Mainstreaming Equitable Decision-Making Under Uncertainty at the Water User Association Level Using a Reallocation Model in the Western Cape, South Africa

A thesis submitted in fulfilment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

of

RHODES UNIVERSITY

by

B. SINETEMBA XOXO

ORCID ID: 0000-0003-3979-4326

August 2024

Declaration

I, Beaten Sinetemba Xoxo, student number 613x2945, hereby declare that this thesis for the degree of Doctor of Philosophy is my own work except where explicitly stated. I also declare that the thesis has not been previously submitted for assessment or completion of any postgraduate qualification to another University or another qualification.

Abstract

This thesis demonstrates how uncertainty can be explicitly incorporated into equitable decision-making in ungauged basins to support fair water reallocation strategies among conflicting uses and reduce vulnerability to water shortages. First, a methodological framework is developed to collect the required socio-economic data. Second, a role-playing game (RPG) is developed in collaboration with stakeholders to increase awareness and assess the implications of different allocation strategies and stakeholder actions. Thirdly, a reallocation decision-support system (Water-Sharing Tool) with dam storage and uncertainty is tested to inform strategic water planning under dry conditions.

The study was carried out in collaboration with stakeholders in the upper reaches of the Koue Bokkeveld, Western Cape, South Africa. The study area is a winter rainfall area with commercial farming activities targeting the domestic and cross-border markets. Irrigation from numerous farm dams and run-of-river extraction compete with in-stream environmental protection targets for streamflow. The study area can be described as resource-poor in terms of institutional capacity, with water management decisions taken individually at a farm level.

The key water users are the environment, farmers, lifestyle farmers (residents), and weekenders. The farmer group has three sub-groups: corporate-owned farms, family-owned commercial farms, and downstream less well-resourced farmers. Results from the user risk profiles show that the least influential actors reside downstream and are more vulnerable to water shortages, which could be attributed to upstream developments and their productivity-driven nature.

The thesis pulls together the socio-economic data, the information contributed by the stakeholders during the RPG, uncertain natural runoff estimates, and water demands. It evaluates these using the Water Sharing Model to map water users' vulnerability under four different management strategies and assesses equitable reallocation outcomes of the proposed strategies to different users. The magnitude and frequency of decision risks and the underlying uncertainty in the water supply are quantified. As expected, results suggest peak risks during months with the lowest streamflow, with negative implications for fruit production in the catchment. Results also showed the negative supply effects of upstream infrastructure development on downstream users and ecosystems.

Game results with the farmers suggested different crop choices in dry periods between upstream and downstream farmers. Downstream farmers were surprisingly more willing to forego their dry season entitlements under water-sharing strategies that resulted in serious production losses upstream, prioritising social stability over their own profits. Farmers reflected on the game as an educational tool

to enhance system understanding. The study confirms that decision-makers' understanding of the implications of water allocation decisions and the surrounding uncertainty is critical to meeting justice/fairness objectives.

Table of Contents

List of Tables

Acknowledgements

This thesis is a product of long hours and a rewarding collaboration among a group of dedicated scholars and landowners unified by a commitment to advance the sustainable management of water resources. These collaborators are from the Institute for Water Research and the Department of Computer Science (Rhodes University, South Africa), Rhodes University, INRAE (Montpellier, in France), the Freshwater Research Centre, and Land Care (Western Cape Department of Agriculture). I would like to express a special thanks to the farmers in the Twee Wyk, who committed their time to the long workshops, which without, this work would not have been possible.

This work was supported by financial support from the National Research Foundation (ref: PMDS23041191086) and the Water Research Commission (Project no. C2020/2021-00607). A special thanks to the National Research Foundation and the French Embassy in South Africa for funding the training visits to France.

Grateful thanks are extended to my supervisors, Dr Jane Tanner and Assoc. Prof. Sukhmani Mantel who challenged me to take this project on. I am indebted to Emeritus Prof. Denis Hughes, Dr Olivier Barreteau, Dr Bruno Bonte, Prof. Karen Bradshaw, and Mr David Forsyth for the methods used here.

And last but not least, I want to thank me.

1. INTRODUCTION

Scarce water distribution decisions carry social, economic, and environmental consequences (Hoekstra et al., 2012; Vanham et al., 2018; Rezaee et al., 2021). Given the growing water scarcity and shortages (Mekonnen & Hoekstra, 2016; Liu et al., 2017; Vanham et al., 2018), water reallocations can be necessary to fulfil environmental water requirements that are largely contested globally (Arthington et al., 2018; Liu et al., 2021). A share for other socially important uses that were previously neglected could be achieved through water reallocation mechanisms (Bark, 2009). In this context, water reallocations refer to a shift in demand management strategy when water is insufficient to fulfil all demands. These water-sharing strategies are temporary and dynamically follow available supply, while the normal year entitlements remain in periods of sufficient supply.

The water reallocation practice differs from water allocation, which is the initial distribution of natural water availability (Marston & Cai, 2016). Semi-arid areas such as South Africa require water reallocation agreements to mitigate limited water accessibility due to physical constraints such as climate and human-driven shortages (Flörke et al., 2018). The temporary farmer-to-urban water transfers in the Western Cape, South Africa, during the 2015/19 drought (Rawlins, 2019; Theron et al., 2023) demonstrate this requirement. During the 2015/19 drought, Western Cape farmers received only 14 to 40% of their standard entitlement, translating to a 35% decline in agricultural outputs, which could persist for a medium to long-term period (Pienaar & Boonzaaier, 2018). Farmers had to prioritise high-value orchards and abandon vegetable production in response to the restrictions (reallocation). Therefore, considering the various options for sharing water in deficit periods, and the consequences of decisions is an essential shift to live up to the social justice and environmental sustainability targets (Hughes & Mallory, 2009; Höllermann & Evers, 2017). These targets are essential requirements for water management in democratic South Africa (RSA, 1998a).

When fairly applied and supported by enabling government frameworks (Bark, 2009; Jackson & Barber, 2013; Movik, 2014; United Nations, 2017; Global Water Partnership, 2024), as well as innovative, practical tools (Keeler et al., 2020), water reallocations can be a source of prosperity and social cohesion as outlined in the recent United Nations Water Report (UN Water, 2024). Fair procedures are characterised by a strategic involvement of society and a recognition of societal conditions to augment fairness/justice by representing all users for a democratic reallocation process (Patrick, 2014; Prieto, 2021; Seigerman et al., 2022). However, practical and financial limitations still constrain the roll-out of decision-support processes tailored to balance environmental sustainability and human needs beyond economic outcomes (Leach et al., 2018). As a result, interventions that promote justice in local water management bodies are still required (Seigerman et al., 2022), and they should be directed by national environmental objectives and social development aspirations while recognising societal disparities (McDermott et al., 2013).

While the focus of equitable water management centres around fair representation of various water use sectors in decision-making, another aspect of water management requiring attention is the variable and uncertain characteristics of water resources (Beven 2016) and the implication of not accounting for this variability and uncertainty in decision making. This points to the need to close the uncertainty-handling gap between research and practice (Beven & Alcock, 2012; Fischhoff & Davis, 2014). As shown in the flood management example in the Yellow River Delta, considering a wide range of hydrological outcomes and scenarios in water resource planning, improves robust decision-making Chen & Hobbs, 2021). The concept of uncertainty and salience of uncertain information in local-level water management should be a critical component of decision support processes given the vulnerability of many stakeholders to decisions based on uncertain information (Mayer & Muñoz-Hernandez, 2009; Höllermann & Evers, 2019; Keeler et al., 2020). Such innovative approaches can deepen the understanding of current complexity and prepare stakeholders for potential and deeply uncertain futures.

The complex nature of water reallocation implies a need for integrated tools to help reduce the underlying complexity and generic uncertainty (Liu & Gupta, 2007; Kumar et al., 2020). Uncertainty is integral to water resources due to non-linear behaviour, and this affects resource reliability (Beven, 2013). Uncertainty also stems from imperfect data (Beven & Westerberg, 2011; Mcmillan et al., 2012). The earlier is natural and irreducible, whereas the latter can be reduced by collecting more reliable data (Beven, 2016; Gupta & Govindaraju, 2023). However, even in areas with plentiful data, uncertainties exist due to human and technical errors (Di Baldassarre & Montanari, 2009; Westerberg & McMillan, 2015). Additional sources of uncertainty include incorrect assumptions about the hydrological process (Beven, 2006; Montanari & Koutsoyiannis, 2012) and dynamic human behaviour with implications on future demands (Sivapalan & Blöschl, 2015; Pascual et al., 2023).

1.1. Research aims and objectives.

Since water reallocation is both a social and a technical challenge, the points above highlight the importance of uncertainty analysis and participatory practices as essential aspects of responsible water management. This points to the need for tools that incorporate both aspects, which will allow decision-makers to see how uncertain information addresses their knowledge gaps and facilitate learning in terms of how different decisions affect all resource users and the system as a whole (Mcmillan et al., 2017; Westerberg et al., 2017). **This work aims to demonstrate how uncertainty can**

be explicitly incorporated into equitable decision-making in ungauged basins to support fair water reallocation strategies among conflicting users and reduce vulnerability to water shortages. This work builds on previous work on the need to consider impacts in water allocation decisions by Hughes and Mallory (2009), the first version of the Water-Sharing Tool by (Pienaar and Hughes (2017), and the guidelines to transfer uncertain outcomes for use in decision-making (Fischhoff & Davis, 2014; Höllermann & Evers, 2019). For the work presented here, water is considered a common good, which is a suitable framing for water governance to balance self-interest and group aspirations.

There are three overarching objectives to achieve the main aim:

- Objective 1: To create a protocol for collecting socio-economic data to facilitate stakeholder engagement activities that will gather the appropriate data from the stakeholders for inclusion in the model.
- Objective 2: To co-develop and utilise a role-playing game to introduce and co-evaluate plausible water-sharing strategies.
- Objective 3: To setup and test the Water Sharing Tool with Dam Uncertainty as a tool for operationalising uncertainty and fairness in water management in the Twee Wyk (River E21H), which is part of the upper Doring Catchment (River E).

Through the above objectives, the research worked towards improving the capability of Water User's Associations to facilitate equitable decisions and entrench the ethos of equitable processes through the co-development of a decision support tool. While the software was largely developed at the start of the project, stakeholders were involved in designing appropriate socio-economic data collection mechanisms, and informed further tool development through feedback on the process and outcomes. Aligned with the key objectives, the thesis is structured in three main parts, described in the following three bullet points.

- The Water Sharing Tool offers four expert-derived sharing strategies for sharing of reduced supply adjusted using stakeholder vulnerability. However, these are conceptually hard to explain to non-experts. The RPG was designed to help the stakeholders collaborate to understand the water use issues in the catchment. The game was also designed to explain the differences between water-sharing strategies and to allow the stakeholders to explore the implications of the alternative options.
- Lastly, the thesis pulls together the socio-economic data, the information contributed by the stakeholders during the RPG, uncertain natural runoff estimates, and water demands. It evaluates these using the Water Sharing Model to map water users' vulnerability due to different management decisions. The thesis also delves into the uncertain information presented to the stakeholders during the exploratory process.

1.2. Project context and overview.

This demonstration was done under a community-scale project looking to develop an inclusive, sustainable water management plan (WRC Project No. C2020/2021-00607; Gwapedza et al., 2024), based on agreed values (Palmer et al., 2023). The Water Research Commission primarily funded the water management planning project. The project aim was to collaborate with stakeholders in the Koue Bokkeveld to understand human and ecosystem dynamics in the catchment, co-develop a suite of tools to facilitate a shared understanding of the system and conduct a series of workshops to explore the developed tools and their outcomes to identify valuable insights for managing contested water supply in dry periods (Gwapedza et al., 2024b).

The project approach was a four-step process, as shown in Figure 1.1. Understanding of the hydrological regime in the catchment was informed by the restructured Soil and Water Assessment Tool (Bieger et al., 2017) and conceptual process-based modelling using the uncertain version of the Pitman model (Kapangaziwiri et al., 2012; Ndzabandzaba & Hughes, 2017). Two participatory models (Basco-Carrera et al., 2017a) informed water-sharing options (Figure 1.1-Steps 2 and 3). The first was an Agent-Based Model co-developed with the stakeholders in the catchment and codified on the Cormas (www.cormas.fr) programming platform. It was aimed at a farm-level analysis and scenarios of changing natural resource use, and this was carried out as a master's degree research study in computer sciences.

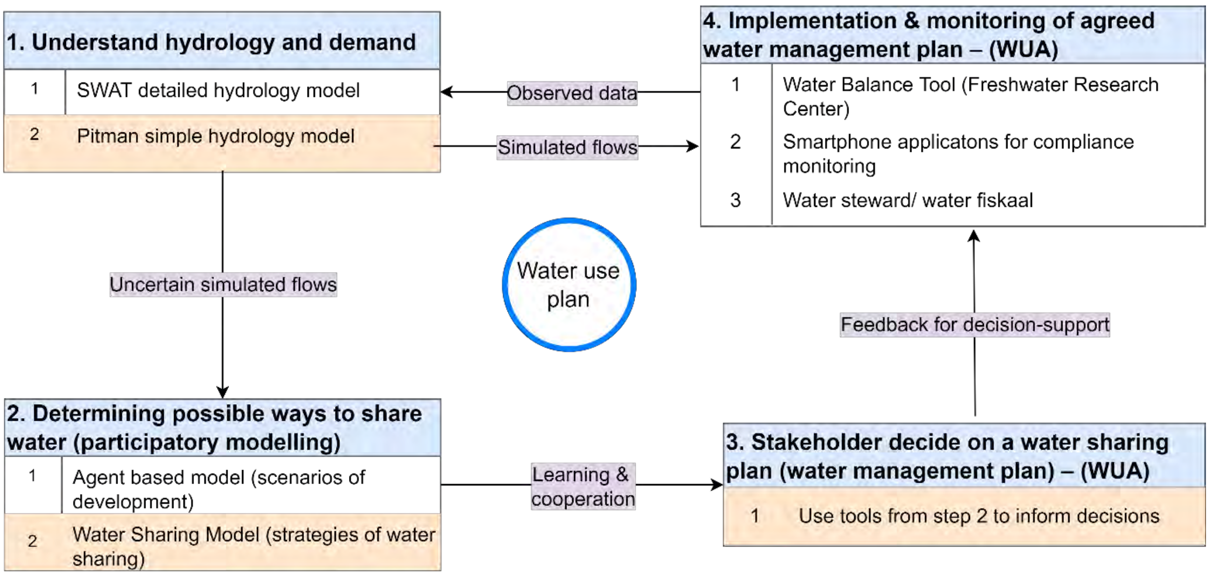


Figure 1.1: Stages of project development towards the shared-vision and fit of this work within the water management planning process. Technical contributions by this research project are highlighted in orange.

The second was testing and further development of Rhodes University's Uncertain Water Sharing Model with Dam Storage (Water Sharing Model), first developed by Pienaar & Hughes (2017). The updated Water Sharing Model is demonstrated in this PhD study. The Water Sharing Model was tested in the catchment to inform strategic water planning and equitable reallocation in dry periods and was designed to capture the preferences and tolerance levels of different users (Hughes & Mallory, 2009; Pienaar & Hughes, 2017). This study accepts the existence of risks and consequences due to water shortage and works with stakeholders to better understand the risks and their vulnerabilities so that they can make more informed water management decisions. By combining socio-economic data and uncertain hydrological dynamics, it should be possible to represent and communicate the relative impacts of water shortage (Hughes & Mallory, 2009).

The Water Sharing Model is a decision-support model for reallocation planning in ungauged basins that have competing uses. The model facilitates the explicit inclusion of uncertainty in decision-making by simulating a range of impacts from reallocation options and produce summary information that are equally accessible and ready for use by decision-makers with the guidance of an expert.

The emphasis on equal access to scientific outputs is relevant for equitable decision-making, as people's ability to bargain in group decision-making processes may be constrained by limited knowledge (an example of procedural fairness). To ensure that previously disadvantaged (e.g., rural use and downstream users) and previously excluded users (e.g., the environment) are involved in the decision-making process (an example of recognitional fairness). Equal awareness of deficit-impacts may also encourage water solidarity, characterised by prioritisation of the less empowered and highly vulnerable users to supply shortages (distributive fairness). For instance, the Twee Wyk users agreed on a shared vision to conserve endemic fish species by avoiding zero flows in the dry summer months. The language choice of communicating the model outcomes is determined by the locally spoken language (recognitions fairness, while the choice of methods for the socio-economic data collection is determined with societal context in mind (another example of recognitions equity). These societal contributions are not limited to the case study area but can be extended to similar contexts.

- The first relates to the methods developed to collect socio-economic data, such as stakeholder vulnerability to water shortages and stakeholder preferences to prioritise local water user groups. These socio-economic parameters are inputs into the Water Sharing Tool but can be collected using various socio-ecological science methods. Options other than the ones designed in Chapter 3 can be found in the Book of Methods by Biggs et al. (2021).

Stakeholder participation is a key prerequisite in the approach demonstrated here. Expert stakeholders are also involved as data and advisory support stakeholders at the community scale (or Water Users' Association level). Combined, the comprehensive evaluation framework (Water-Sharing Tool), direct stakeholder involvement, and the inclusion of hydrologists in participatory modelling and planning (Voinov et al., 2016) can allow water users and decision-makers to plan strategically in the short term based on a long-term historical view. It is envisioned that a better understanding of social preferences and sectorial consequences can cultivate roots of social cohesion and conflict resolution. The work presented here is also relevant to various regional and global development imperatives described in Table 1.1 below.

Table 1.1: Alignment to development targets.

Development Target	Justification
Global Development Agenda and Global Change (United Nations, 2015)	
SDG 6a	*"Supporting and strengthening the participation of local communities in improving water and sanitation management."* Stakeholder involvement in water management is a key prerequisite for effective resource management (Jackson & Barber, 2013; Patrick, 2014; Seigerman et al., 2022). By emphasising the importance of equal voice and equal access to information (McDermott et al., 2013; Pfaff et al., 2013), using interdisciplinary approaches, it is envisioned that local communities can better contribute to decision-making with capabilities to co-learn, cooperate, and resist manipulation, supporting Partzsch (2017).
TARGET 15-9 INTEGRATE ECOSYSTEM AND BIODIVERSITY IN GOVERNMENTAL PLANNING	The sustainability focus of the research is directly linked to freshwater ecosystems, the life they support, and the benefits enjoyed by society, conscious of the in-stream biodiversity in the Cape Floristic Region highlighted by the threatened endemic fish species in the Koue Bokkeveld (Ellender et al., 2017), and the need to balance human needs with environmental integrity (Leach et al., 2018; Richardson et al., 2023). Understanding environmental impacts and communicating these to water users/ decision-makers in accessible formats is critical to protecting environmental ecosystems. The research also acknowledges the significance of stakeholder-developed cooperation agreements for environmental protection.
SDG 13.1.3	"*Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies*" The water shortage focus of this research responds to the climate challenge of a skewed distribution and unpredictable future patterns that affect society disproportionally and could hamper economic growth (IPCC, 2022; Theron et al., 2023). The environmental protection and water reallocation strategies proposed here are seen as a drive for Water Users' Associations to proactively adopt fair and sustainable water restrictions as drought management strategies.
Regional Aspirations: African Union Agenda 2063 (African Union, 2015)	
Aspiration 3: An Africa of good governance, democracy, respect for human rights, justice, and the rule of law."	Upfront with experts' involvement as advocates of sustainable development and the equitable use of water (RSA, 1998a; Department of Water and Sanitation, 2017), this research is relevant to Goal 3 of the 2063 African Union Agenda as it seeks to transfer a decision-support tool to improve the capability of Water User's Associations to facilitate equitable decisions and entrench ethos of equitable processes.

1.1. Theoretical frameworks.

1.1.1. Fair/just process.

Two theoretical constructs informed this work. The first is equity as a means of justice, which brings together issues of water, environment, society, and governance as environmental (Olden & Poff, 2003; The Brisbane Declaration Environmental, 2007) and human rights (Kibler et al., 2014; Patrick, 2014; Lukasiewicz & Dare, 2016). The former means setting aside water or procuring water for environmental needs, and the latter implies a need for inclusive interventions to maintain social stability under increasing demand (Marston & Cai, 2016; Mehrparvar et al., 2016). It also implies the need for regulative control to ensure compliance with required quotas for environmental protection. This work is motivated by the call to researchers to lead towards achieving fairness/justice through the development and roll-out of comprehensive tools capable of facilitating procedural fairness to reach equitable objectives (Borowski & Hare, 2007; Voinov et al., 2016; Prieto, 2021). The study represents an interdisciplinary approach to promoting stakeholder inclusion or representation in water management (Edmunds & Wollenberg, 2001; Pfaff et al., 2013; Partzsch, 2017).

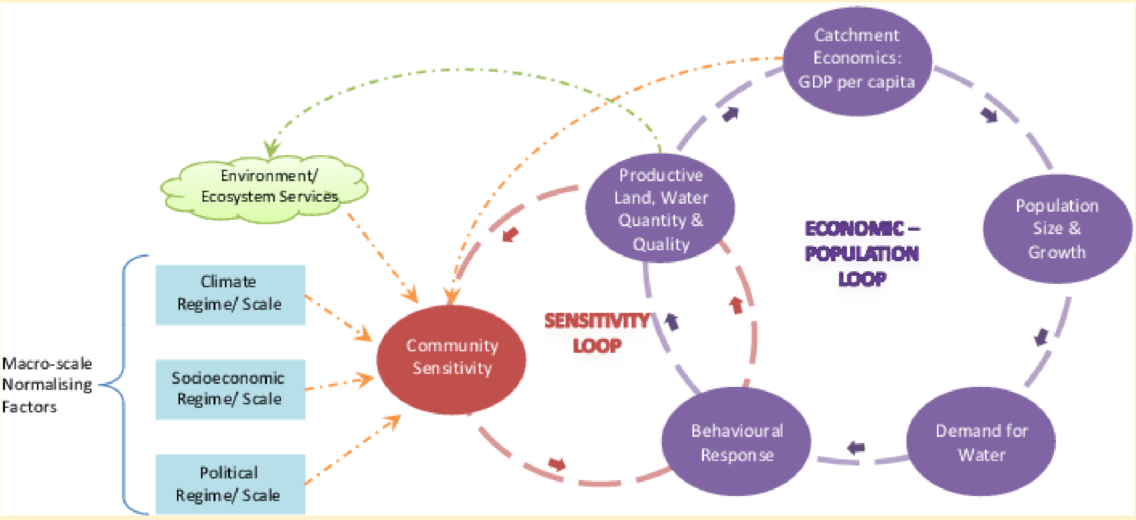
1.1.2. Socio-hydrological thinking.

The second is the socio-hydrology concept that focuses on evidence of the two-way dynamic relationship between water and human systems (Sivapalan et al., 2012; Blair & Buytaert, 2016). Three main aspirational goals of socio-hydrology research are discussed by Sivapalan et al. (2014) and Elshafei et al. (2014) used those to derive a socio-hydrological framework to explain the socio-hydrological process in catchments (Box 1.1). In socio-hydrology research, humans are treated as a part of the socio-hydrology system, capable of changing hydrological dynamics (Montanari et al., 2013) and whose behaviour is influenced by water availability (Elshafei et al., 2014).

It is important to note that prediction uncertainty is inevitable in attempts to achieve sustainable water management, and it stems from various sources. Therefore, explicit inclusion and improved communication of prediction uncertainty to decision-makers can be seen as a good practise towards sustainable and equitable decision-making. The explicit inclusion of uncertainty allows decision-makers to better account for natural variability in water supply, heterogeneous impacts of water shortages to different water users (including the environment), and the users' adaptation to water shortage impacts (Matrosov et al., 2013; Pienaar and Hughes, 2017). Without understanding or considering uncertain outcomes in decision-making processes, it can be expected that the decisions could lead to expensive investments as well as inequitable and unsustainable outcomes that may be unacceptable to society (Mcmillan et al., 2017).

Box 1.1: Organisational framework highlighting key principles for placed-based models that capture bi-directional and dynamic relationships between humans and society (Elshafei et al. 2014).

Elshafei et al.'s (2014) framework (image below) consists of six socio-hydrology components that can be used to highlight how case-specific conditions can be explained using closure relationships or parameters. The six components are: catchment hydrology, population, catchment economics, environment, socio-economic sensitivity and behavioural response. The last two are novel in hydrological evaluations and are tied to the perceived threat to human wellbeing and adaptive capacity.
The framework hypothesises that socio-hydrological relationships at local scales are demand-driven by a positive feedback mechanism (i.e., the economic-population loop) and regulated by a negative feedback mechanism (community sensitivity loop).



2. AN OVERVIEW OF WATER REALLOCATION, FAIRNESS, AND COLLABORATIVE MODELLING

2.1. Introduction

Signatories of the global development agenda (United Nations, 2015) committed to "ensuring availability and sustainable management of freshwater resources with targets ranging between 2020 and 2030"—Goal 6. Although Sustainable Development Goal (SDG) goal 6 shows moderate improvements globally (Sachs et al., 2023), most countries, particularly low-income countries, remain off-track on the targets. Only 44% of countries are close to the Integrated Water Resources Management target, showing slow progress (Sachs et al., 2023). Approximately 2.4 billion people reside in water-stressed countries, and 2.2 billion remain without safely managed drinking water, indicating worsening conditions. Besides the limited progress, Sachs et al. (2020) argue that the sustainable development principles (United Nations, 2015) are still achievable through good international cooperation, effective governance by different jurisdictions, and allocating 0.7% of each country's gross income towards innovation.

This chapter presents an overview of some barriers and innovations that could be leveraged to meet equitable water management, which is closely tied to SDG 6. The review attempts to bring together four related themes: (i) the current understanding of water reallocation; (ii) defences for mainstreaming justice/fairness in water reallocation; (iii) decision-making under unreliable and unknown water supply; and (iv) the potential benefit of collaborative modelling for equitable and sustainable water distribution. The focus on water reallocation alongside allocation is due to the understanding that current water shortages are in part driven by fully allocated available supplies, prompting the need to reallocate or transfer water between users (Meinzen-Dick & Ringler, 2008; Marston & Cai, 2016; Vanham et al., 2018). The review will draw on theoretical and empirical evidence in sustainability science, hydrology, and closely related fields.

By definition, water reallocation refers to the transfer of water between users under formal or informal arrangements (Dinar et al., 1997; Meinzen-Dick & Ringler, 2008; Wang et al., 2008). Water reallocations can be permanent or temporary; they can be achieved through mandatory state-derived measures, market-based initiatives, and private arrangements between water holders (Meinzen-Dick & Ringler, 2008). Such arrangements are triggered when insufficient supply meets new or previously overlooked demands [e.g., environmental demand (Poff et al., 1997; Crespo et al., 2019)]. Reallocation could also be due to emerging economic inefficiencies of current arrangements or changing socio-economic conditions (Scheierling, 2011; Roobavannan et al., 2017; Garrick et al., 2019; Rezaee et al., 2021).

2.2. Conceptualising Water Reallocation to Realise Equitable Supply

2.2.1. Overview of water reallocation.

Water reallocation is crucial to realising the imperatives of sustainable and equitable water sharing among competing and growing demands. As discussed in global reviews on water reallocations (Scheierling, 2011; Marston & Cai, 2016), they have been used as an adaptive management strategy to balance historical injustices, including environmental use (Bark, 2009; Movik, 2014; Arthington et al., 2018). They have also been used to resolve conflicts among evolving and competing uses at different scales (Patrick, 2014; Arthington et al., 2018). Water reallocations can also be implemented as water restrictions to offset climate variability impacts in a just manner (Hughes & Mallory, 2009; Mallory et al., 2013).

Viewing the environment as a user is essential, given the effect of human decisions on global environmental integrity (Crutzen, 2002; Richardson et al., 2023). Nevertheless, there is a misalignment on whether or not the first abstraction of natural runoff water counts as reallocation from the environment to the economy (Vaux, 2012) or whether only allocated supply could be considered for reallocation (Marston & Cai, 2016). If Marston & Cai (2016) consider the environment as a legitimate user, then initial abstractions in a virgin basin become reallocation from the environment because of its entitlement to natural flows (Poff et al., 1997; Arthington et al., 2018).

2.2.2. Complexity surrounding the implementation of water reallocation.

There are four mechanisms/decision types that facilitate water reallocation: state-driven decisions, market transactions, court decrees, and private negotiations (Meinzen-Dick & Ringler, 2008). Reallocation in South Africa is mainly state-driven, as enabled by its water legislature, viewing water as a public good (RSA, 1998a; Sand, 2004). The transformative law follows a complex history of evolving water rights (Tewari, 2009) from a hybrid [public (*dominus fluminus* status of the river) to private ownership (*riparian ownership*) (Tempelhoff, 2017)]. This hybrid approach to water entitlement was preceded by purely private rights (*riparian ownership*) under the Water Act of 1912 to encourage property investment from European settlers in the colony. The legacy of this complex evolving history can still be traced through negative attitudes towards non-economic uses (Du Toit et al., 2013; Garrick et al., 2019), inadequate representation in decision-making (Kemerink et al., 2013; Adom & Simatele, 2022). Court decrees also facilitate resolutions where conflicts/injustice exist (Garrick et al., 2019), although financially empowered historic water users have the bargaining power to resist these decisions (Schreiner, 2013). All these limitations, in addition to those from the governance side (Stein, 2006; Colvin et al., 2008; Pollard & du Toit, 2011; Schreiner, 2013), constrain progress to realise sustainable and equitable use.

To facilitate the state requirement of balancing social, economic, and environmental needs for water resources, the state as the trustee of all water resources regulates water allocation for socio-economic use through compulsory licensing. The same applied to groundwater use. Without compulsory licensing, it becomes impossible to regulate existing lawful use and therefore meet the aspirations of the National Water Act (Act 36 of 1998). While restrictions are applied to surface water use, clear guidelines on how this is done for groundwater use could not be found, signalling a persisting difference in how surface water resources are regulated compared to the hidden groundwater use.

Market-based transfers are possible at transboundary scales, with the Lesotho Highlands Project as an example (Mirumachi & Van Wyk, 2010). The water statute and policies also allow Catchment Management Agencies to enter into transactional agreements of inter-basin transfer of surplus water to mitigate water shortage in recipient basins. Although not straightforward, individual farmers or irrigation schemes may also enter intra-basin transfers through farm ventures or collective negotiations (Mapedza et al., 2016).

Despite the anticipated adaptive management and equitable benefits, water reallocations may stall due to their contested and complex nature. Hence, much research enthusiasm (Meinzen-Dick & Ringler, 2008; Garrick et al., 2009; Marston & Cai, 2016; Rawlins, 2019; Rezaee et al., 2021; Dionisio Pérez-Blanco et al., 2024) has been placed on moving towards a wide view that captures most of the underlying social, economic, and political complexities. The Lesotho Highlands Project, for example, has been hailed as a successful transboundary arrangement due to good bilateral cooperation (Mirumachi & Van Wyk, 2010), reinforcing the significance of Integrated Water Resource Management practice in water management. Balancing human-biosphere needs through a trade-off analysis underpinned by clearly defined rights has been identified (Marston & Cai, 2016) as a good practice. Such a holistic impact assessment is vital given the growing evidence on the downstream impacts of reservoirs on both ecosystems and humanity (Hamada, 2017; Di Baldassarre et al., 2018; Keeler et al., 2020; Van Loon et al., 2022).

2.2.3. Benefits: water reallocation for both demand and supply management.

As argued by Marston and Cai (2016), water reallocations can be leveraged to improve efficiency (water savings or demand management) and reduce the uneven distribution of water-related benefits (supply management). The reform strategy of the Republic of South Africa (1998) exemplifies how reallocations can serve both ends. The efficiency principle of the legislature focuses on reducing wasteful use or hoarding of the resource, availing the surplus to other users within or beyond the basin. Introducing basin footprint thresholds is another emerging demand management strategy focusing on sustainable use (Hoekstra, 2014). On the supply side, the allocation priority under the redress objective is biased towards historically disadvantaged users as a strategy to reduce socio-economic inequalities due to water accessibility (Kidd, 2016).

2.3. Mainstreaming Fairness in Water Reallocation Planning

As outlined in section 2.3.2 above, the mitigative role of water reallocations alongside the interdisciplinary recommendations underscores the significance of fairness/justice (equity or fairness are used interchangeably in this thesis) in water management. Calls to mainstream fairness can be traced in international policies such as the UN (1997) Principles for equitable use, the Bellagio Principles for valuing water (United Nations, 2017), and some national regulations (RSA, 1998a; Bark, 2009). In water research, fairness is reflected in adaptive management (Kingsford & Biggs, 2012; Biggs et al., 2015), the Integrated Water Resource Management Practice (Pollard & du Toit, 2011; Overton et al., 2014; Woodhouse & Muller, 2017; Palmer et al., 2018; Candido et al., 2022; Global Water Partnership, 2024), and recently, socio-hydrology (Lane, 2014; Sivapalan et al., 2014). The examples above affirm the remaining need for capable leadership for effective water management (Du Toit & Pollard, 2009; Joy et al., 2014; Weaver et al., 2019), founded on the links between the biosphere and beneficiaries of the services provided by nature (Rockström et al., 2018). Such a coupled human-nature approach may produce sustainable outcomes (Blair & Buytaert, 2016; Pascual et al., 2023), as opposed to the short-term benefits offered by technical interventions that are subject to neglect (Fisher et al., 2015), or they may transfer risk to other beneficiaries (Hughes & Mantel, 2010; Di Baldassarre et al., 2018; Kellner, 2021; Van Loon et al., 2022).

2.3.1. How is fairness understood in the natural resource management and water allocation realms?

There is consensus in literature over the definition of fairness and its association with justice (McDermott et al., 2013; Neal et al., 2014; Patrick, 2014; Valipour et al., 2024), linked to accepted principles of sharing public goods. Defining equity with justice in mind creates a clear barrier between equity and equality, although equality metrics are sometimes used to report on fairness/justice (Farriansyah et al., 2018). Ultimately, the concept of fairness/justice concerning the human right to water (Mirosa & Harris, 2012) is about fairness and moving away from personal interests to address contemporary inequalities (Neal et al., 2014; Prieto, 2021). These inequalities encompass environmental justice (Gleeson & Low, 2002), bringing together equity and sustainability (Leach et al., 2018).

At a global scale, most researchers map fairness using three dimensions (recognitional, procedures, and distributive), while others (Delorit & Block, 2018; Law et al., 2018) split the recognitional domain into two parts, separating contextual from recognitional, as outlined in the theoretical papers contained in Table 2.1. Based on a recent review of water injustice globally, Canfield et al. (2023) reported a limited focus on recognitional and contextual aspects of fairness/justice in research. Here, fairness is considered using the three-pillars, and contextual equity is combined with recognition's equity, which is more in line with the conceptualisation of fairness in water law.

Insights into the dimensions of fairness.

Figure 2.1 visualises the nature of fairness conceptualisation, which is rooted in recognition, supported by fair procedures, and produces acceptable outcomes (Seigerman et al., 2022). The recognitional dimension avoids subjugating marginalised and historically disadvantaged groups by promoting respect for societal differences, cultural norms, and differences in knowledge styles (Jackson & Barber, 2013; Pfaff et al., 2013). Seigerman et al. (2022) cautions that equity is achieved only when all dimensions are considered. Against the finding that research is still lacking in the recognitional aspects (Canfield et al., 2023), it is clear that more still needs to be done to ground equity to justice.

By recognising societal conditions, a democratic process of equal voice in water governance arises (Kirchner, 2006; Jackson & Barber, 2013; United Nations, 2017). Some critical aspects to consider are local voices, indigenous worldviews (Jackson & Barber, 2013), and amenities for marginalised groups (Leeuwis, 2000).

Lockwood et al. (2010) define procedural fairness through a list of items encompassed by the concept, which include equal treatment of stakeholders, transparent and consistent procedures over time, and fair execution by authority. The condition of equal treatment relates to ongoing inequalities (Brisbois & de Loë, 2016) and diverse values/objectives for water use (United Nations, 2017; Pascual et al., 2023; Zuo & Wheeler, 2024). For instance, acknowledging inequalities in the level of understanding and the general understandability of scientific information used in decision-support prompts a better dissemination strategy (Pfaff et al., 2013; Ncoyini et al., 2022). Polk and Diver (2020) posit that experts involved in equitable decision processes take responsibility for mainstream equity through fair approaches while improving their assumptions. However, societal inclusion requires skilled facilitation and planning, making it an expensive exercise, although necessary (Leeuwis, 2000).

Positive fairness outcomes — distributive equity (Leeuwis, 2000; Barnaud & van Paassen, 2013) — emanate from strategically removing constraints against fair representation in water management platforms. By recognising societal conditions and deploying fair procedures, all voices that matter can be represented, and needs can be adequately considered (Larson et al., 2013; Syme, 2013; Patrick, 2014). However, this is not possible if officials and practitioners lack a clear understanding of equitable outcomes and local preferences, both of which are site-specific. Table 2.1 shows fewer studies looking at groundwater equity (Jackson & Barber, 2013; Larson et al., 2013; Hoogesteger & Wester, 2015; Iftekhar & Fogarty, 2017) compared to surface water use. Neglecting groundwater issues may worsen societal well-being and environmental integrity imbalance, requiring greater attention.

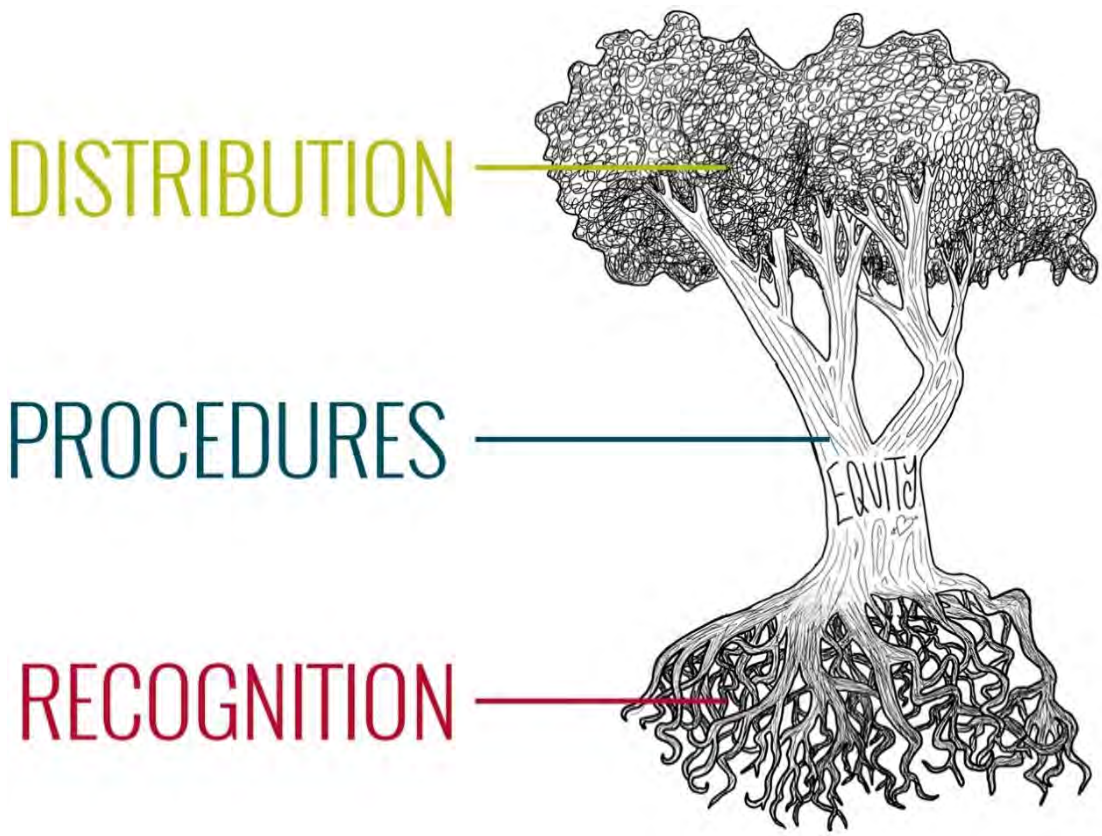


Figure 2.1: Analogy of fairness using a tree, sourced from Seigerman et al. (2022). The roots denote recognition, the trunk invokes procedures, and the canopy denotes distributive outcomes.

Table 2.1: A global comparison of equity definitions in environmental sciences and water management realms, 2012 to 2023.

Article examples	Decision Focus	Fairness principles considered			
				Recognition	
		Distributive	Procedural	Recognition	Context/ Capabilities
Description of equity dimensions (McDermott et al., 2013; Law et al., 2018)		Acceptance of benefits and costs of outcomes.	Inclusion and equal treatment of all stakeholders and welcome of different knowledge systems in decision-making. Also includes the accessibility of the process.	Give respect to all, cultures, values, and rights (social differences).	Regard all factors that lead to existing disparities, which may act against the fair participation of all stakeholders (e.g., power imbalance, language, historical contexts).
McDermott et al. (2013)	Ecosystem restoration	✓	✓	✓	✓
Farriansyah et al. (2018)	Rivers and multi-reservoir allocations	✓	✓	✓	×
Law et al. (2018)	Biological conservation	✓	✓	✓	✓
Leach et al. (2018)	Sustainable	✓	✓	✓	×
Keeler et al. (2020)	Freshwater access	✓	✓	✓	×
Fletcher et al. (2022)	Water resource planning	✓	✓	✓	×
Campanhão et al. (2021)	Impact of water markets	✓	✓	✓	×
Seigerman et al. (2022)	Integrated Water Resource Management	✓	✓	✓	×
Bowman et al. (2023)	Unsustainable consumption	✓	✓	✓	×
Canfield et al. (2023)	Non-drinking water	✓	✓	✓	✓
Valipour et al. (2023)	Water allocation	✓	✓	✓	×
Yang et al. (2023)	Multi-purpose water systems	✓	✓	✓	×

Fairness/justice to the environment.

Freshwater ecosystem resilience and their functioning can be sustained through satisfying environmental water requirements (E-Flow) (Poff et al., 1997; The Brisbane Declaration Environmental, 2007; Arthington et al., 2018), ensuring a distributive fairness of environmental benefits and burdens across society (Gleeson & Low, 2002). E-Flows serve as both proactive measures to preserve intact rivers and as a reactive solution for restoring impaired ones (Arthington et al., 2003). Reaching environmental justice is impossible without an enabling legal framework at the country level, despite global recognition. Recently, a stronger argument has been made for the need to couple social equity with environmental sustainability (Leach et al., 2018; Keeler et al., 2020). Of particular concern is the operational aspect of reservoirs, which can be reduced through an improved understanding and regulation of operation rules (Mallory et al., 2013; Owusu et al., 2021, 2022).

Various E-Flow assessment approaches exist (King & Louw, 1998; King et al., 2003; Hughes et al., 2014a), accounting for biodiversity, natural flow regime, hydraulic aspects, and socio-economic factors specific to each basin. These holistic approaches highlight the complexity and contextuality of E-Flow assessments, although with different levels of confidence (Opperman et al., 2018). Since the biophysical and socio-economic circumstances are too diverse and may be site-specific to include in one assessment, the global development agenda through Sustainable Development Goal 6.4.2 uses a flow duration curve threshold as a minimum requirement (Vanham et al., 2018; UN-Water, 2019). Some major limitations of Goal 6.4.2 are (i) its annual scale, missing the intra-annual dynamics, and (ii) its coarse spatial scales (national level) as sub-national reports are voluntary. Verification and validation of E-Flows at sub-national levels is an impossible task without granular data. Of concern is that the global scale assessments remain without a universally agreed threshold (Pastor et al., 2014).

Hydrological-based assessment of E-Flow is the earliest and simplest technique often used to estimate the amount of water that is required to maintain a waterway (Tharme, 2003). This approach uses mathematical models to simulate water flow through a system. It can be used to estimate the amount of water needed to maintain a certain water level or discharge at different temporal scales (Smakhtin et al., 2006). Changes in hydraulic variables based on hydrology, hydraulic and biological data have been later tracked to maintain the integrity of aquatic ecosystems through hydraulic rating (Loar et al., 1986). In general, a combination of different methods is likely to be the most effective way of estimating E-Flow to account for the needs of the entire riverine ecosystem (King & Louw, 1998; Arthington et al., 2003). Hence the emergence of hybrid methods (or comprehensive models) that estimate E-Flow by combining several other methods, such as hydrology, hydraulics, ecology, and social data (Arthington et al., 2003).

2.3.2. Some remaining issues against mainstreaming equity in water allocation.

Recent scholarship from southern Africa and worldwide has highlighted concerns regarding the pursuit of equity in water distribution. Scholars argue for a balanced approach that considers both the process and the outcomes. As noted (Strauß, 2011; Lukasiewicz & Dare, 2016; Petersen-Perlman et al., 2017; Leach et al., 2018), the emergence of diverse values and preferences among water users leads to conflicts of interest both within countries and across national borders. Some major impediments to realising equity objectives are related to political and economic power imbalances, aggravated by the exclusion of some users (Marston & Cai, 2016; Partzsch, 2017). Although work is in progress (Iftekhar & Fogarty, 2017; Rodina et al., 2017; Siddiqi et al., 2018; Fletcher et al., 2022; Yang et al., 2023), equity remains without universally agreed metrics, making it difficult to report on the process or the outcomes consistently. Furthermore, the focus on optimal outcomes is being re-evaluated to better account for uses that yield indirect economic benefits, including cultural (Wutich et al., 2012; Jackson & Barber, 2013) and environmental purposes (Larson et al., 2013; Rodina et al., 2017; Leach et al., 2018; Campanhão et al., 2021). Furthermore, the focus on optimal outcomes is being reevaluated to better account for uses that yield indirect economic benefits, including cultural (Wutich et al., 2012; Jackson & Barber, 2013) and environmental needs (Larson et al., 2013; Rodina et al., 2017; Leach et al., 2018; Campanhão et al., 2021).

2.4. Complexity Due to Hydrological Uncertainty and Infrastructure Development Impacts

2.4.1. Overview of uncertainty.

Since decision-makers depend on experts in water resources for a trustworthy body of knowledge, the economic, social, and political nature of water allocation renders it a technical issue. Hydrological models are the most affordable option suited to provide the necessary quantitative evidence (Horlitz, 2007). Although they have limitations, their strength is in their flexibility and ability to reduce the complex interactions of the hydrological cycle and to output reliable estimates of the water balance components, including available supplies (Fu et al., 2019).

However, as natural systems, water resources are generically uncertain (Beven & Westerberg, 2011; Beven, 2013), recognised limitations of hydrological model outputs include structural adequacy (Gupta et al., 2012), expert assumptions (Gupta et al., 2012; Beven, 2016; Di Baldassarre et al., 2016), irreducible errors due to natural variability and the lack of perfect knowledge of historical and current hydroclimatic conditions for validation and verification (Beven & Westerberg, 2011; Mcmillan et al., 2012). The declining hydroclimatic networks and erroneous records (Coxon et al., 2015; Westerberg & McMillan, 2015) indicate the unavoidability of uncertainty. Meanwhile, the reliance on global estimates may further propagate uncertainty in water resource allocations (Hughes et al., 2014b; Sun et al., 2018). Meanwhile, humans are characterised by changing preferences, values, and decisions, all of which are unique and unpredictable (Leeuwis, 2000). Human decisions are primarily relevant to decision-making and span social, economic, and political factors. Experts responded with practical approaches to understand, work with, and reduce this uncertainty for decision-making support (Hrachovitz et al., 2013).

Handling of uncertainty.

Hydrological uncertainty is typically acknowledged and reduced through a stochastic treatment of inputs or parameters (Yadav et al., 2007; Hughes et al., 2010; Kapangaziwiri et al., 2012), or both, in one modelling framework (Hughes et al., 2011; Hughes & Farinosi, 2021). The stochastic modelling process offers a better description of the hydrological process by expanding the maximum number of possibilities, which is essential given information gaps (Reichert et al., 2021). Allowing maximum possibilities in parameter sampling is also beneficial for dealing with issues of equifinality since sub-surface processes remain largely unknown (Hughes, 2010; Blöschl et al., 2019). Confidence intervals, probability distributions and sensitivity analysis have predominantly featured in handling hydrological model uncertainties (Yadav et al., 2007; Beven & Binley, 2014; Ndzabandzaba & Hughes, 2017; McMillan, 2020). This set of methods aims to characterise all sources of uncertainty to identify areas where uncertainty distribution can be reduced (Gupta & Govindaraju, 2023).

