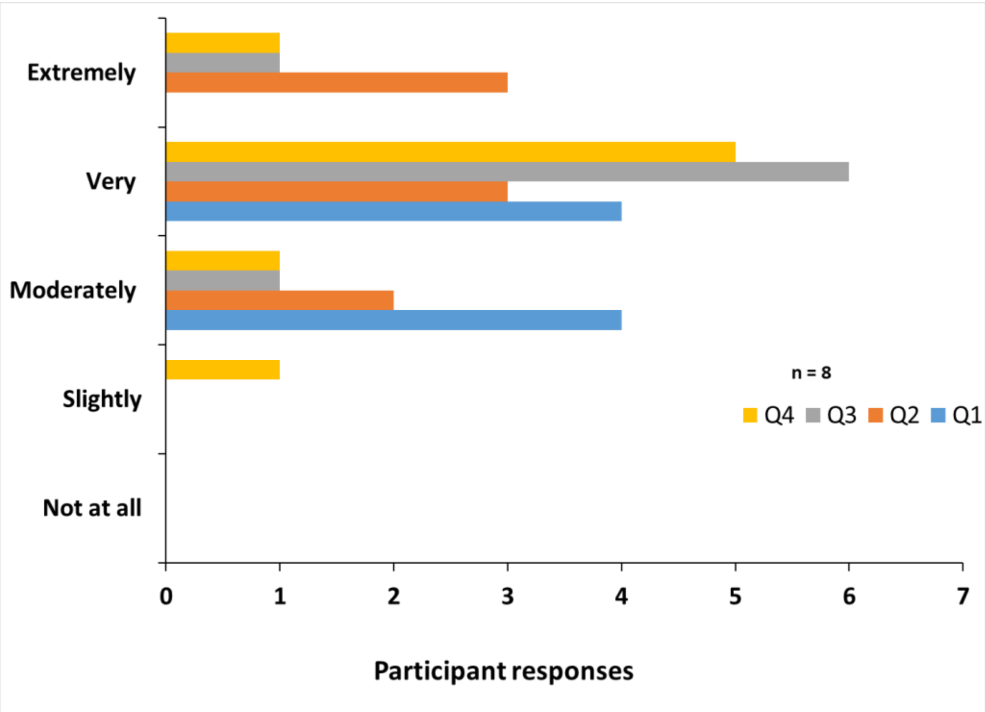


Figure 6.1 Illustrated stakeholder reflections summary from the first workshop

The outcomes indicate that stakeholders were moderately and very satisfied with the communication regarding the purpose and content of the first workshop. In workshop two, attendees more than doubled, and satisfaction with pre-workshop communication improved significantly. The improvement in attendees' numbers and satisfaction points to efforts by the project team to improve communication prior to a workshop. A similar trend in increased satisfaction levels is noted for Question 2. However, when asked what could be done better after the first workshop, most participants did not respond, and the team understood this to be a sign of satisfaction. Only three participants responded. A single participant used the section to compliment the process stating, "*Very well organised*". However, two other participants offered advice for improvement; one responded with

"*More clarity on purpose/expected outcomes,*" while another recommended a "*Less ambitious conceptual integration!*".

In terms of workshop structure and facilitation, most participants reported being very and extremely satisfied. The high participant satisfaction with the workshop reflects the high-level planning and preparation that the team invested in before the workshop. In addition, the team engaged a skilled professional workshop planner and facilitator. Only one person in both workshops reported moderate satisfaction; the rest of the participants were 'very' and 'extremely' satisfied with the facilitation. For Question 4, most participants (~76%) found the workshop more than very valuable in both workshops; less than 20% said it was moderately valuable, while only one participant in the workshop found the workshop to be slightly valuable. A slight improvement is therefore recorded in Workshop Two, where no participant was below moderate in terms of the value of the workshop.

A potential language barrier could have impacted the delivery of concepts; it may be necessary to consider active translation from English to Afrikaans during workshops. The following reflection from a participant supports the previous aspect "*Some more clarity was required on the last session with the stickers, language challenges, understanding the terminology*". In general, participants demonstrated an eagerness to get to the outcomes of the models; they want to get to the business of actual interaction with simulation models. While the project team was aware of the participants' enthusiasm, they remained cautious about taking participants through the necessary stages of co-modelling so that the output simulation models are well understood and legitimate. These reflections allowed the team to evaluate how the participants received the workshop and its related content. The participants' feedback will help the research team improve future workshops.

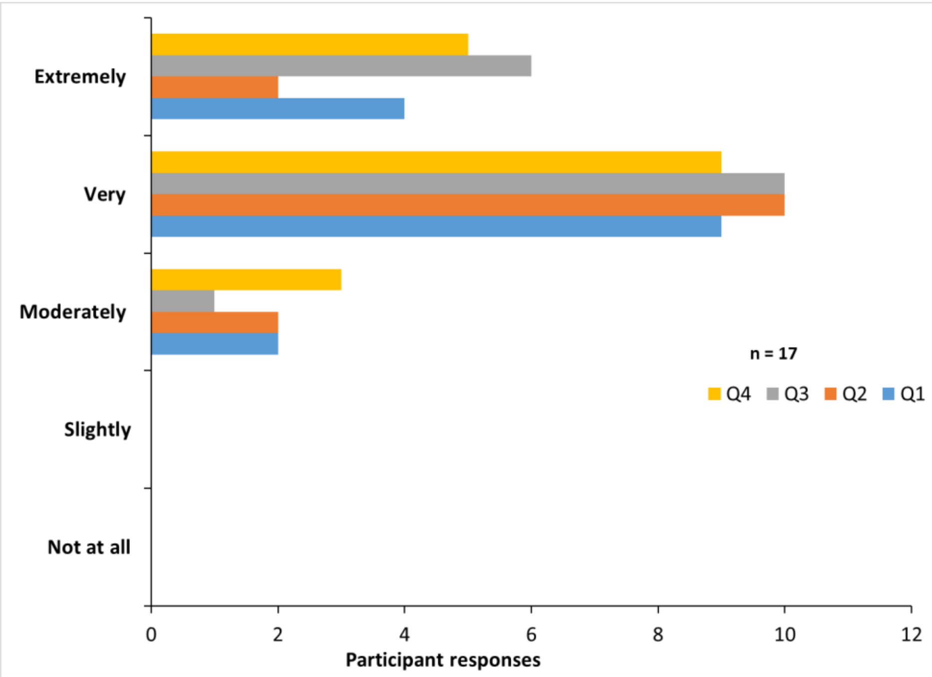


Figure 6.2 Illustrated stakeholder reflections summary from the second workshop

6.2.1 Preparation for the stakeholder engagement workshops

The stakeholder engagement process benefited from collaborating partners with long-standing relationships with the farmers in the KBV and the inclusion of a professional workshop facilitator. Using these individuals and existing communication structures and goodwill, it was easier to plan workshops and have good workshop attendance. Team composition is key to the success of engagement activities, and we strongly believe that the involvement of social scientists enriches the engagement and its outcomes. However, interdisciplinary research teams are challenging because individuals generally lean towards their disciplinary approaches; hence, it was necessary to work in a transdisciplinary way. Routine team meetings were essential to forming and maintaining a shared understanding as the project evolved.