Decision-making under uncertainty.

Decision-making risks can be reduced by harnessing uncertainty (Mcmillan et al., 2017; Hughes, 2019), which is a positive view of uncertainty compared to the classical view of avoiding uncertain outcomes (Pappenberger & Beven, 2006; Gober, 2014). Notably, the explicit inclusion of uncertainty in decision-making remained largely uncommon across the water management arena (Pappenberger & Beven, 2006; Matrosov et al., 2013) until recently (Hrachovitz et al., 2013; Korteling et al., 2013; Matrosov et al., 2013).

However, there remains a lack of interest from the decision-making side in southern Africa (Hughes et al., 2015), which is of great concern as uncertainty and climate variabilities now and into the future are more prevalent in the region (Hughes, 2019; IPCC, 2022). Most of the decade of predictions in ungauged basins (Hrachovitz et al., 2013; Savenije & Sivapalan, 2013) focused on reliably simulating ungauged basins (reducing predictive uncertainty). Decision-makers are particularly interested in understanding how errors may affect the specific adaptation of decision outcomes (Gober, 2014; IPCC, 2022) and a consistent interpretation of uncertain outcomes (Kelly et al., 2013). Thus, a fundamental aspect of using uncertain information in decision-making is promoting the comprehension of uncertainty through simplified communication (Fischhoff & Davis, 2014). This indispensable aspect of decision-making is acknowledged in the larger sustainability domain (Beven, 2011; Laniak et al., 2013; Fischhoff & Davis, 2014; Uusitalo et al., 2015) and within the water resources sub-domain (Pappenberger & Beven, 2006; Mcmillan et al., 2017; Blöschl et al., 2019; Carr et al., 2020).

2.5. Knowledge Co-Construction to Advance Equitable Decisions and Understanding of Uncertainty

Water management is a complex issue that requires a holistic understanding of catchments as systems where human and natural elements interact and influence each other from multiple perspectives (Sivapalan et al., 2012, 2014b). For instance, hydrological processes affect how people make decisions, as shown by the reactions to flooding events (Baldassarre et al., 2013; Di Baldassarre et al., 2015; Behrouz & Alimohammadi, 2016; Ciullo et al., 2017; Yu et al., 2017). On the other hand, societal changes such as reservoir construction (Kellner, 2021), the use of water-saving irrigation technologies (Ilyas et al., 2021), and the global food trade (Sun et al., 2022) in response to water vulnerability, alter the behaviour at smaller scales. These modifications can have unforeseen domino effects downstream and ultimately globally. Therefore, it is essential to focus on the outcomes of the dynamic interactions between human and natural factors at different scales, such as the necessity of water for existence, the feedback loops, and the new thresholds, and how they affect the well-being of society (Sivapalan et al., 2014; Montanari, 2015). Appreciating society-water interactions will aid robust decision-making (avoid undesirable management options) and pave the way for new scientific breakthroughs (Blöschl et al., 2019).

Socio-hydrology, the study of how people and water resources interact and coevolve, faces challenges at the global scale due to its natural inconsistency (Sivakumar, 2012) and the poor collaboration between social and hydrological scientists (Seidl & Barthel, 2017). This hinders our ability to deal with complex human-water interactions, even with the Integrated Water Resource Management framework's goal of adaptive management (Montanari, 2015). Furthermore, the existing debates on how to conduct coupled human-nature research (Di Baldassarre et al., 2015; Gober & Wheater, 2015; Loucks, 2015; Sivapalan, 2015; Troy et al., 2015) have not agreed on how to simulate the two components. A promising suggestion is carefully borrowing suitable methods from other coupled fields (Blair & Buytaert, 2015).

2.5.1. Integrated and participatory modelling in decision-support for equitable and sustainable water management.

Emphasis is widely placed on the need to centre water governance on stakeholder inclusion (Joy et al., 2014). Integrated modelling (as synthesised by Laniak et al. 2013) and participatory modelling (reviewed by Hare (2011) serve as valuable frameworks to investigate the interplay between human and natural systems in decision-making processes (Sivapalan et al., 2012, 2014; Blair & Buytaert, 2015). These two concepts are often confused (Basco-Carrera et al., 2017b), and details about this muddle are discussed later in this section.

Integrated modelling seeks a comprehensive grasp of the socio-economic factors that influence the behaviour of complex adaptive systems (Laniak et al., 2013; Preiser et al., 2018). It uses mathematical expressions or mental models to combine physical, environmental and socio-economic components to achieve system representation and simplification (Laniak et al., 2013). The framework is traditionally quantitative, but qualitative approaches have been implemented (Mirchi et al., 2012; Turner et al., 2016; Nyam et al., 2021), which is decided based on project goals.

Participatory modelling, on the other hand, focuses on direct stakeholder engagement to build collaboration between different stakeholder groups and generate a shared understanding (Reed, 2008; Hare, 2011). By comparison, the traditional computer-based structure of integrated modelling may be inaccessible to other participants; hence it is essential to have a clear plan for information exchange between stakeholders (Barreteau et al., 2010).

Table 2.2 offers a summative overview of the slight differences between the two approaches, with key differences in stakeholder involvement as appraised by Basco-Carrera et al. (2017). According to Basco-Carrera et al. (2017), integrated modelling involves key stakeholders, while participatory modelling includes a broader stakeholder group. However, the complementary nature of the frameworks results in an unclear demarcation between the two approaches in the literature. The poor distinction is despite the structural differences like participation and manifestation of cooperation (Basco-Carrera et al., 2017a). For instance, an investigation of water vulnerability by Sohns et al. (2021) only recruited high-level stakeholders whose decisions drive household water vulnerability to describe household water vulnerability. However, the authors identified this process as a participatory framework. Without a clear distinction of the two frameworks, modellers lose out on structuring their projects to meet the expected outcomes of each framework.

Table 2.1: Distinguishing characteristics between participatory and integrated modelling features adapted from Voinov and Bousquet (2010), Hare (2011), and Basco-Carrerra et al. (2017).

Collaborative modelling framework	Participatory modelling	Integrated modelling
Aspirations	Supporting decision-making by mapping the relationship between planning/decision-making processes, outcomes (social, economic, and environmental), and consequences of these outcomes to stakeholder concerns, all designed as a response to epistemic uncertainty and conflicting objectives.	
Conceptual underpinning of sustainable development	Collaborative modelling is central to equitable decision-making, promotes robust decisions, and increases stakeholder buy-in to policies.	Holistic evaluation of complex adaptive systems to reduce uncertainty through group consensus.
Perspective	Value-driven and information-supported.	System analysis and uncertainty oriented.
Outlook	Desired, possible, and plausible futures	Possible and plausible futures.
Stakeholder involvement	Wide-stakeholder group (Effective participation of interested and affected stakeholders).	Invited stakeholders only.
Extent of participation	Awareness raising, information sharing, participation by consultation, collaborative model design, collaborative decision making.	Collaborative model design, collaborative decision making.
Stakeholder involvement step in the planning process	Data collection, Conceptualisation Model building, model validation and verification, model use, and formulation of management options.	Data collection, Conceptualisation Model building, model validation and verification, model use, and formulation of management options.
Collaborative learning outcomes	Social and shared learning.	Shared learning.
Popular techniques	Companion Modelling, Group Model Building, Shared-Vision Planning, Participatory Simulation, and Systems Dynamic Models.	Interactive Modelling and Fast Integrated Systems Modelling

Relevance to decision-making.

The holistic human-nature understanding provided by the two frameworks aligns with the system comprehension advocated by Kelly et al. (2013). It also emphasises the strength of the two frameworks, hidden in stakeholder participation, that motivates dynamic systems thinking to support robust decision-making (Reed, 2008; Voinov & Bousquet, 2010). Focusing on system feedback offers water users and managers a detailed understanding of the embedded complex relationships and dynamics, proving an untapped potential to derive sustainable decisions (Sivapalan, 2015). Barreteau et al. (2010) group collaborative models into four uses: modelling for scientific inquiry, contributing to decision support, facilitating stakeholder participation and collaboration, and as communication tools.

2.6. Way Forward

Decentralised governance, supported by global development in the 21st century, strives to include all those affected by a decision (Brand et al., 2021; Seigerman et al., 2022). Appropriately representing all interested voices and diverse needs over regular engagements is seen (Reed et al., 2009; Pascual et al., 2017; Karcher et al., 2021) as a strategy to incorporate diverse knowledge systems (scientific, local, traditional, and experimental). Similarly, addressing issues that inhibit equitable processes and outcomes requires an awareness of the multidimensional aspects of water use and, consequently, a social perception of fairness (Patrick, 2014). As recommended by (Hoekstra, 2014), thoughtful planning, negotiation, and enforcement are needed to overcome these hurdles. Patrick (2014) reminisces that fairness outcomes may take time to manifest, manifest differently to different beneficiaries over time, and the perception of fairness is subject to change.

Some key limitations must be addressed despite the growing interest in collaborative modelling approaches as technical support tools to advance democracy through the wider incorporation of complex human-water system elements (Sivapalan et al., 2014; Voinov et al., 2016). The democratic focus of collaborative models implies a direct involvement of stakeholders in the process, which is in different stages and for different purposes (Table 2.2). An emerging question relevant to stakeholder involvement (Reed et al., 2009) relates to recruiting participants to ensure a representation of all affected stakeholders and avoid excluding marginalised groups (McDermott et al., 2013; Patrick, 2014), which will perpetuate existing inequities. Ecosystem restoration, for example (Gann et al., 2019), typically involves leveraging existing social partnerships to help recruit new initiatives.

Also, realising equity through fair processes and outcomes is expensive as it requires multi-stakeholder collaboration, including expert facilitators. This is unavoidable, as good facilitation skills are required to enrich the process (Ralekhetla, 2018; Palmer et al., 2023), and innovative tools have to be rolled out to capture system complexity. Slight increments towards innovation funding through public investments and corporate social responsibility initiatives could allow experts to better roll-out new products at local scales, supporting the 0.7% gross national product target (Sachs et al., 2020). This will also allow knowledge transfer to emerging experts, ideal for sustainable development under global change.

Stakeholders may view outcomes as too narrow or too complex. However, as discussed by Barreteau et al. (2010) and demonstrated through case-study examples by Wolff et al. (2019), a project design that is based on ethical values of transparency and on-going feedback can help reduce false expectations. Kelly et al. (2013) recommend contextualisation collaborative models as exploratory tools to benefit decision-making under uncertainty.

Integrated Water Resource Management and its growing quantitative research focus—socio-hydrology (Blair & Buytaert, 2016) reaffirm the complex nature of water management. Much progress has been made in the research domain to reduce the inherent uncertainty (Hrachovitz et al., 2013; Montanari et al., 2013). An increased appreciation of interdisciplinary practice remains necessary to capture equity's social and political elements better (Hughes & Mallory, 2009; Reddy & Syme, 2014; Troy et al., 2015; Seidl & Barthel, 2017; Carr et al., 2020). Another challenge is sensitising decision-makers to the concepts and advantages of uncertainty in decision-making, which has been demonstrated to be possible and valuable (Hall & Borgomeo, 2013; Korteling et al., 2013; Matrosov et al., 2013; Mcmillan et al., 2017). This challenge can be addressed through science communications for better understanding and consistent interpretation by stakeholders and decision-makers (Fischhoff & Davis, 2014; Polk & Diver, 2020).

The involvement of experts and simulation models as external stakeholders plays a vital role in supporting evidence-based decisions in water management. However, concerns over the legitimacy of both stakeholders may emerge from local stakeholders if the experts' positions and model objectives are not clarified upfront (Leeuwis, 2000; Barnaud & van Paassen, 2013; Barnaud et al., 2014).

2.7. Closing Remarks

This thematic review attempts to bring together water reallocation, fairness, hydrological uncertainty, and the potential of collaborative modelling for inclusive decision support under uncertainty. The review does not represent all the knowledge in these four themes but has covered some basics using review papers where appropriate. The conceptualisation of reallocation from this review highlights that local institutions should search for different strategies for demand management and allow representatives of water users to decide the acceptable option based on societal aspirations. In the context of South Africa for example, water managers implement different levels of fixed percentage restrictions to increase system reliability for all users. However, this deficit-focused approach to demand management does not always result in fair outcomes, especially in basins with diverse user types. In such cases, the less-resourced users tend to face higher consequences. This is where the need for a more targeted focus for fair procedures comes in. Notably, equitable decisions cannot be claimed without covering all three or four pillars of fairness (contextual and/or recognitional, procedural, and distributive) simultaneously.

The review highlights the fact that uncertainty is unavoidable, hence, accounting for- and communicating prediction uncertainty to support decision processes in ungauged settings should be a prerequisite alongside fair procedures. Without the explicit inclusion of uncertainty in planning and management decisions, the risk of poor planning for extreme events and unsustainable outcomes in heightened substantially.

The section on knowledge co-creation is ideal to improve acceptability and uptake of outcomes to support allocation planning. For the experts, co-construction offers an opportunity to better understand social conditions, which enables them to identify ways to support equitable decision making in a manner that better suits the local needs. For democracy, co-creation means a real sharing of decision-making power to citizen control. However, the complex relationships between humans, the environment, and water resources complicate the process, making it a difficult endeavour to fully achieve. For example, different stakeholders have diverse interests and priorities, which are often difficult to balance and may lead to or worsen conflicts. Language differences, cultural differences, and unequal education levels can all limit understanding and participation. Building stakeholder trust is obligatory for successful collaboration, but unreasonable expectations and a lack of openness can demoralise participants. Another impediment is unclear governance structures and roles, which can complicate the process of coordinating activities and decisions among various parties. All these issues, as well as others not listed, must be handled via dedication, open conversation, mutual respect, a willingness to work as a team, and a value for unity/solidarity.

The key take home message from this review is that, when developing robust and reliable methods for the context described above, the ideal approach should include explicit consideration of estimation uncertainty, recognition of diverse water user values and vulnerability to water scarcity, and representation of all water user groups found in a water management area.

3. STUDY AREA AND OVERVIEW OF METHODS

Water resources in South Africa are shaped by a low average rainfall that results in limited water availability for socio-economic activities and the environment, which a testimony to the country water scarcity issue (Department of Water and Sanitation, 2022). Less than 10% of the country's landscape yields 50% of the surface water supplies (Nel et al., 2013). Meanwhile more than 3 provinces, including the hub of gold (Gauteng), rely on imported supplies from the neighbouring Kingdom of Lesotho. Irrigation for commercial crops (mainly for export) have pushed agricultural demand to 63% of the country's resources, which is also worsened by climate change. Combined, these issues result in competition and conflict among diverse users, and the most resourceful often end up with disproportionately more allocation than the rest.

Given the scarcity of the resource, South African water law under the democratic rule (Act 36 of 1998) recognises this predicament and has built in water rights and procedures that should guarantee equitable access, although this not the case in the large part (Stein, 2006). One of the barriers to progress are preexisting water rights that are engraved in the current water act that were carried from the colonial period (Tewari, 2009).

- During the British rule, water rights in South Africa were mainly based on the *riparian doctrine*, where users were entitled to water that is proportionate to their land tenure, which was biased towards the agricultural sector (Irrigation and Conservation of Water Act 8 of 1912). Under the *riparian doctrine* water was private and landowners also own the water that rises and falls on property, as well the small upstream tributaries within the property. The implications of this water right were that downstream users and users away from tributaries (e.g., industry) were left with much less supply.
- In response to urban and industrial developments in the Union of South Africa, the legislative landscape changed once more under the second Dutch rule (or Apartheid era), and the *dominus fluminus* status of water was reintroduced alongside the *riparian doctrine* (Water Act 54 of 1956). Where owners invest resources to divert public water to their own private storage, such water was deemed private water and was affirmed by a permit regulated by the Irrigation Boards (Act 54 of 1956, Section 7a). Unlike predeceasing statutes, the Water Act allowed non-riparian owners some allocation under approval by the water courts or through water trading by willing riparian users.
- In the eve of democratic South Africa, it was recognised that the previous water laws would be inconsistent with the constitution. To ensure consistency with the democratic ideals of South Africa that are primarily based on fairness and human dignity, the National Water Act (Act 36 of 1998) hinges on equity (in terms of distribution), efficiency, sustainability, and representation. The National Water Act is intended to realise a safe environment for all while promoting justifiable socio-economic development through access to sufficient water resources. For democratic South Africa, equitable

> access is an attempt to return to the pre-colonial common law of water resource access; efficiency features the importance of social and economic benefits of water use and the associated environmental costs; environmental sustainability relates to the protection of instream ecosystems and their biological diversity; and decentralisation (with 3 hierarchical levels of governance with a bottom-up decision-making style) is seen as a mechanism for enabling public participation in water governance.

In terms of water management, the act encourages transparency and stakeholder participation. Water management in democratic South Africa aims to overcome the constraints of hierarchical and centralised control to participatory governance through a decentralised management approach. Three institutional levels facilitate the decentralised and representative management of water resources (Figure 3.1). The Ministry of Water Affairs is a trustee of water resources, Water Management Agencies as regional administrative units, and Water Users' Associations as inclusive local management bodies and responsible authorities for maintaining water infrastructure. Paxton et al. (2017) contend that E-Flows can be successfully met when Water User Associations are capacitated, given their close interaction with rivers and day-to-day operational oversight. Although the Koue Bokkeveld is one of the few regions in South Africa that has transformed its white commercial farmer-dominated water management institutions (Irrigation Boards) into an "inclusive" Water Users' Association, the association still lacks a documented water management plan, making it challenging to manage water supply locally in the coordinated and cooperative manner required by the legislature. Sabotage by influential members (Brown, 2013) and a lack of support from poorly established regional support Catchment Management Agencies constrain the effectiveness of associations (Madigele, 2018); but improvements in Catchment Management Agencies have been made toward the end of the 6th democratic government.

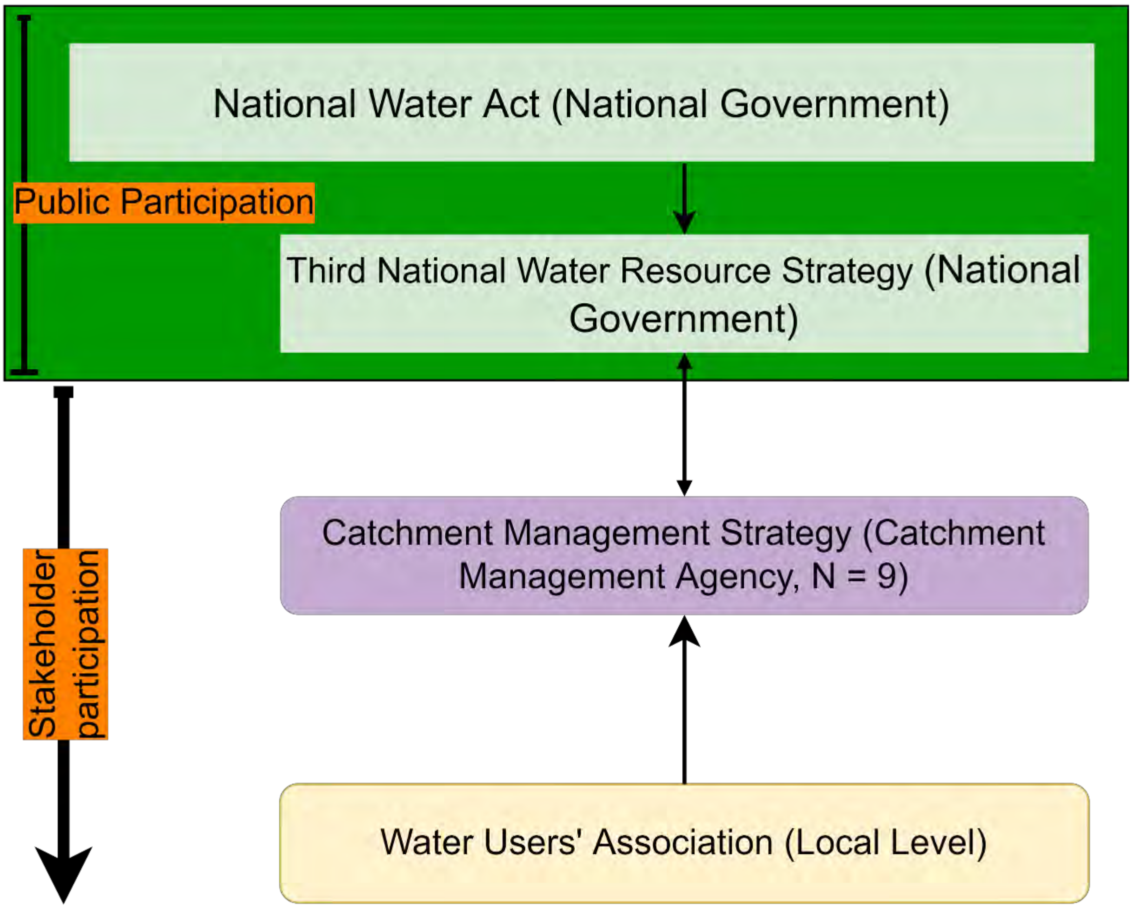


Figure 3.1: Schematisation of the decentralised water governance structure underlying the South African Water Act (Act 36 of 1998). Beneficiaries of the national water resources are included in high-level decisions through invited comments (public participation) and at regional to local levels, beneficiaries are involved through direct participation often via representatives in the Catchment Management Agency (Chapter 7, Act 36 of 1998) and via involvement in a local Water Users' Association.

Before 2012, South Africa had 19 Water Management Areas (WMA) that were established in 1999. These were replaced by nine in 2012 (Figure 3.2). The nine WMA: Limpopo, Inkomati-Usuthu, Pongola-Mzimkhulu, Vaal, Orange, Mzimvubu-Tsitsikama, Breede-Gouritz, and Berg-Olifants, lump a number of rivers to form each WMA. These WMA are more closely aligned with the regional administrative areas, although some drain more than one province or there are more than one in each province. Each WMA has a duty to oversee water management by including local role players in decision-making processes. Each WMA is given the power to derive its own policy objectives under a Catchment Management Strategy, and each strategy is expected to fulfil the national directives given in the National Water Resource Strategy.

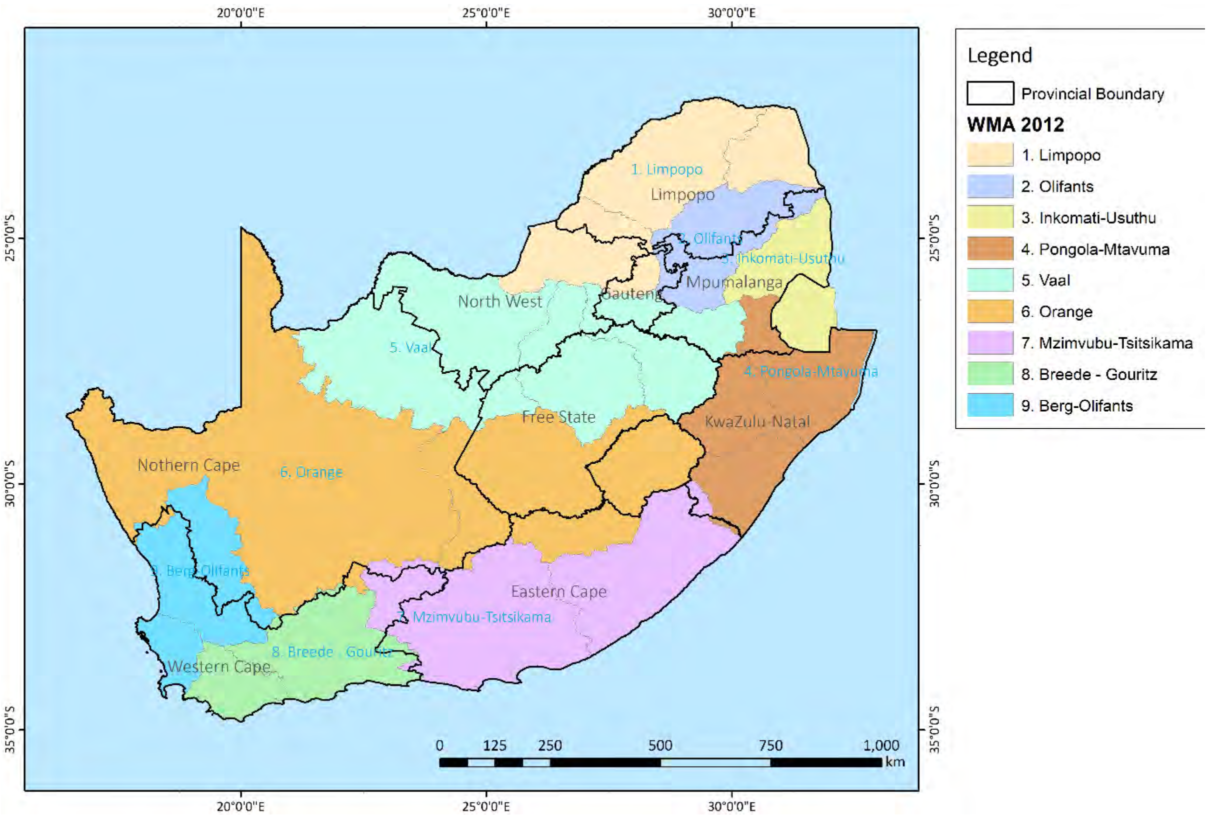


Figure 3.2: Republic of South Africa, Water Management Areas (2012).

3.1. Environmental water allocation.

To enhance ecosystem resilience, the state responded to the biota's vulnerability by upgrading the E-Flow thresholds in the affected quaternary catchments (Figure 3.3, Department of Water and Sanitation, 2017). Water use conflicts arise in dry periods between upstream and downstream users (Rawlins, 2019). Failures to fulfil the E-Flows shown in Figure 3.3 during dry periods (Paxton & Walker, 2018) can be translated as water grabbing, signalling agriculture-environment conflict. Formerly existing *gentlemen's* agreements for E-Flow releases from upstream dams over Dec-April are vulnerable to change in landowners or managers. The issue is worsened by recent developments over the biodiversity importance of E21H (Ellender et al., 2017; Tanner et al., 2022), resulting in increased environmental prioritisation for available water supply (Department of Water and Sanitation, 2017). More water to the environment means less stream water availability for high-value crops (orchards for export markets), mainly affecting the socio-economic resilience of farmers without dam storage. Lack of transparency over the surface and groundwater abstraction generates animosity and erodes trust between upstream and downstream users (DEADP, 2011). Water follows economic gravity as water transfers to the neighbouring upstream catchment are a norm for landowners who own water rights in the Twee Wyk (River E21H) and land tenure in the Leeu River catchment (River E21G). Limiting in-stream storage on quaternary catchments in A/B and B levels and banning in-stream storage in quaternary catchments with higher environmental protection levels (levels A, Figure 3.3) is a strategy to enhance environmental outcomes (Department of Water and Sanitation, 2016). At the same time, the unauthorised raising of existing dam walls (unregulated water use) that are *post facto* condoned by section 24G applications under the National Environmental Management Act of 1998 (RSA, 1998b) also increases the vulnerability of downstream users to water shortage.

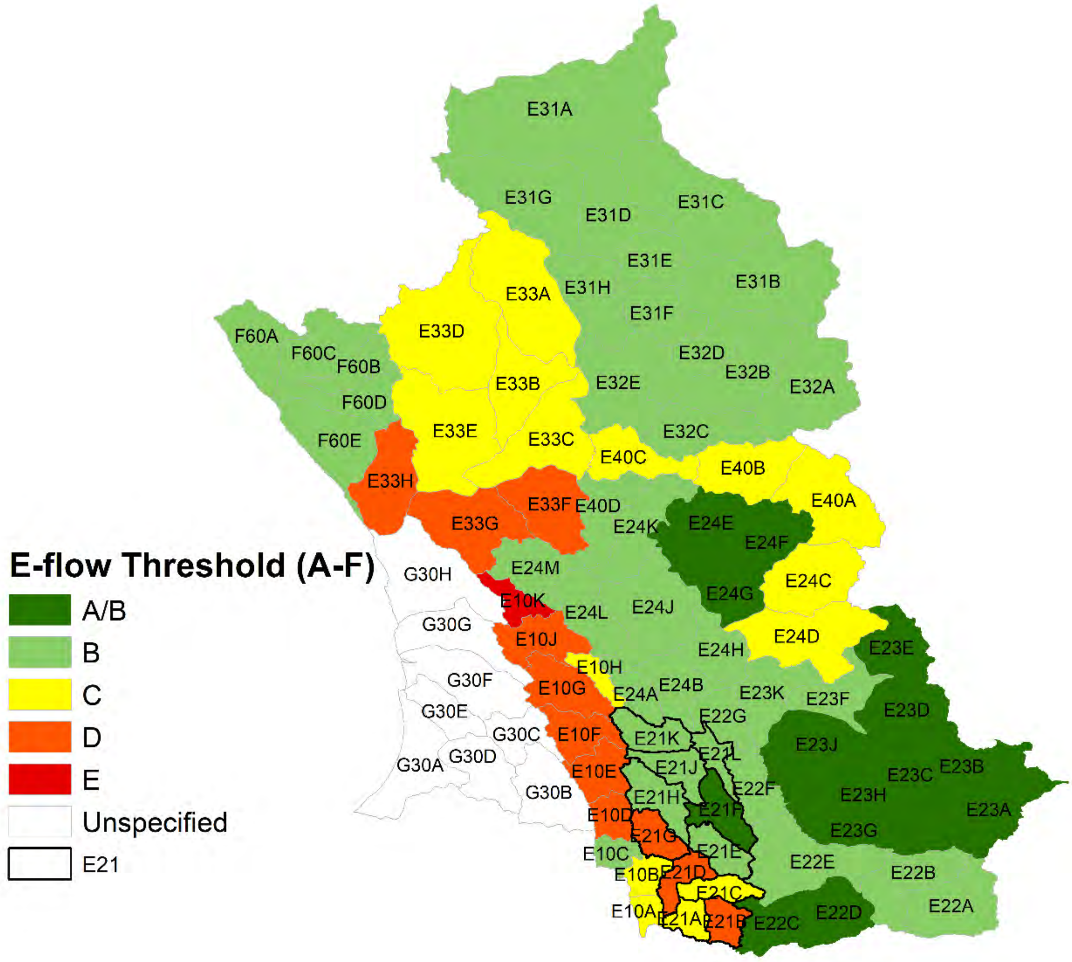


Figure 3.3: Recommended Environmental Water Requirements (E-Flows) for the Olifants-Doring area as of 2017.

Brief description of E-flow thresholds (A-F)

The South African approach of E-flow assessments follows a comprehensive procedure to derive an indicator of river ecological status (E-flow thresholds in Figure 3.5)—a descriptive measure of ecological importance and sensitivity. On the one side, the measure depicts the local to regional importance of river to justify the need to protect river functions and in stream diversity. On the other, the river ecological status describes resilience rationale for rivers to the local scales required to regulate the health of rivers in light of anthropogenic influence, and to sustain ecological conditions of rivers to maintain their functions. The final ecological status classes (E-Flow thresholds) is described in Table 3.1 below, and the flow thresholds for these will differ by water management area. These thresholds range from natural (Category A) to critically modified flows (Category F).

Table 3.1: Description of the ecological status class.

Ecological status class	Description of general conditions
A	Unmodified, natural.
B	Largely natural with few modifications. A small change in natural habitats and biota can take place, but the ecosystem functions should essentially be unchanged.
C	Moderately modified. A moderate change in natural habitat and biota can take place but the basic ecosystem functions should still predominantly be unchanged
D	Largely modified. A large change in natural habitat, biota and basic ecosystem functions can occur.
E	Seriously modified. The losses of natural habitats and basic ecosystem functions are extensive.
F	Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat

3.2. Study Area selection

This study was set in the Koue Bokkeveld region (KBV or River E21) that is located in the headwaters of the Berg-Olifants WMA. The nearest towns to the KBV are Ceres and Citrasdal on the northern parts of the Western Cape Province. The KBV region is administered by the Witzenberg Local Municipality and is charecterised by a rich history of commercial farming, scenic landscapes, and sparse population. The Koue Bokkeveld region is an ideal context for effective participatory modelling since there are established relationships from a former project (Freshwater Research Centre, 2021). The Freshwater Research Centre (https://www.frcsa.org.za/) is a non-profit organisation concerned with freshwater research and conservation. Given the increasing demand for agricultural space in the Koue Bokkeveld, implying a higher demand for water resources, the FRC is collaborating with the landowners/farmers to cultivate sustainable water use in the area. In particular, the FRC is involved in freshwater ecosystems and hydrological data collection and synthesis. It also mobilises and builds landowners' capacity for climate change adaptation through technical support for monitoring (Paxton et al., 2017), which is a national and provincial mandate (Birch et al., 2021).

3.2.1. Socio-economic context.

The Koue Bokkeveld is administered by the Witzenberg Local Municipality (WC022). The intermediate (2019-2024) local municipality targets for the Witzenberg Municipality (2019) were:

i. a reduced competition of natural resources (**water** and land) for economic efficiency,

ii. improved adoption of sustainable development practices,

iii. biodiversity conservation and protection,

iv. building a resilient agricultural sector against climate extremes and urbanisation,

v. and promoting the accessibility and appreciation of natural scenic beauty under the principle of spatial justice.

Socio-economic data in South Africa is available at administrative levels, and Table 3.2 outlines demographic statistics for the Witzenberg Local Municipality, which encompasses the Koue Bokkeveld. According to Census data, the Witzenberg Local Municipality currently has 103,756 people, compared to less than 80,000 in 1996 (Table 3.2). Over 65% of the population in the area has been of working age for the past 30 years. The Witzenberg Local Municipality accounts for less than 10% of agricultural employment in the Western Cape Province, employing around 16,200 people (Table 3.2, EasyData, 2022a). The current employment levels have dropped from nearly 29,000 in 2001. International export data for the primary sectors provided by (EasyData, 2022b) shows a rapid growth in international trade income at the local municipal level from R1.6 million in 1996 to R2,486,970,000 in 2022, representing less than 5% export contributions from the Western Cape (Table 3.2, EasyData, 2022c). All fodder, grains, cereals, legumes, and oil seeds produced in the Witzenberg Local Municipality go down the domestic market value chain (EasyData, 2022c). The exponential growth in export income could be attributed to fruit exports, which have been growing and are less labour-intensive. Farmers strategically rotate employees for harvest from one farm to another. It is impossible to trace the export trend as no public data was available before 2018.

Table 3.2: Socio-economic characteristics of the Witzenberg Municipality, a local administrative level covering the Koue Bokkeveld region. Census and household data were extracted at the Local Municipality level for the Witzenberg Municipality (Stats SA, 1996, 2001, 2011). Agricultural economic data was analysed using data provided by EasyData (2022a, 2022b, 2022c).

Indicator	1995/6	2000/1	2010/11	2018 to 2020/22
Total population	76,386	89,087	115,946	103,765
Working age (15-64 as % of total population)	64.7	66.4	70.4	71.9
Employment in agriculture (% of Western Cape Province)	9.6	9.7	9.7	9.2
International Trade				
Total trade (2015 prices)	R1.60 million	R528.83 million	R896.97 million	R2,486.97 million
International Trade (% of Western Cape Province)	0.0	3.5	3.0	2.9%
Proportion of produced crops exported in 2018				
Deciduous fruit and viticulture (apples, pears, peaches, plums, and table grapes)				47.5% of 597,510 tons
Citrus (oranges, naartjies, lemons, etc.)				36.9% of 3,865 tons
Subtropical fruits (avocadoes and berries)				19.9% of 346 tons
Vegetables (cabbages, carrots, green beans, potatoes, pumpkins, butternuts, and peppers)				11.1% of 168,421 tons

Regional context and local development goals

The Western Cape government is working towards a well-prepared agricultural sector instituted on a systematic and proactive response to future droughts; the strategy includes natural ecosystems that are also vulnerable to drought impacts [Goal 3, Birch et al. (2021)]. This target follows the 2015/19 droughts (Calverley & Walther, 2022; Theron et al., 2023), costing the agricultural sector alone nearly R5 billion and 35,000 jobs shed in 2017/18 (Pienaar & Boonzaaier, 2018; EasyData, 2022a, 2022d). Producer selling prices increased, as shown by income increments in Figure 3.4.

Figure 3.4: Employment and income from primary agriculture in the Western Cape Province (A) and the Witzenberg Local Municipality (B) from 1993 to 2021 (EasyData, 2022a; 2022c)

Within the Koue-Bokkeveld region, the reduction of natural resources (i.e., Fynbos ecosystems) for economic efficiency is represented by vulnerable (11.6% or 357.4 km^2) to critical (5.5% of 169.1 km^2) terrestrial ecosystem threat status (Skowno et al., 2019). More positively, environmental safeguards are in place within the catchment, with over 44.9% or 1,379.4 km^2 of the Koue Bokkeveld region under complete terrestrial protection (Skowno et al., 2019). If sustained, the protection of nearly half the Koue Bokkeveld region could contribute to meeting the Witzenberg Local Municipality targets for biodiversity and scenic beauty. In addition, sustained protection of the Fynbos ecosystems in the Koue Bokkeveld can contribute to meeting the national and international targets for terrestrial ecosystems under SDG 15.3.1—the proportion of land degraded (Liniger et al., 2019; von Maltitz et al., 2019). An opposing pattern, however, can be observed for inland aquatic ecosystems, 33.9% of which are mainly within the unacceptable ecological conditions (i.e., D-F classification) despite some protection (Skowno et al., 2019). The expansion of corporate farms, which are profit-driven and controlled by stakeholders without any relationship to the land, poses an additional risk to biodiversity as intensive agriculture is a known driver of biodiversity loss and a change in the streamflow regimes (Foley et al., 2005; Richardson et al., 2023).

Farmers have mostly moved to precision irrigation systems (micro-jet and drip irrigation sprinklers) to maximise their fruit production in the area and increase water use efficiency (Dzikiti & Schachtschneider, 2015). Each hectare under stone fruit hosts between 1,667 and 2,667 trees and consumes about 10,000 $m^3/ha.a^{-1}$ (Dzikiti & Schachtschneider, 2015). There are typically 2,000 apple stems per ha, with an approximately applied irrigation of 9,520 to 9,660 $m^3.ha^{-1}.a^{-1}$ (Gush et al., 2019). Citrus has the lowest density per hectare, with less than 700 stems of oranges and the highest relative irrigation demand of 8,900 $m^3.ha^{-1}.a^{-1}$ (Gush et al., 2019).

3.2.2. Study area description.

The E21 catchment (Koue Bokkeveld region—Afrikaans for *Cold Buck Shrubland*) is a commercial farming area located approximately 200 km north of Cape Town, in the Republic of South Africa (RSA, Figure 3.5). The remote rural area is one of the upstream drainage areas for the Berg-Olifants Water Management Area located on the north-western border of the Witzenberg Local Municipality in the Western Cape, which is the upper reaches of the Olifants-Doring catchment in the Western Cape (Figure 3.5). The catchment, covering an area of 3,071.9 km^2, consists of 11 medium-sized quaternary catchments (E21A-K), varying between 100 and 500 km^2.

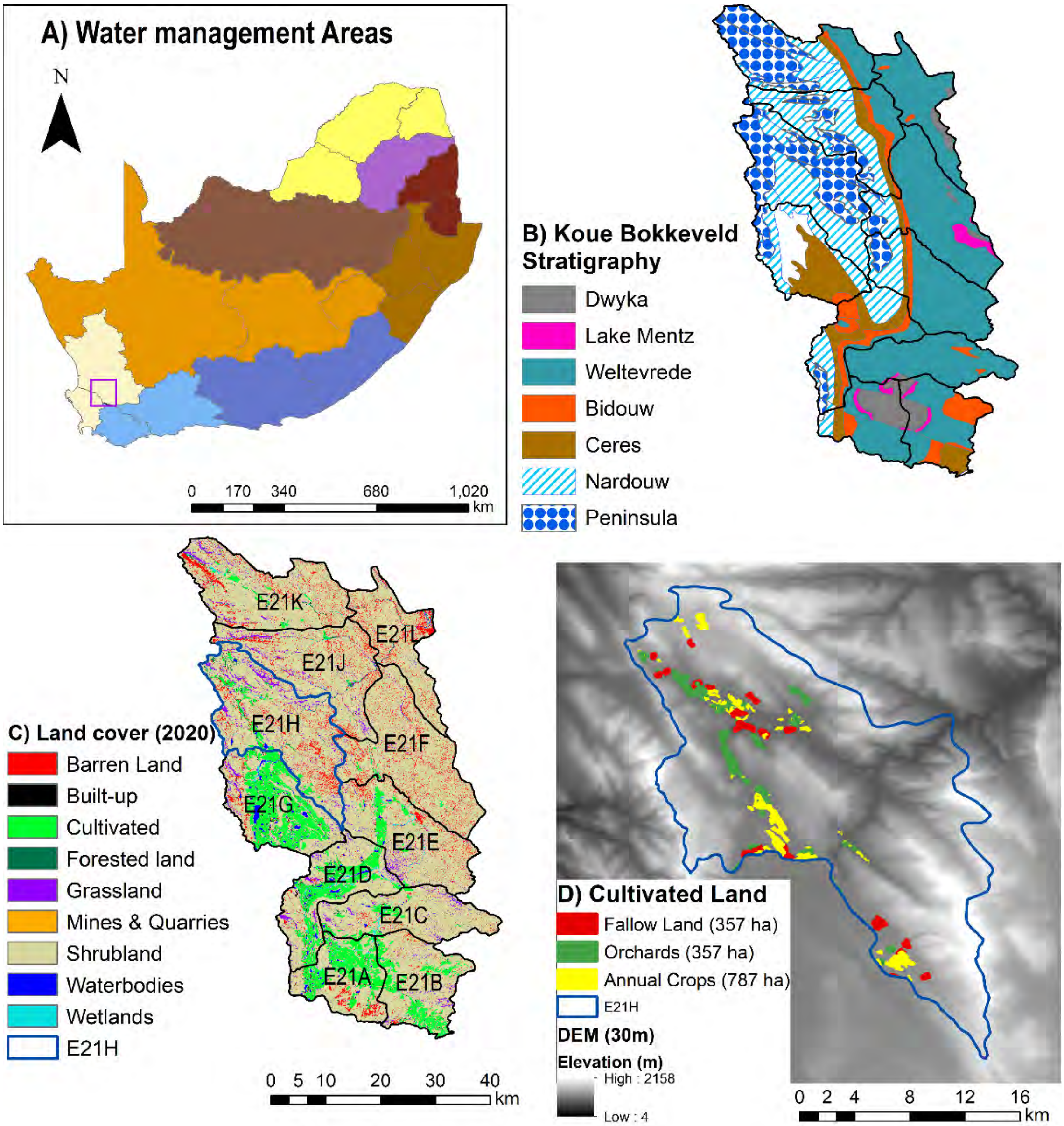


Figure 3.5: Context map of the Koue Bokkeveld catchment. A) Location for the Koue Bokkeveld catchment within South Africa, underlain by the national biomes (SANBI, 2012) B-D) Land cover of the E21 catchment from the 20-30 m National Land Cover datasets (r^2 > 0.85%) (DEFF, 2019, 2021).

3.2.3. Geology and soils.

The Koue Bokkeveld drains the Cedarburg Mountain system within the Fynbos Biome (Rebelo et al., 2006), flowing in the northerly direction, feeding the Doring River. Koue Bokkeveld sits on four sedimentary deposits from the Paleozoic era (Figure 3.5Figure 3.5: Context map of the Koue Bokkeveld catchment. A) Location for the Koue Bokkeveld catchment within South Africa, underlain by the national biomes (SANBI, 2012) B-D) Land cover of the E21 catchment from the 20-30 m National Land Cover datasets (r2 > 0.85%) (DEFF, 2019, 2021).-B), visible as beds in the anti-clinal hills and valleys of the landscape. The sedimentary deposits gave birth to moderate to deep sandy loam soils in the valley and undulating slopes (https://waterresourceswr2012.co.za/resource-centre/), and the soft mudstone areas in the valley are mostly preferred for cultivation (Figure 3.5-D). The Koue Bokkeveld is one of the major groundwater contributors in the Olifants/Doorn area and falls within the Groot Winterhoek Strategic Water Source area, which is essential for the Western Cape's fresh water supply (Nel et al., 2013).

3.2.4. Biosphere importance.

The Fynbos Biome covers a mere 6.7% of the South African landscape. However, it has a high richness and abundance of plant species (over 9,000) that prefer poor soil conditions and rocky terrains (Rebelo et al., 2006). The Koue Bokkeveld hosts some of South Africa's Critical Biodiversity areas through the Cederberg Biodiversity Corridor and the Witzenberg Biodiversity Spatial Area (Skowno et al., 2019), emphasising the need for biodiversity stewardship facilitated by various organisations in the area (herein described before). The Koue Bokkeveld is also home to eleven endemic fish species, with varying threat levels from Near Threatened to Critically Endangered (Ellender et al., 2017) based on the classification system by the International Union for Conservation of Nature.

3.2.5. Land cover.

Based on the South African National Vegetation Map Figure 3.5Figure 3.5: Context map of the Koue Bokkeveld catchment. A) Location for the Koue Bokkeveld catchment within South Africa, underlain by the national biomes (SANBI, 2012) B-D) Land cover of the E21 catchment from the 20-30 m National Land Cover datasets (r2 > 0.85%) (DEFF, 2019, 2021).-A by SANBI (2012), the primary land cover of the Koue Bokkeveld is the Mediterranean-ecosystem shrubland. Patches of grassland vegetation are visible in the high-altitude areas (Figure 3.5-C). The biodiversity of the biome is under immense threat due to anthropogenic activities (i.e. agricultural transformations, invasion by alien plants, and urbanisation (Le Maître et al., 2016). The Koue Bokkeveld is a pristine landscape compared to the global land cover conversion rates to cultivated areas (Foley et al., 2005), however, 10.9% of natural shrubland has been lost to cultivated land over 30 years (Figure 3.5-C). Van Wilgen et al. (2010) also noted the influential role of climate change in threatening the fynbos ecosystem resilience since increasing surface temperature and more unpredictable rainfall conditions are expected to increase wildfire frequency.

The Fynbos biome is regulated by wildfires (ideally every 10-15 years); however, the prevalence of wildfires is said to be more intense in inland areas (such as the Koue Bokkeveld) than in coastal regions (van Wilgen et al., 2010). The fynbos ecosystem's soil and flow regulation function is also modified by increasing wildfire frequency (Le Maître et al., 2014). All the eco-hydrological, climatic, and anthropogenic factors mentioned above require consideration for a realistic representation of present-day streamflow and the impacts of different water-sharing strategies on the system.

Land use activities.

As previously mentioned, the catchment is essential for food production in South Africa, with 11% currently under agricultural land cover, which has grown by 3.5 % since 1990, as shown in Figure 3.5Figure 3.5: Context map of the Koue Bokkeveld catchment. A) Location for the Koue Bokkeveld catchment within South Africa, underlain by the national biomes (SANBI, 2012) B-D) Land cover of the E21 catchment from the 20-30 m National Land Cover datasets (r2 > 0.85%) (DEFF, 2019, 2021).-C. Cultivated areas are distributed in low-lying open valleys (Figure 3.5-D), with the natural shrubland occupying the mid- to high-altitude areas. Based on the recent national land cover dataset (DEFF, 2021), fruit orchards—high-value crops (deciduous, stone, and citrus) account for the most agricultural area, covering 53.9 km^2, followed by 23.1 km^2 pivot annual crops (primarily vegetables). Non-pivot irrigated crops and vines occupy a minor area of 7.3 and 0.9 km^2. This trend slightly differs in the case study area (Twee Wyk, Figure 3.5-D) where orchards dominate the agricultural crop.

Commercial afforestation activities in the Western Cape have been declining since the early 2000s following their economic inefficiency and discouraging policies favouring conservation activities (Louw, 2006). However, some spots in the Koue Bokkeveld (Image 3.1) remain covered by invasive alien plants. Although these cover less than 1% of the catchment (Figure 3.5-C) they remain a concern for biodiversity and water flow regulation (Le Maître et al., 2014; Holmes et al., 2020). Most of the ongoing spread of invasive alien plants in the catchment could be uncontrolled afforestation located in critical areas, like headwaters, as shown in Image 3.1.