Stakeholder mapping prior to engaging stakeholders is vital and has significant implications for the evolution of the engagement process. The team had access to a wealth of information about the KBV stakeholder activities, issues, behaviours, and relations. The information was provided by the collaborating partners, highlighting the importance of building meaningful research teams. We used the stakeholder information to craft an engagement process and mechanism that suited our stakeholder group. Consequently, we held a well-attended workshop and maintained good attendance throughout, making significant progress for the team. The progress is bound to the research team composition and the existence of champions within the stakeholder group. Some farmers and government stakeholders with significant social capital were key in canvassing support for the engagement activity. These influential individuals were identified as champions because they demonstrated a concern for the collective good and rallied other stakeholders to adopt a similar standpoint. Therefore, initial stakeholder mapping should identify such individuals and research teams must prioritise them in pre-engagement activities; their buy-in can determine the success or failure of the engagement.

Inviting many non-decision makers can result in a huge stakeholder group, making engagement more difficult. Ideally, engagement in such spaces should prioritise the key stakeholders who influence resource utilisation and have decision-making power (Conallin et al., 2017). For example, attending farm managers could not make a final decision in real-time without consulting their superiors. The consequences are ambiguity in the engagement process wherein present stakeholders become sceptical about the finality of outcomes agreed on without other key stakeholders. Unfortunately, this adds pressure to the research teams to reassure present stakeholders of the value of the process, regardless of the absent key stakeholders and to follow up on the absent stakeholders. Generally, it is unlikely to have all necessary stakeholders in the room all the time; therefore, the team must be prepared to ensure the engagement process does not stall. More engagement work must be done to ensure absent stakeholders participate in the process. The stakeholder engagement space can be chaotic, requiring the research teams to be adaptive (e.g. the research team had to visit farms after the workshops to gather more data because participants could not attend a workshop spanning more than a day). Additional engagements outside workshops occur consistently through a project team member based in the study area, who acts as a liaison.

6.2.2 Engaging stakeholders using the APP and ARDI approaches

In areas where resources are contested, a shared vision is the goal for a set of objectives (Palmer et al., 2023) based on an agreed set of values. A vision should highlight the issues and concerns; thus, the 'eliciting concerns' step allowed stakeholders to speak out about what was important to them; this is a vital step in developing the specific issues for inclusion in the vision. A shared vision becomes a basis for collaboration and commitment. The visioning process indicated a strong desire by the stakeholders to maintain the region's economic viability and indicated a firm understanding of the role of the ecosystem. A provincial government agricultural department participant remarked that farmers (the most critical stakeholders) are environmental stewards and have strong bonds with their land and environment. The South African Protected Areas database (DFFE, 2023) indicates that almost 80% of the E21H sub-catchment is a nature reserve, which keeps expanding, demonstrating farmers' commitment to environmental sustainability (Xoxo et al., 2023).

The vision outcome in the KBV is evidence of the shared priorities of the stakeholders. It is a consistent signpost of why they are involved in the engagement process and what they wish to achieve. Hence, stakeholder commitment to engagement has been strong, as shown by the participation in the ARDI process and thereafter. More participants attended the second and third workshops, drawing individuals from different catchments. Through their actions, stakeholders in the catchment have exhibited a commitment to the process (e.g. farmers who were initially unwilling to share data indicated during the third workshop that they would share some data with the team and later shared the data). The initial engagements built relationships and galvanised stakeholders towards the shared vision. Pollard et al. (2023) used a similar process in the Crocodile and Olifants Catchments in South Africa and reported that the visioning exercise was a key mediating device in contested spaces if accompanied by benchmarks for achieving the vision.

The stakeholders listed irrigation, crop type and water abstraction as key dynamics in the catchment indicating that farming is the major economic activity in the area. Remarkably, the listed dynamics highlight some concerns raised during the APP session, for example, the value of crops, alien species invasion, water quantity, and related water restrictions. The listed dynamics are key for representation in the system models. The approach used to gather the information ensures that the participants who are the target users of the simulation models are included in the development of the models. The model representations are constructed based on the participants' information and feedback, fostering a sense of involvement, ownership, and legitimacy for the simulation outcomes. A legitimate participatory process of model co-development is vital in situations where the model outcomes are used to discuss and plan the shared use of contested common resources. This research's cooperative use of engagement approaches enabled stakeholders to develop a basis and approach for collaboration despite competing interests and needs.

6.2.3 Stakeholder feedback

Participants gave valuable feedback on what can be improved in workshop facilitation and increasing the value of the workshops. One participant highlighted "*Clarity over what will be achieved*", while another remarked, "*Shorter, punchier explanations of the modelling process. Too much time on vague concepts*". The participants' feedback reflects that better science communication is needed. The participants' reflections also highlight the difficulty of distilling scientific concepts for a non-scientific audience. A potential language barrier could have impacted the delivery of concepts; it may be necessary to consider active translation from English to Afrikaans during workshops following the suggestion of Rangecroft et al. (2021). The following reflection from a participant supports the previous aspect "*Some more clarity was required on the last session with the stickers, language challenges, understanding the terminology*".

Participants were eager to get to the outcomes of the models; they wanted to get to the business of actual interaction with simulation models. While the project team was aware of the participants' enthusiasm, they were careful about taking participants through the necessary stages of co-modelling until the output of the simulation models was well understood and had been validated. The participants demonstrated confidence in the process and validated its usefulness by requesting the water department for surety that they would adopt the outcomes of the process. The team interpreted this as an acknowledgement by the stakeholders that the workshops can indeed culminate in a workable water management plan.