Image 3.1: Upper hillslopes of the Twee River catchment (E21H), showing uncontrolled regeneration of Pinus trees on privately owned land in March 2021 (photo by B.S. Xoxo).

3.2.6. Hydrological network of the Twee Wyk.

Tributaries that drain the KBV region are shown in Figure 3.6. Major tributaries in the KBV are located within the central valley of the catchment. Groundwater recharge in over the Twee wyk area ranges spans about 22.3 to 37.2 Mil.m^{3}.a^{-1}, and natural streamflow ranges from 55.2 to 140.5 Mil.m^{3}.a$^{-.1}$ (Department of Water and Sanitation, 2017). The Koue Bokkeveld system (E21) maintains the downstream Olifants River estuary (E33E) and the health of the Olifants-Doring rivers by contributing 66% to the Doring and Olifants rivers and 33% flows to the Olifants River, aided by a mean annual runoff estimate of 0.055 to 281.6 Mil.m$^{3.}$a^{-1} (Department of Water and Sanitation, 2017). Highly variable water availability in the winter rainfall region results in competition and conflicts during dry periods, Regarding water allocation, the KBV and its sub-catchments (including the Twee River) is a closed catchment, meaning no more water is freely available for new uses (Gleick & Palaniappan, 2010). White commercial farmers dominate the area with either Water-Use Licenses from the Department of Water and Sanitation, but most might still be allocated based on the Preexisting Lawful Use. Some emerging farmers (enabled by the government's land reform project) are still acquiring Water-Use Licenses, which is a general trend across South Africa (Kidd, 2016). The combined agricultural use in the area is estimated at 21% of mean annual runoff.

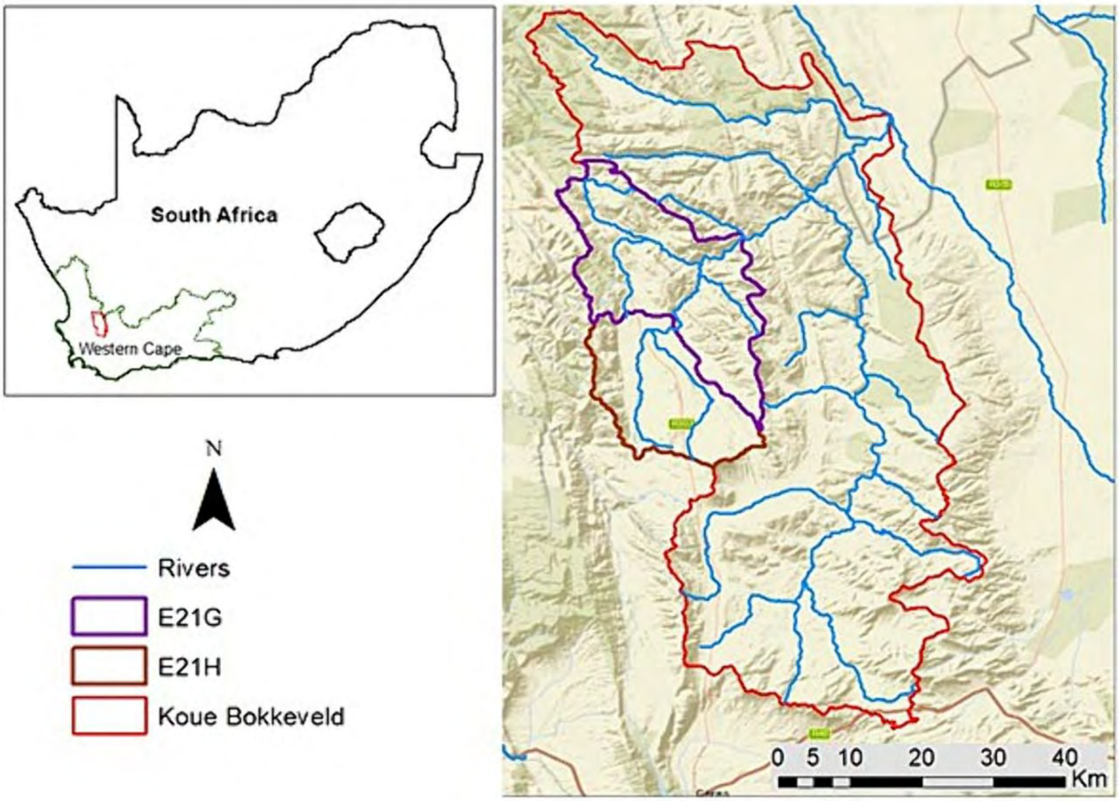


Figure 3.6: Twee wyk location showing the river network distribution.

3.2.7. Climate.

Western Cape context, present and future predictions.

Climate extremes in the Western Cape have been projected (Midgley & Lötze, 2011), and their validity is portrayed by the recent disasters (Calverley & Walther, 2022; Theron et al., 2023). The various drought characteristics (frequency, intensity, and magnitude) are expected to result in different socio-economic and environmental impacts, compelling a reconsideration of management strategies to increase the resilience of the system to change (van Loon & Laaha, 2015; Owusu et al., 2021; Tanner et al., 2022).

The Koue Bokkeveld experiences a Mediterranean climate with a mean annual temperature below 15°C but a daily temperature range of -2.5°C in July and rising above 37°C by February, based on 2008/10 ground observations (Gush et al., 2019). Uncertainty exists over the magnitude of rainfall in the area, as shown in Figure 3.7. The South African Water Resources dataset (WR2012) at quaternary catchment scale and CRU-V.4 dataset (Harris et al., 2020) averaged at a half-grid scale show a 3 to 35% disagreement, mostly on low annual rainfall. Minimum rainfall is estimated at 241.3 to 325.0 mm.a^{-1}, and maximum rainfall is historically estimated at 898.2 to 922.5 mm a^{-1} (Figure 3.7).

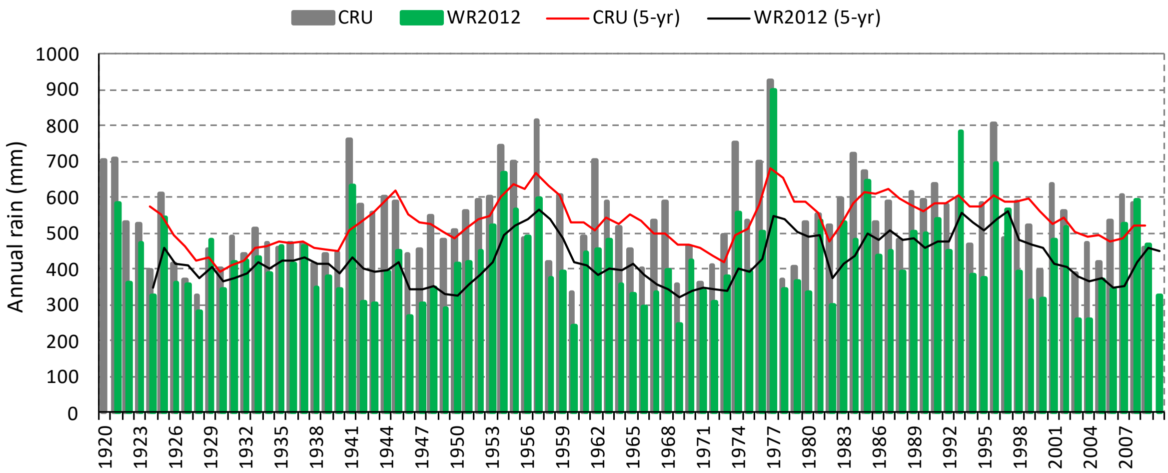


Figure 3.7: Rainfall trend over the Koue Bokkeveld based on the WR2012 and CRU (Harris et al., 2020) datasets.

Local rainfall provided by farmers and regional rainfall from the South African Weather Services.

The rainfall data for the present study was sourced from the South African Weather Services and from local farmers (Table 3.2). These stations were chosen for their proximity to the study area, have a typical record time covering the period of 1990 to 2021, and are mostly distributed in lower elevation points. These rainfall stations were gap-filled with satellite-based rainfall estimates (Funk et al., 2015) and interpolated using the Kriging method to reduce variance (Coulibaly & Becker, 2007; Ly et al., 2013). It can be anticipated that data quality issues due to record gaps, sparse density, and observation points will propagate into the streamflow simulation results (section 6.4.1), but this data is used as the best available information for the assessment.

Table 3.3: Information of input rainfall stations used in the study.

	A) Outside study catchment boundaries		
Gauge name	Gauge owner	Records length	Elevation (m)
Krommiriver	South African Weather Services	1990-2021	827
Grootriver	South African Weather Services	2006-2021	501
Zonderwater	South African Weather Services	2006-2021	954
Excelsior Ceres	South African Weather Services	1993-2021	958
Bokkeveldkloof	South African Weather Services	1990-2021	1,035
Die erf	South African Weather Services	1994-2021	992
Odessa	South African Weather Services	1990-2021	957
Matjiesrivier	South African Weather Services	1998-2021	739
Malabar Farm	South African Weather Services	1990-2010	979
	B) Within study catchment boundaries		
Kunje	Kunje Farm	1990-2016	730
Suiker	Freshwater Research Centre	2021-2022	724
Balies	Freshwater Research Centre	2021-2022	781
Zuur	Freshwater Research Centre	2021-2022	1152
Ysterplaat	Ysterplaat Farm	2003-2021	804
Reolofs	Stellenbosch University	Jan – Dec 2022	1,247

3.3. Methodological Framework: Water-Sharing Tool Overview

The Institute for Water Research at Rhodes University in South Africa has developed a collaborative model for water allocation assessment, referred to as the Water-Sharing Tool with Dams and Uncertainty (Water-Sharing Tool). This tool is designed for use in ungauged basins, and its first version was published by Pienaar and Hughes (2017) using a hypothetical case study of the Crocodile River Catchment, South Africa. The model takes into account streamflow uncertainty (Blöschl et al., 2013; Hrachovitz et al., 2013), environmental flows (E-Flows, Poff & Matthews, 2013), socio-economic use (direct from a river or abstracted from a reservoir), the risk profile of individual users (Hughes & Mallory, 2009), and a stated equity measure (community allocation preferences). The model is not aimed at directly making water allocations, but its goal is to guide the decision-making process by analysing decision options and communicating their uncertain outcomes to stakeholders, decision-makers, or policymakers. This way, the model sees uncertainty as a hidden opportunity to better manage water-shortage risk, supporting Gober (2014).

The work presented here encourages decision-makers to consider impact as a common measure of fairness/justice when making reallocation decisions. This addition is especially relevant in South Africa, considering the ambiguity and lack of a universal measure for distributive equity (Seigerman et al., 2022; Valipour et al., 2024). The model supports fairness/justice through the following interventions:

- **Recognitional justice:** The knowledge forces the experts and water users to represent socio-economic values and needs of all water users found within a water management area (including rural and environmental users) to ensure that the unique requirements and possible impacts of scarcity management to each group are considered.
- **Procedural justice:** The model emphasises stakeholder involvement in allocation planning, which is in line with global policies and the South African water legislation. To setup the model, user representatives contribute water demands and socio-economic values. This way, the model ensures that all voices are equally heard and considered in the allocation planning process.
- **Distributive justice:** The model allows for a fair distribution that is in line with societal objectives and ensures that reallocation decisions are made based on the relative importance and level of vulnerability of different users to supply shortfall. This distributive justice is facilitated by the novel use and involvement of water users in the definition of water allocation preferences and the deficit-impact index.

To answer the question if the Water-Sharing Tool's approach will result in more equitable outcomes or if the stakeholders will accept the outcomes more is left to the participatory process of setting up the model and communicating the outcomes. Representing and involving all water user group's representations is assumed to allow a realistic and local-specific setup of the model. Continuous engagement or stakeholder participation is also envisaged to expose decision-makers to alternative approaches to demand management. Communicating the likelihoods of streamflow and evaluation outcomes of water reallocation strategies will allow the decision-makers to imagine the possible impacts of decisions and collectively agree on a preferred option. Once this decision has been made, it should be possible to track the performance of the strategy over time and readjust the decision as required.

The updated structure of the Water-Sharing Tool is illustrated in Figure 3.8. The Water Sharing Tool is a comprehensive framework designed to address the equitable allocation of water resources across various user groups (Pienaar & Hughes, 2017). The Water-Sharing Tool employs three interconnected modules to estimate risks associated with plausible water allocation options, as shown by the model structure in Figure 3.8. These modules consider uncertain water availability (Kapangaziwiri et al., 2012; Ndzabandzaba & Hughes, 2017), environmental and socio-economic demand, community development goals, and user risk profiles. The evaluated impacts are produced for each user within a sub-area and for the system as a whole. The Water Sharing Tool's explicit incorporation of uncertainty is targeted for deployment in poorly gauged catchments (Pappenberger & Beven, 2006; Lerat et al., 2011; Matrosov et al., 2013; Pienaar & Hughes, 2017).

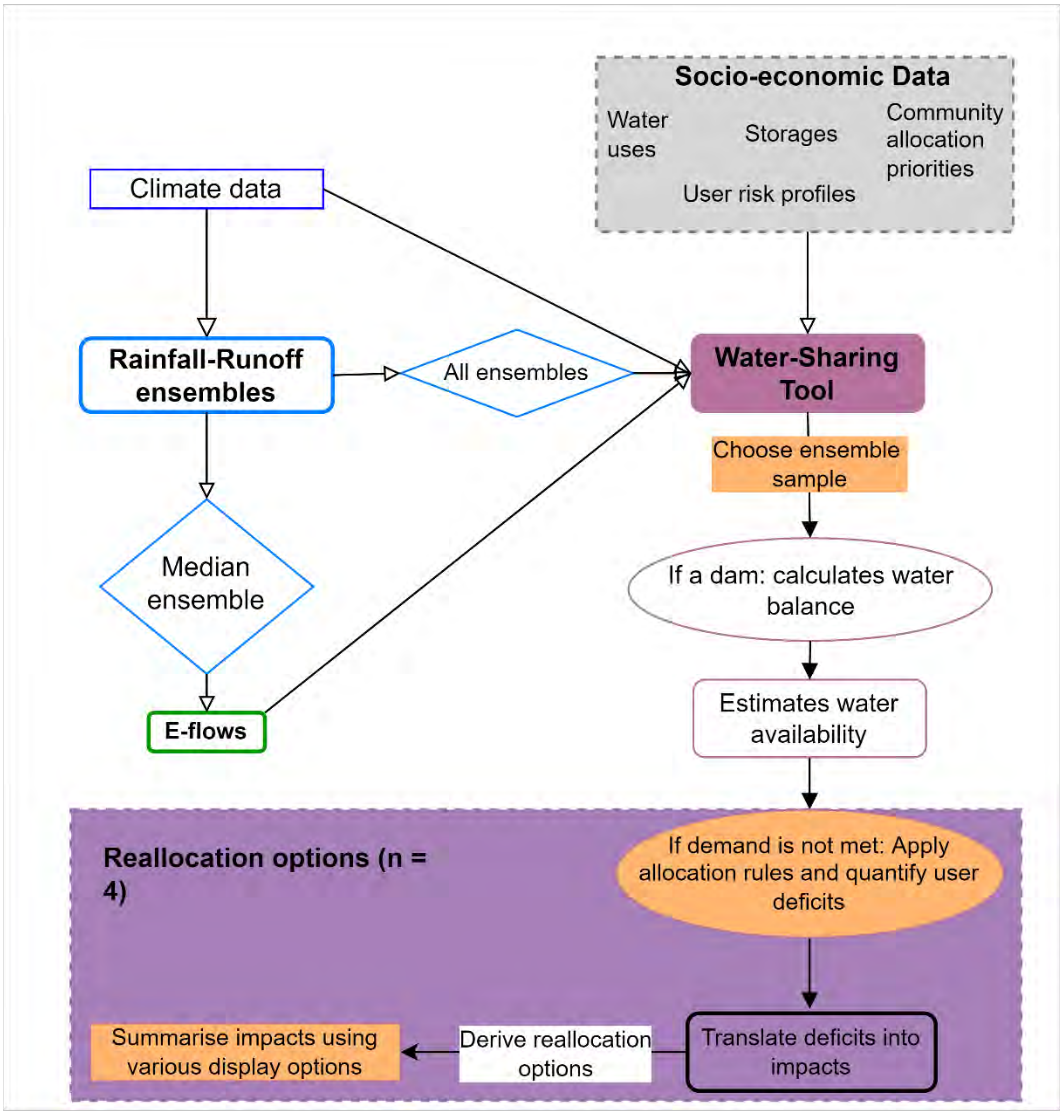


Figure 3.8: Flow diagram describing the updated Water-Sharing Model structure.

3.3.1. Spatial distribution of socio-hydrological system.

The spatial distribution system is based on nodes (input 1 in Table 3.2) representing sub-areas within the total basin area. Associated with each node is a set of inputs representing the natural incremental streamflow (defined as uncertain time series ensembles, input 7 in Table 3.2), the details of any reservoir storage (input 4 in Table 3.2), as well as the downstream environmental flow requirements and the abstraction demands for up to four user groups. Associated with each user group is a set of socio-economic data that defines the group's risk profile and allocation priority level. Abstractions from any node can be used within that node or transferred to any other node (upstream or downstream) in the basin. More details about the model inputs and parameters and where they are sourced from are given in the following subsections.

Table 3.4: Water Sharing Tool data requirements and optional input attributes.

Model input attributes	Feature/Attribute Type (and Units)	Description
1. Demand site (Basin ID)	Feature point and text	Identification name for the sub-catchment where users share a withdrawal supply location.
2. Single time series of rainfall data	Time series attribute (mm/month)	A continuous time series of rainfall data (future rainfall estimates could be included).
3. Monthly evapotranspiration data	1-D Array attribute (% monthly distributions)	Array attribute containing mean monthly evapotranspiration distribution for the sub-area.
4. Reservoir storage parameters	1-D Array attribute	Array data showing monthly distributions of annual water parameters, including five levels of operation rules (14 parameters in total).
5. Water-use distributions	1-D Array attribute	Array data of annual water demands (including the E-Flow)
6. Baseflow separation parameters	2-D Array attribute	Baseflow contribution to streamflow (with a typical range of 0-1 in South Africa).
7. Ensemble outputs of natural monthly flows	Time series attribute (Mil.m^3/month)	A continuous time series of flow without water uses within the sub-areas.
8. FDC for natural flows	Array attribute (Mil.m^3/month)	Median values of the flow ensembles or single run flow output.
9. FDC for E-Flow at a higher environmental protection level	1-D Array attribute (Mil.m^3/month)	Flow duration curves for the required E-Flow level in the sub-area.
10. FDC of E-Flow at a lower environmental protection level	1-D Array attribute (Mil.m^3/month)	Flow duration curves for the lowest E-Flow level that could be met in the sub-area.
11. User water requirements and risk profiles	2-D array attribute	Parameters for water users (Table 1.3)
12. Output 1	Text file	A risk report containing model outputs for decision-making (yet to be finalised).

3.3.2. Simulated inputs: Uncertain streamflow inputs and E-Flows.

The first group of inputs required by the Water-Sharing Tool represent the details of the sub-area climate and streamflow at monthly intervals, all of which are required for estimating the available water supply (inputs 2 to 3 and 6 to 8 in Table 3.2). The natural streamflow inputs (2) include uncertain ensembles, sourced from an appropriate hydrological model, while the other inputs are used in the reservoir water balance estimations or in facilitating the environmental water requirements (E-Flows).

E-Flows are similarly sourced from an appropriate external model [the RDRM and DRIFT models in this study (King et al., 2003; Hughes et al., 2014a; Tanner et al., 2022)] and are defined as calendar month flow duration curves (FDCs) for two levels of ecological protection (inputs 9 and 10 in Table 3.2). The two levels considered are, for example, based on the proportions of the near-natural (level B) and modified flows (level D) E-Flows relative to the natural flows for all the percentage point values in the monthly FDCs. The same proportions can be applied to all the input streamflow ensembles. Input 8 in Table 3.2, therefore represents the FDCs of a representative (median) natural flow time series, and this would be used in the environmental assessment model to generate the FDCs at the two levels (inputs 9 and 10) for evaluation of low and high E-Flow thresholds, which will vary by water management area. The E-Flow impact-deficit index (part of input 11, Table 3.2) represents the expected environmental consequences of E-Flow requirements only being met at a level of protection lower than the defined upper, or target, level (input 9 in Table 3.2).

The justification for the above inputs is that key sources of uncertainty, due to poor observation data quality and complex physical catchment conditions that make is difficult to reliably predict hydrological processes to support decision-making. Meanwhile, accounting for these uncertainties is not a norm in decision-making, especially in southern Africa. although these need to be interrogated to improve the beneficial use of limited water supplies (Hughes & Mallory, 2009).

3.3.3. Socio-economic data.

Table 3.3 provides a detailed description of the user information, including the community allocation preference (community weights), a relative impact index (user risk profiles), a scaling factor, and an annual demand. These form part of the socio-economic parameters and are sourced from the water users using the procedure described in **Chapter 3**. Of the socio-economic parameters, community weights reflect the relative importance of water users within water management areas or social distributive equity goals. The impact index simply reflects the relative effect or impact different levels of deficits have on different users, including the E-Flow. The community weights and the impact index are flexibly sourced using interdisciplinary approaches in collaboration with water users/stakeholder representatives. The E-Flow impact index is simply estimated by the percentage difference between a high and a low protection level. As noted by Hughes & Mallory (2009), the main objective behind the impact index is to distinguish between the different users and not to capture the deficit-impacts accurately. The annual demand is supported by an array file of seasonal fractions for all identified user groups (input 5 in Table 1.3). Since E-Flow demands are variable, the annual demand is coded as 1 in the Water-Sharing Tool, and the model targets inputs 9 and 10 in Table 1.3. Intra- and inter-basin transfers are specified using input 5 in Table 3.3. However, downstream releases are treated as normal flows/ E-Flow contributions.

Table 3.5: Description of water user parameters for the Water-Sharing Tool, sourced from the water users.

Parameter	Description
1. Community weight (range = 0-1)	A community-derived hierarchical structure describing the distributive equity criteria for dry periods.
2. Impact index (0-100%)	User risk profiles describe the holistic impact faced by each user, reflecting the exposure, sensitivity and adaptive efficacy of users when faced with water shortages
3. Scaling factor (%)	A ratio of available supply and allowed abstraction, showing operation rules
4. Annual Demand (Mil.m^3)	The sum of monthly water demands for all users.
5. Transfer destination	A spatial record of a receiving sub-area if it's a transfer.

3.3.4. Translation of deficit into impacts and deficit-impact relationships for all users.

Following Hughes & Mallory (2009), Water-Sharing Tool takes all sample ensembles and calculates water deficits for each user in each sub-area (Figure 3.9-B) as a starting point to assess uncertainty and impacts/risks associated with possible reallocation options (Figure 3.9Figure 3.9: Parameter setup in the Water-Sharing Tool. -C). These supply shortfalls are multiplied by user risk profiles (input 2 in Table 3.3), and both the deficits (frequency of shortfalls at 100% normal demand) and impacts are converted into percentages and ranked from low to high (0 to 100%). These two outputs are transformed into a normal distribution and shown as asymmetric s-curves (deficit-impact index or impact curves) that allow direct comparison across sectors/users/user groups.

The parameters (impact index, community weight and scaling factor) can be recalibrated by selecting the relevant sub-area in Step 1). The updated model allows users to explore the supply management effects of inter-basin transfer (Step 1-A). The model translates user deficits into deficit-impact curves at the click of a button (B). These deficit-impact curves are used to simulate the impacts of each water-sharing strategy (C).

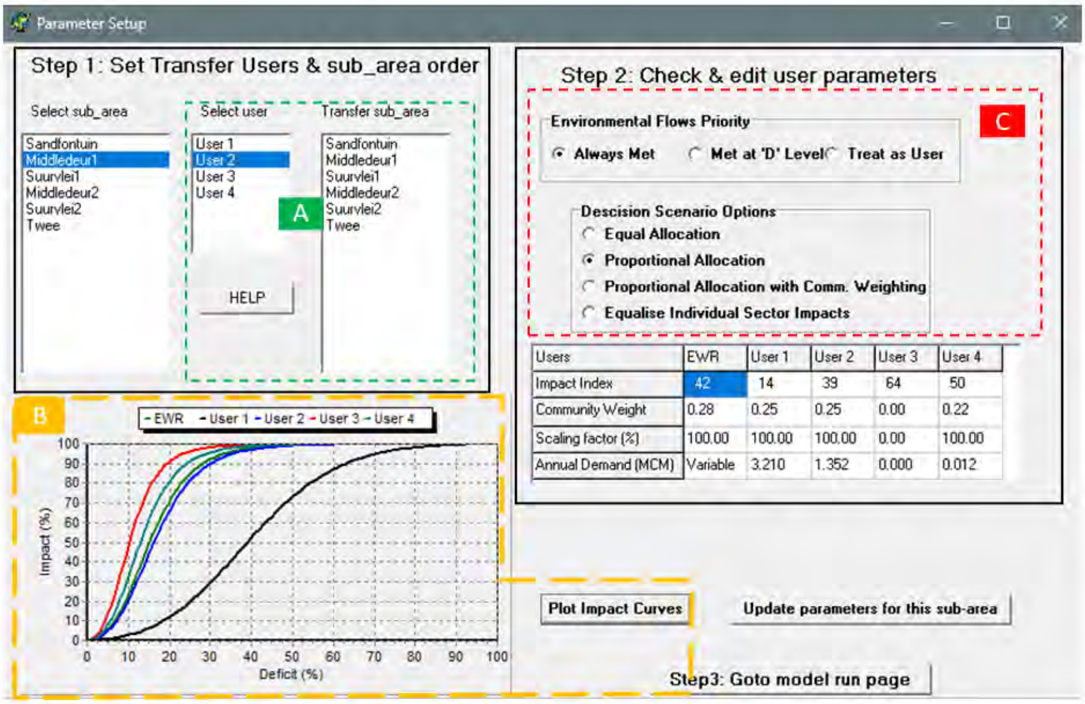


Figure 3.9: Parameter setup in the Water-Sharing Tool.

3.3.5. Reallocation Structure of the Water-Sharing Tool

In cases when downstream sub-area users depend on run-of-river supplies or user needs exceed dam supply, reallocation strategies take effect. The supply volume that is considered is the streamflow volume that can be used for socio-economic demands after E-Flows are satisfied at the designated protection level. The community allocation preference hierarchy is used to plan the new allocations.

The reallocation options and distribution of available water during a deficit period only apply to the users in a single sub-area. In the updated model version, it is possible to include downstream users as part of the upstream supply by adding a 'user' in the upstream sub-area that allows for downstream use. In cases with transfer agreements, the updated model version also has a 'transfer destination parameter to specify where that water use goes. This transfer parameter works the same way to manage an inter-basin transfer as part of the allocations.

Two reallocation decisions must be made in the decision-support model (the Water-Sharing Tool, Figure 3.9Figure 3.9: Parameter setup in the Water-Sharing Tool. -Step 2). The first is to fulfil the E-Flow priority level, which can be met at the desired level (i.e., Always met), the minimum possible level (Met at 'D' level) or treated as a user. Treating E-Flows as a user implies that instream environmental ecosystems compete with other users within the sub-area but is not applicable in South Africa as specific E-Flow requirements exist for each quaternary catchment. The second decision relates to how the drought/reduced supply is shared between user groups in each node to balance demand and supply considering user risk profiles. The model offers four options: Equal share, Proportional allocation, Proportional allocation with community weights, and Equal impact, which decision-makers can consider as a starting point for equitable water reallocation. These allocation options are derived from the deficit-impact plots (described in section 3.3.4) to achieve a supply-demand balance and meet the distributive equality criteria specified by users.

Initially, the water-sharing strategies were descriptively named Proportional Sharing, Equal sharing, Proportional allocation with community weights, and Equalised impacts (Pienaar & Hughes, 2017). However, following a day-long discussion with an interdisciplinary team of experts in water resource management specialists and a catchment manager, it was decided to simplify the linguistic terms so that they could be understood by a wide range of decision-makers and stakeholders. The reallocation rules/ water-sharing strategies were renamed as follows: Proportional Allocation became *Split-the-Bill*, Proportional allocation with community weights was renamed to *Beehive*, whereas Equal sharing became *Pizza Slices*, and Equal impact became *Equal impact*. Key elements of each water-sharing strategy are discussed below.

Pizza Slices or Equal Sharing.

The first option to consider is safeguarding small-volume users such as hydro-power operators and rural domestic users, which is a form of redress since historical water laws in South Africa were biased towards commercial agriculture (Tewari, 2009). *Pizza Slices* safeguards small-volume users by progressively allocating available supply to all users until all demands are met, or supply runs out. Large-volume users face higher shortages as supply will run out before they reach their full assurance level. In the context of the South African water allocation reform targets (Pienaar & Van Der Schyff, 2007), this strategy can be considered fair since it is fair towards addressing the water allocation reform targets that favour previously disadvantaged individuals and new uses (e.g., hydropower). However, as commercial irrigation will be the most affected user, this strategy may be criticised for constraining economic progress as the larger user will face disproportionate impacts.

Split-the-Bill or Proportional allocation.

The second reallocation strategy to consider is *Split-the-Bill,* which is based on equality or equal treatment principle. This strategy is typically used to manage demand during drought periods in South Africa. As shown in the groundwater trading case by Iftekhar and Fogarty (2017), proportional allocation reallocates water based on a fixed percentage-cut approach, ensuring that deficits are imposed equally across users. Because of the inherent inequality in water entitlements (Rockström et al., 2009a), the strategy ensures supply reliability for large-volume users without a careful consideration of the resilience and vulnerability of small-volume users. This approach can be considered fair because of the substantial contributions to the economic growth of this user group. However, when applied to diverse users or without recognising social conditions (McDermott et al., 2013), *Split-the-Bill* may be problematised to generate lopsided outcomes for the most vulnerable users in a water management area, especially given the variable nature of impacts across users. Affected users/stakeholders may perceive the high-impact exposure under *Split-the-Bill* as inequitable given complex historical realities (Hellegers & Leflaive, 2015; Pienaar & Hughes, 2017; Seigerman et al., 2022). The strategy is straightforward to implement, as shown in Equation 3.1, where QAvail is the allocable supply after E-Flows are met, UD_x denotes user demand, and UDi is the combined socio-economic demand for the water management area.

$$User_x = QAvail * (UDx/\Sigma UDi) \qquad (3.1)$$

Beehive or Proportional allocation based on community weighting.

Beehive combines equal per-capita and Kantian allocation rules (Roemer, 2010), wherein users in a community expand the fixed-percentage restriction by a socially stated factor. *Beehive* proposes that water fixed-percentage cuts should reflect community aspirations while balancing the diverse water-use values as recommended in the Bellagio Principles (United Nations, 2017). As shown by Equation 3.2, in addition to the variables of *Split-the-Bill*, *Beehive* considers community-stated equity that indicates the relative importance of a user with respect to others in the community (Xoxo et al., 2023). The community priorities for allocation (or community weighting index) represents users that the community wishes to protect against water shortages and the community's attitude towards the environment, Equation 3.2 shows how reallocation for user x under *Beehive* is achieved, where CW is community preference for allocation:

$$QAvail \frac{CWx * UDx}{\Sigma(CWi * UDi)} \qquad (3.2)$$

Equal impact.

Equal impact is a fourth plausible reallocation option that ensures distributive equity by searching for equal impacts from water deficits across users to balance available supply, water use and social equity objectives. These impacts are considered in a holistic fashion, designed to capture user vulnerability (Hughes & Mallory, 2009; Abdulla et al., 2014). *Equal impact* is considered a viable reallocation strategy as it first considers *the* fairness of user exposure to impacts originating from underlying vulnerability. The underlying vulnerability may depend on historical policy design, such as the historical water legislature in South Africa (Tewari, 2009) that favoured irrigation over other uses. By searching for equalised sector/user impacts, *Equal impact* avoids disadvantaging one user group over others when restrictions are applied if each user experiences a similar impact or recovery effort when facing water restrictions. Unlike other options, outcomes of *Equal impact* will also affect the proactive environmental entitlement, meaning that decision-makers need to configure how E-Flows can be met when using this option.

Step 1, Start by co-identifying an impact level that all users can recover from using the deficit-impact curves.
Step 2, determine the deficit percentage corresponding to Step 1.
Step 3, Compute user allocation using Formula 3.3:

$$User_x = UDx - (Step\,2 * UDx) \qquad (3.3)$$

3.3.6. Water balance calculations.

The main part of the Water-Sharing Tool is a set of relatively simple water balance calculations using either the total channel flow (incremental streamflow plus any flows from upstream nodes) or the available reservoir storage to determine how much water is available to meet the demands of the water users and the E-Flows. The calculations include an evaluation of the amount of flow (including the E-Flows) that will pass downstream to the next node in the distribution system. If a reservoir exists at a specific node, the water balance calculations include estimates of the net evaporation (evaporation – rainfall) based on the surface area of the dam (derived from the current storage volume and the two parameters of the volume-area relationship). For a reservoir situation, the downstream spillage is also used to partly or entirely satisfy the E-Flow requirements, and all the water balance components are calculated for ten equal iterations to overcome the problem of which order to apply them. These calculations are performed for each uncertainty ensemble (typically 500 but could be more depending on computer processing power). If the amount of water available is insufficient to meet the demands (users and E-Flows), then the total deficit in supply is calculated, and the available water is distributed across all users and the E-Flows according to the selected allocation strategeis.

3.3.7. Tolerance levels of users.

Recognising the relationship between water security and risk tolerance among water users within a community (Grey et al., 2013), the Water-Sharing Tool simulates the frequency and of months where users face no impacts and displays these on top of each user’s histogram (Figure 3.10-C). These risk tolerance values are computed for each water-sharing option but have previously not been considered of value for decision support (Pienaar & Hughes, 2017). The histograms themselves do not seem to be of any worth and are confusing to understand. Thus, model users are advised not to consider these in their decision-support setups. The tolerance levels communicate the maximum annual impacts computed based on water shortage, user-risk profiles, and community weights. Pienaar and Hughes (2017) note that the worst option could be ruled out by decision-makers based on the impact group histograms. The community-weighted summary communicates collective user tolerance for all the users within a sub-area (including the environment). The community weights are also used to integrate user impacts across the basin to give the community-weighted total of impacts. The community-weighted summary may be useful to spatially compare the performance of each water-sharing option.

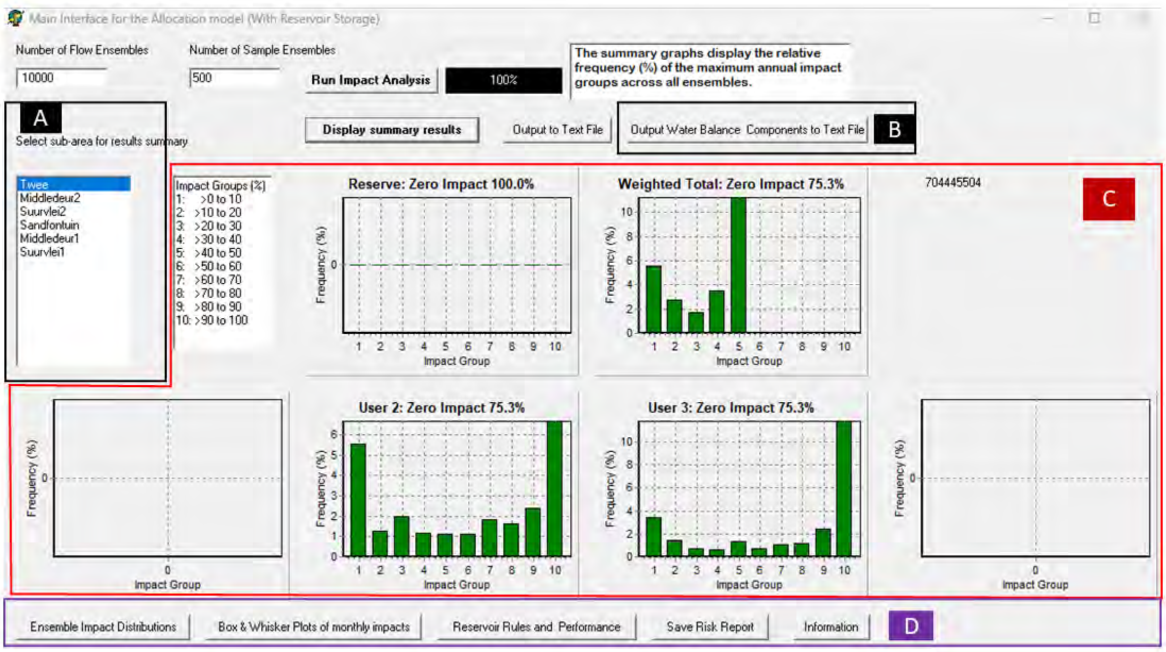


Figure 3.10: Risk tolerance interface of the Water-Sharing Tool for each user and the community within a sub-basin (A, C). Hydrological impacts of reservoir storage and surface water withdrawal are given by the water balance component output (B). Uncertainty assessment of impacts is explored using the summary outputs in D.

3.3.8. Reservoir storage performance.

It is possible to explore the anthropogenic storage performance for each sub-area using a lumped reservoir storage. Where applicable downstream flow requirements are satisfied using reservoir operating rules (up to 5 levels of abstraction curtailment) that can be modified using input 4 in Table 1.3 or directly in the model using the storage level and fraction of demand matrix (Figure 3.11-A). Operation rules are intended to mitigate the downstream impacts of reservoirs (Mallory et al., 2013; Owusu et al., 2021; Van Loon et al., 2022).

In the Water-Sharing Tool, reservoir storage performance is assessed using an FDC plot with flow ensembles shown as Box and Whisker plots (Figure 3.11-B) to highlight the uncertainty in storage across ensembles. This interface can also be used to explore planned reservoir storage as done in the synthetic examples in Pienaar & Hughes (2017). The model returns the frequency of exceedance graphs for the upper and lower limit of the reservoir volume (as % of full supply volume) simulations across all the ensembles. A monthly description based on a time series evaluation of storage dynamics like the one described above is also provided for sub-areas with reservoirs. This set of Box and Whiskers plots represents storage levels' mean and standard deviations. Impact assessment of increased storage can be done by adjusting the reservoir volume in the input table. However, this is not a straightforward approach for users who wish to build a new on-channel dam. In this case, the peak flow E-Flow rules might also need to be included.

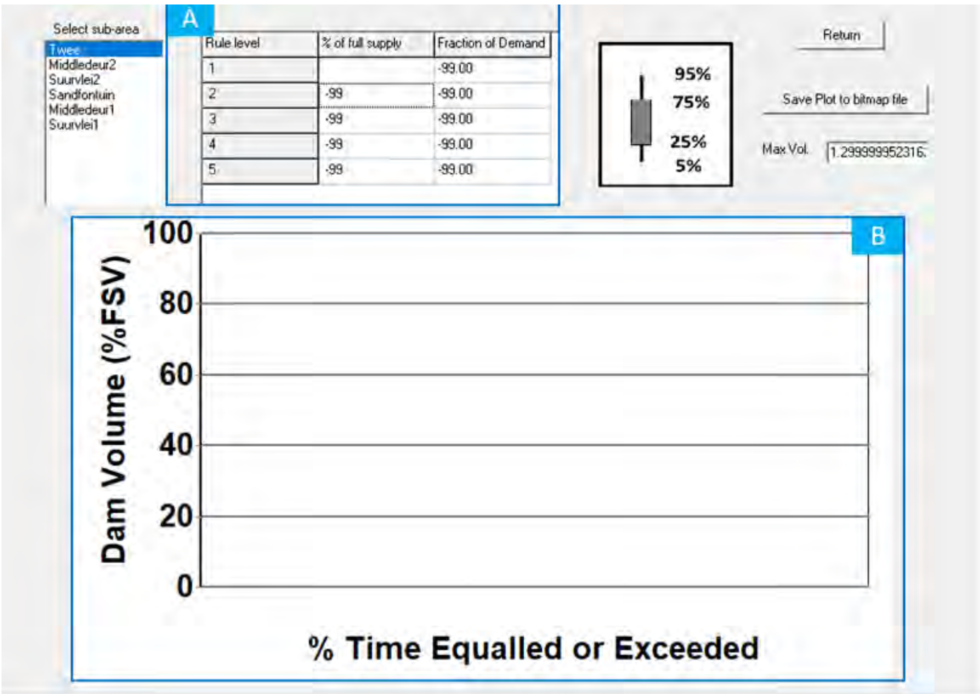


Figure 3.11: Reservoir rules and performance assessment interface.

3.3.9. Description of the different output/display options.

The impact levels described above represent short-term impacts ranging from no impact to catastrophic impacts (0 to 100%). The model evaluates allocation impacts over the assessment period, enabling the appraisal of supply uncertainty and the effects of different scarcity management options. The long-term impact scores are derived similarly from those making up the tolerance level, but for the same approach as the impact scores, monthly impact scores and summarises as Box and Whisker plots to show the ensemble distribution of monthly impacts and the uncertainty range of each impact across the ten groups and relates the impacts to sample streamflow ensembles.

The Water-Sharing Tool counts the number of months in each impact group and summarises these as an ensemble distribution (Box and Whisker plots) in each impact group. This step is intended to represent uncertainty from simulated streamflow and increase acceptance of uncertainty in water policy (Mcmillan et al., 2017). The Box and Whisker Plots represent an ensemble of plausible but uncertain outcomes. The boxes represent the 25-75% flow ensemble distribution, and the whiskers represent the upper and lower 5%.

The next three chapters focus on the main research objectives and report on the demonstration of the Water-Sharing Tool in collaboration with stakeholders in the Twee Wyk (Twee River Catchment). **Chapter 4** elaborates the methodological choices for the socio-economic data. **Chapter 5** details the use of a serious gaming technique to communicate the water reallocation structure and co-evaluate some environmental and socio-economic impacts of water scarcity management outcomes. In **Chapter 0**, the Water-Sharing Tool is deployed in the Twee Wyk using the socio-economic outcomes from **Chapter 4**, the process described above, and interpreted based on the understanding gathered from the serious game discussions. Lastly, the conclusions and recommendations are made in **Chapter 7**.

4. DEVELOPING A METHODOLOGICAL FRAMEWORK TO COLLECT THE REQUIRED SOCIO-ECONOMIC DATA: FROM VISIONING TO IMPACT ASSESSMENT

The community weighting index (4.2.3, 4.3.2, 4.4.2) has been published as: **Xoxo, S**., Tanner, J., Mantel, S., Gwapedza, D., Paxton, B., Hughes, D. and Barreteau, O., 2023, May. Equity-Based Allocation Criteria for Water Deficit Periods: A Case Study in South Africa. *In 9th International Conference on Decision Support System Technology* (pp. 137-155). Cham: Springer Nature Switzerland. DOI: 10.1007/978-3-031-32534-2_11

Methods sections 4.2.1 and 4.2.2, as well as the results sections 4.3.1 and 4.2.2 have been published as a special issue contribution in the *Journal of Hydrology* as: Gwapedza D, Barreteau O, Mantel S, Paxton B, Bonte B, Tholanah R, **Xoxo S**, Theron S, Mabohlo S, O'Keeffe L, Bradshaw K, Tanner J. 2024. Engaging stakeholders to address a complex water resource management issue in the Western Cape, South Africa. *Journal of Hydrology* **639**: 131522. DOI: https://doi.org/10.1016/j.jhydrol.2024.131522

4.1. Introduction

Previous studies have shown that climatic and human system changes have lasting impacts on water users and hydrological systems (Beven & Alcock, 2012; Montanari et al., 2013; Sivapalan et al., 2014; Mekonnen & Hoekstra, 2016; Campanhão et al., 2021; Tanner et al., 2022). However, there is still a lack of water reallocation planning frameworks that simultaneously account for the uncertainties and surprises caused by variability in supply, human agency, and issues relating to incorrect modelling outcomes (Mayer & Muñoz-Hernandez, 2009; Beven & Westerberg, 2011). Consequently, decision-makers are unfamiliar with practical approaches to incorporate these uncertainties and surprises into water allocation planning frameworks (Hughes & Mallory, 2009; Sivapalan et al., 2014).

Traditional water allocation processes aim to distribute water resources fairly and efficiently among users while avoiding system failure (Loucks & van Beek, 2017). To achieve this, decision-makers often rely on calculus-based optimisation methods or model simulations that provide evidence for negotiation. However, these methods have practical limitations. Firstly, they cannot account for the non-mathematical aspects of water use, such as socio-cultural, environmental, and legal factors, meaning user groups who value water differently have a reduced chance to access the resource (Blair & Buytaert, 2016; Tian et al., 2019). Secondly, they assume perfect information and ignore the uncertainty and unpredictability of human-water systems, which may lead to unexpected outcomes or "black swans" (Di Baldassarre et al., 2016; Null et al., 2021). They also overlook the distributional impacts of the reallocation alternatives on different stakeholders (Skurray et al., 2013; Thompson et al., 2013; Kelly et al., 2015).

Although not a fool-proofed solution, participatory approaches focused on communal exposure and sensitivity to climate extremes and variability as well as likely impacts, are suggested as one of the potential alternatives (Di Baldassarre et al., 2016). Such mixed-methods approaches could offer an understanding of the complex human-hydrology interactions that partly inform preference for water use (Wiek & Larson, 2012; Valipour et al., 2024). As understood for sustainable development (Pascual et al., 2023), integrating nature's values and the impact of resource shortage enhances the identification of win-win alternatives or acceptance of unavoidable losses (Patrick, 2014) between the socio-economic and environmental outcomes of natural resources. This benefit is the most relevant to less privileged user groups.

This chapter demonstrates a socio-economic data collection approach to capture multiple values for water supply and sectorial impacts of water deficits at a Water Users' Association level. The results of the approach presented here will be used in a decision-support model setup with stakeholders to explore uncertainty in the fair reallocation of water resources during periods of low availability in poorly gauged environments (demonstrated in **Chapters 5 & 6**).

4.1.1. Re-introducing the deficit-impact index (deficits versus impact).

To incorporate the likely impacts of water deficit in policy-making, Hughes & Mallory (2009) proposed a stakeholder-informed user risk profiling—a social parameter for a comprehensive representation of the relationship between water deficits and their consequences for each user group. They reasoned that effective policy and sustainable management of restricted water resources must include the socio-environmental and economic consequences of water shortages, and those choices must be appropriate to account for many possible situations, as emphasised by Korteling et al. (2013). Thus, the index's unique characteristic is that it is determined by water users themselves (or their representatives), based on their water-dependent socio-economic activities and value systems, and may be used to inform alternative distribution policies (Pienaar & Hughes, 2017). While future impacts cannot be known with exactness, planning for a desired state based on historical experience is a sound enough strategy to build adaptation and prevent severe water shortage impacts from occurring (Schulze, 2011; Rosner et al., 2014; Preiser et al., 2018; Streefkerk et al., 2023).

Hughes & Mallory (2009) stress the need for user risk profiles to express users' adaptive efficacy in the interest of procedural fairness and concerning user resilience to water constraints. The user risk profiles can be used to handle the effects of scarce water distribution by comparing the effects of different water reallocation strategies on the overall well-being of the community, considering the uncertainties in both water resources and water demands (Pienaar & Hughes, 2017). This comparison would explicitly incorporate uncertainties in available water supply and water deficits. However, no socio-economic data collection framework exists for understanding these impacts and compiling the user risk profiles. At best, Hughes & Mallory (2009) and Pienaar & Hughes (2017) indicate that different approaches and criteria can be used to assess the impacts.

One aim of the chapter is to fill this methodological gap by demonstrating an approach used with Water User Association members in the Western Cape, South Africa, to establish this index. The application area is characterised by multiple uses and diverse objectives that can generate conflict during severe water shortages. The research team had to find indirect research tactics to incorporate the powerful stakeholders without necessarily their approval of the process.

Links to socio-hydrology.

In socio-hydrology, such an assessment promotes the understanding of human agency, one of the key research areas to move towards explicitly accounting for human-water coupling shaped by human values and norms at different levels (Sivapalan et al., 2012). It does so by focusing on place-based knowledge or rules around water use as a basis for system understanding to generate outcomes (Kelly et al., 2013). Human agency is described as the ability of human actors to impact the interconnected human-water system through their decisions and behaviours, which are influenced by various elements such as their adaptive and autonomous character, economic interests, technology advancements, and conventions. Individuals, their households, communities, and institutional activities can all have complex and emergent impacts on system dynamics and results.

Considerations of fairness.

Fulfilling democratic governance of water resources, the fairness/justice aspirations of water use depend on the engagement and cooperation of water users or representatives within a boundary (UN, 1997; RSA, 1998a). During the engagement component, it is critical to carefully identify all stakeholders and water user groups, as well as their social relationships (Etienne et al., 2011; Barreteau et al., 2013; Perez et al., 2013). Involving water users at the local levels or their representatives can help improve the water policy planning process and its outcomes, foster cooperation, and community cohesion, and improve water governance effectiveness (Colvin et al., 2008; Basco-Carrera et al., 2017a; Keeler et al., 2020; Adom & Simatele, 2022). An inclusive approach to water governance is also valuable for identifying barriers to participation in the governance process, which has been cited as a key driver behind the slow realisation of the objectives of the democratic water legislation in South Africa (Schreiner, 2013; Knüppe & Meissner, 2016; Movik et al., 2016). Water users or their representatives at lower decision-making levels should actively participate in various phases of water governance for all of the aforementioned reasons, among others (Palmer et al., 2018). Accessible communication is necessary to increase involvement in decision-making, as concerns about misunderstandings and gaps in potential decisions might weaken the case for fair access and reasonable usage.

4.2. Methods

This study demonstrates a four-step participatory approach (Figure 4.1) for collecting the required socio-economic data to set up an equitable Water-Sharing Tool (Pienaar & Hughes, 2017) that distributes water based on likely impacts in ungauged catchments. As shown in Figure 4.1, the four steps involved are building a shared catchment vision (step 1), stakeholder mapping and conceptual model co-design (step 2), peer judgements of the relative importance of water users in the catchment (step 3) and impact indicators of water shortfall to individual users (step 4).

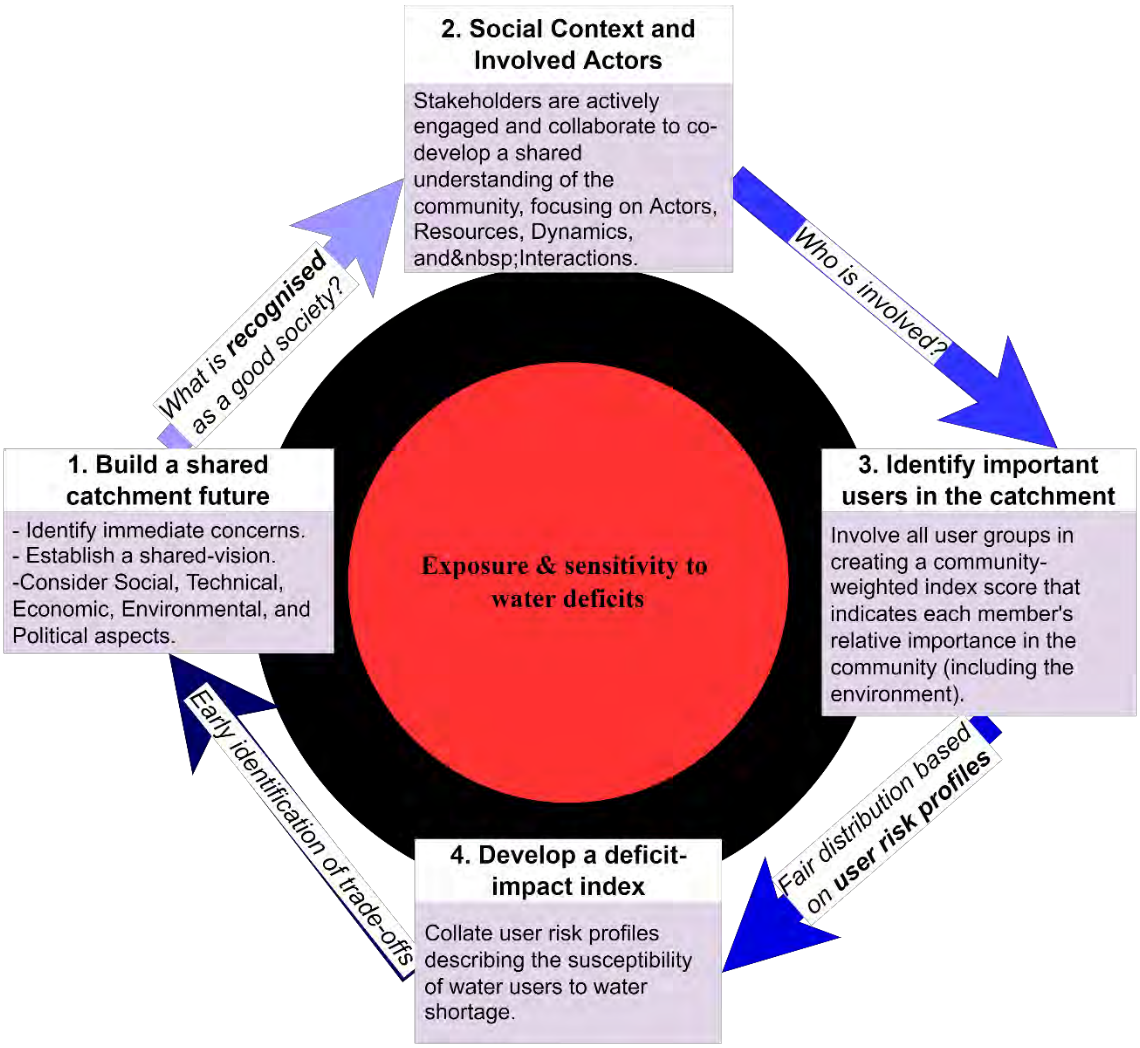


Figure 4.1: The proposed flow diagram of the four-step process of socio-economic data collection for equitable water allocation planning with water users or decision-makers.

4.2.1. Stakeholder participation in developing a common system representation.

In 2022, an interdisciplinary team of researchers from South Africa and France (11 team members and 10 experts making a research grant advisory panel) proposed using a Companion Modelling approach to engaging stakeholders who rarely cooperate in decision-making and whose individual actions often generate conflict. The ARDI (Actors, Resources, Interactions, and Dynamics) technique was used to understand and model the coupled human-water system (Etienne et al., 2011). This proposed approach was in response to ineffective governance of water resources and recurring conflicts in parts of the Koue Bokkeveld region, as discussed elsewhere (Knüppe & Meissner, 2016). Some of the workshop stages are shown in Figure 4.2.

Recruitment of stakeholders.

As mentioned in the study area selection, this project was enabled by a university-NGO partnership between the IWR, Rhodes University and the Freshwater Resource Centre. The NGO partner had been working in the catchment for some time, working with a catchment coordinator invited the project team to a knowledge transfer meeting organised by the World Wild Fund-South Africa, in November 2021. The meeting was attended by all landowners from Rivers E21G-H, or their representatives. This is where the Rhodes University team introduced the project and its objectives. All landowners were invited to take part in the project, but all those from E21G refused to take part, same as the upstream landowners in the Twee Wyk. Even though powerful stakeholders did not fully commit to the participatory process, the methods described here allow for an indirect representation of these users based on inputs from knowledgeable stakeholders. Flexibility was also built into the participatory process to allow stakeholders to come and go as they pleased, so they did not feel obligated to participate, and out of respect for the variations in farming strategies.

Figure 4.2: Workshop images. A) shows the research team planning for the workshop at Kunje Guest Cottages. B) shows attending stakeholders playing the complexity game as an icebreaker during the Visioning and ARDI workshop (May 2022) at Kunje Pre-School. C) shows the English/Afrikaans facilitator (Ms. Lucy O'keafe) and the ARDI expert (Dr. Olivier Berrateau) arrange the concerns in the STEEP categories. D) shows some stakeholder contributions to the shared-future vision.

After setting the future vision in May 2022, a French/English-speaking facilitator (Dr. Olivier Barreteau) introduced the ARDI technique in a plenary session. The facilitator explained the purpose and objective of the technique. The stakeholders were asked four successive questions to complete the ARDI diagram (Figure 4.3). The questions were:

- Who are the main actors (individuals, groups, or organisations) with a stake or influence in the *Wyk*?
- Which resources are involved in the system (natural, physical, human, or financial assets affected by the human-water system), and how do the identified stakeholders influence them?
- How does each stakeholder use the resources and modify water resources?
- Which interactions are involved between the actors identified?

Responses to these questions were collated into four simple diagrams representing actors (a diagram of stakeholders and management entities, Figure 4.3). A draft ARDI diagram was computerised and projected on-screen in a plenary session in November 2022 for validation by participants.

Figure 4.3: Actors and Resources diagrams identified by stakeholders in the Twee Wyk during the May 2022 ARDI workshop.

4.2.2. Planning towards a shared future for water management.

Water demand by multiple actors with diverse expectations, preferences, and worldviews was a defining characteristic of the complex social system. To work towards achieving sustainable water governance in the case study punctuated by competing interests of a heterogeneous stakeholder group, it was observed that a shared catchment vision was an effective pathway to coalesce stakeholders (Knüppe & Meissner, 2016). A participatory visioning technique [the Adaptive Planning Process (APP)] adopted from the Strategic Adaptive Planning process (Rogers & Luton, 2011) was adopted to ensure that the process was based on shared principles and targeted to a common future.

The APP adopts a workshop setting as a style of engagement and is ideal for knowledge facilitation through inclusive stakeholder dialogue (Roux et al., 2022). A roadmap to a desired socio-hydrological system is created through this process, with the cooperation of all interested and willing actors. The existing undesirable condition of the system is noted (Roux et al., 2011). Other participation methods that enable social dialogue for visioning exist, and the project team and available expertise determine the approach used (Lang et al., 2012). Alternative approaches include futures analysis (Hamann & Reese, 2020) and participatory systems dynamics modelling (Ford, 2010; Mirchi et al., 2012).

To effectively guide decision-making in the future, the APP emphasises a holistic framing of common-pool resource problems, recognising the complex influences of individual values, expectations, and social, technical, economic, environmental, and political (STEEP) context in which these values and expectations exist. Stakeholders participated equally in setting a shared vision; the process is facilitated by prioritising facilitated equal respect (Palmer et al., 2018; Ralekhetla, 2018). To create a vision, stakeholders responded to the prompt, "*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?*". They used sticker notes on a STEEP table to express their concerns and vision in their preferred language. The process took less than 45 minutes in Twee Wyk, thanks to an experienced research team and facilitator (Ms. Lucy O'Keeffe).

The facilitator presented the stakeholders' concerns and vision, organised by theme, in a plenary session for validation and comment. Based on these, the facilitator provided a three-statement future vision and guiding principles, which the stakeholders reviewed and agreed upon. Ideally, this process would be repeated for each interaction to include fresh individuals; however, time restrictions prevented this. As a result, we displayed the vision statement and driving principles at the beginning of each workshop and posted them on A2-sized posters in the workshop area. This was done to maintain understanding and trust as Palmer et al. (2023) indicate.

4.2.3. Equity-based reallocation criteria for water deficit periods: community weighting.

The AHP procedure (Saaty, 1987) is demonstrated and recommended as a quick and robust participative method for understanding water user contribution to community well-being based on other users' subjective socio-economic and environmental preferences. The Hierarchical Analytical Process (AHP) had a pre-defined goal, with water users and the environment as criteria and decision-makers. Four water user groups emerged from a previous ARDI workshop in South Africa (4.2.1). The workshop had 14 attendees from these groups: farmers, residents, lifestyle farmers, and interest groups. Four water user group classifications were needed to match the Water Sharing Tool requirements (Pienaar & Hughes, 2017), an inherent limitation in the model. Consistent with the

National Water Act (RSA, 1998a), the water user groups can be classified based on volumetric use, economic circumstances, and return flow contribution. All but the largest farmer consented to the AHP exercise. Only half of the Lifestyle farmers participated. Since E-Flows cannot speak for itself, proxies in the form of interest group stakeholders who know the tributaries were used. Each tributary (n=3) within the catchment was allocated a single representative. Judgement pairs for filling up the matrix were based on water users' subjective judgments (e.g., operation costs, sentiments, and preferences) originating from knowledge, experience, and expertise and are standardised to one standard measurement scale.

Each water user (n = 13, representing the four main water user groups locally) completed the judgment matrix with the help of a research team member and an Afrikaans-English translator in less than 30 min. After explaining the AHP procedure, each user provided six pairwise comparisons to complete the decision matrix using a pre-set spreadsheet (Box 4.1). Given the subjective nature of the procedure (decision uncertainty) (Saaty, 2000), consistency was improved by slightly adjusting the judgments by plus or minus one or two points in the scale to achieve a consistency index of ≤0.1 (Saaty, 2013), while adhering to the original hierarchy.

Combining the multiple matrices to get the community weight index.

The AHP method generates group preference from individual judgments by using individual priorities or lumping judgments (Forman & Peniwati, 1998). This depends on whether decision-makers act together or separately. When water users with special interests willingly give up their preferences for the socio-hydrological system, they form a group (Aczél & Saaty, 1983; Forman & Peniwati, 1998). When community members act as individuals with little willingness to sacrifice their values/objectives, individual weights are used to merge preferences (Forman & Peniwati, 1998). Then, geometric or arithmetic means are used to compute the group's preference. The merged weights must be consistent (below the consistency index threshold of 10%) to form a valid AHP matrix (Grošelj & Zadnik Stirn, 2012).

The completed decision matrices were used to build a database of individual judgments, which were later used to compute the community weight index of the four water user groups. To better understand stakeholder motives, we assessed for uniformity using the Analysis of Similarity (ANOSIM) statistic, which interprets individual judgments as distances, via the R-studio software (R Core Team, 2020). The matrices were combined using geometric and arithmetic means since both approaches are recommended as the two mathematical procedures for AHP aggregation (Aczél & Saaty, 1983; Forman

& Peniwati, 1998). The community weight results were shared with the water users 6-months later in a follow-up group interaction for verification.

Box 4.1: Establishing the community weighting index using the AHP method.

Objective**:** To establish water supply priority for distribution during periods of water shortage.

Prompt: "Which of the two water users is the most important in the catchment/ should be prioritised in times of reduced water supply?"

E-Flow User1

By how much on a scale of 1 (representing equal importance) to 9 (representing extremely more important)

9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
Extremely		Very strongly		Strongly		Moderately		Equal		Moderately		Strongly		Very strongly		Extremely

Why?

The pair-wise matrix table below is used for attribute scoring using the AHP method. Participants fill in the grey-shaded area following the explanation above. The yellow-shaded cells show two examples of how the matrix works. The matrix should be read top-down (e.g. Column A vs Row 1). Please note that an acceptable matrix should not surpass a consistency ratio of 0.1; the MS Excel/online program will warn participants to reconsider the allocation options.

Users	E-Flow	User1	User2	User3	User4	Sum	Community weight
E-Flow	1	1/5	1/3			∑(E-Flow)	∑(E-Flow)/ A
User1	5	1				∑(User1)	∑(User1)/ B
User2	3		1			∑(User2)	∑(User2)/ C
User3				1		∑(User3)	∑(User3)/ D
User4					1	∑(User4)	∑(User4)/ E
Total	A	B	C	D	E	∑(Sum)	NB: ∑(CW) == 1

4.2.4. Compiling the user risk profiles for environmental user.

For the E-Flows, the impact criteria are conceptualised based on the consequences of not satisfying instream flow requirements at the gazetted ecological status *[i.e., "if we drop from an E-Flow category of level B (near-natural) to B/C (slightly modified) or lower (severely modified), what does that mean in terms of the E-Flow assessment?"].* In the study by Tanner et al. (2022), the low flow category B and B/C levels for E-Flows Site 6 differ by 11%, with the level B E-Flow requiring 29.528 Mil.m^3 (or 18.4% of mean annual runoff) and the B/C level possibly requiring 6.249 (or 16.3% of mean annual runoff). In comparison, E-Flows categories B and D differ by 45%.

Deriving the criteria for socio-economic user risk profiles.

Since some influential actors were not part of the engagement, an alternative method was used to compile the user risk profiles, an essential attribute for recognitional equity in water allocation planning (Seigerman et al., 2022). This technique focused on the capability of users to offset the impact of water deficits (Table 4.1), which is the adaptation angle (Abdulla et al., 2014). By focusing on adaptation interventions currently being implemented at farm levels, the technique offers decision-makers a perceived grass-roots level understanding (Lesnikowski et al., 2015). Therefore, the criteria in Table 4.1 were defined based on the outcomes of the ARDI exercise and ongoing engagement with the water users over the three-year project period.

Table 4.1: Criteria for how farms adapt to water deficits at a farm level.

Scope of adaptation	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 & 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
	Insurance	Financial resources to smoothen the losses	High and variable buy-in costs
	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
	Location in the catchment (upstream>downstream)	Spatial advantage for water access	Free-riders behaviour amplifies water deficit externalities to downstream users

Stakeholder mapping information and other key-informant data were used to complete an impact rating for the severity of residual impacts following water shortage mitigation (Table 4.2). Since the user risk profiles combine multiple indicators with different measurement units, a five-point scale representing severe to negligible damage was used to maintain consistency.

A user risk profile is then calculated by comparing the fraction of residual risk (representing impact) severity for each user to the maximum adaptive efficacy value (4 * count of specified strategies). Table 4.2 sums the response efficacy values and transforms them into an impact rating. For triangulation purposes, the derived criterion and the rating results were presented to all stakeholders in a plenary session, with the floor open for discussion.

Table 4.2: Level of impact prioritisation.

Response efficacy value	Impact Level	Impact level (%)	Description
≥30	None to minimal	0-15	High response efficacy results in insignificant risks that have little to no harm.
20-30	Low	15.1-35	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	35.1-55	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	55.1-75	Severe vulnerability due to low to no response efficacy (i.e., environmental and socio-economic functions will be severely impacted because a user cannot 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	Catastrophic	≥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. Results

4.3.1. Shared future vision and common system understanding.

After grouping all issues (Table 4.3) and ideals for future water usage and governance based on the STEEP aspects, the facilitator presented the draft future vision statements, which were validated by stakeholders and adopted as their 2050 vision. The vision statements are presented below and as an appendix in section 9.1.2.

"Our vision is to work together in managing water resources sustainably and equitably, with transparency and accountability in ways that balance social, economic, and environmental needs. We want an agricultural sector that produces economic value through evidence-based management practices and the adoption of ecosystem-based solutions. We envision a healthy, resilient ecological system with clean year-round water flow."

The overarching vision was supported by a set of guiding principles listed alongside current concerns (Table 4.3). Like-mindedness in the guiding principles is shown as black-highlighted themes, showing consensus on a strategy to reach the shared future. Seeing the thinness of responses in the economic and political category, a prompt question was asked to the farmers by one of the research team members:

Question: What can be read from the sparse responses on the economic category, is it an unimportant attribute for the future in this catchment?

Collated answer: "Agricultural production and profits are, of course, fundamental to all farmers, but in terms of a shared strategy, we know that achieving all the other aspects of the ecosystem will translate into good economic returns."

4.3.1. Using the ARDI technique for system scoping and building consensus for system representation.

The ARDI diagram (Figure 4.5) has been simplified to fit the design requirements of this project. Stakeholders indicated that the key water users in the Wyk are the environment (E-Flows), farmers (Users 1,2 and 3), and (lifestyle farmers (residents) and weekenders) User 4. The farmer group has three sub-groups: corporate-owned farms (User 1), family-owned commercial farms (User 2), and downstream farmers (User 3). These farmer sub-groups all have overlapping agricultural activities (**Chapter 1**). Lifestyle farmers own property in the Wyk, but do not produce at a commercial scale. Lifestyle properties in the Wyk are often only visited for short vacations. All user groups (but not all landowners) are involved in tourism to diversify their economic activities. Government entities and non-profit interest groups were also identified as influential actors because of their policy implementation roles.

Table 4.3: A list of stakeholders identified concerns for current water use and management. These concerns were co-grouped by the water users and the research team on the STEEP categories.

Framing dimension	Threats/Concerns	Solutions/ Guiding principles to achieve the future vision
Socio-cultural	Fairness; Human impact on water resources	Ways of working together "Transparency, Accountability, Cooperation" Social value "Producing nutrient-dense foods that are healthy to eat"
Technical	Data and monitoring; Inadequate water storage; Increased consumption	Use of science & technology "Water management is driven by data, transparency, and cooperation; Far more scientifically managed farming – correctly utilizing all resources; Better technology; Water usage is comprehensively measured and information on usage and efficiency is accurate and publicly available; To use better irrigation methods such as drip irrigation; Better soil management; Better irrigation management; More effective agricultural production." Water management "Seeing a constant flow of water through the year; More dams will lead to better summer flow in the river but then the hectares of the fruit must stay the same to create the surplus for summer; More stored water for use all over." Cost of inputs "Lower energy costs"
Economic	Eroded economic value of agriculture; Downstream impact on economic activity; Land value in relation to water availability;	Sustainability "Find a balance between ecological needs agricultural/ economic needs' Diverse economic income streams produced in a catchment that is less dependent on water availability"
Environmental	Vegetation growth in and off-stream; Water quantity and quality; Changing climate; Soil quality.	Healthy systems "Healthy ecological systems that are managed sustainably; Unclogged riverways with good summer flow of clean water; The river system is healthier and more robust than in 2020; Open and clean flowing river system" Nature-based solutions "Utilising alien plants to benefit agriculture (e.g., through mulching and composting)
Political	Governance and compliance	Cooperative governance "That we all work together, especially with the amount of water that we are using."

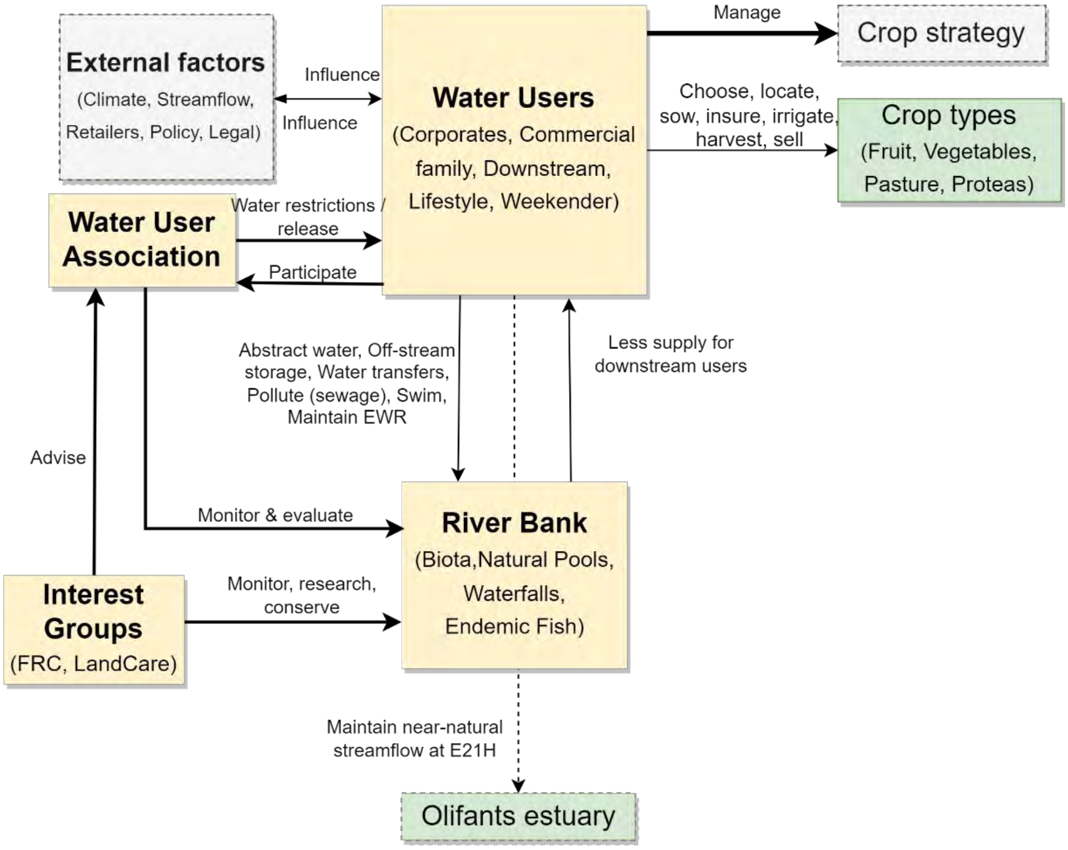


Figure 4.5: Interactions diagram created by stakeholders in the Twee *wyk*. The diagram focuses on water users and the main decisions relating to water use. Direct actors and players in the game are shown in yellow boxes. Interactions are represented by arrow descriptions.

4.3.2. Community preference for allocation.

The ANOSIM test showed a dissimilar judgment (indicated by R=0.1008, p-value = 0.018), implying that Twee Wyk water users act separately and resist group preference. Table 4.4 lists the reasons. Eight of fourteen users favoured economic productivity over environmental protection, and six vice versa (Figure 4.6). This preference mismatch led to priority-based integration, using arithmetic and geometric means for aggregation. Figure 4.6 shows the dissimilarity, with the most preference for environmental protection (E-Flows priority) and water productivity (farmer priority). All consistency ratios were acceptable (CR ≤ 0.1).

Table 4.4: Summary table of water user justifications (preference statements) for community weights.

Preference of the environment	Preference of farmers
Protection of endemic fish species (e.g., Twee Red fin and Clanwillan yellow fish). Delivery of environmental benefits downstream. Managing the environment for the benefit of the larger society and the natural ecosystems.	Food security considerations at different scales. Primary livelihood & survival. Employment creation. Technological investments. Need to repay bank loans/dividends to farm stockholders. Inadequate storage facilities are leading up to reliance on run-of-river abstraction.
Preference of the Resident	**Preference of the Lifestyle Farmer**
Mostly uses spring water. Generates income elsewhere. Not an active player in the catchment. economics; Do not abstract surface water. Rural domestic users enjoy a constitutional guarantee of human use rights.	No significant impact on surface water availability. Option to move away to avoid water shortages.

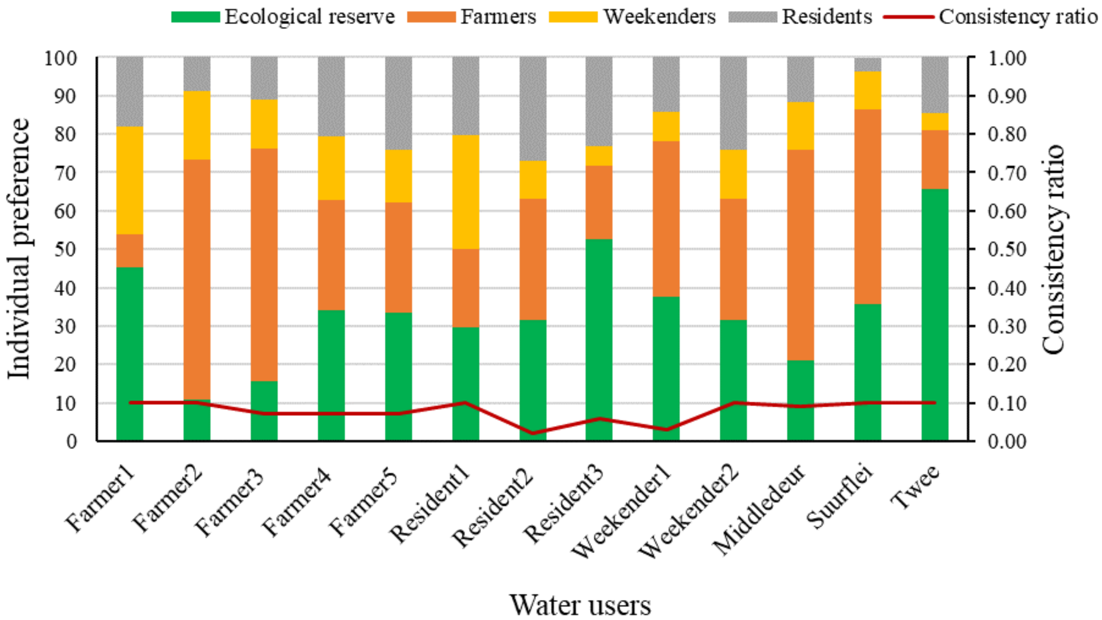


Figure 4.6: Stacked bar plot showing priority vectors for the thirteen water users involved in the study, labelled based on their water user classification/group. Consistency ratios for each water user is also shown on the graph, with all CR ≤ 0.1.

Group objectives for equitable distribution periods of reduced assurance.

Table 4.5 depicts the individual and aggregated preferences of Twee Wyk water user groups, adhering to the AHP aggregation rules of agreement and uniformity with slight differences in priority vectors. During periods of reduced assurance in water supply, farmers preferred economic efficiency, shown by the following hierarchy: farmers > environment > weekenders > residents. The environmental user group established preferential prioritisation of environmental preservation and productive use (as shown by the following preference: environment ≥ farmers > residents > weekenders). Residents favoured environmental preservation, shown by the following hierarchy: environment > farmers ≥ residents > weekenders. Weekenders (tourism operators) slightly preferred economic efficiency (36% to farmers) over environmental protection (34/35% to environment), ending up with the following hierarchy for supply: farmers > environment > residents > weekenders. When these are combined, the community weighting index becomes environment (35%) > farmers (34%) > residents (18%) weekenders (13%).

Table 4.5: Supply preference/objectives for the four user groups using the aggregation of individual judgements (geometric mean and arithmetic mean) given the mismatch in individual water user priorities. Since all judgement matrices were consistent (CR ≤ 0.1), it was assumed that all aggregated matrices were also within consistency limits.

Group preference: Farmers					
Water user groups	Environment	Farmers	Residents	Weekenders	Overall group preference (%)
Environment	1	1	1 1/2	1 1/2	27.9
Farmer	1	1	2	2	37.9
Resident	1	1/2	1	1/2	16.6
Weekender	1/2	1/2	1 1/2	1	17.7
Group preference: Environment					
Environment	1	1	5	4	40.9
Farmers	1	1	2 3/4	7 1/4	40.3
Residents	1/4	1/4	1	2 3/4	10.0
Weekenders	1/4	1/4	1/4	1	8.5
Group preference: Residents					
Environment	1	1 1/2	1 1/2	4	37.9
Farmers	1/2	1	1	2	23.7
Residents	1	1	1	1 1/2	23.5
Weekenders	1/2	1/2	1/2	1	14.9
Group preference: Weekenders					
Environment	1.00	1.00	1.41	4.90	34.6
Farmers	1.00	1.00	2.00	4.00	36.0
Residents	0.71	0.50	1.00	1.41	19.3
Weekenders	0.20	0.25	0.71	1.00	10.1

Community weighting				
User	Environment	Farmers	Residents	Weekenders
Weighting	0.35	0.34	0.18	0.07

Stakeholder reaction.

The water users accepted the aggregated weights following a request to consider rearrangements in water user groups:

"As you present it, the weights make sense and can be accepted. However, in retrospect, weekenders and residents can be almost one user, resulting in an even weighting for the three user groups. ~ Family Commercial Farmer"

This comment was similar to those received during farm visits, where some water users questioned the possibility of decomposing the farmers' group based on economic circumstances or the nature of operations. However, this was not considered earlier in planning because of the Water-sharing tool's limitation on the number of users. In this regard, one resident farmer said:

"It might be interesting to decompose the farmers based on their size or economic activity, as this would reveal interesting trends of water use impact and adaptive capacity. Two commercial farmers may fare differently (due to a secondary source of income) if one is also active in ecotourism, which will generate water quality impacts during peak tourism seasons."

4.3.3. User risk profiles.

The user risk profiles socio-economic and environmental uses in the Twee Wyk is shown in Table 4.6, with variable levels of vulnerability to water shortage across users (low and high). The first striking observation in Table 4.6 is that inefficient governance has a consistent risk impact across users, which justifies the listing of this category under political concerns in Table 4.3. Regarding environmental impacts, aquatic ecosystems and downstream operations may be moderately affected by upstream users' failure to comply with the near-natural flow criteria (or E-Flows level B). Midstream and downstream users have numerous financial, technical, and socio-political obstacles in adapting to water shortage and fluctuation (Table 4.3).

User risk profiles: Towards accounting for distributional impacts in water reallocation.

The first outcome of the Water-Sharing Tool is a relationship between possible water deficits and the likely impacts of those deficits, based on a sample of streamflow ensembles normalised by the user risk profiles (Figure 4.7). The model arranges the selected ensembles on a Gaussian distribution and factorises them using the user risk profiles (Table A-4.3). For this interpretation, severe water impacts refer to 75% damage or more each year in the Twee *Wyk*, which the water users themselves defined as a threshold for unacceptable consequences. These social, economic, strategic, and environmental consequences to a user group/sector, assuming users have access to an unchanged allocation, are summarised as follows:

Table 4.6: Heat diagram showing possible adaptation options based on the resources water users deploy to cope with water shortage in the Twee Wyk.

Response strategy	E-Flows	Agricultural Sector/ Farmers			Residents & Lifestyle
		Corporate (User 1)	Family (User 2)	Downstream (User 3)	User 4
Water storage facilities	Impact of meeting E-FLOWS at Level D instead of Level B	4	3	2	1
Additional water sources		4	2	0	3
Livelihood diversification		4	2	3	1
Access to local & expert knowledge		4	3	2	3
Governance effectiveness		0	0	0	0
Insurance access		4	4	2	3
Access to formal credit		4	4	2	4
Monitoring technology		3	3	2	2
Location in catchment		4	3	1	1
Total response efficacy		31	23	14	18
Total response efficacy (%)		0.861	0.667	0.389	0.500
User risk profile (1-% Total of response efficacy)	Medium 43%	Very low 14%	Low 33%	High 61%	Medium 50%

- A possible outcome of changing the E-Flows from level B (near-natural) to D (largely modified) is that the environment will be exposed to medium effects at about 15% deficits, but serious effects (≥75% impact) can be expected at 20% low flow deficit. In this situation, the integrity of natural pools that act as habitat for juvenile critically endangered endemic fish species would be threatened.
- Downstream farmers (User 3) face the steepest impacts compared to other user groups, threatening smaller-scale farming, and the farming heritage.
- Without further adaptation interventions, family commercial farms (User 2), non-agricultural users (User 4) could face similar impacts to the environment. Conflicts can be expected due to overexploitation of low-flow environmental entitlement.
- Corporate farmers (user 1) can sustain their operations even at high deficit levels as this user group is expected to have a high tolerance to water scarcity due to robust adaptation measures and historical advantages. This user may face profound impacts only when they reach a shortfall of 46%.

Catastrophic impacts—impacts above the 75% threshold that may be a tipping point for affected users, with steep recovery costs followed by conflicts over water use, are expected at different deficit levels due to the assumed user-risk profiles. These impacts may start appearing at the following shortage levels: -15% for User 3, -19% for User 4, -22% for E-Flows (or when met at level C), -29% for User 2, and only at -53% for User 1. This pattern is subject to change, depending on the approach and values used to define the user risk profiles.

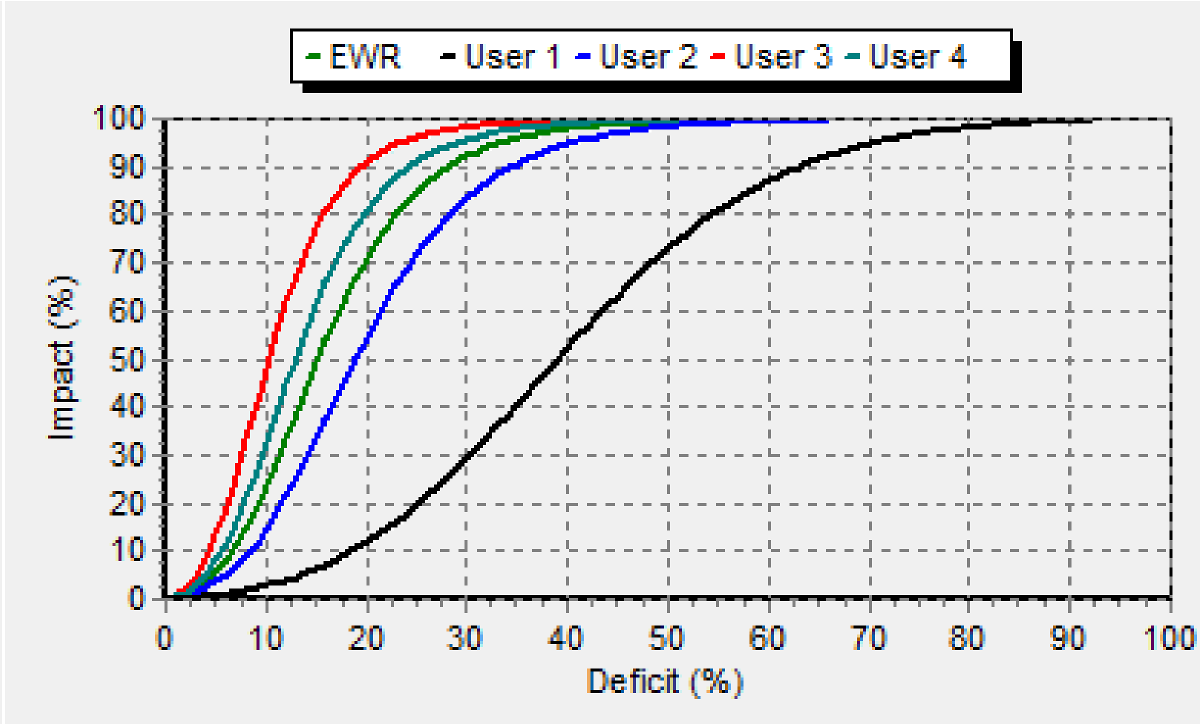


Figure 4.7: Deficit-impact index for users in the Twee Wyk showing the long-term (annual) E-Flow and socio-economic impacts from reduced surface water availability in the Twee Wyk. User 1 represents corporate farms, User 2 represents commercial family farms, User 3 represents downstream farmers, and User 4 represents lifestyle and holiday farmers.

4.3.4. Stakeholder feedback.

During the feedback workshop in November 2023, stakeholders could see the value behind the participatory approach presented here, as shown by stakeholder reflections in the appendices (Table A-4.2).

Users raised concerns over model-specific elements. The first related to the user risk profiles, the way we evaluated and visualised it, as entailed in the next two quotes by the engineering expert in attendance and User 3.

"Groundwater should not be regarded as another source of water. A person's water access includes all water" ~ Engineering Manager.

Despite all efforts to regularly communicate progress and previous milestones, it was evident that the attending engineering manager missed the researchers' commitment to a long-term partnership with the emerging institution (see quote below). The response quoted below could be attributed to the stakeholder only attending one workshop. Engaging this stakeholder separately could have improved their understanding of the process, which was a missed opportunity on the research teams' side. It should also be noted that the research team struggled to communicate the flexibility built into the socio-economic data collection process presented here.

"It may be too complicated for a Water User Association manager to go through that level of complex impact analysis; the best assumption is that each water user will have their on-farm risk assessment and will decide how to use whatever amount they end up with" ~ Engineering Manager.

4.4. Discussion

This work focuses on a comprehensive water reallocation planning strategy incorporating four previously distinct data collection techniques (ARDI, participatory visioning, AHP, and the user risk profiles. The approach addresses stakeholder involvement difficulties by making fairness an operational principle in decision-making (Pollard & du Toit, 2011; Leach et al., 2018; Keeler et al., 2020). It prioritises local acknowledgement of a "good society" above a top-down policy perspective (Roux & Foxcroft, 2011). The bottom-up actor identification method evaluates acceptable recipients of scarce resources (Etienne et al., 2011). Furthermore, the stakeholder mapping and model conceptual design method promotes dynamic system thinking while balancing expert inputs and local knowledge. Given its inclusive and flexible nature, the approach presented here is recommended for addition to the socio-hydrology toolkit to promote the uptake of impact-based water allocation planning among decision-makers. As evidenced by the comment from the engineering manager who joined the last engagement, the novel aspect of the approach may be met with resistance by poorly sensitised users.

Alternative arrangements were made to deal with stakeholders' unwillingness to participate and the potential of power dynamics to undermine equal voice in participation. These methodical arrangements are important in recognitional equity as they consider what is locally recognised as a good society, as opposed to the national sense outlined in the South African National Water Act of 1998 (RSA, 1998a). In a bottom-up manner, the actor's identification approach presented here also answers questions about who the acceptable beneficiaries of the scarce resource are that should also be included in the decision-making process (or equity between whom?). The stakeholder mapping process and model conceptual design approach (ARDI technique) exposes participants to imagining their catchment system as a dynamic system capable of adapting and anticipating changes. From the perspective of socio-hydrological modelling, the procedure presented here guides stakeholders through defining and parameterising system components, thereby balancing expert insights with local knowledge (Parkoo et al., 2022).

4.4.1. Shared-future visioning.

The simplest understanding of the shared vision is to establish a participatory, cooperative, and decision-making context for the water allocation-planning project (Pollard & du Toit, 2011). The collective visioning technique adopted here—the APP, treats fair participation and cooperation as conditioning factors for inclusive decision-making. This note is consistent with previous applications of the technique in conservation and biodiversity, water resource management, and transdisciplinary research development (Roux & Foxcroft, 2011; Palmer et al., 2013, 2018, 2023; Ralekhetla, 2018). The importance of the APP for participatory modelling (detailed in Chapter 2) is collective visioning and building consensus for the principles that should guide water management decisions. Roux & Foxcroft (2011) note that the APP targets adaptive planning through systematic techniques that guide beneficiaries of common-pool resources towards cooperation based on collective symbolic meanings of freshwater resources.

4.4.2. System scoping, building consensus for model formulation, and community weighting.

Time constraints and ethical considerations made it impossible to dive deeper into the influence of actors, which could help uncover power dynamics (Brisbois & de Loë, 2016; Reed et al., 2018). Although necessary, the ARDI outcomes presented here do not indicate the level of agent influence, which could be obtained through the power-influence scaling of actors (Reed et al., 2018). Perceptions about resource availability and dependence on resources were also not interrogated during the ARDI process. The frequency of how the nature of relationships can be improved could benefit cooperation. All these are important aspects to consider, and future projects need to plan to capture these.

Community weighting.

As expected, individual water user ranking of the four main user groups in the sub-catchment allowed water users to contribute equally and consistently to establish priority vectors (community weights), demonstrating AHP's recorded strength for eliciting socio-economic data (Mendoza & Martins, 2006). Platforms that permit equal contribution regarding water resource governance are important for facilitating effective governance (Meissner et al., 2013). Other similar situations can assure inclusive involvement and perhaps plant the seeds of efficient local water governance using the AHP technique. Once processed, such data will provide regulators with user-expressed evidence to support a supply preference for one user group over another, which can also reconcile conflicts due to competing interests (Pahl-Wostl et al., 2012).

Methodically, adopting the AHP method as a tool of stakeholder engagement at a Water User Association level allowed equal participation and inclusion of perceived fairness from all. Including all affected water users that start with classifying water users in the Twee through the ARDI process can be seen as an expression of procedural fairness, one of the essential equity dimensions (Seigerman et al., 2022). This procedural advantage can also help reduce potential participant-induced bias, often confronting group interactions better outlined elsewhere (Booker et al., 2012). The AHP's sensitivity to qualitative and quantitative inputs to arrive at trade-off calculations (subjective nature of AHP) (Saaty, 2000) allowed us to leverage water users' memory to create a foundation for a fair distribution of water risks and benefits among the members of the Water User Association. Computational requirements of the AHP method were overcome by using interactive AHP spreadsheets that allowed water users to focus only on the pairwise comparison and consistency (Munier & Hontoria, 2021).

When the judgement matrices and user preferences are combined, they give a community weighting index indicating a social equity index for deficit periods (Hughes & Mallory, 2009; Pienaar & Hughes, 2017). The AHP survey results show that the Twee Wyk community recognises proportional sharing and is becoming strongly environmentally aware while valuing water's productive benefit. The identified proportionality view of fairness in the Twee indicates that water users acknowledge social differences (Sivakumar, 2012). This is despite the Koue-Bokkeveld being the most farmed area in the Olifants-Doring drainage area (Paxton et al., 2017). Such a discovery would not be possible if the economic index were derived based on purely economic terms such as productivity or profit losses.

Stakeholders perceive the E-Flows and farmers in the catchment as influential users due to the endemic biodiversity of the Middledeur and Twee rivers, as well as the socio-economic importance of farmers (Paxton et al., 2017). Eighty-five percent of terrestrial ecosystems in the Twee Wyk are formally protected, reflecting landowners' commitment to environmental conservation. Concerns arise regarding instream ecosystems, and this note is supported by the alarming findings by Tanner et al. (2022) and unsatisfied low-flow E-Flows (Paxton et al., 2017). Therefore, regulating upstream human actions is necessary. Achieving the catchment vision for 2050 supported by local government (Witzenberg Municipality, 2019), and higher-level policies (Department of Water and Sanitation, 2022) is the right step towards fairness and sustainability. Sustained removal of alien invasive species may also increase hydrological benefits for the catchment (Le Maître et al., 2016). Meanwhile, as stated by water users, overcoming legal and economic constraints that lead to low investments in water storage facilities, which, if successful, could balance demand management and increased supply, remains a challenge. The downstream effects of reservoir construction, as assessed by Van Loon et al. (2022), will require attention from regulators.

Despite the community's stated environmental value for water use, greater attention should be paid to farmers, particularly for complying with low flow releases towards unaltered flow conditions (E-Flows B-level) (Department of Water and Sanitation, 2017). Farmers accept the local role of water releases socio-economically and towards the environment (e.g., protecting endemic fish communities). These provisions can be traced from the motivations of prioritising the E-Flows provided by farmers over themselves in some instances. One concern expressed by the water users during the feedback session (see paraphrased comment below) is the inconsistent application of E-Flows across catchments, which may constrain farmers from complying with water releases.

"The E-Flow for the Doring River integrity will not be successfully provided by upstream users alone; complying with the B-level water discharge is becoming increasingly difficult and an impediment to growth because someone right downstream from us will use up all the water we discharge. In a way, we are essentially benefitting someone else at our expense." ~ Commercial Family Farmer

The previous comment corroborates interview statements collected by Knüppe & Meissner (2016) in the Olifants-Doring catchment, whereby legacy water use patterns remain a barrier to sustainable water management (including giving effect to E-Flows). Farmers behaving as if water entitlement is still linked to land ownership, as previously permitted by the Water Act 54 of 1956 through the riparian doctrine, is a defining feature of the stated barrier (Union of South Africa, 1956; Knüppe & Meissner, 2016). In this context, a recommendation would be to boost assistance for interested organisations already operating in catchment areas. Interested organisations in the catchment have demonstrated their educational impact in sensitising water users to the benefits of biodiversity protection, resulting in considerable terrestrial protection, and may have played a role in shaping the community weight evaluated here (Knüppe & Meissner, 2016).

One of the key take-home messages from the procedure followed here is that fairness is context-specific and time-bound. Although the water users engaged here fall into various water user classes (corporate farmers, commercial family farmers, rural domestic users, recreation, and the often-excluded E-Flows), motivations for their judgement matrices were based on spatially explicit experiences shaped by historical, social norms and future catchment vision (Keeler et al., 2020). Therefore, outcomes from one area may not be generalisable to similar contexts. Instead, investments should be made in multiple case study applications and comparative evaluations of community weights (recognitional equity) as envisioned in socio-hydrology (Lerat et al., 2011).

One limitation that can be highlighted relates to the priority aggregation procedure. In the Twee case, water users were found to not act in harmony, thus resulting in AHP aggregation based on individual priorities. An assumption of the equal importance of water users may be incorrect, as power imbalance exists at all levels of decision-making (Denby et al., 2016). This limitation can be addressed by adopting a weighted geometric or arithmetic mean approach to reflect the relative importance of users (Aczél & Saaty, 1983; Forman & Peniwati, 1998), which could not be done here given the limited access to resources to interact with water users. Voting systems are alternative options for supporting group decision-making in areas with limited data availability or linguistic data. Unlike the AHP aggregation options described above, voting systems do not assume group homogeneity, making them ideal for use in areas where the group is large (e.g., regional scale) and there is no clear preference (Zahir, 1999).

4.4.3. User risk profiles.

User risk profiles for socio-economic use roughly capture how water users (or their representatives) cope with different water deficits in a year. As with the planetary boundaries (Rockström et al., 2009b), water users should be consulted to determine their threshold. The index requires the representation of all users, and the responses can be expressed as proportions. While various impact assessment methods can be used to establish the index, the focus should be to describe the effects of shortfall in a holistic manner, and the responses should be expressed as proportions (Hughes & Mallory, 2009).