CHAPTER 7: SUMMARY OF FINDINGS, CONCLUSIONS & RECOMMENDATIONS

7.1 SUMMARY OF FINDINGS AND CONCLUSIONS

7.1.1 Understanding the Hydrology

- *Model Calibration and Parameters:* Manual calibration, addressing equifinality concerns, resulted in a well-fitted model for the Twee catchment. Selected parameters, including bulk density, plant uptake compensation factor, and runoff curve number, exhibited calibrated values optimizing model performance.

- *Hydrological Dynamics and Human Impact:* The calibrated model effectively captured the natural streamflow dynamics, with notable success in simulating peak flows and wet season low flows. Human development, represented by on-farm reservoirs and irrigation, significantly altered catchment flows, leading to reduced streamflow, particularly during dry years.

- *Water Balance Components:* Accurate simulation of water balance components highlighted the dominant role of evapotranspiration, accounting for 62% of total water input. Seasonal variations in surface runoff, interflow, and groundwater flow underscored the influence of rainfall on catchment hydrology.

- *Reservoir Dynamics and Impact on Flow:* Reservoir water levels varied based on irrigation water withdrawal, with substantial decreases during dry years. Reservoir spillage was reduced under irrigation conditions, impacting downstream flow during dry periods, and exacerbating downstream dryness.

7.1.2 Determining Ways to Share Water Using Agent-Based Modelling

- *ABM Implementation and Validation:* Implemented using CORMAS simulation environment, the ABM for KBV catchment underwent iterative development. Three major versions were defined, addressing the river network, crop fields, and dams, with continuous verification and validation. Objective validation involved comparing ABM output flows to observed data, while subjective evaluation gauged stakeholder acceptance.

- *Farm-Level Validation:* Simulation assessed water demand realism and revealed a disparity which was rectified with a correction parameter. Water shortage validation recognised the absence of historical records and relied on workshops and stakeholder discussions. Stakeholders acknowledged realistic outcomes, though challenges in obtaining precise historical shortage data were noted.

- *Short-Term Future Water Use Analysis, 2025 to 2030:* Scenarios explored moderate and extreme climate change, indicating increased catchment stress and potential water shortages. A scenario that included increased dam storage was also explored. In each scenario, model outputs indicate when farms (and the EWR) will be in deficit and for how long. A trend of increasing deficit was noted under climate change and when farmers increased hectarage. The introduction of increased dam storage led to a significant decline in farm water deficit and increased maintenance of the EWR.

- *Climate Adaptation:* The scenario, incorporating a shared dam and increased dam capacities, proved effective in mitigating water stress and enhancing resilience in agriculture in climate change. Increased dam storage and a new dam managed by the Water User Association, significantly reduced catchment stress. A noteworthy decrease in weeks where Environmental Water Requirements are not met is achieved, highlighting the scenario's success in addressing critical water scarcity challenges.

- *Stakeholder Acceptance and Engagement:* Stakeholders positively accepted the model's outputs, affirming realism with acknowledgement of inherent challenges. The model's ability to engage stakeholders and obtain their acceptance is crucial for refining accuracy and relevance in water resource management.

7.1.3 Determining Ways to Share Water Using the Water Sharing Tool

- *User Groups:* Five user groups, including corporate farmers, family farmers, downstream farmers, residents, and a reserve group. Categorisation is based on workshops and key-informant input, ensuring contextual relevance.
- *Community Weighting:* Analytic Hierarchical Process (AHP) used to establish a community weighting index for deficit conditions; reflects relative importance of user groups, integrating ecological, socio-economic, and legislative factors.
- *Resilience Measurement:* Combination of community weighting index and impact index assesses users' tolerance to water supply disruptions. Transparent ranking of supply priorities through user questionnaires.
- *Vulnerability Assessment:* Impact curves evaluate the consequences of water deficits on sectors. The systematic method assesses adaptive capacity, integrating social adaptation and stakeholder input.
- *Water Use Strategies:* Four strategies were introduced: Equal Sharing, Proportional Sharing, Proportional to Community Weighting, and Equalized Impact. These strategies address societal and environmental concerns, offering subtle water allocation approaches.
- *Serious Game (RPG) Approach:* Role-playing game proposed as an interactive tool for stakeholder engagement. Facilitates co-learning, participatory analysis, and collaborative decision-making in water management.
- *Key Risks (Deficit-Impact Analysis):* Impact curves assess environmental (EWR) and socio-economic vulnerabilities. Shifting in-stream requirements from environmental reserve level B to D exposes the environment to medium effects at 15% deficits. Downstream farmers are the most vulnerable to water deficits. Consortium farmers face the least impacts at 15% and 20% water deficit.
- *Overall Impact from Water Sharing Strategies:* we focus on the *Split the Bill* scenario, which allocates water equally among all users in a sub-catchment. The *Split the Bill* water allocation strategy shows minimal annual impacts (1-5%) for the community, individuals, and the environment, but the intensity can be severe (>7). Despite this, it helps mitigate disastrous impacts at the community level. Considering its overall negligible effects, the strategy is worth exploring further, especially as it aligns with water managers' goals of safeguarding national socio-economic interests like food security and employment.

7.1.4 Stakeholder Engagement, Feedback and Learnings

- *Workshop Satisfaction and Impact:* The outcomes reveal that stakeholders were generally satisfied with communication, which improved in the second workshop. Participants expressed high satisfaction with workshop structure and facilitation, emphasizing the need for clarity and concise explanations. The majority found the workshops very valuable, indicating a positive impact on participants.

- *Preparation and Stakeholder Engagement:* The success of stakeholder engagement is attributed to collaborating partners, a professional facilitator, and a transdisciplinary team. Stakeholder mapping and the identification of influential champions were crucial in planning and executing well-attended workshops. Challenges, such as the absence of key decision-makers, necessitated adaptive strategies and continuous engagement beyond workshop sessions.

- *Engaging Stakeholders Using APP and ARDI Approaches:* The report highlights the importance of a shared vision in contested resource areas. The 'eliciting concerns' step allowed stakeholders to voice priorities, contributing to the development of a shared vision. The visioning process demonstrated stakeholder commitment, leading to increased participation in subsequent workshops. The cooperative use of engagement approaches facilitated collaboration despite competing interests, built relationships, and galvanized stakeholders towards a shared vision.