Farm-level adaptation in the Twee Wyk is evaluated holistically from the adaptation angle (O'Brien et al., 2004; IPCC, 2007, 2022; Abdulla et al., 2014). The approach presented here shares similar traits to drought adaptation and mitigation appraisal approaches that have been deployed in East Africa (Wens et al., 2020; Teweldebrihan et al., 2021; Streefkerk et al., 2023) and India (Pande & Savenije, 2016). The results of this technique are intended to encourage early identification of trade-offs among various preferences and entitlements over water availability regarding exposure and sensitivity to water scarcity. In relation to sustainable development and socio-hydrology research recommendations for trade-off identification (Pascual et al., 2017; Westerberg et al., 2017; Merz et al., 2020; Valipour et al., 2024), the impact appraisal approach is suitable to account for the needs of less privileged users. This user-focused approach was supported by multi-stakeholder involvement, a context-specific understanding, and continuous engagements with the members of the Twee Wyk Water Users' Association. All these enablers were important for building trust and avoiding miscommunication (Barreteau et al., 2010; Carr et al., 2012; Palmer et al., 2023).

As highlighted in the introduction (4.1.1), there is still a paucity of attempts to familiarise decision-makers with the explicit inclusion of impacts in water policy. The holistic approach presented here transcends previous perceptions that equity-based distribution of socio-economic impacts economics is a difficult task (Prasad et al., 2006). Instead of viewing context-specificity, changes in expected impacts over time, power dynamics, and individual preferences for water as hurdles to evaluating fairness, these factors are considered as motivations to build cooperative capacity at the local governance level. This approach is not a template because alternative interdisciplinary approaches can be used by different modellers to determine community preferences for water allocation and user risk profiles. The most crucial point to emphasise is that when gathering socio-economic information from people, care must be taken with regard to power dynamics.

From the socio-economic perspective, results highlight a lack of adequate water storage and alternate water sources as a barrier to drought mitigation, while a lack of observable data impedes water resource planning and management. As a result, it is critical to investigate strategies to strengthen vulnerable users' adaptive capacity, such as enhancing water infrastructure, increasing risk appetite for crop diversification (Sabbaghian & Nejadhashemi, 2020), and strengthening data collecting and analysis (Kirchhoff et al., 2013). All these recommendations were identified by the stakeholders as guiding principles for their 2050 vision. However, trade-offs within each option need to be identified and addressed, which is a key feature of adaptive management (Biggs et al., 2015; Roux et al., 2022). Ecosystem integrity may be jeopardised by the upstream failure to comply with E-Flow requirements (Tanner et al., 2022), with downstream Olifants estuary ecosystem service beneficiaries bearing the brunt of the consequences. These effects justify the yearly E-Flow requirement of 70.21% of annual runoff from the Twee River watershed, compared to 38.5% from the adjacent Leeu River catchment (Department of Water and Sanitation, 2017). Sustainability evaluations must consider the trade-offs of developing water storage facilities, particularly in-stream small dams (Mantel et al., 2010). This economy-environment trade-off assessment is necessary to ensure fairness between the environment and the economy as the stakeholders envision and as the environmental legislature requires (RSA, 1998b, 1998a). The next chapter delves into a fun and interactive procedure that led to the system-wide understanding of why these E-Flow requirements are necessary.

5. A ROLE-PLAYING GAME TO INTRODUCE PLAUSIBLE REALLOCATION STRATEGIES FOR FAIR WATER USE FROM AGRICULTURE IN THE WESTERN CAPE, SOUTH AFRICA

The role-playing game development and its outcomes are being prepared for publication with *Ecology and* Society as: **Xoxo, S**., Barreteau, O., Bonte, B., Tanner, J., Gwapedza, D., Mantel, S. Bradshaw, K, Paxton, B. and Theron, S, May. Knowledge co-creation and harvest: An interactive quest towards equitable water shortage management with multiple stakeholders in the Koue Bokkeveld, Western Cape, South Africa

"The fundamental question we are motivated to answer through the application of a socio-hydrological model is what drives the human response within the human sub-system" (Elshafei et al., 2014: 2143).

5.1. Introduction

This chapter delves into the innovative application of the Role-Playing Game (game) technique that was used as a knowledge transfer medium for the Water-Sharing Tool reallocation structure, learning from Barreteau et al. (2001). This was the second participatory modelling product in a project aimed at helping the Twee Wyk Water User's Association develop a fair water management plan. An agent-based model was also co-developed to explore future land and water development scenarios under different climate projections. The aim of the game was three parts: I) inform and consult stakeholders about the plausible reallocation strategies designed by Pienaar & Hughes (2017); II) Collectively make sense of impacts both due to stakeholder reactions and each reallocation strategy; III) Inspire consequential thinking in connection with other water users.

The game technique, rooted in the participatory modelling framework (Barreteau et al., 2013; Étienne, 2014), is selected to address the three key objectives while responding to the controversies around water reallocation decisions (Scheierling, 2011). This decision was taken acknowledging other available options such as facilitated discussions**,** scenario planning (Amer et al., 2013), stakeholder analysis (Reed et al., 2009), and systems dynamics models (Brent et al., 2017) can be used to fulfil the three objectives. However, a role-playing game approach was chosen since water reallocations represent complex unmonitored processes and affect multiple stakeholders (Pahl-Wostl et al., 2012). These stakeholders also have different learning and communication styles (Voinov & Bousquet, 2010), competing objectives for water use (Rogers & Luton, 2011), and skewed power distribution (Pfaff et al., 2013; Brisbois & de Loë, 2016; Partzsch, 2017).

Although it can be used in other contexts besides the study area, the game is originally co-designed for use in a small commercial fruit farming area primarily geared toward the export markets. The local farmers fall into three distinct categories: Corporate-Owned Farms (upstream)—these entities hold the most power but less interest in collective decision-making and operate in the headwaters; Commercial Family Farms—typically located in the middle reaches of the catchment; and Downstream Family Farms, who are less privileged and rely on run-of-river for their water supply. The environmental water user has legally designated a high environmental protection level (Department of Water and Sanitation, 2017) as it plays a crucial role due to the area's high biodiversity importance (Ellender et al., 2017). However, this protection level remains inadequately met during water-scarce periods (Paxton et al., 2017).

5.1.1. Background

Implementing water reallocations based on transparent strategies aimed at minimising catastrophic shocks to the society and economy may be useful in balancing demand, supply, and societal objectives (Hughes & Mallory, 2009). Hughes and Mallory (2009) propose that socio-economic appraisals at the basin/sub-area scale can better inform water demand management decisions. As shown in Chapter 4 (section 4.2.4) and argued by Gui et al. (2015). Socio-economic appraisals will be effective only when they comprehensively capture the multi-dimensional nature of risks emanating from water shortages for different users. Since the goal is demand management, decision-makers may benefit from indicators of possible impacts/risks at different assurance levels (Hughes & Mallory, 2009).

Pienaar and Hughes (2017) took this work further and proposed four reallocation options to balance demand, available supply, and societal goals. The approach of deriving the water-sharing options follows similar steps to mathematical linear programming to reconciliate multiple competing objectives for water use (Elleuch et al., 2023). However, the four distinct water-sharing options are derived from an asymmetrical relationship between possible risks and uncertain water shortages (Pienaar & Hughes, 2017) for ease of implementation by decision-makers with different education levels. More strategies can be defined through the deficit-impact index, but this task is beyond the present research's objectives. South African decision-makers are unaware of these strategies, and communicating the strategies to non-experts is a great challenge. This dissemination challenge is despite the promising impact of the these reallocation options are for equitable decision-making under uncertainty, which is unsurprising considering the identified (Hughes et al., 2015) stakeholder's unwillingness to explore with uncertainty and emerging models to reduce the uncertainty.

The validity and acceptance of the water-sharing strategies remain unknown as they have never been introduced to stakeholders and decision-makers. Understanding stakeholder perception and possible reaction to plausible strategies is essential to widen perspectives of potential outcomes attached to decision alternatives (Srinivasan, 2013). Considering human behaviour dynamics on future risks is well recognised in different fields such as water policy (Yates et al., 2005; Matrosov et al., 2013), land degradation (Cowie et al., 2018), climate change, and recently socio-hydrology (Elshafei et al., 2014; Aerts et al., 2018). Meanwhile, an assumption-based or expert-driven development of the strategies may deepen the uncertainties at granular levels due to challenges associated with complex social systems (Preiser et al., 2018). Therefore, as discussed in previous reviews on collaborative modelling (Voinov et al., 2016; Basco-Carrera et al., 2017a), including stakeholders in the definition of the strategies is seen as a way of increasing robustness in decision-making. This notwithstanding the barriers associated with stakeholder inclusion in achieving sustainable water management (Halbe et al., 2018).

The proposed water-sharing/reallocation strategies (used interchangeably throughout the thesis) present different pathways to achieving equitable outcomes, which stakeholders may receive differently. However, the strategies are expert-defined (Pienaar & Hughes, 2017) resulting from a combination of social equity goals, available supply, and current demands (Hughes & Mallory, 2009). Therefore, involving water users their representatives when exploring plausible management pathways helps to expose the users to alternative options towards equitable outcomes (Patrick, 2014; Seigerman et al., 2022) and enhance stakeholder's capacity to use uncertain information in decision-making (Mcmillan et al., 2017).

Links to distributive and procedural justice.

Role-playing games are well-documented (Farolfi et al., 2010; Martin et al., 2011; Voinov et al., 2016; Oftadeh et al., 2017; Bonté et al., 2021) for ensuring transparency of procedures for complex and uncertain problems while ensuring equal participation of all stakeholders in common decision-making problems, although limited by game objectives and instructions. For instance, Farolfi et al. (2010) used the companion modelling approach (Barreteau et al., 2013) to co-develop a game to help overcome ongoing water supply disputes among local water users in the Kat River, South Africa. Different allocation strategies between domestic users, small-scale irrigators, large-scale irrigators emerging, scheduled-white commercial-scheduled, and non-scheduled commercial farmers. The allocation part of KatAware captured distributive justice, characterised by diverse users' minimal access to the country's water resources (Prasad et al., 2006). Urban dwellers and large-scale irrigators had higher income and education levels to their advantage over the participation process despite all water user groups being represented (n=3). Equal representation of users displays the game's practical ability to demonstrate decentralised governance to involved stakeholders (Movik et al., 2016). The authors concluded that the game allowed them to combine different information types for better understanding by all stakeholders. This conclusion can be interpreted as role-playing games are useful to address inequality due to power dynamics that manifest as information asymmetry between stakeholders (Pfaff et al., 2013).

To avoid deepening the existing power disparities (Edmunds & Wollenberg, 2001), equal stakeholder representation is not always possible or desired in management decisions. According to Edmunds & Wollenberg (2001), this consideration is indispensable when less influential stakeholders have not yet reached a mutual consensus. Perrotton et al. (2017) also, in their game deployment to explore wildlife-human conflicts, collaborative processes sometimes fail to empower communities to make meaningful contributions to group decision-making equally. In the Twee Wyk, the most influential stakeholders (upstream corporate-owned farmers) were self-excluding, possibly as a bargaining skill to avoid external influence (Adom & Simatele, 2022). The role-playing feature of the game allows for representing the self-excluding stakeholder, as stakeholders can assume roles and play according to game instructions (Barreteau et al., 2001). However, the game could be deemed a strategic intervention to strengthen consensus and coalitions among attending water users (Schreiner, 2013; Fletcher et al., 2022). Moreover, the committing stakeholders may build adaptive capacity against the potential actions of the self-excluding and influential stakeholders through shared understanding (Hare, 2011).

5.2. Methods: Role-Playing Game Components

5.2.1. Collective construction of a conceptual model for the role-playing game.

In 2022, an interdisciplinary team of researchers from South Africa and France (11 team members and 10 experts making a research grant advisory panel) proposed the use of a Companion Modelling approach to design a role-playing game called "*Fair Play*" to promote a comprehensive understanding of reasonable use and inclusive decision-making in water management. This proposed approach was in response to ineffective governance of water resources and recurring conflicts in parts of the Koue-Bokkeveld region, as discussed by Knüppe & Meissner (2016).

The ARDI (actors, resources, interactions, and dynamics, **Chapter 4**) process facilitated the co-creation of the role-playing game (Etienne et al., 2011). During a full-day workshop in May 2022, landowners were asked four successive questions in the Twee *Wyk* to complete the ARDI diagram (Figure 4.5). The questions were: Who are the main actors/entities in the valley? What are the primary resources within the Wyk? What are the most important ecological dynamics at risk, and how do the identified stakeholders influence them? How does each stakeholder use the resources and modify water resources? Responses to these questions were collated into four simple diagrams representing actors (a diagram of stakeholders and management entities), a resources diagram, a dynamics diagram, and an interactions diagram. A draft ARDI diagram was computerised and projected on-screen in a plenary session in November 2022 for validation by participants. The ARDI diagram has been reduced to focus on the parts that give details on the surface water usage-related functioning of the system, which are the most relevant elements to the game (Figure 4.5).

The game was developed in an iterative process over two years, anchored on 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/objectives was followed, starting with defining a shared catchment vision for 2050 using the Adaptive Planning Process (APP, Kingsford et al., 2011; Palmer et al., 2013). The ARDI process permitted a communal articulation of the catchment's main features relating to sustainable water usage (Etienne et al., 2011). In accordance with Pandolfelli et al. (2008), the 'actors' part of the ARDI process helped answer the question "equity to/between whom?" as the Water User Association representatives have not been elected. Once elected, these members would serve as the target stakeholder representatives to provide the socio-economic data. A community preference for allocation, representing social equity goals or water users the community wishes to buffer against water shortage, was determined by local stakeholders on an individual basis, facilitated by the Analytic Hierarchical Process described in section 4.2.3 by Xoxo et al. (2023). It is worth noting that irrigating actors were unintentionally bundled into a single user group, despite their vulnerability to scarcity. However, for the role-playing game, the irrigators were disaggregated according to location, infrastructure investment, and type of ownership, all of which have some influence over the user's adaptive efficacy.

5.2.2. Entities, state variables and scales.

Based on agent-based modelling, actors/entities refer to societal or organisational systems that act as a whole and may evolve with neighbouring entities or be influenced by exogenous drivers (Dibble, 2006; Müller et al., 2013). As seen in the community sensitivity loop (Elshafei et al., 2014), exogenous drivers may include climate conditions, environmental protection, changes in policy or legal frameworks, and market preferences. As a reminder, community sensitivity refers to the societal perception of socio-economic well-being versus the ecological (Turner, 2010). State variables distinguish an entity from others and track its evolution. Changes in the South African water legislature over the past ~380 years with governing regimes (Tewari, 2009) and the changing water policy priorities during the democratic government (Department of Water Affairs and Forestry, 2013;

Department of Water and Sanitation, 2022) are considered as triggers leading to new system trajectories.

To make the game playable, the game board comprises 50 hexagonal tiles (Figure 5.1), 40 of which represent a quantum of arable land per water user and are green in colour, and 10 (brown) represent the riverbank. The game interface is built to represent the shape of the sub-catchment of implementation as a way of mimicking reality. In addition to game tiles, several tokens represent the primary economic activities in the catchment, but dam and groundwater resources were not represented as the focus was the low flow part of the flow duration curve (Table 5.1).

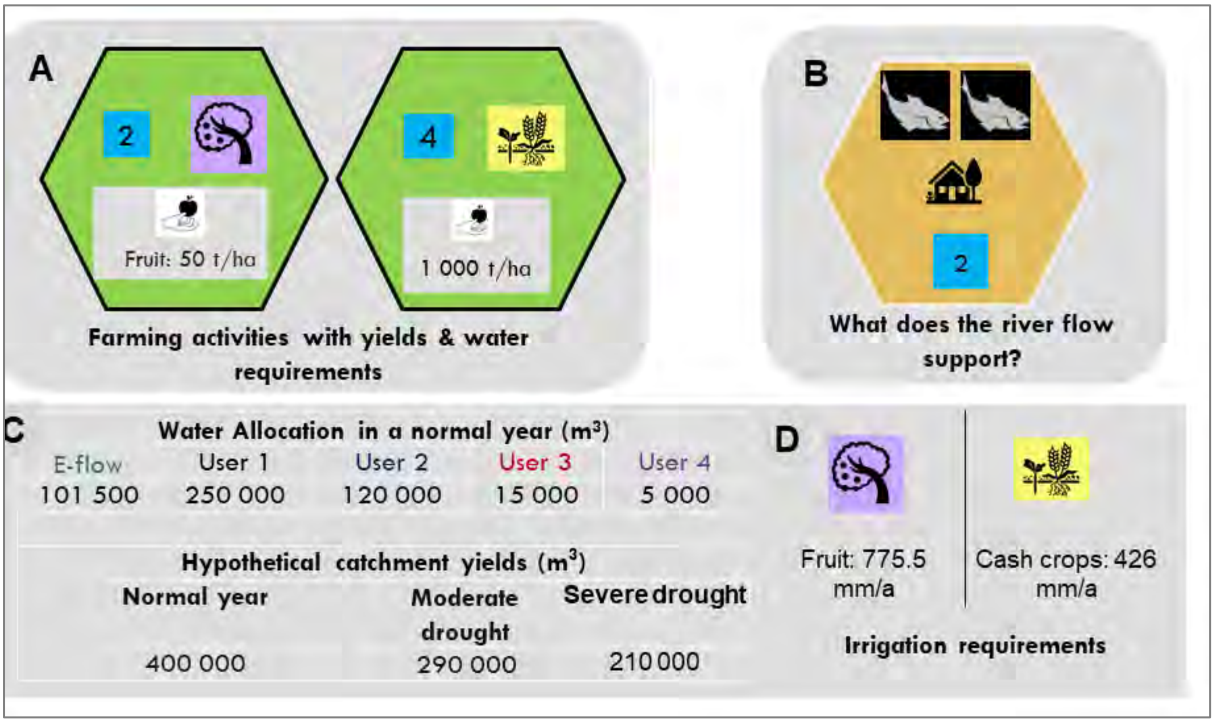


Figure 5.1: Role-playing game props. The hexagonal tiles denote the smallest spatial unit, with A) representing arable land per player and riverbank represented in (B). The tokens shown in farming activity tiles represent the relative water demand for each activity, such that each tile can be occupied by three icons at any given time. The blue rectangles show annual water requirements for each crop category. Support services emanate from meeting E-Flow targets, and these can be traced by the endemic fish species and recreational activities from high pool levels. C) Water allocation, its administration by individual users, and catchment yields.

The *Wyk* has three main economic activities*:* fruit, vegetable production, and tourism. In the game, fruit production represented citrus and deciduous fruits, and field crops represented onions and potatoes. Crop activities and water demands were considered at annual scales in the game situation for simplicity, even though these are evaluated at monthly time steps in the next chapter and for policy decisions. The monthly distributions attached in Table A-5.1 show that potatoes have the largest annual irrigation needs among the different crop types (760 $mm.a^{-1}$), followed by citrus (740.91 $mm.a^{-1}$), deciduous fruit (443.38 $mm.a^{-1}$), and onions (426 $mm.a^{-1}$). These projections are based on crop coefficients and A-Pan evapotranspiration from 1990 Water Resources data (Midgley et al., 1994) for the Koue Bokkeveld catchment (River E21, Table A-5.1). For the game situation, which lumped the different crop types for ease of navigation, fruits were assumed to use half the demand of field crops (Table 5.1). All crops had the same growing rate (annual), but the yield was treated as zero in that year for players that introduced new orchards. Economic impact is based on water productivity, which is the indicator farmers use. In terms of climate, farmers played a severe drought level, but the students elected to play a moderate drought scenario in the final version.

Table 5.1: Abstracted game indicators 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 representing vegetables, and accommodation, which reflects tourism.

A) Land use information						
Player (farmer)	Irrigation activities			Corresponding game tiles(n)		
	Fruit (ha)	Cash crops (ha)	Total (ha)	Fruit	Field crops	Total (n)
Corporate-Owned (User 1)	160	100	260	13	8	21
Commercial family (User 2)	141	20	161	12	2	14
Downstream (User 3)	55	10	65	5	1	6
Lifestyle (User 4)	0	5	5	0	1	1
Riverbank (E-Flow)	Endemic fish species			Species abundance (n = 10)		
Total (Socio-economic use)	356	135.5	491	30	12	42
B) Water use						
	Irrigation demand (m^3)			**Corresponding game icons**		
User 1	90,106.8	50,377.5	140,484	26	32	58
User 2	79,406.6	10,309.9	89,717	24	8	32
User 3	30,974.2	5,037.7	36,012	10	4	14
User 4	0.0	2,518.9	2,519	0	4	4
Riverbank	19 or 29% of MMQ			20		
Total (Socio-economic demand)	200,487.6	68,244.1	268 ,31.6	60	48	108
C) Economic indicators						
Potential yield (ton/ha)	~55	~1,000	2 people/ unit	Sourced from farmer questionnaire		

Definition of main stakeholders/ game players

Four water user groups were identified in the catchment because of the ARDI exercise for stakeholder mapping (**Chapter 3**, Gwapedza et al., 2024) during workshop 2 (May 3rd, 2022) and the individual farm visits to create a socially derived equity index (Xoxo et al., 2022, **Chapter 3**). The identification of four user groups was informed by the Water-Sharing Tool's limitation on the number of water users/user groups/ sectors to consider in each sub-area. As requested by some stakeholders during the individual farm visits and by a Reference Group of experts in the main project, farmers were split into three sub-groups based on socio-economic status with the help of a research associate working in the catchment (detailed in **Chapter 4**).

Consequently, both game sessions had seven players each, all of whom were familiar with farming. Regarding the division of roles, the only requirement was that farmers do not play themselves; they needed to simulate another farmer's part. User 1 took on the role of managing a corporate commercial farm, User 2 ran a legacy commercial family farm, User 3 played the downstream family farmer with limited resources, and User 4 took the role of a resident and lifestyle farmer. Water restrictions are introduced by the Water Users Association chair (Player 5), who is also responsible for understanding their impacts and plays the moderator role in the game. A technical support officer monitors and reports these impacts to the Water Users Association (Player 6). Other workshop attendees (not stakeholders in the Wyk) allocated the observer role, which is inactive in gameplay. The role of environmental water user (Riverbank)—which supports indigenous fish species and leisure activities, was rotated between farmers and stakeholders from an interest organisation (WWF-SA or Western Cape Government).

5.2.3. Briefing and game instructions.

Two concurrent game sessions (Game Table 1 and Game Table 2) were conducted with similar stakeholder groups. As expressed in the introduction, the game's main goal was three-fold:

I) inform and consult stakeholders.

II) Collectively make sense of impacts both due to stakeholder reactions and each reallocation strategy.

III) Inspire consequential thinking.

These objectives were made clear during a plenary session through a PowerPoint presentation during the workshop on November 2nd, 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 options as narratives, the game developer reminded the participants of their 2050 Vision (Table A-5.2, set in May 2022), which is treated as a guide for all discussions and future decisions. This introductory presentation was an essential building block for the game sessions, generating a lengthy discussion. This discussion was considered as an essential feature for public acceptance and procedural equity (Jackson & Barber, 2013).

The research team drafted the narrative cards (Appendix A-5.1) based on hypothetical inputs shown in Table 5.2 derived from Table A-5.3. The hypothetical inputs, as opposed to the study area outputs (coming up in **Chapter 5**), were chosen for simplicity and because players were 'playing' users other than themselves (i.e. a hypothetical situation). This way, players can focus on the game's primary goal rather than diverge to numerical uncertainties that may arise from using catchment outputs for the Twee *Wyk*. Regarding uncertainty, the focus is on hydrological data and human decisions.

Table 5.2 Details the proposed water-sharing options on supplied water to four socio-economic users with a baseline monthly demand of 268,700 m³ compared to a catchment yield of 400,000 m³, assuming environmental water requirements are met at level B. It is assumed that 170,000 m³ of surface water is stored in small farm dams. The three water-sharing options (A to C) and their corresponding drought assurance, supply shortfall, and expected impact are shown for two scenarios of meeting environmental water requirements (i.e., modified or level D and near natural or level B). The water restrictions are explored for a severe drought situation (catchment yield = 210,000 m³) to avoid overcomplicating the game with groundwater use under severe droughts.

Water users		Riverbank	User 1	User 2	User 3	User 4
Normal year demand (m³)		116,000	140,484	89,717	36,012	2,519
1. Water sharing options and equitable allocation of water restrictions (level D E-Flow)						
A) Pizza Slices	Deficit (%)	34	53	27	0	0
	Impact (%)	92	80	86	0	0
B) Spit the bill	Deficit (%)	34	37	37	37	37
	Impact (%)	92	40	92	98	96
2. Water sharing options and equitable allocation of water restrictions at (level B E-Flow)						
A) Pizza Slices	Deficit (%)	48	61	38	0	0
	Impact (%)	92	87	92	0	0
B) Spit the Bill	Deficit (%)	48	45	45	45	45
	Impact (%)	92	60	93	98	94
C) Equal impact	Deficit (%)	72	49	23	16	18
	Impact (%)	93	70	70	70	70

How the game works?

The game follows six steps as described in Figure 5.2.

- **First**, the players are briefed using the instructions (Appendix A-5.1) and information presented to the players change with each proposed reallocation strategy. Next, the game board and icons are introduced to all players (Figure 5.1). These two pieces of information are also made available to players throughout the playing session as reference documents.

- **Second,** a research team member who is familiar with the Water-Sharing Tool presents the four possible water reallocation options in a plenary session, focusing on each strategy's principles. Players have an option to select a strategy they wish to explore, or they can explore all strategies randomly. In this study, the latter was the case.

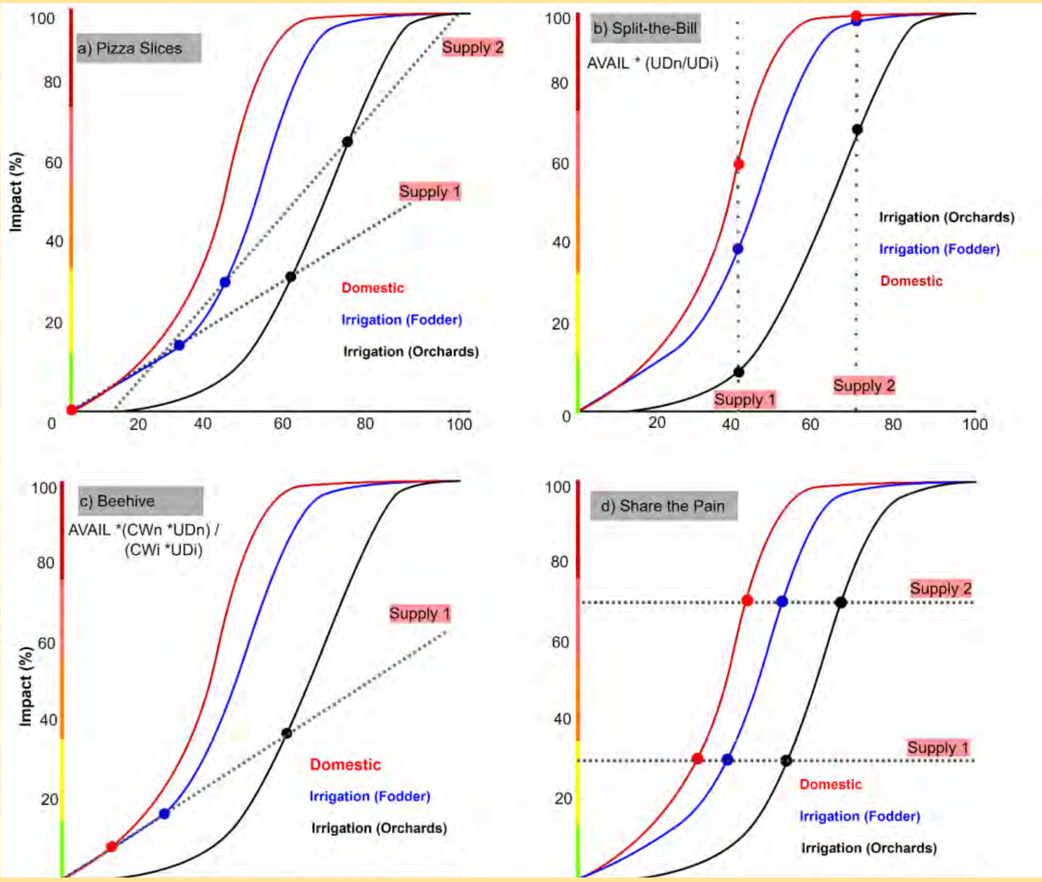
Figure 5.2: Six steps involved in playing the game.

- **Third**, players react to a narrative/reallocation strategy by deciding how the reduced allocation will be used on their land by dividing the water tokens they receive across their crops. Players also have an opportunity to discuss among themselves the sharing of water. The game also allows players to change land use, with limited options available, based on the ARDI outcome.

- **Fourth**, player decisions are logged in Table 5.2 by the technical officer, who facilitates the computation of water shortage effects. The game dynamics are aided by a live spreadsheet of the simplified water balance and was also in charge of the PowerPoint presentation containing the narrative cards. The game facilitators have an option to present the results of each round to the players, or these can be left to the end of the game to inform the debriefing session as was done in this study.
- Once all the agreed strategies have been explored and all the dynamics have been logged, all players and workshop participants are invited to a plenary debriefing session (described under section 5.3.4), where they discover the distributive outcomes of the reallocation strategies combined with individual player decisions. This would be right time to select a preferred reallocation strategy in cases where all water use sectors are represented by legitimate players.

Box 5.1: Balancing allocation supply and demand considering user risk profile. The four plots show how reallocation strategies are defined for A) Pizza Slices, B) Split-the-Bill, C) Beehive, and D) Equal impact.

The determinants of supply reductions shown below are the reallocation strategeis introduced by Pienaar and Hughes (2017), which are discussed in section 3.3.5. The plots show a hypothetical case of Hughes and Mallory's (2009) deficit-impact index. Notably, the deficit-impact index reveals that the orchard irrigation sector can withstand significant water shortages compared to the fodder irrigation and domestic user groups. In scenarios where available supply decreases (possibly due to droughts, environmental priority, or a growth-driven increase in demand within a water management area), decision-makers must deliberate and choose a strategy carrying the least impact. For all allocation strategies, a change in available supply alters the percentage of water deficits, which also implies a change in socio-economic impacts faced by users. Given the overarching goal of enhancing distributive fairness, decision-makers are expected to choose the one that aligns with community development objectives.
Pizza Slices (Equal share) refers to an allocation strategy wherein a constant amount is withdrawn by users until all demands are met or the allocable supply runs out (Box 5.1-A).
Split-the-Bill (Proportional allocation) refers to sharing the allocable supply based on individual proportional demands relative to the sum of demands in the node (Box 5.2-B).
Beehive (Proportional allocation with community weights) follows a similar mechanism as Split-the-Bill but is applied with a supply prioritisation specified by the community allocation preference (Box 5.1-C).
Equal impact, refers to an allocation strategy that tries to equally distribute the relative impacts of scarcity across users, resulting in different supply shortfalls (Box 5.1-D).



Player Instructions.

The research team tested three game prototypes between May 2022 and November 2023. The first finalised version (Fair Play V1) was rolled out in two parallel sessions in the catchment with a multi-stakeholder group on November 2nd, 2023, at Kunje Guest Farm. Each session consisted of the seven players described in the briefing section above. All the players had first-hand knowledge of farming activities in the catchment. None of User 1 (the corporate farmers) attended. The two who had committed to attend could not make it because of harvesting commitments. Therefore, the role of the User 1 player was allocated to other attending stakeholders in the workshop. All players adopted another user's role to build awareness and ensure a fair participation procedure.

Each table played four rounds representing two sharing options (either *Split-the-Bill and Equal impact* or *Pizza Slices* and *Equal impact* at low and high environmental protection levels, all introduced by the game facilitators as narratives based on Table 5.2 and Table A-5.3 to promote long-term risk appraisal (van Duinen et al., 2015). Facilitators introduced themselves as the newly elected Water User Association chairs and indicated they would hold the role for the next five years. Facilitators then introduced the game, its objectives, instructions. A complete game introductory manual is available in the appendices (Section 9.2.3). Players were allowed to pose questions to deal with language differences.

In the game case study, the catchment had a mean annual runoff yield of 400,000 $m^3.a^{-1}$, compared to a socio-economic demand of 268,700 $m^3.a^{-1}$ (Figure 5.1-C). It was assumed that there are no in-stream dams to maintain consistency with the Twee *wyk*. The hypothetical low flow E-Flow for categories B and D is 29% and 19% of mean annual runoff, respectively (Figure 5.1-C). The relationship between deficit and impact (residual impact from adaptive strategies) ranges between tolerable and moderate for the players, with the under-resourced farmer facing the highest risk. Groundwater abstraction and water storage were both implicit in the game, assuming the players could comprehend the inclusion of these two water sources in the deficit-impact index assessment that is used to compute the allocations under different strategies (Table A-5.2, which is the base of all in-game decisions). Farmers with limited resources (User 3) presumably do not store water, nor can they abstract groundwater because they lack the financial means to do so.

While improvements in the game were progressively made over the two years to simplify it, farmer realities tended to interfere with the game's playability. This is largely because of the distributed nature of water management in the catchment with farm-level decisions, which would have been too complex to integrate into the game. Game instructions had to be made flexible to allow some game evolution to match player needs. Players are also allowed up to 5 minutes of discussion during playtime.

5.2.4. Gameplay and individual decisions.

Figure 5.4 presents an overview of water users in the Wyk and their roles in the game. Commercial farmers (User 1 to User 3) engage in productive water use activities and sometimes accommodates tourists during peak tourism seasons. Except for User 3, all these users have private reservoirs and farm dams that may be operated to release water downstream to fulfil streamflow needs, privately negotiated water transfers ('gentleman's agreements', or in preparation for heavy rains. User 4 participates in small-scale vegetable production and tourism-related activities, subject to E-Flow approval and the number of tourists in the catchment. Productive farmers may also trade their water entitlement with other users in the basin, which is an ongoing action in the Wyk, but may change as discouraged by the new water policy (Department of Water and Sanitation, 2022). The Riverine ecosystem conveys the environmental water user (Riverbank) that must be protected for its environmental and ecosystem service (Ellender et al., 2017; Paxton et al., 2017) importance in prioritised for Consistent with the South African National Water Act (RSA, 1998a).

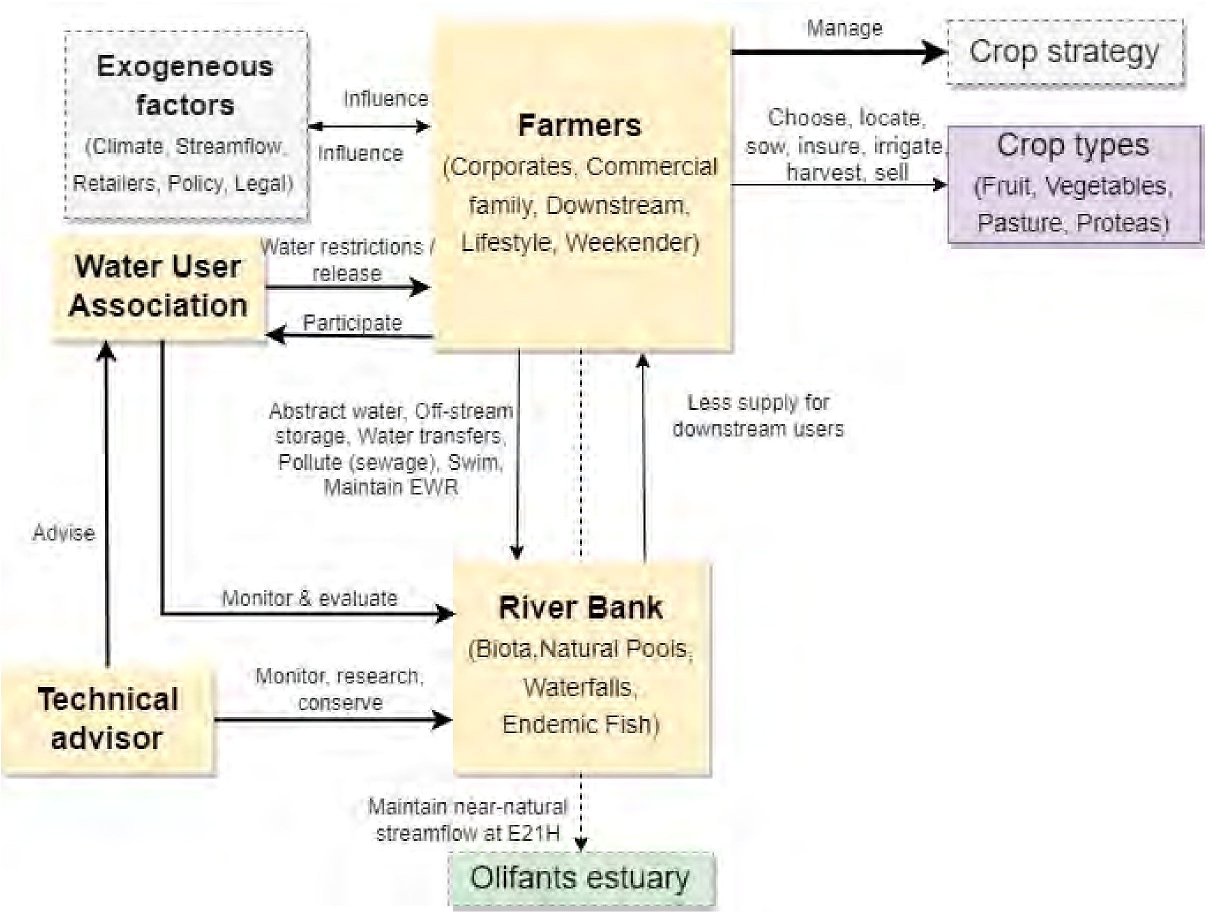


Figure 5.4: Schematic diagram of players involved in Fair Play based on the ARDI diagram produced in Figure 4.4.

5.2.5. Data collection and analysis.

To reach the study's second purpose of understanding water users' attitudes towards water-sharing alternatives, we evaluated the implications of water shortfalls produced by issued limits and user compliance. We observed how water users respond to proposed restrictions and how their decisions affect the situation. Player's water use choices were transcribed with the help of an automated operator spreadsheet by logging the decisions into Table 5.3 and using the multiplies in Table 5.1.

Table 5.3: Modified game tracking sheet for logging player decisions in each round to determine outcomes of plausible water distribution strategies to deal with water scarcity.

Water User/ Player	Fuit production pieces	Field crops pieces	Tourism pieces
User 1			
User 2			
User 3			
User 4			
Riverbank		Count of fish pieces	

Each reallocation strategy's economic impacts or outcomes were analysed using the percentage change in water productivity (crop yield) under each scenario. The economic impact experienced by the most vulnerable users compared to the rest of society is used to report on the impact of the strategies on social equity. Environmental protection performance is monitored in the river and at the catchment outlet. Failure is considered when the in-game E-Flow satisfaction level drops below 29% of annual runoff or 19% of annual runoff for E-Flow at level D. All these indicators were summarised into the operator spreadsheet to give a comparative analysis of the water-sharing options. The final indicators were displayed as colour-scaled tables on a projected screen during the debriefing plenary session.

Crop yield was computed based on crop hectarage and farmer-stated tonnage per hectare. A questionnaire survey was circulated in May 2023 with questions about on-farm water use and crop production to get the farmer's expected tonnage per hectare. Respondents indicated that orchards in the *wyk* yield between 30-70 tons/hectare (median 55 tons/hectare), and field crops yield approximately 1,000 tons/hectare (Table 5.1-C). The median was used for fruit yield.

5.2.6. Feeding back.

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 (Barreteau et al., 2007). Game outcomes were evaluated through a plenary discussion guided by questions listed in Box 5.2 focusing on attitude changes (Matthews et al., 2011). The attitudes were explicitly targeted to the catchment's collective future vision. This process was guided by an experienced facilitator who understood the English and Afrikaans language well. One debriefing session was run for both groups, including the observers (Image in Box 5.2). The debriefing session went on post-game, where additional information was provided by the players.

Box 5.2: Guiding questions for the debriefing session.

How did you feel playing the game?

Were the sharing scenarios easy to understand and plan with?

Did playing the game influence how you think about sharing the water in the catchment?

Has playing this game influenced the way you might act during dry periods in the future?

To what extent do you feel the game reflects reality in the catchment?

Do you imagine one the four strategies would appeal for use in the catchment?

5.2.7. Playing the updated game with post-graduate students.

Experience with playing the game with the farmers indicated that the game needs further refinements to be a suitable tool for the players. Taking advantage of the iterative nature of game development, the game was further refined, and the refined product was tested with a participant group that was not part of the co-design process. This option was mainly due to the updated version being outside the project timelines and therefore could not be re-played with the farmers. An updated game version was played with five post-graduate students from the Geography Department at Rhodes University, South Africa, who were exposed to the game to learn about equity in decision support through imaginary action and dialogue in April 2024 (Image 5.2: Fair Play 2 in session with postgraduate students.). This session aimed to allow students to discover critical and consequential thinking in water allocation decisions. For the game developer, this session aimed to introduce the water-sharing strategies to the students.

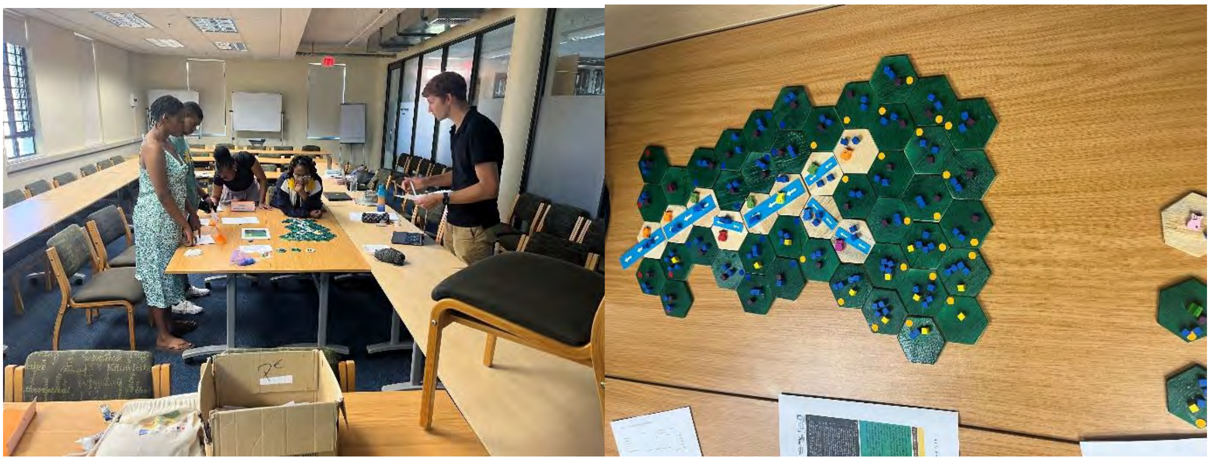


Image 5.2: Fair Play 2 in session with postgraduate students.

Students followed a similar game journey as the farmers as they played the roles of Corporate Farmer (User 1), Commercial Family Farmer (User 2), Downstream Farmer (User 3), and the Riverbank, with similar characteristics as those in Tables 5.2 and Figure 5.4. The session began with thoroughly introducing the strategies over a plenary discussion. Students managed the farms and learned the consequences of their reactions to different water reallocation strategies (Table 5.2). In the updated game version, students elected to play the currently applied strategy under low environmental protection as a business as usual or round 1. During this game, the assumptions were:

- It's a moderate to severe dry year (MAR = 250,000 m^3).
- All users (User 1, User 2, and User 3) depend on run-of-river runoff.
- E-Flow for environmental protection at level D was 19% of MAR.
- E-Flow for environmental protection at level B was 33% of MAR.
- Initial crop choices were kept similar to the farmer's version.

High environmental protection was prioritised for subsequent rounds. Students elected to play the subsequent rounds in the following order, round 2 was *Split-the-Bill,* round 3 was *Equal impact,* and round 4 was *Pizza slices*.

5.3. Results

5.3.1. Game validation by farmers: fair play V2.

Compliance with river supply water restrictions in the game.

The modelling process faced challenges in logging game decisions due to the rapid pace of gameplay with farmers. This summary focuses on in-game water restrictions and compliance, excluding water use conversion. The game began with a low environmental protection scenario (level D E-Flow), demonstrating conservation impacts on river ecosystems and downstream users. Assigning the Riverine ecosystem's (E-Flow) role to an ecologically informed player helps others realise that not meeting E-Flow requirements, even at the lowest level, threatens juvenile endemic fish by destroying their instream habitat (Table 5.4, Table 5.5). Players initially misunderstood the game's focus on river flow, with dam owners managing water scarcity from their reserves. For instance, under the *Split-the-Bill* @ D directive, users were to cut river withdrawals by 37%; User 1 complied fully, while others did not. Environmentally, this led to the unsustainable outcome of endemic fish being wiped out.

Image 5.3: Two parallel sessions of Fair Play V2 at Kunje Guest Farm, Western Cape South Africa. Left: PhD student (Sinetemba Xoxo - green shirt) facilitating Game Table 1; Top right: final state of Game Table 2; Bottom-left: Research team member (Prof. Karen Bradshaw) facilitating Game Table 2 with an NGO practitioner (grey shirt) as an observer. Two MSc students (Rodney Tholanah-left and Sakikhaya Mabohlo-right) played as Technical Officers.

Players recognised that higher E-Flow levels (from D to B) meant reduced water availability for agriculture and that the extent of this reduction varied among farmers (Table 5.4). In subsequent rounds, players aimed to maintain healthy in-stream ecosystems without compromising social stability. Surprising dynamics emerged among the most vulnerable users (downstream farmers, based on my vulnerability assessment section 4.2.4), who, together with lifestyle farmers, chose to forego their entitlements to drought relief in favour of upstream farms. This was despite being exempt from restrictions under *Pizza Slices* or facing equal restrictions as upstream users under *Split-the-Bill* (Table 5.4). These players cited the importance of upstream farmers for seasonal employment offered by annual crop production and social stability in the region. Players seemed to understand the high-impact implications associated with *Equal impact,* propelling the players in both sessions to collaborate in protecting the endemic fish as shown by a minor decrease in E-Flow satisfaction (-10% and 0% in round 3) compared to an anticipated 68%. It is important to note that Users 1 and 2 still had untapped farm dam supplies to mitigate any run-of-river shortages they faced and supplement E-Flow dissatisfaction.

Table 5.4: User compliance or non-compliance with run-of-river restrictions across users and strategies, shown as percentage decreases relative to normal year demand. Severe drought level (MAR = 210,000 m³). Drought restriction is shown in brackets.

Player	Normal demand (N° of icons)	Round 1	Round 2	Round 3
	Normal demand (N° of icons)	Pizza Slices @ D	Pizza Slices @ B	Equal impact 1
Game Table 1				
User 1	58	-22% (-53%)	-14% (-61%)	-38% (-49%)
User 2	32	-0% (-27%)	-19% (-38%)	-13% (-23%)
User 3	14	-0% (-0%)	-14% (0%)	-7% (-16%)
User 4	4	-0% (-0%)	-0% (0%)	-75% (-18%)
Riverbank	20	-65% (-0%)	-20% (0%)	-10% (0%)
Game Table 2				
Player	Normal demand (N° of icons)	Split-the-Bill @ level D	Split-the-Bill @ level B	Equal impact2
User 1	58	-33% (-37%)	-36% (-45%)	-33% (-49%)
User 2	32	-16% (-37%)	-13% (-45%)	-19% (-23%)
User 3	14	-7% (-37%)	-57% (-45%)	-29% (-16%)
User 4	4	0% (-37%)	-75% (-45%)	0% (-18%)
Riverbank	20	-30% (0%)	-10% (0%)	0%

5.3.2. Efficacy of plausible strategies against production: fruit vs cash crops.

User 1 prioritised cash crops that accounted for the most land use and water consumption. Unskilled agricultural employment in the Wyk is closely tied to cash crops. Reducing fruit yield to increase water savings was an articulated strategy in the Wyk, and it is achieved through pruning the lower portion of orchards. In contrast, Users 2 and 3 prioritised high-value crops (fruit), which is linked to a lower water footprint and basin reputation of high-quality fruit produce for the export market.