- *Stakeholder Feedback and Model Co-Development:* Valuable feedback from participants emphasized the need for improved science communication, including active translation during workshops. Stakeholders expressed eagerness for practical interaction with simulation models, which demonstrated their confidence in the process. The team remained cautious, ensuring participants understood and validated simulation model outcomes before transitioning to water management planning.

7.2 RECOMMENDATIONS

- Conduct a more detailed groundwater investigation, as SWAT did not fully capture the complexities of groundwater and other hydrological dynamics in the conceptual model.
- Extend ABM future scenario simulations beyond the 2025-2030 period for a comprehensive, long-term assessment of water availability.
- Enhance models by obtaining detailed farm water use and yield information through increased engagement with farmers.
- Model current and future evaporation and increase in crop water demand under climate change scenarios.
- Adequately map invasive alien species and incorporate into the hydrological modelling to ascertain the impact of aliens clearing on water availability. Explore potential trade-off between availing more water by clearing alien species and constructing new dams.
- Advocate for more extended engagement and funding, as short-term projects like this one may risk incomplete outcomes after project completion.
- Simplify and improve communication of water sharing model strategies to enhance understanding.
- Present the findings to other Western Cape WUAs to encourage broader implementation in various catchments.
- Establish robust WUAs in catchments like KBV to accelerate engagement and adoption of water resource management initiatives, aligning with growing global concerns about sustainable food production.

REFERENCES

Adom R.K, Simatele M.D. (2022). The role of stakeholder engagement in sustainable water resource management in South Africa. *Natural Resources Forum* 46: 410-427. DOI: 10.1111/1477-8947.12264

Arnold J., Kiniry J.R., Srinivasan R., Williams J.R., Haney E., Neitsch S. (2012a). Swat Input Data: Res (Chapter 29). 393-406.

Arnold J.G., Bieger K., White M.J., Srinivasan R., Dunbar J.A., Allen P.M. (2018). Use of Decision Tables to Simulate Management in SWAT+. *Water* 2018, Vol. 10, Page 713, 10(6), 713. https://doi.org/10.3390/W10060713

Arnold J.G., Kiniry J.R., Srinivasan R., Williams J.R., Haney E.B., Neitsch S.L. (2012b). Soil & Water Assessment Tool.

Barreteau O., Bousquet F., Attonaty J.M. (2001). Role-playing games for opening the black box of multi-agent systems: method and lessons of its application to Senegal River Valley irrigated systems. *Journal of Artificial Societies and Social Simulation* 4

Berglund E.Z. (2015). Using Agent-Based Modeling for Water Resources Planning and Management. *Journal of Water Resources Planning and Management*, 141(11). https://doi.org/10.1061/(asce)wr.1943-5452.0000544

Beven K. (2001). How far can we go in distributed hydrological modelling? *Hydrology and Earth System Sciences*, 5(1), 1-12. https://doi.org/10.5194/hess-5-1-2001

Beven K.J., & Kirkby M.J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 24(1), 43-69. https://doi.org/10.1080/02626667909491834

Bieger K., Arnold J.G., Rathjens H., White M.J., Bosch D.D., Allen P.M., Volk M., & Srinivasan R. (2017). Introduction to SWAT+, A Completely Restructured Version of the Soil and Water Assessment Tool. *Journal of the American Water Resources Association*, 53(1), 115-130. https://doi.org/10.1111/1752-1688.12482

Birkmann J., Cardona O.D., Carreño M.L., Barbat A.H., Pelling M., Schneiderbauer S., Kienberger S., Keiler M., Alexander D., Zeil P., Welle T. (2013). Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards* 67: 193-211. DOI: 10.1007/S11069-013-0558-5/TABLES/1

Blewett S.C.J., Phillips D. (2016). An Overview of Cape Fold Belt Geochronology: Implications for Sediment Provenance and the Timing of Orogenesis. September, 45-55. https://doi.org/10.1007/978-3-319-40859-0_5

Booth, P.W.K., Shone R.W. (2002). A review of thrust faulting in the Eastern Cape Fold Belt, South Africa, and the implications for current lithostratigraphic interpretation of the Cape Supergroup. *Journal of African Earth Sciences*, 34(3-4), 179-190. https://doi.org/10.1016/S0899-5362(02)00017-9

Boyle E.A., Hainey T., Connolly T.M., Gray G., Earp J., Ott M., Lim T., Ninaus M., Ribeiro C., Ao Pereira J. (2016). An update to the systematic literature review of empirical evidence of the impacts and outcomes of computer games and serious games. *Computers & Education* 94: 178-192. DOI: 10.1016/j.compedu.2015.11.003

Brown C., Hartnady C., Hay R., David Le Maître. D (2003). Ecological and Environmental Impacts of Large-scale Groundwater Development in the Table Mountain Group (TMG) *Aquifer System Discussion Document* for. 1-40.

Chen Y., Marek G.W., Marek T.H., Porter D.O., Moorhead J.E., Heflin K.R., Brauer D.K, & Srinivasan, R. (2020). Watershed scale evaluation of an improved SWAT auto-irrigation function. *Environmental Modelling and Software*, 131(November 2019), 104789. https://doi.org/10.1016/j.envsoft.2020.104789

Conallin J.C., Dickens C., Hearne D., Allan C. (2017). Stakeholder Engagement in Environmental Water Management. In *Water for the Environment: From Policy and Science to Implementation and Management*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-803907-6.00007-3

Moriasi D.N., Arnold J.G., Van Liew M.W., Bingner R.I., Harmel R.D. (2007). *Model Evaluation Guideline for Systematic Quantification of Accuracy in Watershed Simulation*. Colombia Medica, 39(3), 227-234.

Tetzlaff D., Soulsby C., Waldron S., Malcolm I.A., Bacon P.J., Dunn S.M. (2007). Advanced Bash-Scripting Guide: An in-depth exploration of the art of shell scripting Table of Contents. Okt 2005 Abrufbar Uber Http//www Tldp OrgLDPabsabsguide Pdf Zugriff 1112 2005, 2274(November 2008), 2267-2274. https://doi.org/10.1002/hyp

Department of Water Affairs and Forestry. (2005). Olifants/Doorn WMA: Internal Strategic Perspective.