Table 5.5: Possible water-limited yield, showing economic impact using crop yield (tons). Percentage decrease in yield is shown in brackets. These estimated impacts on production did not consider the backup water resources in reservoirs and groundwater use. The colours denote the impact level from tolerable (green) to catastrophic (dark red).

Crop type		**Fruit**					
Game progression		Round 1	Round 2	Round 3	Round 1	Round 2	Round 3
Player	Potential yield (tons)	Pizza Slices @ D	Pizza Slices @ B	Equal impact2	Split-the-Bill @ D	Split-the-Bill @ B	Equal impact1
User 1	8,000	4,000 -50%	5,539 -31%	4,000 -50%	2,769 -65%	2,769 -65%	1,231 -85%
User 2	7,050	7 050 0%	7 050 0%	5,581 -21%	6,756 -4%	5,875 -17%	7,050 0%
User 3	2,750	2 750 0%	2 750 0%	2 750 0%	2,750 0%	1,650 -40%	2,750 -0%
User 4	0	-	-	-	-	-	-
Catchment	17,800	-22%	-14%	-35%	-31%	-42%	-38%
		Cash crops					
User 1	100,000	100,000 0%	100,000 -0%	70,792 -29%	93,750 -6%	86,154 -14%	98,154 -2%
User 2	20,465	20,465 0%	5,116 -75%	2,938 -86%	10,233 -50%	23,500 15%	11,750 -43%
User 3	10,000	100,000 0%	5,000 0%	0 -100%	7,500 -25%	0 -100%	8,250 -18%
User 4	256	-100%	205 -20%	0 -100%	256 0%	0 -100%	0 -100%
Catchment	130,721	0	-16%	-44%	-15%	-16%	-9%

5.3.3. Participants thoughts of what happened during the game and the proposed strategies.

Although Fair Play V1 was judged as tricky to play, farmers seemed to have enjoyed playing the game despite some resistance due to the abstract design nature. Farmers appreciated the climate simulation of their recent experience between 2015 and 2019. Regarding learning and behavioural adaptation, farmers reported a change in conceptual understanding of equitable use following gameplay. The respondents used the term “conceptual breakthrough” to describe this shift in perception. Some of the respondents said the following to support the impact of the game:

“The game makes one see the impact on other users. E.g., losing a portion of water means a lot more loss for smaller farmers” ~ User 2.

“The game is ideal for perspective; it helps understand the entire catchment” ~ User 1.

Players also appreciated the exposure to the regulatory role of an adequately functioning institution, which is a key feature of the water legislature.

“The game is powerful in showing the role of a manager / co-developed water management plan as a ‘referee’” ~ User 4.

When asked if any of the strategies are attractive for future use, the downstream farmer on the one side of the valley responded no and said they would stick with their informal agreements locally. This comment could be tied to farmers' low trust in government authorities.

We don't need any water-sharing strategies because farmers all work together and can easily request water from our upstream neighbour. ~ User 3.

Meanwhile, a family commercial farmer on the other side of the valley opposed their counterparts. This opposition could be linked to the player's recent exposure to water scarcity due to the erosion of the long-standing *"gentlemen's agreements*" of water sharing between the farmers from December to February.

"Yha, there has to be some form of variation. "~ User 2.

The debriefing session continued post-game. Unreliable energy supply was flagged as an emerging exogenous cause of changes in consumption patterns (User 2 quote below), making it increasingly difficult to reduce water use. These surprises could be included in the game, such as a source of demand uncertainty, yet it is important when interrogating reasonable use.

"We now irrigate during the day because of load shedding – this increases irrigation demand because of evaporation" ~ User 2

Users with a deeper understanding of systems thinking questioned the considered boundaries for giving effect to E-Flows. This inquiry is beyond the scope of this Chapter but better captured by Chapter 5.

"Should we also not focus on E-Flow compliance downstream of the Twee?" ~ Attending NGO practitioner.

5.3.4. Improved game (Pair Play 3): Tested with post-graduate students at Rhodes University.

Change in water supply due to restrictions and students' choices.

Water use outcomes of testing the game with a post-graduate students' group are summarised in Table 5.6, showing a difference in magnitude for the abstract versus the actual case. Students also learned that inequality in water use is an intrinsic characteristic of water use in developed basins. As the game progressed, User 1 in the student version decided to slightly prioritise cash crops over fruit production, which was opposite the other user's crop strategies and similar to the farmers' strategy. Meanwhile, User 3 gradually moved away from cash crops to 100% fruit production by the last round (*Pizza Slices*), citing better economic returns with lower supply. Interestingly, students complied with some restrictions throughout the game despite having supplementary water resources in the dam (Table 5.6). This strategy was cited as saving water if the drought worsens in subsequent years. Students showed their environmental awareness as they often reached a consensus on E-Flow satisfaction.

Table 5.6: Description of in-game water use by students as farmers faced with moderate to severe drought (MAR = 250,000 m^3 instead of 400,000 m^3). The values in brackets represented imposed restrictions for the user. A reservoir (Volume = 170,000 m^3), shared by Users 1 and 2 was introduced from round 2. E-Flow requirements at level B were increased to 33% of MAR to close the basin.

In-game curtailment					
Player	Initial conditions (N° of icons)	Round 1 Split the Bill @ Level D	Round 2 Split the Bill @ Level B	Round 3 Equal impact	Round 4 Pizza Slices
User 1	58	-12% (-25%)	-24% (-38%)	-10% (-43%)	0% (-54%)
User 2	32	-9% (-25%)	-34% (-38%)	-9% (-18%)	-9% (-29%)
User 3	14	-71% (-25%)	-43% (-38%)	-14% (-12%)	0% (0%)
Riverbank	20	-10%	-0%	-0%	-0%
Transformation into a realistic scenario					
	Initial conditions (m3)	Round 1	Round 2	Round 3	Round 4
User 1	140,000	-8%	-21%	-9%	0%
User 2	90,000	-7%	-39%	-7%	-7%
User 3	36,000	-66%	-41%	-17%	20%
Riverbank	82,500	-10%	-12%	-12%	-12%

Change in demand satisfaction under the different water-sharing strategies.

Socio-economic and environmental impacts generated by the plausible water-sharing options are visualised in Table 5.7. Students discovered that partial compliance to equalised restrictions accompanied by poor environmental protection generated the highest impact on the environment and smaller farmers (User 3). Insurance in the form of dam storage was introduced from round 2 (*Split-the-Bill* @ level B) onwards, but the dam was shared by Users 1 and 2. Taking advantage of the additional storage, students complied with all subsequent restrictions but still failed to satisfy environmental demand under *Equal impact.* This failure was due to students' reluctance to release water from the dam, prioritising storage for future droughts. However, students recognised the importance of upstream dam releases in meeting environmental targets, as evidenced by the 100% fish survival rate under *Split-the-Bill* and *Pizza Slices* (Table 5.7*).* Negotiations between players were also observed, where User 3 requested support from other Users to buffer water shortages.

Table 5.7: Water-limited yield relative to normal potential yield (tonnes, % change) for fruits (A) and cash crops (B).

A) Normal fruit yield (50 t/ha)		Split the Bill @ Level D	Split the Bill @ Level B	Equal impact	Pizza Slices
Player 1	8,000	7,785 -2.7%	6,769 -15.4%	7,385 -7.7%	8,400 5.0%
Player 2	7,050	6,576 -4.2%	4,113 -41.7%	6,576 -4.2%	6,756 -4.2%
Player 3	2,750	1,100 -60.0%	1,650 -40.0%	2,200 -20.0%	3,850 40.0%
Catchment	17,800	15,641 -12.1%	12,532 -29.6%	76,180 -8.2%	19,006 6.8%
B) Potential cash crop yield (1,000 t/ha)		**Split the Bill @ Level D**	**Split the Bill @ Level B**	**Equal impact**	**Pizza Slices**
Player 1	100,000	81,250 -18.8%	68,750 -31.3%	87,500 -12.5%	100,000 0.0%
Player 2	20,465	15,349, -25.0%	17,907 -12.5%	15,349 -25.0%	15,349 -25.0%
Player 3	10,000	0 -100.0%	5,000 -50.0%	10,000 0.0%	0 -100.0%
Catchment	130,465	96,599 -26.0%	91,657 -29.7%	53,010 -59.4%	115,349 -11.6%

Collective debriefing.

The post-game discussion was focused on integrated catchment management, highlighting the usefulness of the game for operationalising equity and raising awareness. They reflected on Fair Play as a learning-by-doing approach to understanding plausible water reallocation strategies and their socio-economic and environmental outcomes. One student said, "*At first, I was struggling to imagine how I would conceptualise the introduced strategies based on the presentation alone*, *but* as I played the game, the strategies and the *meaning of impact became clearer."*

They also highlighted that the fairness of outcomes is mainly informed by personal interest, which is why the game is preceded by a shared-catchment vision to guide the process. Most importantly, students validated the game as an equitable decision-support tool. It ensures that marginalised actors (e.g., the environment and less privileged users) get exposed to a platform where concerns and grievances can be ventilated. One student said, "*It was quite fun and interesting that everyone neglected the environment when under pressure until the environmental advocate brought the issue up. The game provides a good example of how to collaboratively achieve environmental fairness*".

Other students saw the game as a tool to help "define strategies of the game" or catchment management strategies relating to water use. Students applauded the simplified introduction of restrictions using narratives. One student said, "*It was easier to understand the restriction levels, so I could focus my attention on balancing my decision impacts on farm production and environmental impact*".

Students were also creative, such that User 1 appointed an environmental advisor in the form of another student who dialled in virtually. Maintaining relationships was also mentioned as another critical element affecting individual decisions in the game, water was often transferred to User 3 on request. Their lecturer, who played the role of “Technical Support”, also mentioned that the game seems to adequately communicate complexity to stakeholders, a holistic picture of catchment dynamics, and it helps stakeholders work together in reducing undesired impacts.

5.4. Discussions

5.4.1. Inform and consult stakeholders about the plausible allocation strategies.

Although additional strategies can be formulated (Okereke, 2010), those introduced above were specifically selected (Pienaar & Hughes, 2017) as a starting point for inclusion in an integrated water allocation co-assessment model. Key distinguishing features of the strategies are their fundamental base of freshwater as a common good, their numerical ability for integration into allocation models (Pienaar & Hughes, 2017), and their explicit consideration of impact to achieve shared visions and mitigate conflicts. These distinguishing attributes follow the reasonable use criteria of the United Nations (UN, 1997), the South African water legislature (RSA, 1998a) and allocation equity studies, such as Farriansyah et al. (2018). As will be seen in the next chapter, the reallocation strategies and the collaborative model are used for an integrated assessment of the strategies by explicitly incorporating data uncertainty, natural seasonality, and community sensitivity (Hughes & Mallory, 2009; Mayer & Muñoz-Hernandez, 2009; Turner, 2010; Matrosov et al., 2013). Introducing the strategies in a participatory modelling framework—a Role-Playing Game (Barreteau et al., 2013; Kelly et al., 2013) was our way of validating the strategies for their potential acceptance on the ground. The strategies were unclear in V2 of the game as farmers were more fixated on the game dynamics.

In the context of balancing human well-being versus environmental integrity (Turner, 2010; Elshafei et al., 2014), exploring individual actions at local scales could foster cooperation (Mostert, 2018) towards community preferences, national imperatives (Department of Water and Sanitation, 2017, 2022), and international development goals (UN, 1997; UN-Water, 2019). The game was deliberately designed to provide a virtual platform to co-evaluate the behavioural response to the plausible strategies for equitable water reallocation (Pienaar & Hughes, 2017) as triggers. Results insinuate that upstream farmers with dam storage (User 1) may continue to prioritise cash crops over fruits, but blueberry production is also rising. In contrast, midstream and downstream users (Users 2 and 3) are expected to focus on the basin's reputation as one of the major deciduous fruit exporters in the country. These observations remain realistic due to players’ familiarity with local water and land use dynamics.

Additionally, the game allows players to adapt their decision strategies as they learn; this is done by substituting crops or choosing which crops to sacrifice to demonstrate deficit impacts.

Players were able to witness the hidden water-related costs and social benefits of entertaining different perspectives in water management decisions, which are often conflicting (Rogers & Luton, 2011). In reality, during water-scarce periods, downstream users and the environment bear the brunt of water stress, as stated by water users in earlier engagements (**Chapter 4,** Xoxo et al., 2023). This phenomenon has also been documented elsewhere (Vanham et al., 2018; UN-Water, 2019; Du et al., 2022). Moreover, transforming irrigation boards—previously dominated by farmers—into Water Users Associations unintentionally fosters an inequitable participatory environment for non-farmer stakeholders. During the game, players equally contributed to deliberations, enhancing the game's credibility as a tool for equitable decision-making consistent with Barreteau et al. (2001, 2007). Player comments in the debriefing session further underscore the importance of well-functioning Water Users Associations.

"The game is powerful in showing the role of a manager / co-developed water management plan as a 'referee'" ~ User 4.

Limitation: Lack of measurement of fairness concepts/ how the strategies satisfy fairness objectives.

In the game application described here, players explored with three of the four allocation strategies. Farmers seemed to not focus on the strategy principles, but more on the impacts, which is good for distributive fairness. However, the current game design misses a pre- and post-game questionnaires that can allow for the evaluation of the impact of the game in cultivating fairness and tracking the level of acceptability of outcomes by different decision makers. While these can be raised during the debriefing session, a more formalised approach to monitoring these will also enable comparison from different cases, and hep track changes over time.

5.4.1. Collectively making sense of the impacts of reallocation strategies both due to stakeholder reactions and each allocation strategy.

The reallocation strategies are robust but produce dissimilar outcomes with changing conditions (Lempert & Collins, 2007). Each reallocation strategy ensures that all users' basic needs (including the environment) are met after reallocation. To promote fairness/justice, all four water-sharing options allow decision-makers to consider the possible impact/risk faced by water users, which is used to build consensus on the preferred pathway for the community. For this study and the South African context where water is deemed a public good (Pienaar & Van Der Schyff, 2007; Lukasiewicz & Dare, 2016), it is envisaged that the reallocation strategies can be used to satisfy administrative regulations, court decrees for scenarios with new water users, and privately negotiated water transfers (Garrick et al., 2019).

Farmers, deeply engaged in game dynamics and contributed to further refining the game itself. By exploring the strategies one after another, they gained insights into the dynamics associated with each reallocation option. This process empowered farmers with limited participation power in group decision platforms (i.e., the Water Users Association) by sensitising them to potential outcomes and risks associated with each strategy. Learning through acting is a type of empowerment (Partzsch, 2017) that could improve power redistribution and enhance fairness in decision-making. As will be discussed in the following sub-section, committed involvement of less influential water users in the process is seen as a strategy for them to build consensus on their concerns while building capacity and coalitions to better participate in decision-making (Barnaud & van Paassen, 2013).

On the researcher's side, drawing wisdom from diverse research fields during game development highlighted the importance of interdisciplinarity for integrated modelling (Seidl & Barthel, 2017) and contributions to the socio-hydrology movement (Sivapalan et al., 2012; Thompson et al., 2013). Secondly, communication between players during the game rounds enormously helped expand the research team's understanding of the "farmer's world" and their priorities. Such an understanding may be useful when devising strategies to resolve emerging trade-offs due to shortage impacts associated with alternative scarcity management options.

What does equal participation look like in a Water User's Association?

Fletcher et al. (2022) recommend the use of participatory modelling as a strategy to empower marginalised communities and change the salience of decision-support tools from serving managers to serving communities. Without adequate participation and representation, water policies risk perpetuating inequalities in opportunities and distribution of outcomes from using the resource (Movik, 2014; Leach et al., 2018), undermining the well-being requirements of the missing stakeholders. Power imbalance from an array of sources, including knowledge disparity, is one of the key considerations for fair participation in decentralised governance (Pfaff et al., 2013). Fletcher et al.'s recommendation links well with the second objective of developing the game: providing an abstract environment for equal participation.

As recommended for communicating uncertainty (Fischhoff & Davis, 2014), and dam operation strategies for low-skilled operators (Mallory et al., 2013), the deficit-impact-based reallocations are introduced in the game as narrative cards. Players in both setups could focus their attention on crop strategies as they could easily comprehend the curtailments under each strategy. Allowing water users to choose between complying with a water cut or not can be seen by others as promoting wrongdoing. However, the game developer acknowledges poor regulation and a lack of system awareness as barriers to achieving reasonable and sustainable (Du Toit et al., 2013; Bauer, 2015) resource use. It is also a way of testing the stakeholder's commitment to their shared-future vision (**Chapter 4**).

Limitations observed during game play.

Stakeholders were initially reluctant to play the game, mainly due to the representation of some game dynamics. After a brief discussion and some compromising, stakeholders were willing to play. By observation, stakeholders had fun with the game. One feedback comment was that the players learned a lot about the big picture of water sharing in a catchment with not enough water for everyone (they used the term conceptual breakthrough). The end-users of WAT-A-GAME in the Kruger National Park in 2009 also identified the ability of role-playing games to teach lay stakeholders about complex human-nature interactions (Abrami et al., 2012). However, tracking the game dynamics seemed time consuming, and this important stage needs some adjustments. The endowed farmers had more land icons to manage than they could keep track of at times, which caused delays in between sessions, and tempered with the player discussions. For future applications, it might be ideal to limit the number of plots to 10 per farmer as in Wat-A-Game applications.

5.4.2. Inspire consequential thinking in connection with other water users.

Environmental awareness has also been identified as a change motivator for community conduct based on economic satisfaction, as evidenced by the Pendulum-Swing Paradox in Australia (Kandasamy et al., 2014; van Emmerik et al., 2014). The influence of environmental awareness and reaction to population change is based on the IWRM understanding that water use decisions are driven by the interests of beneficiaries and their attitude towards the environment (**Chapter 4**). As such, the game can be used as a participatory scoping process to understand the nature of factors that act as a barrier to realising E-Flow satisfaction, supported by Aubert et al. (2018). This understanding will be constrained by the allocation strategies explored but enriched by player interactions during playtime.

With regards to Fair Play V2 (played with farmers), players seemed to think about the real consequences when they played the game, and their actions sparked useful discussions. Players in the two separate tables resorted to safeguarding endemism, and social stability in the catchment was often cited as a priority principle. This surprising choice was defended as a strategy for minimising employment losses, which was ventilated in the catchment visioning process (**Chapter 4**). In this case, less privileged water users (User 3) and low-volume users (User 4) willingly sacrificed benefits associated with fewer restrictions in favour of upstream water users.

5.5. Closing remarks

Fair Play was co-developed with a multi-stakeholder group over three years to assist the research group in introducing the four plausible expert-derived strategies to implement water reallocations equitably. In terms of fairness/justice, there are two key points this chapter communicates in relation to the game and fairness. **First, the game is presented as in instrument for fairness in the decision-making process. Where the game has an advantage that people with different backgrounds can discuss in the same environment and on the same level**. **Second, the game is presented as an instrument to test the equity of the different allocation strategies.** The advantage of gaming is that not only the rational decisions are taking into account, but also the emotions, personal and other 'non-calculatable' of the stakeholders are part of the decision-making process. **In term of evaluation, outcomes of the game can be used to analyse the fairness of the decision-making process (or different components of fairness).**

6. Assessment of Alternative Water Allocation Strategies and Linking Uncertainty to Equitable Decision-Making

6.1. Introduction

This chapter describes and demonstrates the use of an updated version of the modelling approach for evaluating impact-based water reallocation strategies (Pienaar & Hughes, 2017). This is the first application of the Water-Sharing Tool that includes interaction with water users (Pienaar & Hughes, (2017) used a hypothetical case study). The participatory model was updated based on lessons learnt in the stakeholder engagement process, including the game development reported in **Chapter 5**. The Twee Wyk basin (detailed in **Chapter 1.5**) in the north of the Western Cape Province, South Africa, was chosen for application. This study is conducted in the context of the South African water legislation (RSA, 1998a). The original model of Pienaar & Hughes (2017), which consisted of separate versions for run-of-river abstraction and reservoir storage and could only be applied to a single sub-basin, has been structurally modified as part of this study. The Water-Sharing Tool is a conceptual, semi-distributed, process-based socio-hydrological model operating at monthly intervals, which quantifies the impact of reallocation (rather than just the deficit) and incorporates uncertainty analysis into the simulation. Although the model structure is detailed in **Chapter 3,** key points are summarised in sections 6.2 and 6.3 below. While User 4 was present in all the workshops and project stages, they use a negligible amount of surface water compared to the other three users. Therefore, for the purposes of reporting in this chapter, the impacts faced by users 1 to 3 were focused on.

As competition over the limited water resources in scarce regions increases, holistic assessments are needed to ensure that reallocation plans are equitable and do not impact agricultural production and food security (Scheierling, 2011; Marston & Cai, 2016). Such integrated assessments can guide data-driven decision-making by considering a wide range of outcomes and avoiding options with undesirable possibilities (Roa-García, 2014), subsequently improving governance effectiveness (Joy et al., 2014). These integrated assessments should explicitly consider uncertainty (Mayer & Muñoz-Hernandez, 2009; Korteling et al., 2013; Mcmillan et al., 2017) as the science underlying water policies is fraught with imperfect knowledge (Beven, 2006; Mcmillan et al., 2012; Di Baldassarre et al., 2016), diverse and changing preferences over water use (Poff et al., 1997; Reed, 2008), increasing demand and unreliable supplies (van Vliet et al., 2021; IPCC, 2022).

The need to consider uncertainty in water management is tied to the uncertain nature of the resource and the risk of socially unacceptable outcomes that may further marginalise disadvantaged communities by exacerbating existing vulnerabilities, which is unsuitable for fairness, equity and justice (Fletcher et al., 2022). Transparency over underlying assumptions and uncertainty is recommended to avoid unwarranted faith in model outputs (Fischhoff & Davis, 2014). The scientific community has made strides in reducing hydrological uncertainty (Montanari et al., 2013), with some progress in southern Africa (Hughes, 2013; Ndzabandzaba & Hughes, 2017; Kabuya et al., 2020; Hughes & Farinosi, 2021). Innovations that promote decision-making under uncertainty in water resources also exist (Beven & Alcock, 2012; Korteling et al., 2013; Matrosov et al., 2013; Pienaar & Hughes, 2017), but these are yet to be instituted within southern Africa (Hughes et al., 2015).

Investing in decision-makers' understanding and appreciation of uncertainty and stressing the inherent presence of uncertainty in water resources decision-making is essential, although this has obstacles (Pappenberger & Beven, 2006; Fischhoff & Davis, 2014; Beven, 2016). Experts are expected to be central in advancing decision-making under uncertainty, which will subsequently help to reduce vulnerability (Matrosov et al., 2013; Mcmillan et al., 2017). Experts also have a role in addressing the identified (Hughes et al., 2015; Farriansyah et al., 2018) lack of effective practical instruments to address and explicitly include various forms of uncertainty in water allocation decision-making and equitable policy analysis. These are especially needed in southern Africa, where many uncertainties exist due to relatively poor observation networks (Stewart, 2015; Hughes, 2019), where there is a low level of specialist capacity (Hughes, 2012), and where water availability is in decline and where future climate extremes are projected to be severe.

6.2. Key methods overview – Water Sharing Model Use in the Twee Wyk

The Water-Sharing Tool was applied to the upper reaches of the Koue Bokkeveld in the Twee River Basin (E21H or Twee Wyk, 404.309 km^2), described in section 0. Six sub-basins (Figure 6.1) were delineated within the Twee Wyk using a 5 m digital elevation model (Van Niekerk, 2001). As shown in **Chapter 3,** the Twee Wyk is drained by three tributaries (Suurvlei and Middledeur that feed the Twee River). Beneficiaries/water users were identified based on the ongoing stakeholder engagements, and generally, two or three user groups withdraw water from each tributary (Figure 6.1, but detailed in section 6.2.3).

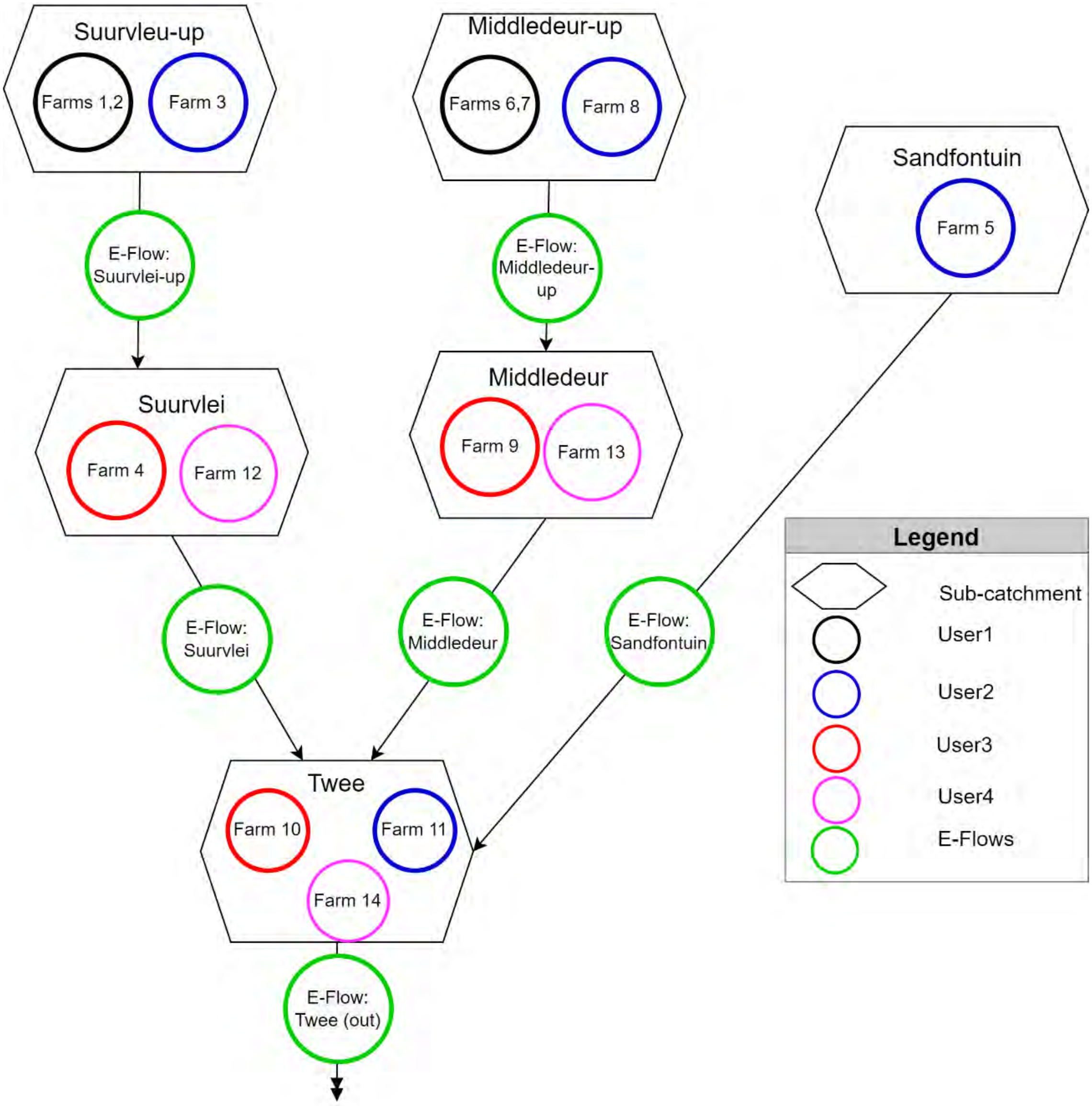


Figure 6.1: Node network structure, containing water user groups and entities in each group within a node.

There are no long-term monitoring points focusing on the Twee, despite the commercial-scale irrigation (EasyData, 2022c), which is also home to threatened endemic fish species (Ellender et al., 2017). Stream flow is mostly understood based on measurements from the adjacent Leeu River Basin (E21G, Gauge E2H007). The Freshwater Resource Centre recently installed a flow gauge at the Twee River outlet, although it has malfunctioned on a few occasions, leaving measurement gaps.

Farmers measure rainfall with different rain gauging instruments, but they have no central data storage that can be made publicly available. The data were gathered by visiting each farm individually. The three upstream sub-basins have small to -medium-sized farm dams (0.170 to 6.3 * $Mil.m^3.a^{-1}$). Additional uncertainty over water availability is introduced by unknown dam operation decisions upstream.

The model description is given in section 3.3, highlighting the model structure, the reallocation structure, water balance calculations, translation of deficits into impacts, user tolerance to deficits, reservoir storage performance and the description of outputs. The water distribution structure prioritises environmental use via three environmental protection options: meet E-Flows at the higher protection level, at the lower level or treat E-Flows as a user. Treating E-Flows as a user implies that E-Flows compete with other uses within the node. The model offers the four reallocation options described in section 3.3.5 for decision-makers to consider as a starting point:

Pizza Slices (Equal share) refers to a reallocation strategy wherein a constant amount is withdrawn by users until all demands are met or the allocable supply runs out.

*Split-the-*Bill (Proportional allocation) refers to sharing the allocable supply based on individual proportional demands relative to the sum of demands in the node.

Beehive (Proportional allocation with community weights) follows a similar mechanism as Split-the-Bill but is applied with a supply prioritisation specified by the community allocation preference.

Equal impact, which refers to a reallocation strategy that tries to distribute the relative impacts of scarcity across users equally, resulting in different supply shortfalls.

However, only three of the water-sharing strategies were evaluated in this study, maintaining consistency with the participatory exercise in **Chapter 5**.

6.2.1. Uncertain streamflow ensembles.

The Pitman model—a semi-distributed, monthly rainfall-runoff model (Pitman model; Hughes, 2013), was used in this study to generate deterministic streamflow estimates with uncertainty, although other models could also serve this purpose (Pienaar & Hughes, 2017). The Pitman model continues to evolve with a focus on practical use, with nearly half a century of application in southern African hydrology (Hughes, 2013). It is well-documented in water resources research (Hughes, 2004; Hughes et al., 2010, 2014a; Tanner & Hughes, 2015; Tumbo & Hughes, 2015; Ndzabandzaba & Hughes, 2017; Kabuya et al., 2020), contributing to the understanding of the region's hydrology and the effects of human and climate factors. The Pitman model also has features to simulate anthropogenic influences on the availability of water resources, such as managed forestry plantations, small farm dams, and substantial reservoirs (Hughes & Mantel, 2010; Le Maître et al., 2019).

The Pitman uncertainty run is a two-step approach (Figure 6.2, Ndzabandzaba & Hughes, 2017). **Step 1** focuses on the incremental contribution of each sub-basin. Step 1 has two steps: manually calibrating the model to match the observed streamflow time series (where available) and constraining streamflow behaviour using six hydrological constraints (defined using either observed data or regionalisation). Parameter ranges that describe the natural process are defined, and the first step runs for at least 10,000 permutations to find 1,000 behavioural ensembles (Hughes, 2016; Ndzabandzaba & Hughes, 2017).

The six streamflow constraints describe the hydrological regime at different points during a hydrological year. The magnitude of streamflow and groundwater recharge are represented by long-term mean monthly runoff (MMQ in $*10^6$ $m^3.a^{-1}$) and long-term mean monthly local recharge (MMR in mm). Streamflow intermittency or drought frequency is described using the expected periods of no flow (%Zero). The seasonal timing of peak flows and other flow events, the duration of these events, and the frequency of changes in streamflow conditions may be described by the ratio of MMQ to flow duration curve points at 10, 50 and 90th percentiles (Q10, Q50, Q90).

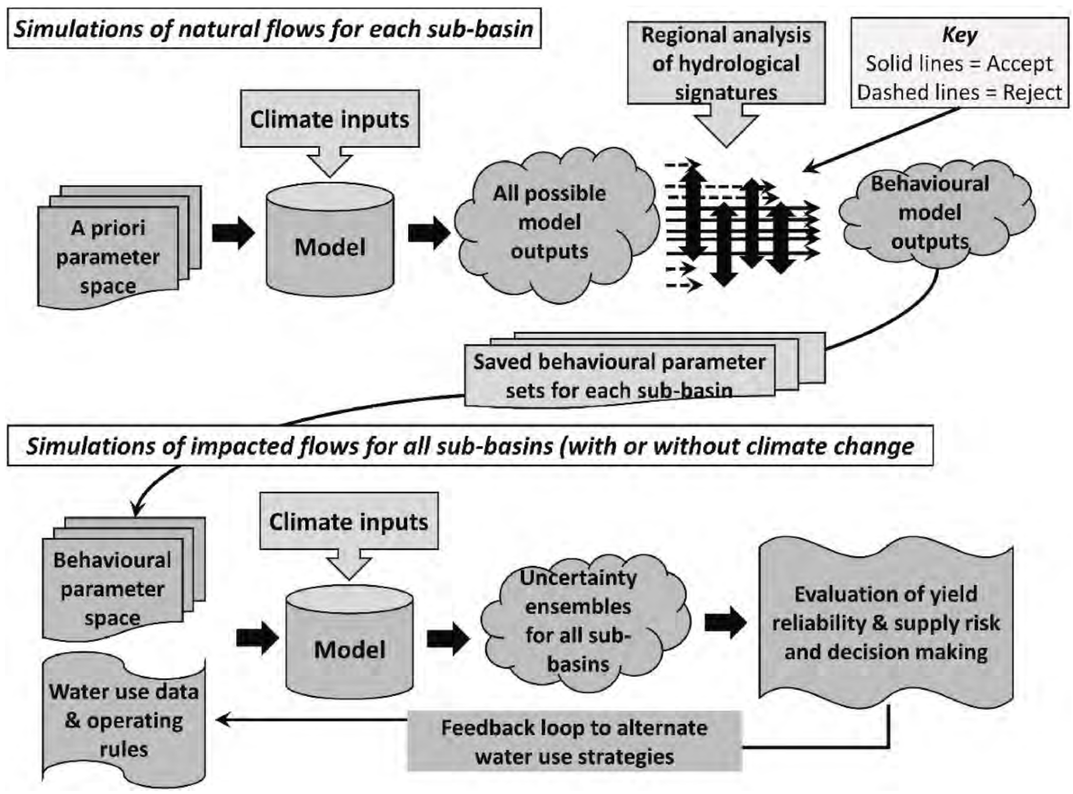


Figure 6.2: Generic overview of the uncertain version of the Pitman model structure.

Step 2 is the hydrological simulation step, which combines the climate inputs, the six streamflow constraints, and the uncertain parameter ranges to produce up to 250 000 streamflow ensembles and their water balance descriptors (Figure 6.2). Wetland and water use impacts are also simulated at this stage. Step 2 of the uncertain simulation was set to run 10 000 times since the WST runs on at least 10 000 ensembles. The streamflow volumes are checked against observed flows for validation, this is done using performance measures (e.g., Nash-Sutcliffe efficiency, Percent Bias).

The Pitman model was forced using local rainfall data covering the period 1993 to 2021 that was sourced from farmers in the Twee Wyk. Potential evapotranspiration is a second climatic data source needed to force the Pitman model. The WR90 (Midgley et al., 1994), A-Pan evapotranspiration data was used (Table A-6.1). Since there are no reliable streamflow observations for the basin, this study relied on the most recent expert-derived national streamflow dataset—the South African Water Resources database (WR2012). The WR2012 product represents the best dataset available for the ungauged quaternary basins of South Africa, Lesotho and Swaziland (over 600 quaternary basins). The dataset was compiled by a group of experts working using the most popular models in the region (including the Pitman model). WR2012 contains an array of regionalised hydrological outputs at a quaternary scale, including long-term rainfall, natural runoff parameters, evapotranspiration distributions, and natural streamflow time series. Groundwater recharge was the most uncertain parameter, but it was estimated to range from 0 (no recharge) to 5 mm/month, based on the second groundwater assessment in South Africa (DWAF, 2005). The groundwater assessment is a coarse but national dataset of recharge values in South Africa (DWAF, 2005).

Streamflow hydrological constraints were established from the flow duration curves of existing time-series data sourced from WR2012. A priori hydrological constraint ranges for this assessment are listed in Table 6.1 and represent the incremental streamflow dynamics of the Twee Wyk, based on regionalised outputs from 1920 to 2009. These hydrological constraints were based on area contribution ratios for each sub-basin relative to the quaternary basin (the output scale of WR2012). These constraints were achieved after a few adjustments from 20% to 60% bounds for the Q10/MMQ constraints. There is no streamflow intermittency, reflecting groundwater and interflow contributions in the basin, typical of the Cape Fold belt geology (Levy & Xu, 2012).

Table 6.1: Streamflow signatures describing hydrological response characteristics of the Twee *Wyk*, based on the 19920 to 2010 national water resource assessment (WR2012).

Sub-basin	Suurvlei-up	Middledeur-up	Sandfontuin	Suurvlei	Middledeur	Twee
Incremental Area (km^2)	40.84	89.94	19.4	22.21	19.82	33.4
Runoff ratio	0.101	0.0549	0.222	0.049	0.048	0.083
MMQ ($*10^6$ $m^3.a^{-1}$)	0.434 to 1.013	0.627 to 0.980	0.109 to 0.190	0.176 to 0.339	0.109 to 0.254	0.235 to 0.352
MMR (mm)	0.740 to 2.067	0.744 to 4.900	0.744 to 5.000	0.200 to 5.000	0.744 to 5.000	0.000 to 5.000
FDC10 (Q10/MMQ)	1.367 to	1.747 to 2.729	1.820 to 3.155	1.622 to 3.129	1.504 to 3.510	2.003 to 3.005
FDC50 (Q50/MMQ)	0.527 to 4.398	0.463 to 0.723	0.385 to 0.621	0.422 to 0.853	0.221 to 0.515	0.440 to 0.660
FDC90 (Q90/MMQ)	0.044 to 0.271	0.067 to 0.104	0.022 to 0.038	0.088 to 0.171	0.043 to 0.101	0.023 to 0.034
%Zero	0	0	0	0	0	0

The model uses a set of constraints (Table 6.1) and the defined parameter space (Table A-6.2) to identify 1,000 behavioural streamflow ensembles for each sub-basin. Therefore, step 1 focuses on finding 1,000 behavioural incremental flow ensembles for each sub-basin. Ensembles are deemed behavioural if they fit within the defined constraint ranges. A parameter validation utility (Figure 6.3) that uses frequency distributions for the ensembles and parameters as a reference to avoid mismatches and poor compatibility between streamflow signatures and ensemble parameters. The uncertain simulations began with using the default parameter values provided in the WR2012 dataset. These default values are from the single-run version of the Pitman model, and parameter ranges around these values were established. Further manual calibration was often necessary to obtain 1,000 behavioural ensembles out of 10,000 total flow ensembles per sub-basin (calibrated against the hydrological constraints). The Pitman hydrological model incorporates uncertainty based on Monte Carlo sampling of the defined parameter space and the generation of ensembles. Behavioural parameters were identified after successfully aligning input parameters and manually recalibrating the Q50/MMQ and Q90/MMQ constraints.

Figure 6.3: Platform for reducing uncertainty in Pitman model parameters for the Twee wyk sub-catchment. The histogram bars denote the frequency of runoff generated from low to high flow groups. Top Left Box: Displays the frequency distribution of six hydrological constraints across five ensemble groups. Other Five Boxes: Show the performance of parameter constraints organised into 10 groups. Users can explore any of the 19 uncertain streamflow-generating Pitman parameters by selecting from the first column.

Figure 6.3 demonstrates the initial process of checking the distribution of each uncertain parameter range and seeing how the ensembles generated align with the constraints. Incremental flows from the WR2012 (waterresourceswr2012.co.za) data were used as a reliable dataset with which to compare the simulated outputs (detailed in section 6.4.1). The constraints produced using the WR2012 flow data were used to determine which ensembles were behavioural, which is what the model was calibrated against. The study avoided wide constraint ranges (range of uncertainty within hydrological indices), which would ensure that 1,000 behavioural ensembles were successfully identified quickly. Instead, intensive calibration was undertaken to find the specific parameter ranges that produced behavioural ensembles within a narrower constraint range, making the outputs more acceptable to the stakeholders.

6.2.2. Disaggregating environmental water requirements from regional to Twee Wyk sub-basins.

The Department of Water and Sanitation sets the E-Flow value is set at a high protection level (level B or near natural). However, a lower protection level (level D or extremely modified) was also utilised in the model, given that, realistically, Level B is often not achieved during dry conditions. The monthly volumes of E-Flows in the study area were determined using the median ensemble of natural flows. There have been two E-Flow models utilised in the study catchments, including the RDRM (Revised Desktop Reserve Model —Hughes et al., 2014) and DRIFT (Downstream Response to Imposed Flow Transformations—King et al., 2003). Outputs for E-Flow Site 6 (in the study catchment) are described in (Hughes et al., 2014a; Tanner et al., 2022).

Although the E-Flow monitoring site 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 *Mil.$m^3.a^{-1}$. This makes E-Flow Site 6 outputs a larger scale than the upstream Twee wyk for the Koue Bokkeveld. Therefore, the FDC lookup table technique was used to disaggregate E-Flow outputs from E-Flow Site 6 to small sub-basins. This was done for each of the six sub-areas in the Twee *Wyk.* Calibration errors may arise in the E-Flow estimates for the Twee Wyk as they must be disaggregated from those observed at Olifants E-Flow Site 6 (section 3.2.4), which monitors cumulative irrigation impacts of three quaternary basins.

The focus was on low flow requirements for E-Flow, as no large reservoirs in the sub-basin can adjust operation strategies (Mallory et al., 2008). Instead, the farm-operated reservoirs manually pump water out of the dam as needed, or there is overtopping during the wet season. The low flows are also the most critical from the E-Flow perspective as the basin reservoirs do not hold enough storage to capture all winter flow (frequent overtopping occurs), but high demand during the dry summer months means the impact on E-Flows is significant. Figure 6.4 shows the E-Flow strategies for the Olifants/Doorn E-Flow Site 6, suggesting that 70.2% of the mean annual runoff (or 36.66 Mil.$m^3.a^{-1}$), including 44.0% (or 14.46 to 24.20 Mil.$m^3.a^{-1}$) from low flows needing to remain in the river to satisfy E-Flow requirements at a B-level (Tanner et al., 2022). The environment is subject to curtailments with changing natural streamflow regimes, as expressed by the seasonality of the E-Flow strategies (Figure 6.4).

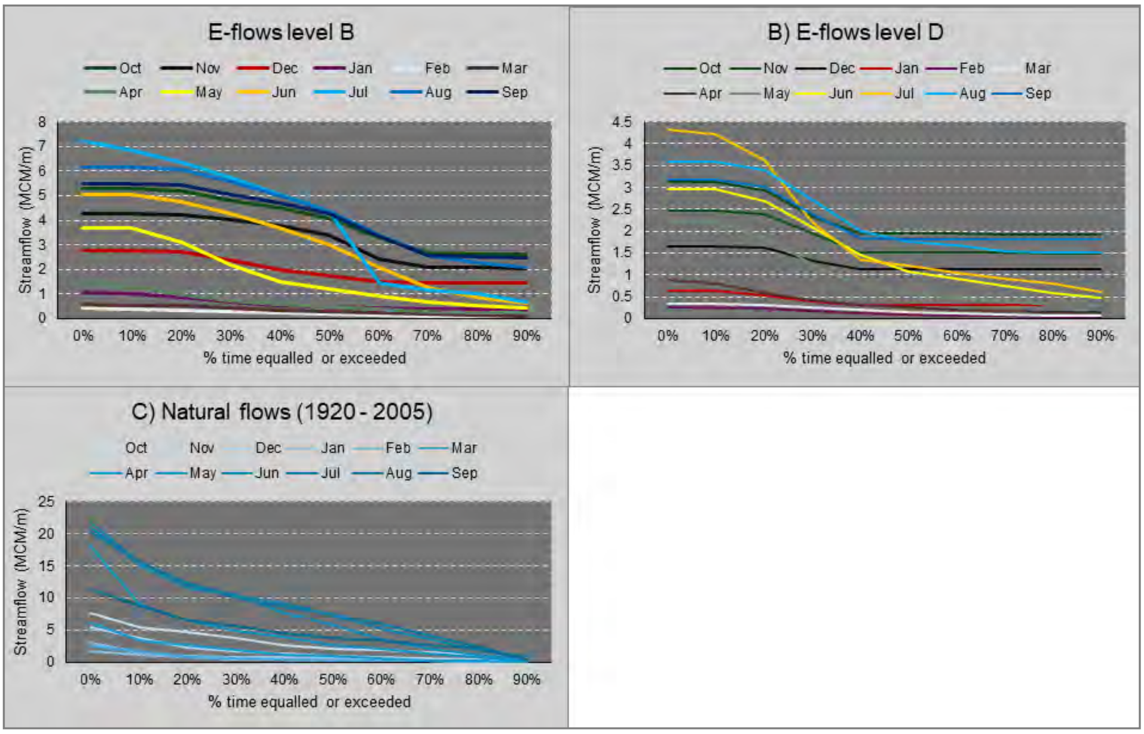


Figure 6.4: Rule curves for Environmental Water Requirements (E-Flow) at Olifants/Doorn E-FLOW Site 6 (Tanner et al., 2022). The natural flows were estimated using the Pitman model, and the E-Flow rules for B and D levels (near natural and largely modified conditions) were established using both the Downstream Response to Imposed Flow Transformations and Revised Desktop Reserve Model.

6.2.3. Water withdrawal for consumptive water use.

Socio-economic water demand is considered for three main sectors of the sub-basin that emerged during the ARDI exercise for social scoping as described in Xoxo et al. (2023) or (section 4.2.4). The sectors are irrigation (deciduous and citrus fruits, onions, and pasture), tourism, and rural household use. The actual property names corresponding to water use are concealed, and only code names are used to refer to the users to comply user requests and with human research ethics requirements at Rhodes University (Reference: 2022-5386-6678).

The monthly water demand for irrigation is based on satellite-derived land use by the Western Cape—Cape Farm Mapper (Western Cape Government Department of Agriculture, 2023). Surface water demand (m^3/month) was calculated based on WR90 crop water coefficients for the E21 basin (Table A-5.1, Midgley et al., 1994), farmed area per entity per crop type (Table 6.2), and effective rainfall. Crop coefficients for agricultural land use were sourced from the WR90 database (Midgley et al., 1994). Supplementary water requirements for washing fruits, herbicides and pesticide spraying at a farm level determined in a nearby basin by Gush et al. (2019) were also used better to represent the minimum water withdrawals for consumptive activities. In the Twee Wyk, the supplementary requirement amounts to 2-8% of the total annual demand.

The eleven farms in the Wyk (Table 6.2) were classified as consortium-owned corporate farmers (User 1), family-owned commercial farms (User 2), downstream/ under-resourced farms (User 4), and Lifestyle farmers (User 4). This classification was achieved with the help of key informant practitioners who have experience with the *Wyk*. Corporate commercial farms are typically located in the upper reaches, whereas the lesser economically advantaged farmers are found downstream.

Table 6.2: Consumptive land use activities in each entity at the Twee Wyk in 2020 (m3/a^{-1}). Black cells denote User 1, blue = User 2, and red = User 3.

Entity	Citrus	Deciduous	Onions	Pasture	Potatoes	Total Demand
Farm 1	0.00	139,627.37	108,007.40	302,194.53	0.00	549,829.30
Farm 2	0.00	529,533.08	0.00	15,047.55	0.00	544,580.62
Farm 3	91,495.73	705,132.57	12,997.50	0.00	0.00	809,625.80
Farm 4	0.00	206,687.38	77,801.94	0.00	0.00	284,489.33
Farm 5	0.00	334,538.29	0.00	0.00	0.00	334,538.29
Farm 6	121,512.93	2,061,168.73	299,208.60	420,597.58	145,259.13	3,047,746.97
Farm 7	825.22	322,668.53	70,131.28	13,573.21	0.00	407,198.24
Farm 8	289,444.21	575,682.18	0.00	0.00	0.00	865,126.39
Farm 9	60,859.62	140,074.99	0.00	0.00	0.00	200,934.61
Farm 10	9,902.58	88,832.04	0.00	12,203.30	0.00	110,937.92
Farm 11	49,100.30	209,699.11	0.00	0.00	0.00	258,799.41
Total	623,140.58	5,313,644.27	568,146.73	763,616.17	145,259.13	7,413,806.88

Water storage parameters.

There are many reservoirs within the Olifants/Berg Water Management area intended to support irrigation needs in the region. Most of these are farm dams under the control of User 1. The reservoirs evaluated here are those registered with the Department of Water and Sanitation's dam safety office, and these structures are at least 5 m in dam wall height and have a storage capacity exceeding 50,000 m^3. These reservoirs are in the headwaters within the Twee Wyk, but their distributed nature makes it difficult to consider them individually in hydrological assessments, hence they were lumped for each sub-basin. Reservoir data (Table 6.3) forms part of the socio-economic data from the water users. Despite varying access levels, these storages were lumped for all users sharing a sub-basin, as shown in Table 6.4. Operation strategies were omitted based on water user advice regarding farm dam operations. No operation strategies were provided for larger dams upstream (Middledeur-up and Suurvlei-up), and they were treated as zero.

Table 6.3: Parameters for reservoir storage, specifying storage capacities, the non-linear relationship between reservoir surface area and storage volume, operation strategies and potential evapotranspiration.

Array Parameter	Parameter description	Middledeur-up	Suurvlei-up	Sandfontuin	Middledeur	Suurvlei	Twee
1 Reservoir Capacity (*10^6 $m^3.a^{-1}$)	Reservoir size/volume.	6.361	1.225	0.170	0	0	0
2 Dead Storage (% Capacity)	The lowest possible storage level below which no withdrawal is permitted.	~15	~	~15	0	0	0
3 Initial Storage (% Capacity)	Initial storage at the start of the simulation.	~70	~70	~70	0	0	0
4 A in Area (m^2) = A * Volume(m^3) [B]	The coefficient in a power relationship between the reservoir volume and sub-area.	0.8	0.8	0.8	0	0	0
5 B in Area(m^2) = A * Volume(m^3) [B]	The exponent in a power relationship between the reservoir volume and area.	0.6	0.6	0.6	0	0	0
6 Reserve level 1 (% Capacity)	Five levels of possible reservoir operation strategies expressed as a proportion of abstraction and storage	0	0	0	0	0	0
7 Reserve level 2 (% Capacity)		0	0	0	0	0	0
8 Reserve level 3 (% Capacity)		0	0	0	0	0	0
9 Reserve level 4 (% Capacity)		0	0	0	0	0	0
10 Reserve level 5 (% Capacity)		0	0	0	0	0	0
11 Annual Evaporation (mm)	Annual expected evaporation from the reservoir.	1670	1670	1670	1670	1670	1670

6.2.4. User risk profiles and community preference for allocation.

The relative user risk profiles for the users and the community weighting scores used as inputs in the Water-Sharing Tool are shown in sections 4.3.3 and 4.2.4. To recap, (I) water users were consulted to identify a shared future vision. (II) They worked together in a facilitated session to identify legitimate beneficiaries of the scarce resource and collaborate with experts in building a conceptual model for their basin representation. (III) Individual users were invited to establish a community weighting index (often called community allocation preference) that represents important users in the community who should be prioritised for supply during events of water shortage. (IV) Information relating to user risk profiles was extracted from all the stakeholder engagements and collated to develop an impact index describing the adaptation efficacy of individual users. Informed by Hughes and Mallory (2009) as well as Loucks (2011), this understanding of potential risks faced by different water users is instrumental in comprehending the costs of the water reallocation options in a consistent manner to all water users within a water management area.

Table 6.4 lists the model input details for all users in the Twee Wyk, organised by sub-basin. Community weights from Chapter 4 were used in this set-up. As seen in Table 6.3, none of the sub-basins have all the user groups, which is expected to be the case in many other water management areas. Therefore, the Water-Sharing Tool was further upgraded to accommodate cases with fewer than five users in a sub-basin. The new version of the model has a built-in processor to adjust community weights for active users only to ensure that the community weights in each sub-basin are proportional to those of five users. This way, the model always allocates 100% of the allocable supply to the rightful beneficiaries. Since all users in this study fall within the same Water User Association, the user risk profiles were kept constant across sub-basins. The deficit-impact index, which is also used by the model to reallocate available supply was already described in **Chapter 4**.

As described in section 3.3.4, the Water-Sharing Tool uses the user risk profiles to translate water shortages into a percentage of possible impacts, following Hughes & Mallory (2009). It does so by multiplying each deficit by the user risk profile from the flow ensembles to get a matrix of deficits and their associated impacts. A frequency distribution is constructed from the matrix of deficits and impacts. Both are arranged as ten groups of equal intervals ranging from tolerable (group 1 or 0-10% impact) to unacceptable loss (group 10 or 90-100% impact). The Water-Sharing Tool uses this deficit-impact index to quantify the impacts of possible reallocation strategies designed to manage water scarcity equitably, considering community development goals and ecosystem resilience. It is up to the decision-makers to decide on the threshold of unacceptable impact, but here impact group 10 is considered as the level at which all users would face unacceptable losses.

Table 6.4: Input details of the users in each sub-basin of the Twee Wyk, including annual demands (*10^6 $m^3.a^{-1}$), and the level of user importance in the community. Cell colour depicts impact thresholds from tolerable levels (0-15%) to catastrophic levels (>75%)

Parameters	E-Flow	User 1	User 2	User 3	User 4
			A) Suurvlei-up		
Annual demand	Variable as in Figure 6.3	0.585	1.465	0.000	0.012
User risk profile (%)	42	14	33	64	50
Community weight (fraction)	0.28	0.25	0.25	0.00	0.22
			B) Middledeur-up		
Annual demand	Variable as in Figure 6.3	3.210	1.352	0.000	0.012
User risk profile (%)	40	14	33	64	50
Community weight (fraction)	0.28	0.25	0.25	0.00	0.22
			C) Sandfontuin		
Annual demand	Variable as in Figure 6.3	0.000	0.179	0.00	0.012
User risk profile (%)	43	14	33	64	50
Community weight (fraction)	0.37	0.00	0.033	0.00	0.33
			D) Suurvlei		
Annual demand	Variable as in Figure 6.3	0.00	0.000	0.300	0.012
User risk profile (%)	43	14	33	64	50
Community weight (fraction)	0.37	0.00	0.00	0.33	0.30
			E) Middledeur		
Annual demand	Variable as in Figure 6.3	0.000	0.000	0.213	0.012
User risk profile (%)	44	14	33	64	50
Community weight (fraction)	0.37	0.00	0.00	0.33	0.30
			F) Twee		
Annual demand	Variable as in Figure 6.3	0.000	0.275	0.154	0.012
User risk profile (%)	43	14	39	64	50
Community weight (fraction)	0.28	0.00	0.25	0.25	0.22

6.3. Interpretation of the model outputs

The Water-Sharing Tool was tested in a stakeholder-inclusive process (Gwapedza et al., 2024a) with the understanding of participatory modelling. Each step of the modelling process was communicated to stakeholders in workshops, one-on-one meetings, and group meetings over 2022. Emphasis was placed on being transparent about uncertainty as part of the modelling process. An experienced researcher in the team offered a series of presentations and was involved in discussions with the stakeholders over the project period. The presentations focused, amongst other things, on the modelling implications of uncertainty from incomplete or imperfect climate data, lack of streamflow monitoring gauges, and a limited understanding of subsurface processes (Mcmillan et al., 2012; Fischhoff & Davis, 2014). The alternative water-sharing options were introduced to stakeholders using a Role-Playing Game in two parallel sessions (**Chapter 5**). The summary outputs of the Water-Sharing Tool were interpreted based on the case study experience to improve contextualisation.

6.4. Results

The results section starts with streamflow simulation outputs (uncertain hydrology), followed by disaggregated E-Flows for each tributary in the Twee Wyk [the desired environmental flow conditions and a less acceptable environmental flow state as set by the Department of Water and Sanitation, (2017)]. Thereafter, summary outputs are shown in text boxes (direct outputs from the Water-Sharing Tool) and in figures and tables (reconstructed to simplify the model outputs for stakeholders). This two-step approach was partly due to the realisation that the possible water reallocation risks and the epistemic and aleatory graphics directly exported from the model may be difficult for decision-makers to understand.

6.4.1. Water availability.

Step 2 of the uncertainty version of the Pitman model includes using the saved parameter sets from Step 1 and then connecting all the sub-basins to generate 10,000 cumulative streamflow ensembles for each node/sub-basin (Figure 6.5). The streamflow simulation outputs illustrated in Figure 6.5 show a considerable variation in monthly and annual natural runoff from the Twee Wyk for the period between 1993 and 2020. Based on the simulated outputs shown in Figure A-6.3, dry season flows (October to March) account for at least 20 to 29% of annual flows, supporting the trend of low summer flows in Figure 6.5. Simulation runs with the farmer-provided rainfall consistently under-simulated peak flows even for the lower ensembles, resulting in the poor envelopment of the WR2012 flow data (Figure 6.5-A to C). This is likely due to the underestimation of rainfall on the mountain peaks where no measurement is taking place. Further, capturing the low flows based on the national-level groundwater study alone was challenging, resulting in low flow bias. It was fairly straightforward for most of the basins to determine appropriate parameter ranges that produced behavioural ensembles within the hydrological constraint ranges. However, some sub-basins were more challenging, such as the upper Middledeur, where maintaining behavioural ensembles within the streamflow constraint was challenging. In this case, the parameter ranges were widened considerably to identify behavioural ensembles.

Incremental flows from the WR2012 data were used as a reliable dataset with which to compare the simulated outputs. The constraints produced using the WR2012 flow data were used to determine which ensembles were behavioural, which is what the model was calibrated against. The study avoided wide constraint ranges (range of uncertainty within hydrological indices), which would ensure that 1,000 behavioural ensembles were successfully identified quickly. Instead, intensive calibration was undertaken to find the specific parameter ranges that produced behavioural ensembles within a narrower constraint range, making the outputs more acceptable to the stakeholders. The impact of this narrow constraint range was a narrow range of streamflow outputs, as will be seen in step 2 below, which was also propagated into the reallocation model outputs. A narrow range in the reallocation model outputs is not ideal for decision support, even though the observed data used for streamflow constraints and parameter ranges may justify some level of confidence in the uncertain outputs.

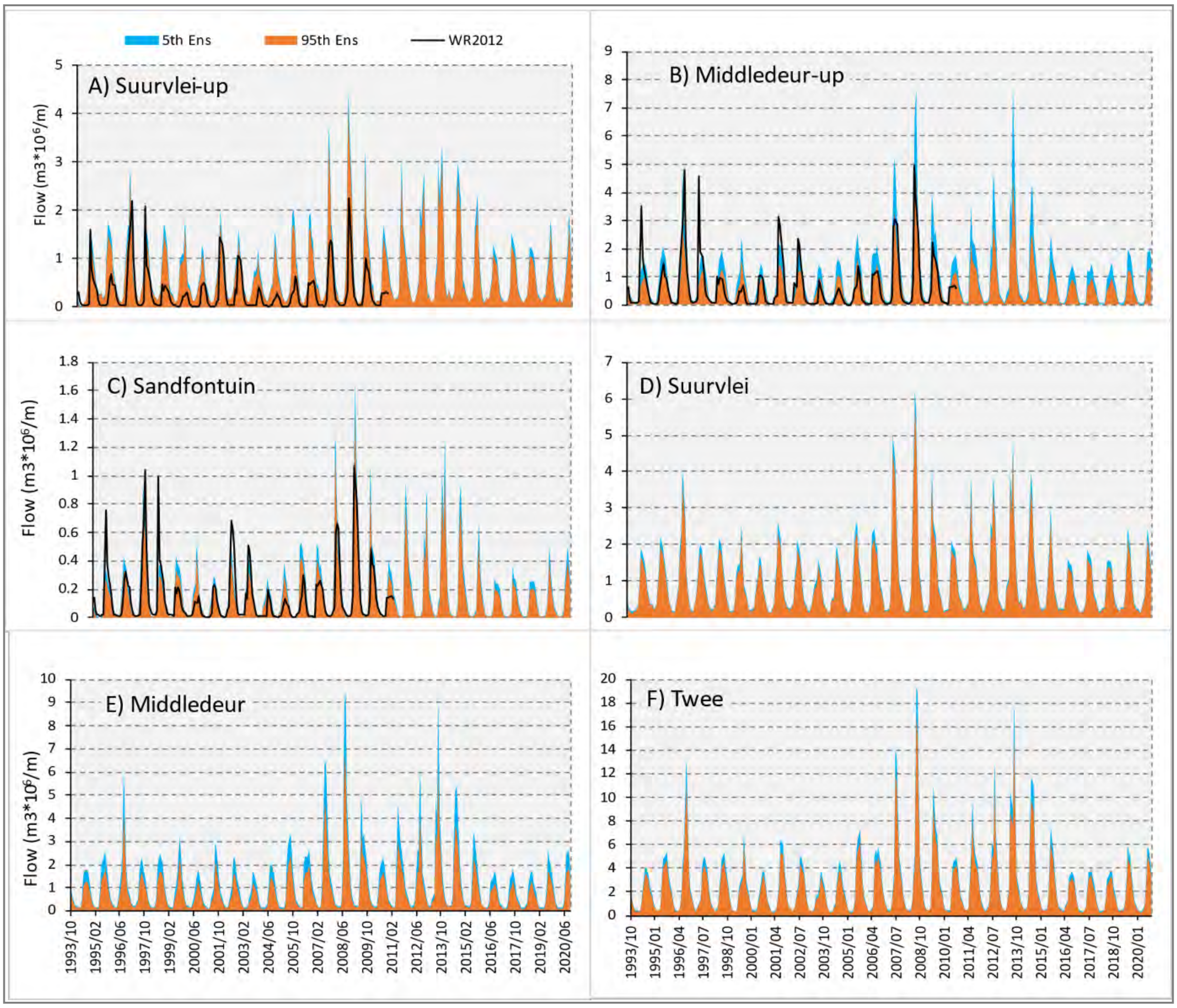


Figure 6.5: Time series showing the 90% distribution of reconstructed streamflow for the Twee Wyk covering the period Oct 1993 to Sep 2020, based on the 2-step approach of the Pitman model. The natural flows were benchmarked against the area ratios of WR2012 incremental flows.

6.4.2. Desired monthly environmental water requirements (E-Flows).

Although the E-Flows for the sub-basins are set at B level (due to high biodiversity and pressure to maintain downstream estuary connectivity), based on discussions with stakeholders, it was assumed that E-Flows in the catchment are often pushed to level D (modified flow regime) during dry periods. The reallocation model can incorporate two E-Flow levels to represent this common situation. Subsequently, level D E-Flows were used as the minimum possible E-Flows for all the sub-basins. The model simulates environmental demand as a proportion of median natural flows, and the risk profile of the instream ecosystems in the Twee Wyk was estimated as a percentage difference between the desired level B E-Flows and the modified E-Flow threshold (level D).

Annual estimates of natural flows, desired E-Flows, and minimum level E-Flows are illustrated as FDCs for each node of the Twee Wyk (Figure 6.6). A clear seasonality shown by the pattern indicates higher

E-Flow requirements during the wet winter months and lesser contributions in the dry summer months, mimicking a similar pattern as the strategy curves at E-Flow Site 6 in the Olifants/Doorn (Figure 6.4, Figure A-5.2). The simulated E-Flows low-flow E-Flows often account for 40% of the simulated median streamflow, which is more than half the time across the catchment. The E-Flow budget from the Twee Wyk was estimated at 29.1% of the median flows for the simulation period, with the most contribution from Suurvlei River headwaters (34.2% E-Flow contribution). In contrast, the low-flow E-Flow demand at the lower protection level accounts for 15.1% of the median natural flow.

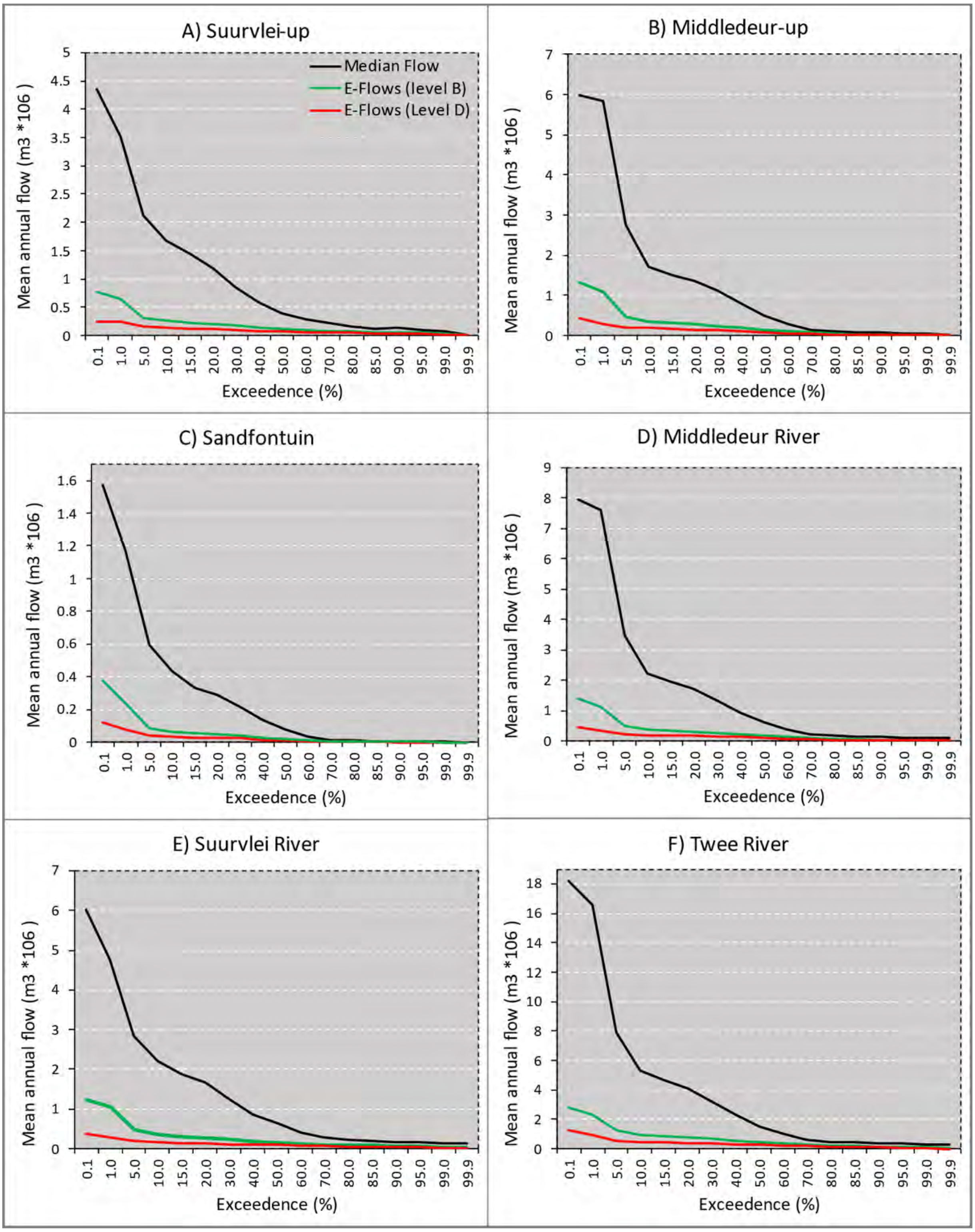


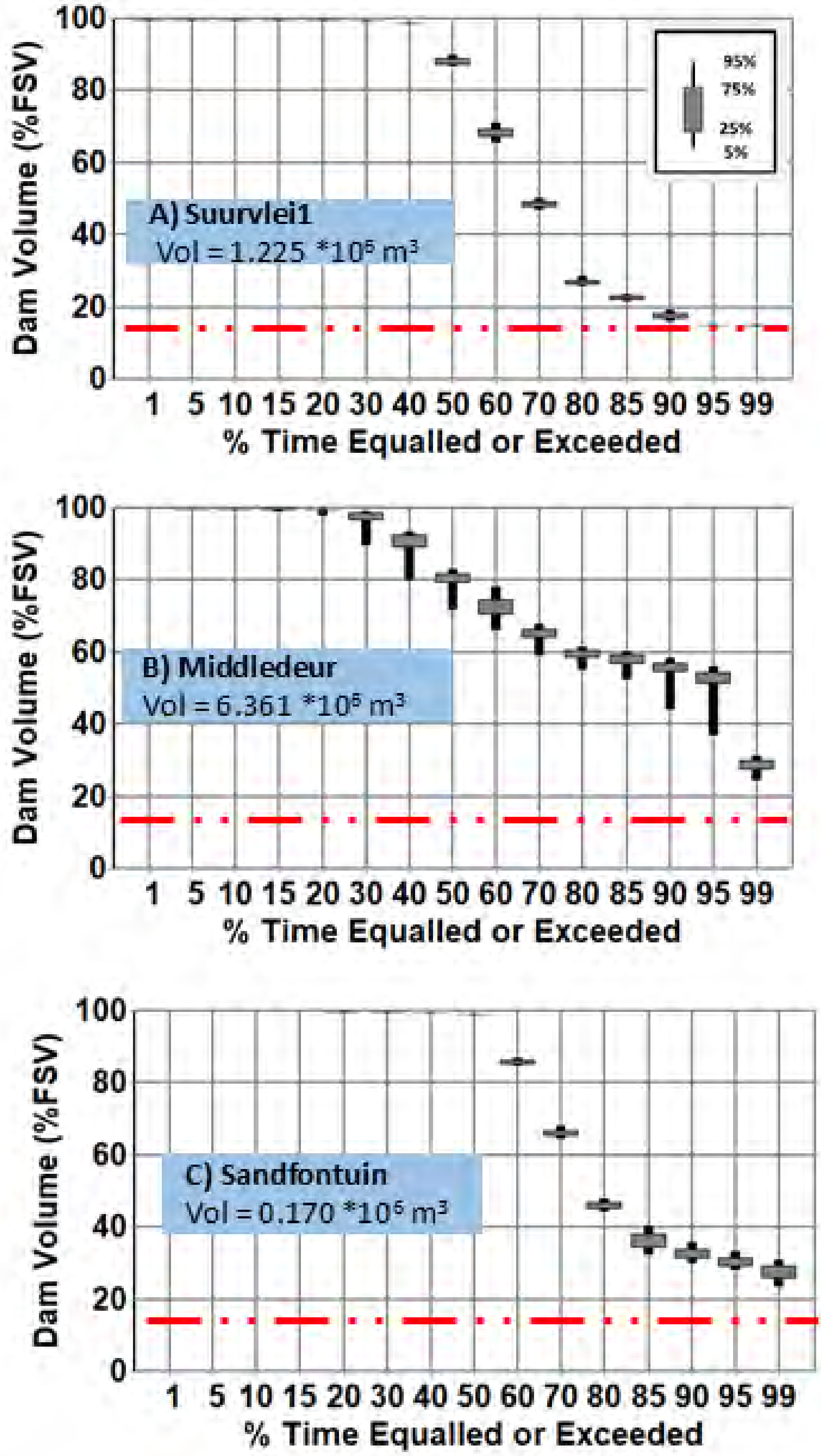
Figure 6.6: Annual flow duration curves showing estimated median flows, desired low flow E-Flows and medium risk E-Flows in the Twee Wyk. The E-Flow demands were disaggregated based on the E-Flow assessment outcomes for Site 6 of the Olifants/Doorn catchment (Tanner et al., 2022).

6.4.3. Summary of output 1: Reservoir storage and performance from the Water-Sharing Tool.

Reservoir storage and performance are reported first to set a transparent baseline for decision-makers over the available supply. In practice, storm flows are stored in reservoirs up to the full storage level before any run-of-river abstraction occurs. In addition, the reservoirs in the study catchment are all located upstream. Screenshots of model outputs of uncertain reservoir storage performance for all registered dams in the Twee Wyk are shown in Box 6.1 as Box and Whisker Plots. The time series plots show monthly reservoir performance using a sum of ensemble average impacts and standard deviation, showing dynamic storage over time. The exceedance plots show the consistency of reservoir performance as annual summaries for the 500 selected ensembles. The narrow interquartile range (less than 10% spread) results from the streamflow uncertainty described in section 6.2.1. Estimates in Box 6.1 are based on the assumption that demand remains constant and there are no unforeseen losses in storage.

The plots in Box 6.1 show the lumped dam storage for the three sub-basins with reservoirs. Suurvlei1 and Sandfontuin are full 40% and 50% of the year, respectively (on average), while Middledeur reservoirs are full only 20% of the year. None of the reservoirs ever run dry, although Suurvlei-up reservoirs do almost reach dead storage (the point at which water is not extractable) for a small percentage of time. The higher storage volume in Middledeur is apparent by the comparatively slower drawdown of the dam levels. These plots were not shown to users as they were deemed too complex.

Box 6.1: Percentile plots depict annual reservoir performance analysis, with an estimated dead storage level of 15% (indicated by red lines). The Box and Whiskers plots here represent reservoir performance uncertainty within the selected ensembles.



Water storage susceptibility to streamflow dynamics.

The Water-Sharing Tool also produces long-term monthly reservoir performance analyses (Figure A-6.5), which are generally too difficult to work within a stakeholder setting but can be useful to explore the effects of seasonality and ensemble uncertainty. The plots are reconstructed as a time series overlain with the drought events in Figure 6.7 (these were shown to stakeholders and discussed). The model allows the outputs in Figure A-6.5 as a text file for each reservoir, which has been used to produce Figure 6.7 overlain with a streamflow drought index. This analysis highlights differences in site-specific characteristics of the basin, with four mild to severe droughts (Standardised Runoff Index below -0.5) occurring in 1993/4, 2000, 2003/04, and 2015/19. Peak water availability was estimated between 1994/96, 2007/09, and 2010/14 (Figure A-6.3). Moderate dry periods (Standardised Runoff Index below -1) did not influence storage performance in the Suurvlei-up and Sandfontuin (Figure 6.7-A and B). Model results (Figure 6.7) indicate that the dam storage never runs dry as needed, and this was supported by User 2 in Suurvlei-up through the quote below. This steady supply is often shared with downstream users through dam releases on demand, which partially explains the downstream user's (User 3 in Suurvlei) rejection of the plausible water-sharing strategies during the role-playing game debriefing (**Chapter 4**). Figure 6.7 also presents a surprising result regarding drought events. In the model inputs, water demands fluctuations were not accounted, and transfers outside the catchment were not simulated. The lumped reservoir setup also results in a large enough storage that is capable of buffering drought impacts to crop production. These three model assumptions could partially explain the limited impact of droughts on dam performance.

"My dam is big enough (storage = 1,000,000 cubic meters) that I never have to abstract from the river during the summer months, and I had to increase the dead storage level to be high enough that the endemic fish that inhabit the dam are not threatened" ~ User 2-Suurvlei-up.

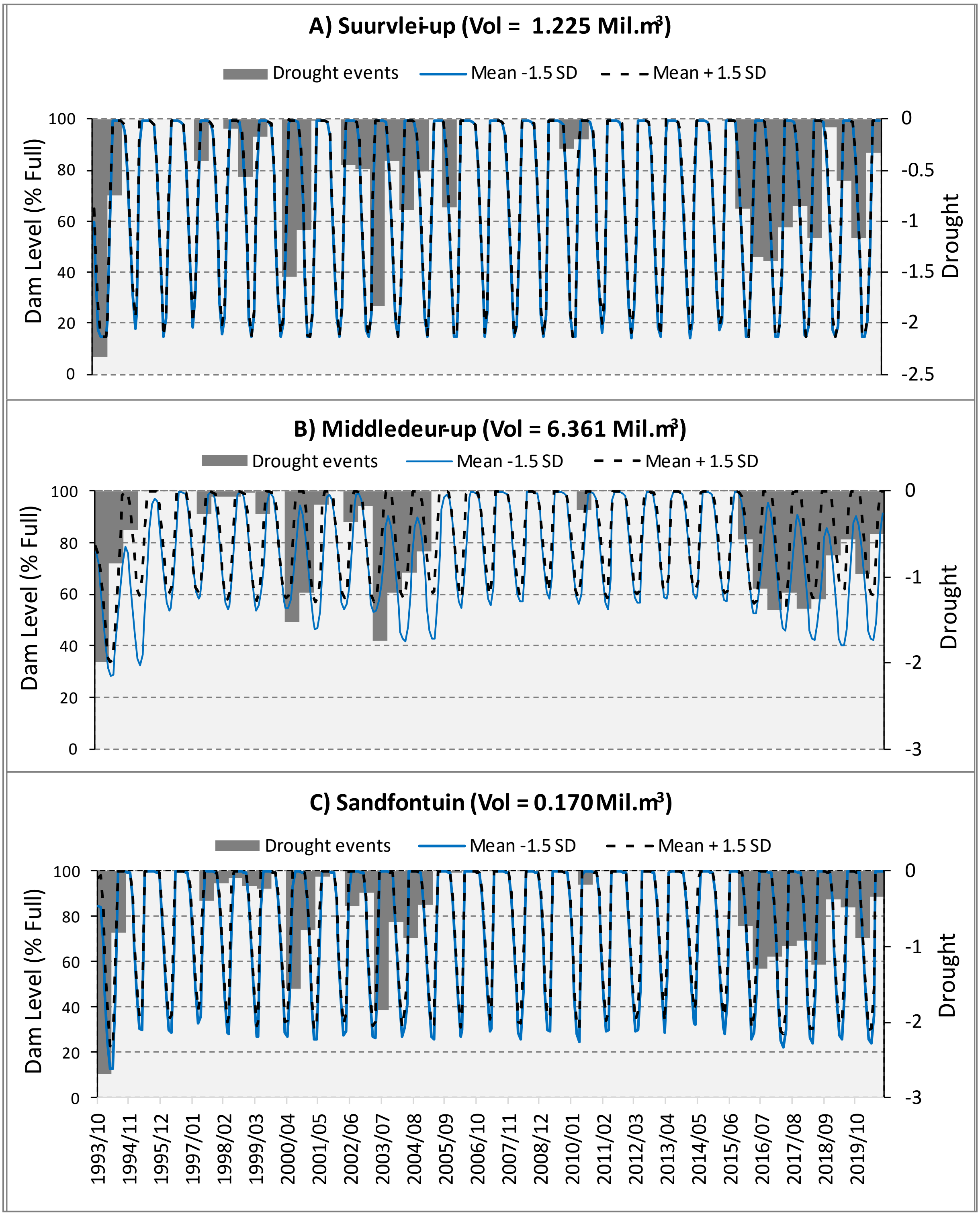


Figure 6.7: Monthly reservoir performance analysis for a lumped storage in the Twee Wyk for October 1993 to September 2020. The drought index is calculated using the Standardised Streamflow Index based on a 6-month accumulation. This index helps us understand unusually wet (numbers above zero) and dry (numbers below zero) times. It does this by seeing how much the monthly water flow deviates from the average yearly water flow.

Seasonal distribution of reservoir performance.

The model-produced time series in Figure A-6.5 were further reproduced as a monthly distribution (Figure 6.8) to characterise the monthly performance of the reservoirs. Unlike the Middledeur and the Sandfontuin storages, there is no clear uncertainty for the Suurvlei reservoir storage, which is an unintended consequence of the narrow uncertainty band for the simulated streamflow, as noted above. Model results suggest that the Middledeur storage, which is the largest, never falls below the 50% storage level, but it should be noted that this simulation was run without accounting for the inter-basin transfers from this area. Operators (corporate farms or User 1) of the largest reservoirs in this area were not cooperative to help improve the simulation of these upstream developments. The model simulated the most abstraction from two sub-basins, which is expected to occur between February and March (Figure 6.8). The next sub-section focuses on summary outputs that characterise the downstream impacts of these upstream developments.

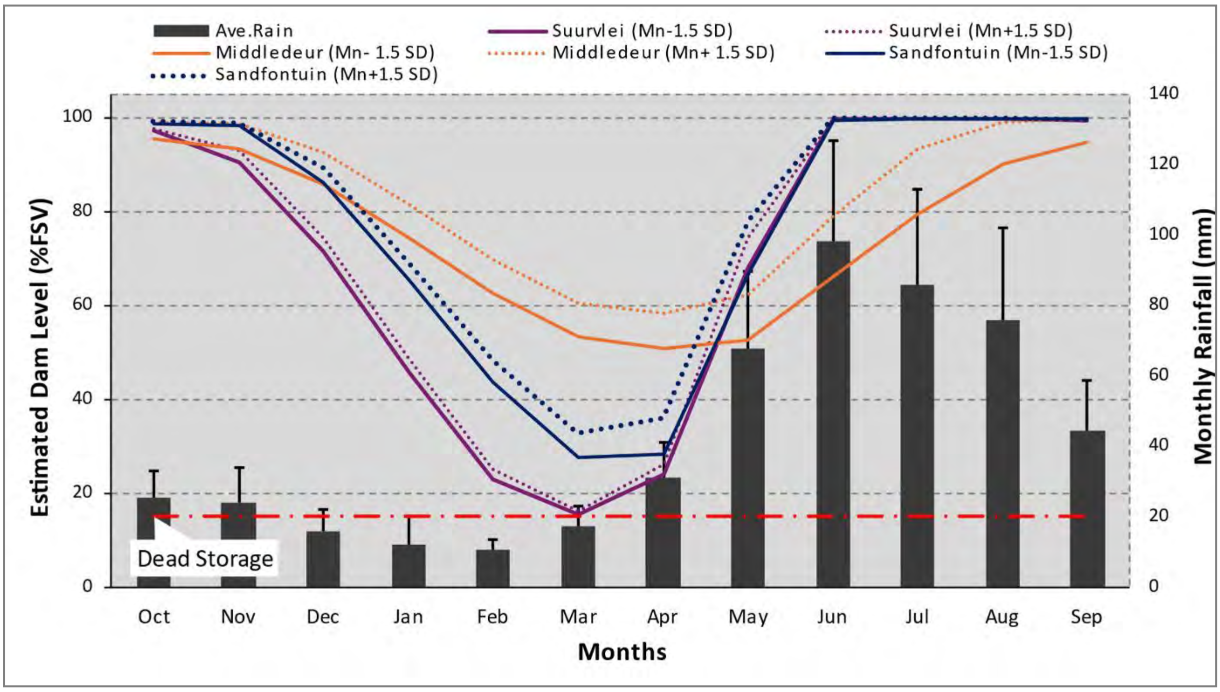


Figure 6.8: Monthly distribution of reservoir performance analysis for a lumped storage of all 18 reservoirs in the Twee Wyk upstream reaches, showing storage dynamics as a mean (Mn) and 1.5 standard deviations (SD) of storage level. The red line denotes averaged from farmer-supplied operations.

6.4.4. Summary outputs 2: Water balance outputs for each reservoir to assess human impacts on hydrology.

The original model did not explicitly output changes in the water balance (inflow to the system and outflow from the system after water use). This was one of the structural changes made to the model, partly so that the impacts of water use in each sub-basin could be clearly demonstrated to the stakeholders. The model now outputs a table which includes upstream inflows, net evapotranspiration from dams, water usage, outflows, and the change in storage for each sub-basin, for all 500 ensembles, The accumulated inflow and outflow (the remaining flow after dam storage, net dam evapotranspiration, and water use have been satisfied) are shown in Figure 6.9, highlighting water balance differences in the upstream sub-basins (large scale users with reservoirs) compared to downstream sub-basins (smaller scale users without reservoirs). Figure 6.9 shows that the hydrological impacts of upstream developments are more pronounced in the upstream Suurvlei and Middledeur nodes, where there is considerable storage (Figure 6.9). In comparison, the downstream areas had a marginal human impact on streamflow, shown by the inter-quantile range overlap of inflow vs outflow boxes.

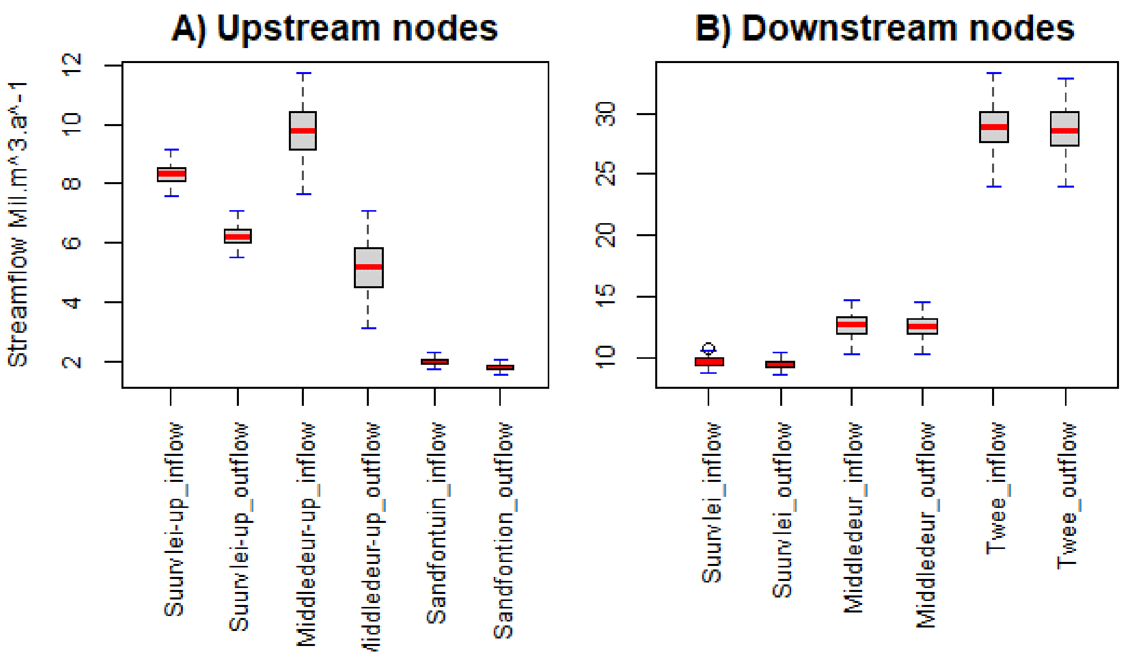


Figure 6.9: Comparison of inflows and outflows for each sub-basin, with the upstream users with reservoirs shown in A, and the downstream run of river users shown in B. Each user has an inflow and an outflow.

6.4.5. Summary output 3: Tolerance of risks by different users across the basin.

The Water-Sharing tool allows for the evaluation of water shortage risk tolerance among different users in a water management area. Risk tolerance in the model is represented by the frequency of months without impact (defined in section 6.2.4). This is termed risk tolerance as the users examine their impacts under each water sharing strategy and collectively decide a strategy to use. Therefore, each user needs to agree on their own tolerance level to balance out the impacts for the wider system according to the collective priority. Here, the risk tolerance is presented as a heatmap with users arranged in a hierarchical cluster in Figure 6.10 to provide a holistic view of all users. Tolerance levels are indicated by a colour gradient, with red representing low tolerance and green indicating high tolerance. Based on the available information, the overall impact output (Figure 6.10) suggests that currently, the fifteen irrigating entities represented fall into four clusters: high tolerance (green cells), medium tolerance (orange and green cells) and low tolerance (red cells).

Although water shortage affects downstream users disproportionately, the model simulated one upstream catchment with water shortage (Suurvlei-up). While streamflow and water demand uncertainties exist, a farm located in Suurvlei-up (a User 2) recently raised their dam wall to increase storage, and this information is currently unavailable (the reservoir storage used in the model was from the registered dam use). During engagements with this farm in the Suurvlei-up node, the farm manager clearly indicated that they have enough storage to support fruit production year-round, even during dry years. Hence, this simulation outcome would probably be different if we ran the model with the updated dam volume. Despite the uncertainty, these results signpost that *Pizza Slices* may allow the greatest number of users to avoid intolerable impacts (representing frequency of months with possible loss). This strategy prioritises smaller users and although User 1 in Suurvlei-up is a corporate farmer, the farm uses less water than the two User 2 farms (commercial family farms). Looking at risk tolerance scores, *Split-the-Bill* and *Share-the-Pain* may not perform well in reducing unwanted risks to downstream users who rely on run-of-river for their diversified irrigation needs. The fourth strategy not explored with stakeholders (*Beehive*) and not included in the analysis would probably have also resulted in the impacts on the downstream users being high, given that downstream farmers voted to prioritise upstream farmers during water shortages to prevent social instability due to rises in unemployment (during the role-playing game).

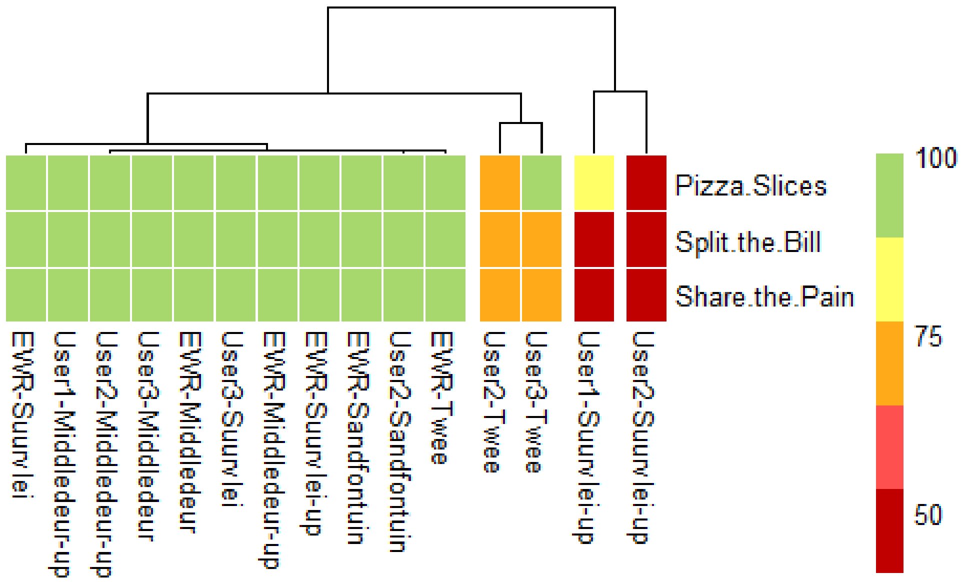


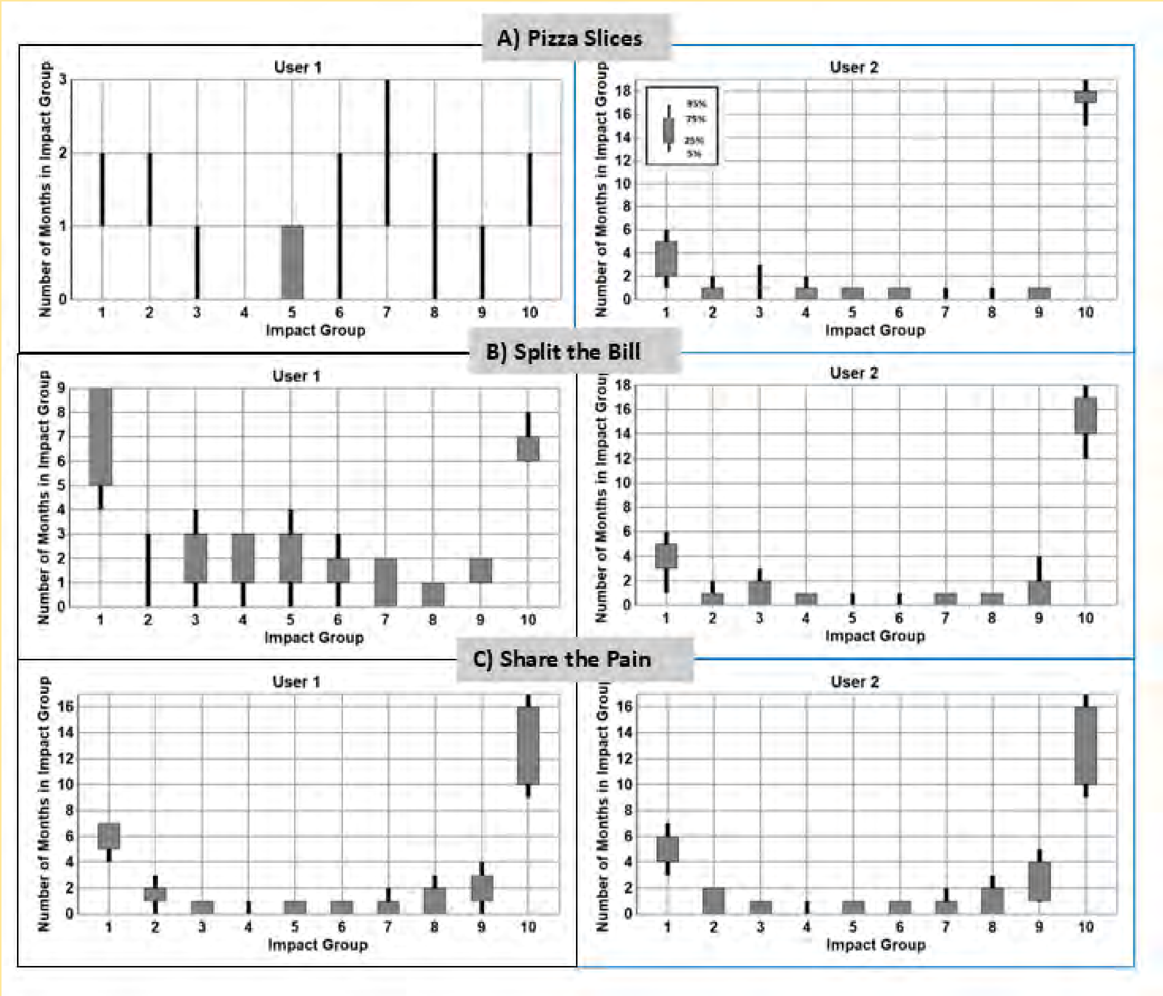
Figure 6.10: Heat map and hierarchical clustering of water assurance risk tolerability among users in the Twee Wyk based on the frequency of months without water shortage impacts for all users in the Twee Wyk for the three evaluated water-sharing options during the assessment period.

6.4.6. Frequency distributions of the number of months within the ten impact groups across the selected ensembles.

The screenshots in Box 6.2 illustrate the uncertainty y range (number of water-short months for each user) as Box and Whisker plots of the simulated flow ensembles for each water-sharing strategy. The model arranges these uncertain outputs as progressive impact groups (0-10, 10-20, …, 90-100%) (see section 6.2.4 for definition). This is done for each user in each sub-basin, as exemplified in Box 6.2 for users in the Suurvlei-up node. The model was run with static land use data from Cape Farm Mapper, although, in reality, the cash crops (planted annually) vary depending on farm-level crop strategies that may change depending on perceived water availability or recent rainfall trends. These changes were not simulated in the model, but could be included as a scenario if the specific farm information is available. It is possible to assess these crop strategies individually as scenarios by changing monthly crop demands. As previously observed, *Pizza Slices* returned the least impact for the small-volume users. *Equal impact* and *Split-the-Bill* resulted in similar impacts. These results confirm those in Chapter 4 that the commonly used strategy (*Split-the-Bill*) is biased against the smaller and often more vulnerable users. However, it is up to decision-makers to reach a consensus about the strategy they wish to adopt when managing demand during periods of scarcity.