Dile Y., Srinivasan R. & George, C. (2022). QGIS Interface for SWAT+: QSWAT+. 1.2.2(April), 118.

Duethmann D., Zimmer J., Gafurov A., Güntner A., Kriegel D., Merz B., Vorogushyn, S. (2013). Evaluation of areal precipitation estimates based on downscaled reanalysis and station data by hydrological modelling. *Hydrology and Earth System Sciences*, 17(7), 2415-2434. https://doi.org/10.5194/hess-17-2415-2013

DWAF. (2013). National Water Resource Strategy. Water for an Equitable and Sustainable Future. (Department of Water Affairs and Forestry, Pretoria. https://www.dwa.gov.za/nwrs/NWRS2013.aspx.

DWAF. (2003). Breede River Basin Study, groundwater assessment. Department of Water Affairs and Forestry, South Africa., No. PH 00/, 103.

DWS. (2017). Proposed reserve determination of water resources for the Olifants-Doorn Catchments (Public Law 356 of 2017). Department of Water and Sanitation: South Africa, 106-167

Elshafei Y., Sivapalan M., Tonts M., Hipsey M.R. (2014). A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. *Hydrology and Earth System Sciences* 1: 2141-2166. DOI: 10.5194/HESS-18-2141-2014

Farolfi S., Müller J.P., Bonté B. (2010). An iterative construction of multi-agent models to represent water supply and demand dynamics at the catchment level. *Environmental Modelling and Software*, 25(10), 1130-1148. https://doi.org/10.1016/j.envsoft.2010.03.018

Ferber J., Gutknecht O., Michel F. (2004). From Agents to Organizations: *An Organizational View of Multi-agent Systems*. 214-230.

Goovaerts P. (2000). Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. *Acta Polymerica Sinica*, 228(3), 442-445.

Guan H., Wilson J.L., Makhnin O. (2005). Geostatistical mapping of mountain precipitation incorporating autosearched effects of terrain and climatic characteristics. *Journal of Hydrometeorology*, 6(6), 1018-1031. https://doi.org/10.1175/JHM448.1

Hughes D.A. (2013. A review of 40 years of hydrological science and practice in southern Africa using the Pitman rainfall-runoff model. *Journal of Hydrology*, 501, pp.111-124.

Hughes D.A. (2010a). Hydrological models: mathematics or science? 2201(June), *Hydrological Processes Journal.* 2199-2201. https://doi.org/10.1002/hyp.7805

Hughes, D.A. (2010b). Unsaturated zone fracture flow contributions to stream flow: Evidence for the process in South Africa and its importance. *Hydrological Processes*, 24(6), 767-774. https://doi.org/10.1002/hyp.7521

Hughes D.A., Desai A.Y., Birkhead A.L., Louw, D. (2014). A new approach to rapid, desktop-level, environmental flow assessments for rivers in South Africa. *Hydrological Sciences Journal.* 59, 673-687. doi: 10.1080/02626667.2013.818220

Hughes D.A., Mallory S.J.L. (2009). The importance of operating rules and assessments of beneficial use in water resource allocation policy and management. *Water Policy* 11: 731-741. DOI: 10.2166/wp.2009.035

Hughes D.A. & Mantel S.K. (2010). Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. *Hydrological Sciences Journal*, 55(4), 578-592. https://doi.org/10.1080/02626667.2010.484903

Intergovernmental Panel on Climate Change [IPCC]. (2012). Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. [Field C.B., V. Barros T.F., Stocker D., Qin D.J., Dokken K.L., Ebi M.D., Mastrandrea K.J., Mach G.-K., Plattner S.K., Allen, M., Tignor. Cambridge, England. https://doi.org/10.1017/CBO9781139177245

Kapangaziwiri E., Hughes D.A. (2008). Towards revised physically based parameter estimation methods for the Pitman monthly rainfall-runoff model. *Water SA,* 34(2), 183-192. https://doi.org/10.4314/wsa.v34i2.183638

Kapangaziwiri E., Hughes D.A., Wagener T. (2012). Incorporating uncertainty in hydrological predictions for gauged and ungauged basins in southern Africa. *Hydrological Sciences Journal*, 57(5), 1000-1019. https://doi.org/10.1080/02626667.2012.690881

Kelly R.A., Jakeman A.J., Barreteau O., Borsuk M.E., El Sawah S., Hamilton S.H., Henriksen H.J., Kuikka S., Maier H.R., Rizzoli A.E., van Delden H., Voinov A.A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling and Software* 47. DOI: 10.1016/j.envsoft.2013.05.005

Khan H.F., Yang Y.C.E., Xie H., Ringler C. (2017). A coupled modeling framework for sustainable watershed management in transboundary river basins. *Hydrology and Earth System Sciences*, 21(12), 6275-6288. https://doi.org/10.5194/hess-21-6275-2017

Kumar P., Avtar R., Dasgupta R., Johnson B.A., Mukherjee A., Ahsan M.N., Nguyen D.C.H., Nguyen H.Q., Shaw R., Mishra B.K. (2020). Socio-hydrology: A key approach for adaptation to water scarcity and achieving human well-being in large riverine islands. *Progress in Disaster Science* 8: 100134. DOI: 10.1016/J.PDISAS.2020.100134

Lamarque P., Artaux A., Barnaud C., Dobremez L., Nettier B., Lavorel S. (2013). Taking into account farmers' decision making to map fine-scale land management adaptation to climate and socio-economic scenarios. *Landscape and Urban Planning* 119: 147-157. DOI: 10.1016/J.LANDURBPLAN.2013.07.012

le Roux P.A.L., du Preez C.C., Bühmann C. (2005). Indications of ferrolysis and structure degradation in an estcourt soil and possible relationships with plinthite formation. *South African Journal of Plant and Soil*, 22(4), 199-206. https://doi.org/10.1080/02571862.2005.10634708

Lin L., Lin H., Xu Y. (2014). Characterisation of fracture network and groundwater preferential flow path in the Table Mountain Group (TMG) sandstones, South Africa. *Water SA*, 40(2), 263-272. https://doi.org/10.4314/wsa.v40i2.8

Mair A., Fares A. (2011). Comparison of Rainfall Interpolation Methods in a Mountainous Region of a Tropical Island. *Journal of Hydrologic Engineering*, 16(4), 371-383. https://doi.org/10.1061/(asce)he.1943-5584.0000330

Marahatta S., Aryal D., Devkota L.P., Bhattarai U., Shrestha D. (2021). Application of SWAT in Hydrological Simulation of Complex Mountainous River Basin (Part II : Climate Change).

Martin G., Felten B., Duru M. (2011). Forage rummy: A game to support the participatory design of adapted livestock systems. *Environmental Modelling & Software* 26:1442-1453. DOI: 10.1016/J.ENVSOFT.2011.08.013

Matrosov E.S., Woods A.M., Harou J.J. (2013). Robust Decision Making and Info-Gap Decision Theory for Water Resource System Planning. *Journal of Hydrology* 494: 43-58. DOI: 10.1016/J.JHYDROL.2013.03.006

Matthews K.B., Rivington M., Blackstock K., McCrum G., Buchan K., Miller D.G. (2011). Raising the bar? – The challenges of evaluating the outcomes of environmental modelling and software. *Environmental Modelling & Software* 26: 247-257. DOI: 10.1016/J.ENVSOFT.2010.03.031

Ndzabandzaba C., Hughes D.A. (2017). Regional water resources assessments using an uncertain modelling approach: The example of Swaziland. *Journal of Hydrology: Regional Studies*, 10, 47-60. https://doi.org/10.1016/j.ejrh.2017.01.002

Nkwasa A., Chawanda C.J., Jägermeyr J., Van Griensven A. (2022). Improved representation of agricultural land use and crop management for large-scale hydrological impact simulation in Africa using SWAT+. *Hydrology and Earth System Sciences*, 26(1), 71-89. https://doi.org/10.5194/hess-26-71-2022

Nkwasa A., Chawanda C.J., Msigwa A., Komakech H.C., Verbeiren B., van Griensven A. (2020). How Can We Represent Seasonal Land Use Dynamics in SWAT and SWAT+ Models for African Cultivated Catchments? *Water 2020*, Vol. 12, Page 1541, 12(6), 1541. https://doi.org/10.3390/W12061541

Nkwasa A., Waha K., Griensven A. van. (2023). Can the cropping systems of the Nile basin be adapted to climate change? *Regional Environmental Change*, 23(1), 1-14. https://doi.org/10.1007/s10113-022-02008-9

Nolte A., Eley M., Schöniger M., Gwapedza D., Tanner J., Mantel S.K., Scheihing K. (2021). Hydrological modelling for assessing spatio-temporal groundwater recharge variations in the water-stressed Amathole Water Supply System, Eastern Cape, South Africa. *Hydrological Processes*, 35(6), e14264. https://doi.org/10.1002/HYP.14264

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N. K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Cisneroz, B. J., Kattsov, V., Lee, H., Mach, K. J., Marotzke, J., Mastrandrea, M. D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J. J., Pichs-Madruga, R., Plattner, G.-K., Pörtner, H.-O., Power, S. B., Preston, B., Ravindranath, N. H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T. F., Tschakert, P., van Vuuren, D., van Ypserle, J.P. (2014). Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 2014.

Palmer C.G., Rogers K., Holleman H., Wolff M. (2013). How to use Strategic Adaptive Management in (SAM) and the Adaptive Planning Process (APP) to build a shared catchment future. *WRC How To Handbooks*

Palmer T., Tanner J., Akanmu J., Alamirew T., Banadda N., Cleaver F., Faye S., Kabenge I., Kane A. (2023). The Adaptive Systemic Approach: catalysing more just and sustainable outcomes from sustainability and natural resources development research. *River Research and Applications*, August 2022, 1-15. https://doi.org/10.1002/rra.4178

Pappenberger F., Beven K. J. (2006). Ignorance is bliss: Or seven reasons not to use uncertainty analysis. *Water Resources Research*, 42(5), W05302. https://doi.org/10.1029/2005WR004820

Paxton B., Walker J. (2018). Appendix A – Synthesis Report. Freshwater Research Centre. South Africa.

Pienaar G.W., Hughes D.A. (2017). Linking Hydrological Uncertainty with Equitable Allocation for Water Resources Decision-Making. *Water Resources Management*, 31(1), 269-282. https://doi.org/10.1007/s11269-016-1523-3

Pollard S.R., Riddell E., du Toit D.R., Retief D.C., Ison R.L. (2023). Toward adaptive water governance: the role of systemic feedbacks for learning and adaptation in the eastern transboundary rivers of South Africa. *Ecology and Society*, 28(1). https://doi.org/10.5751/ES-13726-280147

Pouladi P., Afshar A., Afshar M.H., Molajou A., Farahmand H. (2019). Agent-based socio-hydrological modeling for restoration of Urmia Lake: Application of theory of planned behavior. *Journal of Hydrology*, 576(June), 736-748. https://doi.org/10.1016/j.jhydrol.2019.06.080

Putthividhya A., Tanaka K. (2013). Optimal rain gauge network design and spatial precipitation mapping based on geostatistical analysis from co-located elevation and humidity data. *Chiang Mai Journal of Science*, 40(2), 187-197. https://doi.org/10.7763/ijesd.2012.v3.201

Rangecroft S., Rohse M., Banks E.W., Day R., Di Baldassarre G., Frommen T., Hayashi Y., Höllermann B., Lebek K., Mondino E., Rusca M., Wens M., Van Loon, A. F. (2021). Guiding principles for hydrologists conducting interdisciplinary research and fieldwork with participants. *Hydrological Sciences Journal*, 66(2), 214-225. https://doi.org/10.1080/02626667.2020.1852241

Refsgaard J.C. (1997). Parameterisation, calibration and validation of distributed hydrological models. *Journal of Hydrology*, 198(1-4), 69-97. https://doi.org/10.1016/S0022-1694(96)03329-X

Rockström J., Falkenmark M., Allan T., Folke C., Gordon L., Jägerskog A., Varis O. (2014). The unfolding water drama in the Anthropocene: Towards a resilience-based perspective on water for global sustainability. *Ecohydrology*. https://doi.org/10.1002/eco.1562

Roux P.A.L., Preez C.C. (2006). Nature and distribution of South African plinthic soils : Conditions for occurrence of soft and hard plinthic soils. *South African Journal of Plant and Soil*, 1862. https://doi.org/10.1080/02571862.2006.10634741

Savenije H.H.G. (2010). HESS opinions “topography driven conceptual modelling (FLEX-Topo).” *Hydrology and Earth System Sciences*, 14(12), 2681-2692. https://doi.org/10.5194/hess-14-2681-2010

Schlüter M., Lindkvist E., Wijermans N., Polhill G. (2021). Agent-based modelling. *The Routledge Handbook of Research Methods for Social-Ecological Systems*, 332-346. https://doi.org/10.4324/9781003021339-28

Schmocker-Fackel P., Naef F., Scherrer S. (2007). Identifying runoff processes on the plot and catchment scale. *Hydrology and Earth System Sciences*, 11(2), 891-906. https://doi.org/10.5194/hess-11-891-2007

Senarath S.U.S., Ogden F.L., Downer C.W., Sharif, H. O. (2000). On the calibration and verification of two-dimensional, distributed, Hortonian, continuous watershed models. *Water Resources Research*, 36(6), 1495-1510. https://doi.org/10.1029/2000WR900039

Sivapalan M., Savenije H.H.G., Blöschl G. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes* 26: 1270-1276. DOI: 10.1002/hyp.8426

Stolk A., van Huyssteen C.W. (2019). Clay and iron oxide contents of prismacutanic B, G, soft plinthic B, and E horizons described during the land type survey of South Africa. *South African Journal of Plant and Soil*, 36(3), 165-172. https://doi.org/10.1080/02571862.2018.1544381

Tarboton, D. G. (2017). Exercise 5. Height above Nearest Drainage Flood Inundation Analysis GIS in Water Resources, Fall 2016.

Tarboton D.G., Sazib N., Dash P. (2015). QUICK START GUIDE TO USING THE TAUDEM ARCGIS TOOLBOX October 2015 David G. Tarboton Nazmus Sazib Pabitra Dash. October.

Tanner J., Mantel S., Paxton B., Slaughter A., Hughes D. (2022). Impacts of climate change on rivers and biodiversity in a water-scarce semi-arid region of the Western Cape, South Africa. *Frontiers in Water*, 4(36). https://doi.org/10.3389/frwa.2022.949901

Tumbo M., Hughes D.A. (2015). Uncertain hydrological modelling: Application of the Pitman model in the Great Ruaha River Basin, Tanzania. *Hydrological Sciences Journal*. 60 (11), 2047-2061. https://doi.org/10.1080/02626667.2015.1016948.

van Huyssteen C.W., Ellis F. (1997). The relationship between subsoil colour and degree of wetness in a suite of soils in the Grabouw district, Western Cape I. Characterization of colour-defined horizons. *South African Journal of Plant and Soil,* 14(4), 149-153. https://doi.org/10.1080/02571862.1997.10635099

van Tol J J., Hensley M., Le Roux P. (2013). Pedological criteria for estimating the importance of subsurface lateral flow in E horizons in South African soils. *Water SA*, 39(1), 47-56. https://doi.org/10.4314/wsa.v39i1.7

van Tol J.J., le Roux P., Hensley M., Lorentz S.A. (2010). Soil as indicator of hillslope hydrological behaviour in the Weatherley Catchment, Eastern Cape, South Africa. *Water SA*, 36(5), 513-520. https://doi.org/10.4314/wsa.v36i5.61985

van Tol J.J., Roux P.A.L.L., Hensley M. (2010). Soil indicators of hillslope hydrology in the bedford catchments, South Africa. In: *South African Journal of Plant and Soil* (Vol. 27, Issue 3, pp. 242-251). https://doi.org/10.1080/02571862.2010.10639993

Booth P.W.K. (2020). A Review of the Structural Geology of the Cape Fold Belt and Challenges Towards Future Research. September, 481-485. https://doi.org/10.3997/2214-4609-pdb.241.booth_paper

Winter T.C. (2001). The concept of hydrologic landscapes. *Journal of the American Water Resources Association*, 37(2), 335-349. https://doi.org/10.1111/j.1752-1688.2001.tb00973.x

Wolock D.M., Winter T.C., McMahon G. (2004). Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. *Environmental Management,* 34 Suppl 1, 71-88. https://doi.org/10.1007/s00267-003-5077-9

Wolski P., Hewitson B., Jack C. (2017). Why Cape Town's drought was so hard to forecast? [Online]. Cape Town: UCT Climate Systems Analysis Group. Available: https://theconversation.com/why-cape-towns-droughtwas-so-hard-to-forecast-84735 (Accessed 22 June 2020)

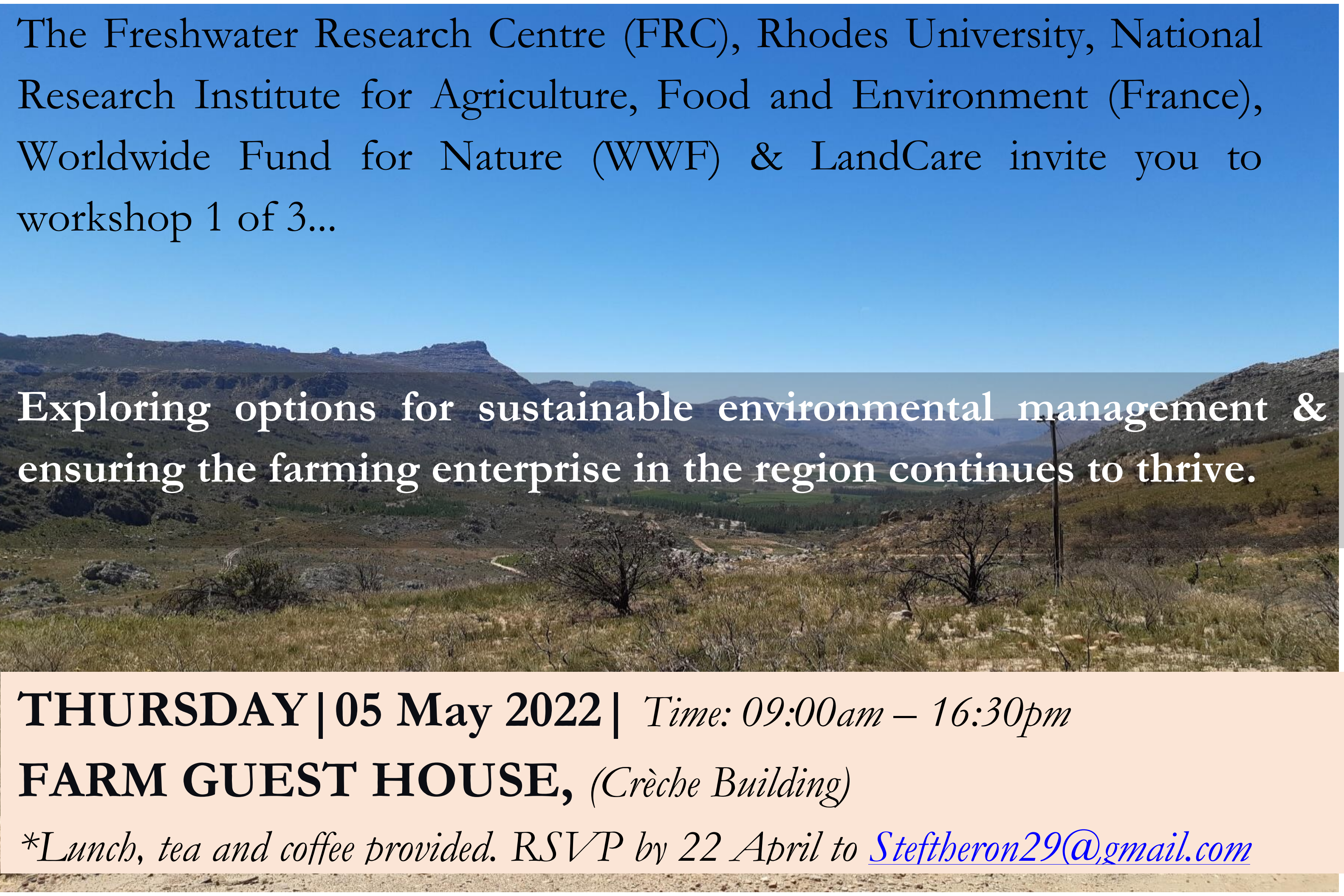
Wu J., Yen H., Arnold J.G., Yang Y.C.E., Cai X., White M.J., Santhi C., Miao C,, Srinivasan R. (2020). Development of reservoir operation functions in SWAT+ for national environmental assessments. *Journal of Hydrology,* 583(December 2019), 124556. https://doi.org/10.1016/j.jhydrol.2020.124556

Xoxo S., Tanner J., Mantel S., Gwapedza D., Paxton B., Hughes D., Barreteau O. (2023). Equity-Based Allocation Criteria for Water Deficit Periods: A Case Study in South Africa. *Lecture Notes in Business Information Processing*, 474 LNBIP, 137-155. https://doi.org/10.1007/978-3-031-32534-2_11

Xu Y., Beekman, H. E. (2019). Review: Groundwater recharge estimation in arid and semi-arid southern Africa. *Hydrogeology Journal*, 27(3), 929-943. https://doi.org/10.1007/s10040-018-1898-8

APPENDICES

Appendix A. Two posters that were used to invite stakeholders to the workshops.



The collaborative model building process for the Twee River will take place over 3 workshops in 2022. We invite you to join the 1st workshop to actively contribute to the design of hydrological and system models that fit your representations and experience of your catchment.

*Workshop **2**: Planned August 2022*

*Workshop **3**: Planned November 2022*

The Freshwater Research Centre (FRC), Rhodes University, National Research Institute for Agriculture, Food and Environment (France), Worldwide Fund for Nature (WWF) & LandCare invite you to workshop 2 of 2022.

Exploring options for sustainable environmental management & ensuring the farming enterprise in the region continues to thrive.

THURSDAY | 24 November 2022 | *Time: 09:00am – 16:30pm*

FARM GUEST HOUSE, *(Crèche Building)*

**Lunch, tea and coffee provided.*

RSVP by 22 October to Steftheron29@gmail.com (cell: +27 79 931 6765)

workshops in 2022 & 2023. We invite you to join the 2nd workshop *(of 2022)* to receive feedback on the last workshop, see how the data was used for model development, see the prototype models, and contribute to collectively refining the models.

*Workshop **3**: Planned May 2023*

Appendix B. A tool for collecting stakeholder reflection after the workshops

Workshop participant feedback

BEFORE

1. How satisfied were you with the communication you received about the purpose and content of the workshop?

Not at all	Slightly	Moderately	Very	Extremely

2. How satisfied were you with the information you received before the session about logistical arrangements?

Not at all	Slightly	Moderately	Very	Extremely

3. What could we do better next time?

DURING

4. How satisfied are you with the venue, catering and set up of the workshop today?

Not at all	Slightly	Moderately	Very	Extremely

5. How satisfied are you with the workshop structure and facilitation? *(e.g. Was it engaging? Were there sufficient breaks? Was the pace good? etc.)*

Not at all	Slightly	Moderately	Very	Extremely

6. How valuable did you find the workshop today?

Not at all	Slightly	Moderately	Very	Extremely

7. What could we do better next time?

AFTER

8. What kind of feedback and communication would you like after this workshop?
9.

Appendix C. Water Use Plan Template

Water Use Plan Template

The water use plan template was provided by the DWS in Western Cape. During the workshops, the DWS confirmed that it would accept a Water Use Plan that emerges from this project and the engagement process. The project has generated data and information that goes directly into the sections marked in blue font. The rest of the sections must be completed by the WUA. The WUA will use the information from the models and select sharing strategies of their choice to include in the plan with some assistance from the project team.

WATER MANAGEMENT PLAN FOR THE
TWEE RIVER WATER USER ASSOCIATION

02 November 2023

Submitted by:

Koue Bokkeveld Water Users Association
PO Box ________

____

____
____

4.OPERATIONS AND OPERATING PROCEDURES

4.1. General scheme options
4.2. Reporting
4.3. Water Transfers
4.4. Water Pricing Structure

5.EQUITABLE WATER DISTRIBUTION

5.1. Water Use Authorization
5.2. Water Losses
5.3. Control of Alien Vegetation [WWF]

6.WATER MANAGEMENT ISSUES AND GOALS

6.1. Overview of the management issues
6.2. Flow measurements and water accounting – Telemetry
6.3. Operational water management issues

7.KBWUA WATER MANAGEMENT PLAN

7.1. Setting of targets
7.2. Implementation Plan

8.CONCLUSIONS AND RECOMMENDATIONS