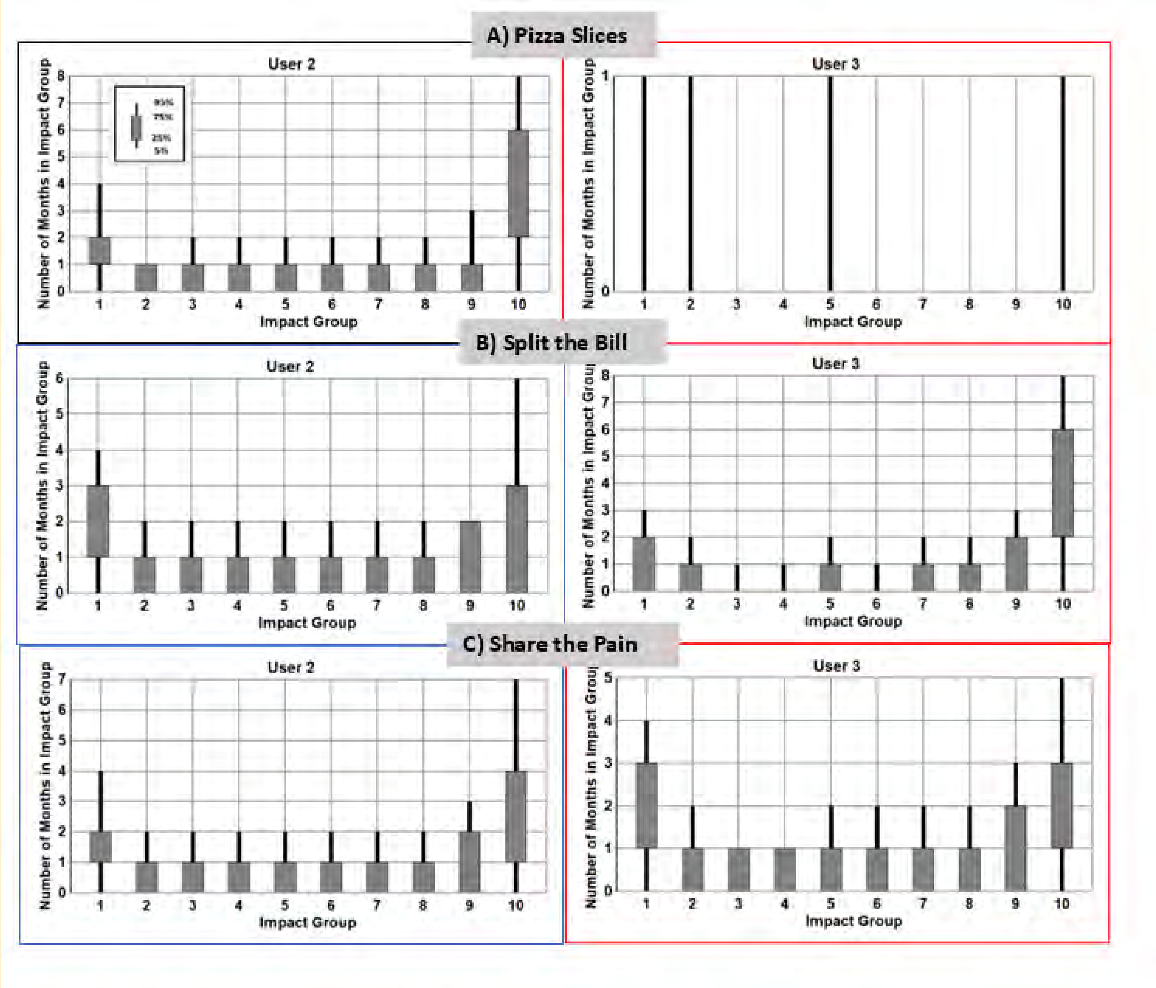
The users shown in the plots below share reservoir storage of 1.225 Mil.m^3 to irrigate citrus, deciduous fruits, onions, and pasture. An annual irrigation demand of 0.422 Mil.m^3.y^{-1} was estimated for User 1, and the combined demand for farmers categorised as User 2 was estimated at 1.119 Mil.m^{3}.y^{-1}. As seen in Chapter 4 and in Table 6.3, User 2 is assumed to have a medium-risk profile, while User 1 is assumed to be more protected from risk, despite both users having access to reservoir storage infrastructure. As a result, the low-volume user in the sub-area (User 1) faces less group 10 impacts under *Pizza Slices*, compared to User 2 (17 to 18 months in impact group 10). Under *Split-the-Bill,* User 2 may spend 14 to 17 months in Impact Group 10, compared to User 1, who may spend 6 to 7 months in Impact Group 10. As expected, *Equal impact,* exposes both users to similar impacts (10 to 16 months in impact group 10). These upstream users may be exposed to lower-impact groups, but these

Box 6.2-A: Screenshots of Box and Whisker plots of monthly impacts relating to the four plausible water reallocation strategies for upstream Users 1 and 2 in the upper Suurvlei node. The impact groups (x-axis) represent the progressive frequency of impacts, from group 1 (0-10%) and group 2 (10-20%, up to group 10 (depicting 90-100%). The y-axis in these plots is variable. The Box and Whiskers denote the percentage of selected ensembles (n = 500 out of 10,000).



The users shown in Box 6.2-B below irrigate using run-of-river. The estimated dry season demand for citrus, deciduous fruit, and pasture for User 2 is 0.225 $Mil.m^3.a^{-1}$ Whereas User 3's orchards require at least 0.097 $Mil.m^3.a^{-1}$As seen in Chapter 4 and in Table 6.3, User 2 is assumed to have a medium-risk profile, while User 3 is assumed to be more vulnerable, given their limited access to water supply and position in the catchment. Consistent with upstream simulation outputs in Box 6.2-A above, *Pizza Slices* produces the most tolerable impacts for the least-volume user (User 3), shown by one month under the catastrophic impact group (impact group 10). The same strategy may not be favourable for User 2 as it exposes this user to two to six months and up to two months for the lower-level groups. *Split-the-Bill* might be more feasible for User 2, who may be exposed to only three months for impact group 10. This strategy might be the most unfavourable to User 3, who may spend somewhere between two and six months in impact Group 10. The reallocation option that equalises impacts or *Equal impact* produces similar impacts for both users, as they are both expected to spend one to four months in impact group 10. Similar to their upstream counterparts, both users are expected to face some impacts in the lower-impact groups. However, these were overlooked in this interpretation to focus only on the disastrous impacts, from which the users may not recover.

Box 6.2-B: Screenshots of Box and Whisker plots of monthly impacts relating to the four plausible water reallocation strategies for downstream Users 2 and 3 in the Twee River node.



6.4.7. Simulation output 4: Time series impacts of water reallocation option outcomes.

The number of months under impact (Box 6.2 A & B above) could be due to either hydrological uncertainty or prolonged unfulfilled demand due to variability in supply. Box 6.3 contains the Water-Sharing Tool summary outputs that were designed to interrogate the influence of hydrological uncertainty on simulated impacts, focusing on the *Split-the-Bill* option (the remaining strategies are shown in Table 6.5 below). This strategy is currently used in the Olifants/Doorn water management area. The model produces these outputs for each affected user by transforming the frequency of impacts in Box 6.2 into a time series of impacts. The time series includes mean and standard deviations of impacts, as shown by the screenshots in Box 6.3. These figures are meant to be dynamic (and zoomed in) to obtain specific details of water availability over time.

The plots show that for each user, exposure to impacts and the level of uncertainty for each impact likelihood vary over time. Recalling the streamflow anomaly analysis (Figure A-6.3), model results also suggest that catastrophic impacts (impacts above the 75% level) coincide with assurance shortfalls due to hydrological droughts. One example of this observation can be seen during the 2015/19 drought or between months 270 and 300 in Box 6.3-A. The level of uncertainty for the simulated impacts upstream is narrow, which is consistent with the streamflow ensemble range. In contrast, downstream are expected to experience more frequent impacts (at times outside the severe drought periods) with a wider uncertainty band, shown in Box 6.3-B.

Concurrent months for which impacts occur.

The outputs in Box 6.3 above can be exported as a time series containing dates and mean ± the standard deviations of impacts each month. This export file can be used to investigate high-risk years or months of potential concern, as done in this study (Table 6.5). This additional analysis revealed that downstream users are exposed to at least tolerable to low impacts (0-35% impact level) between January and March most years. It is important to note that this finding is based on a long-term average and that the simulated impacts reached catastrophic levels in some years (e.g., 2001, 2004 and 2018), although not shown here. This is why the table only indicates tolerable and low-impact, even though high-impact months are included in the data.

Box 6.3: Impact time series for users, illustrating the degree of risk and uncertainty under the *Split-the-Bill* option. Uncertainty is expressed as Box and Whisker Plots across the assessment period and relates to agreement from all the 500 selected ensembles.

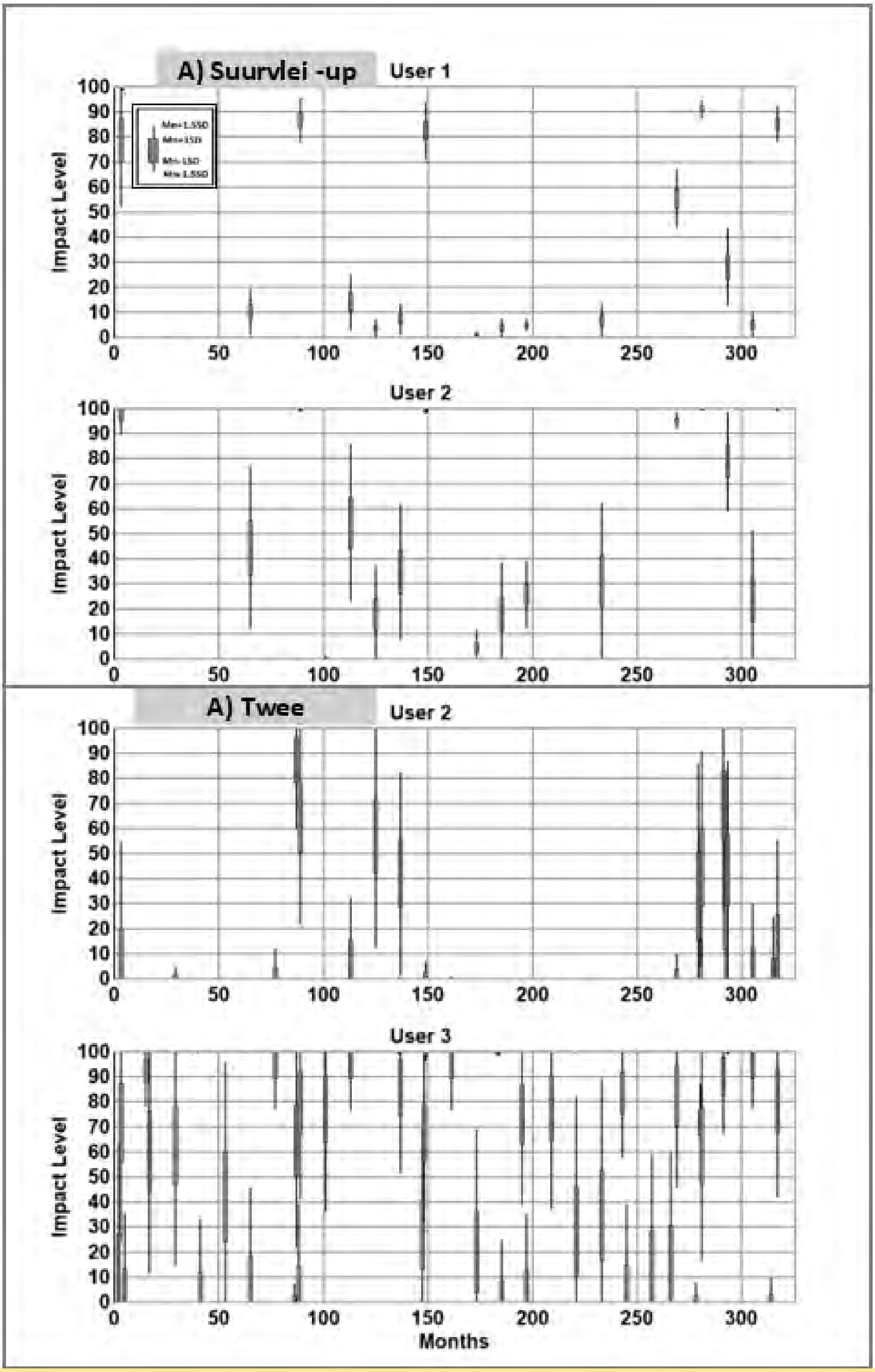


Table 6.5: Concurrent months in which impacts occur in association with the three sharing strategies for downstream users. Green cells denote tolerable impacts (0-15% impact level), and yellow months denote low impacts (15-35% impact level), averaged from the 27-year assessment period.

Months	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
A) User 2 ($\sum = 0.277 *10^6$ m^3)	0.018	0.026	0.041	0.048	0.050	0.041	0.015	0.010	0.005	0.005	0.006	0.010
Pizza Slices (Mn-1.5SD)	0.00	0.00	0.00	4.26	0.00	4.09	0.00	0.00	0.00	0.00	0.00	0.00
Pizza Slices (Mn+1.5SD)	0.00	0.00	0.00	13.64	5.23	28.47	0.00	0.00	0.00	0.00	0.00	0.00
Equal impact (Mn-1.5SD)	0.00	0.00	0.00	3.51	0.00	2.77	0.00	0.00	0.00	0.00	0.00	0.00
Equal impact (Mn+1.5SD)	0.00	0.00	0.00	13.09	4.73	25.37	0.00	0.00	0.00	0.00	0.00	0.00
Split the Bill (Mn-1.5SD)	0.00	0.00	0.00	4.71	0.00	5.01	0.00	0.00	0.00	0.00	0.00	0.00
Split the Bill (Mn+1.5SD)	0.00	0.00	0.00	15.16	4.63	29.28	0.00	0.00	0.00	0.00	0.00	0.00
B) User 3 ($\sum = 0.118$ $0.277 *10^6$ m^3)	0.007	0.011	0.018	0.021	0.022	0.018	0.006	0.004	0.002	0.002	0.003	0.004
Pizza Slices (Mn-1.5SD)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pizza Slices (Mn+1.5SD)	0.00	0.00	0.00	10.81	2.15	5.53	0.00	0.00	0.00	0.00	0.00	0.00
Equal impact (Mn-1.5SD)	0.00	0.00	0.00	1.71	0.00	2.14	0.00	0.00	0.00	0.00	0.00	0.00
Equal impact (Mn+1.5SD)	0.00	0.00	0.00	12.80	4.41	24.87	0.00	0.00	0.00	0.00	0.00	0.00
Split-the-Bill (Mn-1.5SD)	0.00	0.00	0.00	4.56	0.00	4.71	0.00	0.00	0.00	0.00	0.00	0.00
Split- the-Bill (Mn+1.5SD)	0.00	0.00	0.00	15.06	5.03	29.23	0.00	0.00	0.00	0.00	0.00	0.00

6.4.8. Reception by Stakeholders

The model structure and preliminary outcomes were presented to the stakeholders in a plenary session before introducing the game in Chapter 5. This session was followed by a discussion with all the attending stakeholders, including the simulated water users. One attending NGO practitioner questioned the model setup in terms of spatial scale. The model is limited at an upstream catchment boundary (see quote below). This simulation scale decision aligned with the Twee Wyk Water User Association area, but the concern was evidence of impacts over E-Flow compliance beyond the Wyk outlet. However, satisfying E-Flow demands at the outlet will be a sufficient contribution for the subsequent nodes leading to the Olifants Estuary. The Department of Agriculture, Western Cape, attended all the workshops and plans to introduce the tool to other Water User Associations. Therefore, there is a possibility that the tool could be applied at a wider spatial scale in future.

"Should we also not focus on E-Flow compliance downstream of the Twee" ~ Attending NGO practitioner.

It was also clear that more targeted engagement is needed to ground systems thinking to overcome historical legacies of private ownership of water and to mainstream fairness/justice/equity. This gap can be drawn from the following comment, which could also be attributed to inconsistent participation by the stakeholders:

"Each farm should do its risk analysis. We should have indicators from the previous months determining a quota" ~ Attending engineering expert.

It was evident that experts will remain important stakeholders in water resource management for data support.

The tool (given the user categories) may be challenging to roll out at a broader scale "~ Attending engineering expert.

"The model can be used to identify risk and that will change with application space" ~ Attending government practitioner.

As expressed in the quote below, increasing water storage was a motivational aspect behind the water users' involvement in the participatory process.

"What about dams and dam capacity? We are here for dams. How many dams can be added? That is the only way we can expand farming. We do not expand based on groundwater but surface water." ~ User 3.

The various farmers were mostly invested in the process from the start, and this was largely due to the stakeholder relationships built over time by project partners and the presence of the Department of

Agriculture, Western Cape, who were very enthusiastic about the model. There were several issues which hindered progress. Firstly, the difficulty in communicating model outputs, with the farmers finding abstract or conceptual aspects of the model (and the game) difficult to comprehend. In parallel with working out how to communicate more effectively with farmers, the model was also being modified and tested which added a further level of complexity.

6.5. Discussion

This chapter aimed to demonstrate a process of incorporating uncertainty in data-driven decision support to promote distributive fairness. Consistent with **Chapter 5**, only three water-sharing strategies were assessed in this study: *Pizza Slices, Split-the-Bill,* and *Equal impact*. The fourth strategy (*Beehive*) incorporates community prioritisation of supply into *Split-the-Bill*. As mentioned previously, this strategy would likely lead to higher impacts on vulnerable downstream users, as during the role-playing game (**Chapter 5**) it emerged that in a water crisis, upstream commercial users would be prioritized to ensure social stability due to labour force job losses.

The Water-Sharing model demonstrated here uses uncertain natural hydrological simulations from the Pitman model, water use data defined using WR90 parameters alongside crops and extents from CapeFarmMapper. The model is also forced with allocation preferences (also called user weights) from the involved land owners (section 4.3.2) and user risk profiles (section 4.2.4) that were validated by the water users themselves in two separate workshops. This model auto-assesses the relationship between supply deficits (as a % of full requirement) and 'impact' (0–100 scale) for all water users, including E-Flows, focusing on impacts rather than actual deficits (see section 3.3.4). The model is flexible enough to allow users to decide on metrics to establish the deficit/impact relationships for various users, on condition the selected metrics are holistic enough to capture the potential impacts of water deficits as well as the costs/benefits of adaptation arrangements (Hughes & Mallory, 2009). For instance, user risk profiles for consumptive and beneficial uses such as irrigation can be in evaluated economic terms such as percentage loss of productivity, meanwhile domestic uses could be captures using socio-economic impacts for rural/urban domestic supply, and habitat availability could be uses for E-flows as exemplified in the role-playing game in Chapter 5. The goal of this deficit-impact relationship is to evaluate the impacts of reallocation options across the uncertainty range of natural hydrology ensembles using a common impact metric. The decision-relevance of the outcomes produced by the Water-Sharing Tool is linked to the implied definition of water security—the ability of users to tolerate the consequences of water shortage (Grey et al., 2013).

6.5.8. Structural improvements of the Water-Sharing Tool.

The Water-Sharing Tool underwent a series of structural modifications because of this modelling experience. Some of these modifications include:

Merging the run-of-river and dam use runs into a single setup to better account for interdependence. As implied by Schlüter et al. (2012), characterising interdependence and uncertainty may be difficult if the run-of-river and dam-use sub-system components are evaluated separately.

The updated Water-Sharing Tool now offers an export file that allows for a coupled feedback evaluation of upstream developments on streamflow availability downstream (Section 6.4.4). As detailed in section 3.3.6, the water balance components include accumulated upstream inflows, net evapotranspiration from dams, outflows, water demand, and changes in storage.

The updated model accounts for intra- and inter-basin transfers on the condition that the transfer is not to a downstream user. All downstream transfers are treated the same way as spillages (i.e., normal streamflow or downstream releases). Although this facility was not used in this study, it was recognised that this is an important part of water management in South Africa and needs to be represented in the model.

The previous version of the model allowed up to four users/user groups in each sub-area. In the updated version, an additional user has been added. In future, more user groups could be added, but a consideration for the level of complexity that can be handled by the decision-makers will need to be made. The nature and the number of legitimate water resource beneficiaries will also vary by context.

An in-built feature to rescale community weights so that available supply is only allocated to users present in each sub-area. This automation was intended to reduce the number of steps required to set up the model, and future model versions will focus on reducing these steps.

While integrating the two setups, it became apparent that the software behind the previous version of the model misrepresented evapotranspiration demand from reservoirs; secondly, in the previous model software, E-Flow contributions were not flowing downstream when environmental demands were already met in the downstream sub-area; thirdly, the previous software led to instances where impacts above impact group 7 were not simulated. All these structural errors have been corrected. One outstanding feature is the project report, which is yet to be developed but can be based on the interpretations shown in section 6.4.

6.5.9. Advantages of the Model And its Links to Society and Decision-Making

Setting up the model in collaboration with the water users and other interested stakeholders is intended to ensure Water User Associations have a realistic understanding of likely relative impacts linked to different possible allocation decisions. This collaborative setup warrants the model as a participatory model (Voinov et al., 2016; Basco-Carrera et al., 2017a). Novel features of the model are the incorporation of uncertainty and translation of allocations into deficit-impact scores to guide deliberations (Pienaar & Hughes, 2017). This way, the model allows decision-makers to proactively plan towards reducing unwanted social and environmental impacts while avoiding unacceptable economic costs. Most importantly, unlike its hydro-economic counterparts applied elsewhere (Pérez-Blanco et al., 2021), it is possible and advisable to consider broader impacts than the economic costs and benefits of supply or lack thereof (Hughes & Mallory, 2009; Hall & Borgomeo, 2013).

"Finding a balance between economic outcomes and environmental needs".

The integrated evaluation outcomes can serve as evidence when devising a cooperative strategy for equitably protecting the environmental benefits of E-Flows (Ellender et al., 2017; Arthington et al., 2018). Results showed that the recently upgraded [in 2016 E-Flows in the catchment were increased from level C to B (Department of Water and Sanitation, 2017)] low-flow E-Flow threshold can be consistently met under unchanged land use. However, this results in many users (particularly downstream users) enduring high impacts due to water deficits. While the current model setup sets the E-Flows at 'always met', in reality, users would have access to that water, and it is used for irrigation during severe dry periods (it is, however, possible to treat the E-Flows as a user in the model setup).

It would be up to the decision-makers to decide how to manage their crop strategies best to satisfy the B-level E-Flow requirement (at a high level due to the local and regional ecosystems' biodiversity (Ellender et al., 2017; Paxton et al., 2017). Given the differences in value systems between corporate farms upstream (more profit-driven and less environmentally conscious) and family farms downstream (more environmentally conscious), an effective Water User Association will be crucial to mediate the E-Flow satisfaction agenda in the study area. For this study, the lack of an effective Water User Association hindered the results significantly, as the members (mostly upstream corporate farmers) refused to engage and share information. Stakeholder representation within the institution will require close attention to ensure equitable outputs (Voinov et al., 2016; Leach et al., 2018).

Propagation of water shortage to downstream users.

While evaluating reservoir storage and performance, assessing the model's capability for testing alternative reservoir operation scenarios was not possible. The main challenge leading to this prohibition was that most of these privately owned farm dams belonged to User 1, who was less interested in the project but had more influence in the Water User's Association. User 2 owns some farm dams and was interested in testing the model's salience for the Water Users Association, although with less influence. Results in Box 6.1, supported by Figure 6.7, reveal that the dam storage currently works well for upstream users. However, the current operations are not necessarily optimum for all downstream users (as seen in section 6.4.4). Unfortunately, upstream users (predominantly User 1s) are incredibly protective of their water use information, so alternative management regimes which might be better for downstream users could not be reliably explored. In hindsight, this catchment was not ideal because the corporate farms refused to share data and ran the WUA. Although the downstream farms were very invested in this model and project, exploring the model's full functionality was impossible without the upstream user's participation. This does not take away from the value of this project for the catchment as all the stakeholders involved in the process (all Users 2 to 4) have a greater appreciation of the collective and individual user group impact on the system and are better able to challenge the status quo in future (either through electing new members to the Water User Association or through applying for new water use authorisations). From the more vulnerable user's perspective, this project was valuable and timeous, and this was one of the main motivators for selecting this catchment as the case study.

The water balance outputs of the model highlight the consequences of upstream storage for streamflow reliability to downstream users. Despite their in-situ benefits, reservoirs have been associated with extending the severity and duration of streamflow droughts (Cody, 2018; Di Baldassarre et al., 2018; Van Loon et al., 2022; Mantel et al., 2023), confirming the model simulation results reported here. The desired E-Flow level for the Twee Wyk was recently set for near-natural flows (Department of Water and Sanitation, 2017), implying that only a limited number of reservoirs can be constructed in instream (Department of Water and Sanitation, 2016: Table 2). The downstream farmers however, will use the information from this project to motivate for a new dam which supplies a number of under-resourced Users. From an environmental perspective, this should be somewhat beneficial to the system as it will reduce the dry season strain on the ecosystem (as well as strain on the farmers)

Simplifying water security as tolerable impacts.

Grey et al. (2013) simplify water security by linking the phenomenon to tolerable impact to water users. This definition of risk characterises a secure socio-hydrological community as one that can avoid undesirable outcomes of water-related hazards in relation to community and sustainability objectives. In support, the Water-Sharing Tool uses the deficit-impact index of Hughes & Mallory (2009) derived with water users to help decision-makers imagine the costs of various water-sharing options/reallocation strategies. While no individual reallocation option is necessarily the best, results of the risk-tolerance suggest the *Pizza Slices* (equal sharing) as the most promising option. However, reaching a consensus to move from *Split-the-Bill* (proportional sharing) will require buy-in from affected users, and such negotiation will need to be facilitated with fair procedures, as exemplified by the role-playing game in Chapter 5. The impact tolerance results presented here can serve as a reference point in the equitable process.

Use of an impact-based approach to better manage hydrological variability and reduce vulnerability.

The salience of the approach presented here is providing decision-makers with evidence of possible risks and uncertainty related to drought allocation decisions, which can be used to reduce vulnerability to society and instream ecosystems. With limited confidence, model appraisal results of the water-sharing options presented here reveal that January to March is the high-risk period across reallocation strategies, threatening the fruit production capacity of farmers relying on run-of-river midstream and downstream of the basin. This finding signals to decision-makers that a dynamic water management intervention during the identified period is crucial to maintaining the identified Western Cape's reputation for fruit production. This decision consideration is also crucial given stakeholders' voiced concern of eroded economic value for agriculture in the catchment.

As the research is contextualised around the equity/justice framing, selecting an optimal strategy is left with the decision-makers, which may be possible as a functional Water Users Association has since been instituted after the conclusion of this project. It must be reemphasised that fairness is an ongoing process, and whatever strategy is chosen should be based on local development objectives and checked against the shared vision.'

Availing reallocation impacts as a consistent measure of distributive equity.

As shown in section 4.2.4, the impacts depend on the user risk profiles used as input in the model. The profiles were focused on the user group's vulnerability, and it must be noted that the resulting deficit-impact index is subject to change as water users evolve (for example, due to infrastructure development) or as water users begin to understand the relationship between deficit and impact better (Gober & Wheater, 2015; van Duinen et al., 2015). Generating the required socio-economic data is not a straightforward exercise, and many alternative procedures exist within economics and social and science disciplines. The modelling experience showed that expertise from other disciplines is required to profile user risks and to understand community preferences for allocation, which feed into contextualised equity consideration (Du Toit & Pollard, 2009; Xoxo et al., 2023). The most important consideration in deriving the socio-economic inputs is recognising the diversity of water-use values and differences in users' ability to cope with impacts. Therefore, should a Water User Association adopt the tool, the setup can be refined, and the impact better defined as users become more familiar with the components of the model and the outputs. They can then refine as necessary as they better understand the model's representation of their relationship between water deficits, impacts and uncertainty.

6.5.10. Key limitations: Uncertain inputs.

Realistic quantification of water availability.

Uncertainty is here deemed necessary for decision support (Nearing & Gupta, 2018). The observed uncertainty in the results presented here is firstly attributed to the lack of available hydrometric data for model setup. The second source is parameter identification, given the limited knowledge and complexity of the sub-surface water balance components. The hydrological constraints and natural runoff parameter ranges used here were deliberately kept narrow during calibration. This was based on the expectation that decision-makers would be less willing to plan based on a wider uncertainty band. The two-step approach of the Pitman model is designed to allow the modeller to reduce uncertainty in the parameter sampling space (Kapangaziwiri et al., 2012; Ndzabandzaba & Hughes, 2017).

However, this prevented a full exploration of the value of uncertainty for understanding the risk in decision-making with the stakeholders. As model users grow more proficient with the use of the model and communication strategies are better understood, it is recommended that the uncertainty components of the model be incorporated more fully. In this case study, the simulated water availability was characterised by a narrow uncertainty band, risking decision-makers placing false confidence in the outcomes and potentially making risky water resource decisions. While this was consistently communicated during the workshops, the stakeholders had difficulty comprehending the consequences. This difficulty of communicating the value of uncertainty (amongst the complicated development of the model) was another reason that the project did not fully embrace the uncertainty potential of the model. In addition, the stakeholders found the model concepts highly complex, and significant work was undertaken to reduce the complexity in the communications. It was felt that incorporating more of the uncertainty aspects would result in further confusion. Further work that builds on the communication strategies developed in this thesis is needed to utilise the Water Sharing Tool's potential fully.

The uncertainty approach of the model does help the model users to pinpoint opportunities for improving input datasets to reduce uncertainty, following Hughes, (2019). Hydrological input uncertainties synthesised by Mcmillan et al. (2012), can be mitigated by investing in better observation techniques or refining coarse-scale data (Hughes et al., 2014b; Hughes & Farinosi, 2021). In this case, the representativeness of current rainfall datasets remains uncertain due to unknown rainfall measures at mountain peaks where most rainfall is generated. This translated to increased streamflow uncertainty due to biased climate inputs, possibly explaining the lack of impacts along the Middledeur River. The expected impacts due to upstream storage were concealed by possible over-stimulation of streamflow in this low-rainfall area compared to the upstream sub-area. Therefore, it would be interesting to re-run the streamflow ensembles with climate uncertainty included in the Pitman model.

Water demands.

The E-Flow estimates used in the six sub-basins represent a situation where the sparsely distributed observation points could impact the environmental demands. Specifically, the Olifants/Doorn River Basin (River E), with an extent of 56,446 km^2, has six E-Flow monitoring sites (Sites 1 to 6). The upstream site (Site 6), intended to monitor farm dams' impacts on streamflow, monitors cumulative flows for three quaternary basins (E21G, E21H, and E21E). These basins have a cumulative area of 750 km^2, making it incompatible with the sub-quaternary scale used in this study. This was addressed based on lessons from experts involved in the E-Flow assessment in South Africa, who noted the absence of E-Flow monitoring for small tributaries (Water for Africa, 2008). E-Flow assessment from Site 6 was disaggregated into smaller tributaries of the Twee Wyk using the strategy curves of E-Flow Site 6 in the study area and the simulated median ensemble from this study. While the approach is correct, propagation of uncertainty from the simulated streamflow is inevitable, and the E-Flow demands presented here should be understood with this background in mind.

A part of this limitation was improved by considering E-Flow assessments that were derived by combining two commonly used datasets for E-Flow assessment in South Africa to establish the strategies, offering a moderate level of confidence in E-Flow assessment (Opperman et al., 2018;

Tanner et al., 2022). The level 2 DRIFT method uses multi-disciplinary expert opinions to simulate plausible downstream consequences of changes in the hydrological and hydraulic regime (King et al., 2003; Tharme, 2003). These E-Flow strategies incorporate seasonal variations and target site-specific environmental characteristics (King & Louw, 1998; King et al., 2003; Hughes et al., 2014a), unlike the fixed percentage of streamflow used in global assessments (Hoekstra et al., 2012). The Revised Desktop Reserve Model integrates hydrology (natural flows), limited hydraulic indicators, water quality, and ecological data to determine the ecological reserve and evaluate various flow management alternatives (Hughes et al., 2014a). While sparse E-Flow monitoring affects the reliability of outputs, using two different models to determine E-Flow contributions reduce the uncertainty.

Catchment representation.

One of the novel contributions of this study was testing the model performance given a spatially distributed setup to realistically represent the decentralised nature of water use and management in the study area. This approach led to a less distinct evaluation of the impacts across users. That is, while combining all users at a quaternary basin scale, for example, will provide distributive equity impacts across users, differentiating between users with access to reservoirs, for example, and those with none will be difficult. Meanwhile, dividing the basin into smaller sub-basins, as done in this study, will allow the modeller to extract information about the impact of adaptation decisions upstream instead of treating all surface water in the basin as a singular source. At best, only upstream impacts to downstream users will be sufficiently represented. Therefore, future applications of the model should carefully consider the compromise between user-specific and spatially distributed impacts.

User grouping and representation in the model.

The model allows up to five sectors or user groups in each sub-area for simplicity and to reduce computer run times. As discussed in **Chapter 3**, agricultural producers were split into three groups rather than representing each user independently When presented to collaborators in France, the Water-Sharing Model was questioned for lumping socio-economic users into five groups or sectors, but they eventually conceded to the grouped-user representation. They accepted the compromise made to reduce complexity.

In the field, the attending water manager felt that grouping water users this way may be unnecessary and that the risk assessment should be left to the individual farmers. In response, it would be difficult for institutions to promote risk-based decision-making and mainstream fairness if water managers are unwilling to change their methods. Without a comparable measure of impact, it would be impossible to consistently report on equity using the impact measure as proposed here, and water allocation reforms may take even longer to accomplish. To everyone's surprise, the water manager felt that *Share-the-Pain* encourages laziness in vulnerable users. However, it must be noted that the manager only attended one workshop and missed the benefit of being sensitised to the principles behind decision-making under uncertainty and the processes of impact-based allocation planning. Based on the decentralisation principle of the South African National Water Act (RSA, 1998a) decisions on how water must be used and managed are left to members of the Water User Association at the local level.

Communicating model outcomes to stakeholders.

The Water-Sharing Tool offers many outputs that can help decision-makers incorporate uncertainty into water allocation decisions to reduce vulnerability. However, in support of Fischhoff and Davis (2014), appropriate communication is the key ingredient to making a complex model of this nature accessible to stakeholders and, therefore, fully participatory. Significant work focusing on communicating the reallocation structure and the co-evaluation of impacts was undertaken with partial success, as discussed in **Chapter 5**. For instance, the version of the role-playing game tested with the farmers did not effectively communicate the water-sharing strategies to the users. This limitation was addressed in the improved version of the game and remains to be tested with a real Water User Association.

The huge battles with communication could not be avoided as this is the first application of the model in a real-life setting with stakeholders. Hence, the difficulty of working to understand, test, and modify a highly complex tool while trying to bring the users on board in a participatory manner heavily compromised the investment of time needed to make the outputs useful to decision-makers. Frequently, useful insights that could help improve communication emerged Looking towards the future, this study could be used as a proof of concept to better understand the key concepts of uncertainty and improve the appreciation of uncertainty in water-resource policy at local levels.

7. SYNTHESIS, CONCLUSION AND OUTLOOK

"Our vision is to work together in managing water resources sustainably and equitably, with transparency and accountability in ways that balance social, economic, and environmental needs. We want an agricultural sector that produces economic value through evidence-based management practices and the adoption of ecosystem-based solutions. We envision a healthy, resilient ecological system with clean year-round water flow. Twee Wyk 2050 Vision"

Due to various factors affecting supply assurance, water reallocations are increasingly necessary to ensure sustainable and reasonable sharing of the variable water supply in semi-arid areas. Under variable climatic conditions and increasing socio-economic development, water shortage risks across sectors (including the environment) will evolve, pointing decision-makers in the direction of substantial uncertainties (Mayer & Muñoz-Hernandez, 2009; Korteling et al., 2013; Mcmillan et al., 2017). Evidently, there is a reinforced demand to familiarise stakeholders and decision-makers alike with decision-making under uncertainty (Fischhoff & Davis, 2014; Gober, 2014; Polk & Diver, 2020), especially at the lowest levels of decision-making, where adaptive capacities are needed. Meanwhile, existing power asymmetries (both systematic and technical) (Pfaff et al., 2013; Partzsch, 2017) also need to be addressed to ensure fair procedures toward reaching acceptable allocation outcomes. Strategic participatory interventions must focus on fair inclusion procedures underpinned by respecting societal conditions to ensure justice in water reallocation (McDermott et al., 2013; Patrick, 2014; Leach et al., 2018; Seigerman et al., 2022). Water reallocation decisions must go together with efforts to address inequity and vulnerability, which, without water scarcity, risks may result in unacceptable and even irreversible losses.

Motivated by the rationale above, the overarching goal of this thesis is to use a novel participatory water reallocation model to demonstrate how uncertainty can be explicitly linked to equitable water allocation decisions to reduce conflicts and vulnerability from available supply during dry periods. First, I report on a socio-economic data collection process that allows an equal representation of all water uses and diverse preferences in decision-making at the Water Users' Association level (Aim 1, **Chapter 4**). Second, this thesis provides social simulation outcomes of stakeholder reception and co-evaluation of plausible water reallocation strategies; these reallocation strategies are determined based on the likely relative sectoral impacts of water shortage (Aim 2, **Chapter 5**). Lastly, the revised Water-Sharing Tool is used to combine the socio-economic data, uncertain catchment hydrology, and E-Fflows to evaluate the potential frequency and severity of impacts faced by different users from the water-sharing options (Aim 3, **Chapter 6**). The model outputs are interpreted based on the Role-Playing Game experience, focusing on high-risk impacts and associated uncertainties. This research contributes to the adaptive water governance practice, with direct links to socio-hydrology and fairness, by focusing on decision-making under uncertainty and offering different strategies to distribute a limited water resource. Conceptually, this work is guided by equity dimensions (McDermott et al., 2013; Leach et al., 2018) and socio-hydrological thinking (Elshafei et al., 2014).

This conclusion chapter starts by highlighting the central findings and issues encountered in each study objective of the thesis and ends with recommendations for further research. The next sub-section presents the main findings from Chapters 4,5 and 6. Thereafter, the challenges encountered are stated, followed by the future research outlook.

7.1. Main Findings (Chapters 4, 5 & 6)

7.1.1. Objective 1: Creating a protocol for collecting socio-economic data to facilitate stakeholder engagement activities that will gather the appropriate data from the stakeholders for inclusion in the model.

As highlighted in the review chapter (**Chapter 2**), stakeholder inclusion through participatory modelling is vital for mainstreaming social equity into water reallocation decisions. Inadequate participation, diverse/changing societal preferences, and knowledge differences are some of the motivators for relying on participatory modelling approaches in water management (Basco-Carrera et al., 2017a). Local stakeholder and expert involvement were central in applying sound natural resource governance principles (i.e., inclusive decision-making) while adhering to strict ethical guidelines for a reputable participatory process (Barreteau et al., 2010).

Chapter 4 introduces a four-step framework (Figure 4.1) to lay the groundwork for collaborating with decision-makers in setting up the Water-Sharing Tool. The approaches presented here are a first step toward a consistent socio-economic data collection needed to set the model in a manner that is context-specific. **Chapter 4** shows one way to enrich the understanding of the social system, focusing on individual contributions, user risk profiles and preferences regarding water reallocation at a local scale. An underlying objective was to familiarise water users with other stakeholder preferences that may not be economically traceable (Tian et al., 2019).

In Chapter 4, the thesis narrates the shared-future vision centred around sustainable and reasonable use while ensuring efficiency. The catchment vision is consistent with the national (Department of Water and Sanitation, 2022) and international (Cowie et al., 2018; UN-Water, 2019) development imperatives. Alongside the shared-future visioning, the user groups that would be represented in the Water Users Association were identified, wherein the freshwater ecosystems, agricultural producers, residents, and lifestyle farmers (weekenders) emerged as the main entities in the catchment. The agricultural sector emerged as a user group with the most prominent water footprint, consistent with other studies locally (Gush et al., 2019) and globally (Liu et al., 2017; Vanham et al., 2018). I turned my attention to equity as water users individually contributed to the community-stated equity index to identify the most socially important users the community wishes to protect against severe water shortages. Results revealed inconsistent judgments over the preferences for water use in the catchment, where farmers with access to supplementary water sources (e.g., reservoir storage and groundwater pumping infrastructure) positively valued environmental protection during dry periods compared to those without additional water supply. The final phase in social system scoping was to conduct a vulnerability analysis tailored to capture as many causes of low adaptability to periodic water shortages as possible, which are likely to remain under the various water allocation methods. The upstream farmers were found to have a relatively high tolerance to water scarcity due to high preparedness levels compared to their downstream counterparts.

7.1.2. Objective 2: Co-developing and utilising a role-playing game to introduce and co-evaluate plausible water-sharing strategies.

The role-playing game technique is chosen to facilitate learning about the socio-economic and environmental impacts of different water-sharing strategies and water withdrawal during dry periods (**Chapter 5**). As a reminder, collaborative/shared learning arises from the flow of ideas between different stakeholders during the game process (Ison et al., 2007; Voinov & Bousquet, 2010). This learning was achieved by introducing alternative water-sharing options (water allocation strategies) for beneficial use and co-evaluating these impacts with stakeholders in the virtual environment provided by the game. Knowledge acquisition from the researcher's side is essential to validate the fairness of the different allocation strategies.

The research team and knowledgeable key informants tested the conceptual versions of the game over a two-year period in France and South Africa, during which the game was progressively improved. Stakeholders involved in co-constructing the game tested and validated the first versions played with stakeholders in the field on November 2nd, 2023, over two parallel sessions. An updated version was tested with five postgraduate students at Rhodes University, Makhanda, South Africa. Refinements to the game included adding icons of dams for players to use as extra resources and improving how we record the data and token movements. The role-playing game fulfilled its awareness-raising and collaborative learning objectives through a social simulation and quantitatively capturing player reactions.

The game exposed players to three equitable water reallocation strategies: *Split-the-Bill* (currently used in practice), *Pizza Slices,* and *Share-the-Pain.* All players adopted a different role from their sub-sector to enrich the peer-learning process. Using a severe drought scenario and a change in E-Flow requirements from minimal flows (level D) to the desired flow conditions (level B), players saw the generic differences in water reallocation strategies. However, this was not immediately obvious to farmers. Initially, the game excluded the dam storage to maintain focus on run-of-river impacts, but it was later discovered that excluding this resource makes it impossible to explore possible scenarios of dam releases for downstream users. While farmers eventually discovered that they could change crop strategies, irrigate priority crops based on available supply, and enter into water transfer agreements, farmers earlier had challenges with the abstract parts of the game, such as the representation of surface water restrictions instead of their impact on production. These challenges led to the realisation that some farmers prefer specific information and are not familiar with planning based on abstract dynamics. The game was subsequently modified to include some of the key dynamics and validated with a different stakeholder group and can be played in different contexts to introduce the water-sharing strategies and co-evaluate their impacts.

Despite the limitations, farmers hailed the game for its ability to facilitate equal participation in water governance and aid system understanding. The playability of the game was facilitated by introducing the allocation options as narrative cards instead of using the summary plot of the Water-Sharing Tool, shown in **Chapter 6**. **Chapter 5** reports on the discovery that corporate farmers are more likely to forego high-value crops (orchards) in favour of vegetables and animal fodder. Commercial family farmers are expected to act in the opposite way. Prioritisation of high-value crops by downstream users could explain employment losses in the Western Cape over the recent drought and the increase in income shown in Table 3.2 (section 3.2.7). Surprisingly, small-volume users were found to be more prone to sacrifice their drought supply assurance in favour of larger users if drought curtailments substantially impact employment and social stability. This dynamic is also linked to the community allocation preferences (sections 4.2.3 and 4.2.3), which, after the game, it was apparent that the community weighting index would have been different if this knowledge had come earlier in the process. Ultimately, farmers accepted the importance of high environmental protection levels in the Wyk, giving regulators and environmental activists a positive signal about environmental awareness and future protection. Farmers' reactions to the water reallocation strategies were diverse, meaning the ideal plan could not be determined. Nonetheless, the exposure of the attending stakeholders to equitable decision-making and the use of uncertain information provided during the game rounds may be sufficient to prepare these users to represent their counterparts in the Water Users Association, demonstrating the strategic value of the inclusive and multi-stakeholder engagement process (Edmunds & Wollenberg, 2001).

7.1.3. Objective 3: Setting up and testing the Water-Sharing Tool with Dam Uncertainty as a tool for operationalising fairness in water management in the Twee Wyk (River E21H), which is part of the upper Doring Catchment (River E).

Chapter 6 details the application of a water use decision support system model for the Twee Wyk case study in the Western Cape, South Africa, assessing the (sub-)sectorial risks and uncertainties attributable to plausible water reallocation strategies. Social system model inputs include the community weights, and the Deficit-Impact index derived from **Chapter 4**. Essential hydrological inputs include uncertain hydrological estimates based on the Southern African hydrology experience (Midgley et al., 1994; Hughes, 2013, 2019; Ndzabandzaba & Hughes, 2017), disaggregated E-Flow requirements focusing on low flows specific to the Koue Bokkeveld region (Department of Water and Sanitation, 2017), publicly listed dam storages, and locally observed rainfall. These inputs are used to estimate available water supply, predict streamflow dynamics and groundwater recharge, and assess the potential impacts of different water reallocation strategies on water users.

Despite the uncertainty, the interpretation of the model results shows that there is enough surface water in the catchment to fulfil the desired E-Flows, but the costs borne by downstream users could result in E-Flow breaches during moderate to severe droughts and between January to March, which are the low flow months. High-risk impacts are simulated for upstream users, which could explain the recent dam wall improvements in the upstream sub-areas as a strategy to mitigate the variable water availability. However, the impact of inter-basin transfers and possible dam releases could not be explored. Updates to the original model structure of Pienaar and Hughes (2017) allow for the evaluation of upstream adaptation (dam storage) on downstream water availability, consistent with other literature findings looking at reservoirs' downstream impact (Di Baldassarre et al., 2018; Kellner, 2021; Van Loon et al., 2022; Mantel et al., 2023). However, it was impossible to validate reservoir performance as no long-term data is available to enable such an exercise and User 1's lack of commitment to the participatory process also meant it impossible to check if the simulated reservoir assessment was realistic enough.

Ensuring all stakeholders' consistent understanding of model outcomes is a strategic intervention to increase cooperation and learning (Partzsch, 2017) at the Water User Association level, based on the assumption that knowledge asymmetries result in a bargaining power imbalance. This strategy supports the need to capacitate stakeholders' ability to adapt responses through equal awareness, as

Partzsch (2017) discussed. The Water-Sharing Tool uses impact assessment histograms, Box and Whisker plots, and monthly distributions to explore water shortage impacts tied to different allocation options across socio-economic uses. These graphics are intended to ensure a consistent understanding of model outcomes to decision-makers. However, communicating these to non-specialists would be challenging; thus, alternative graphics are used where possible (sections 6.4.3 to 6.4.7).

7.1.4. Encountered Issues

Uncertainty remains about the views of the upstream water users and their reception of the process presented here.

The findings reported here should be interpreted with the understanding that they do not reflect the objectives/preferences of the upstream user, who is the most influential in the catchment. Any change in scarcity management strategy will immediately affect this user group. Engaging all impacted parties (or their representatives) and prioritising equitable contributions to the inclusive process ensures that all stakeholders exercise their democratic right to participate in water management, as outlined in the law and global policies. Consistent participation is ideal for beneficial knowledge exchange, fostering a shared sense of decision ownership, and ensuring equal say in decision-making. Since the upstream user was not represented, a claim on the legitimacy of these outcomes cannot be made. Also, the Water User Association made no efforts to bring these users on board. Nonetheless, committed stakeholders were empowered by the collaborative learning experience, which is anticipated to be handy in future deliberations.

Stakeholders had difficulty understanding the flexibility in collecting the socio-economic data used in the model.

Some stakeholders struggled to grasp how the socio-economic data protocol could be applied flexibly. This is despite efforts to clarify the flexibility of the community preference for allocation (community weights) and user-risk profiles in a plenary presentation. The presentation emphasised that the index can be developed using a variety of approaches, including biophysical impact (e.g., drought effects on crop health), pure economic terms (e.g., proportion of employment and production losses during dry periods), and pure social considerations (e.g., perception of equitable decisions on social cohesion), or a comprehensive approach. I selected the indirect holistic approach to respect time limits while still attempting to represent the embedded complexity in coping with water deficits. As a result, I based the index on information exchanges between water users and specialists over three years in the Wyk. However, decision-makers using the process can always propose a change to how the index is calculated.

Data scarcity affects the ability to reduce uncertainty.

Rainfall data, water transfers, reservoir operations, and a limited understanding of the groundwater regime in the catchment were identified as the major sources of uncertainty affecting the reliable streamflow estimation. As expected, streamflow uncertainties are propagated into the impact analysis outcomes by the Water-Sharing Tool. Nonetheless, decision-makers are implored to embrace such uncertainties as integral features of water resource management and invest in interdisciplinary relationships with experts and practitioners to help understand and reduce the propagated uncertainty.

The model should be applied with caution and clearly stated objectives.

The Water-Sharing Tool, which operates on a sub-area scale with monthly time steps, belongs in the conceptual semi-distributed category. It evaluates the relative impacts (such as water deficit risk due to streamflow variability and uncertainty due to imperfect knowledge) of different allocation procedures for distinct users. By realistically modelling water use and access in the catchment, this model facilitates a thorough analysis of distributive fairness because of plausible allocation strategies. In the Twee Wyk case study, the model explores the local socio-economic repercussions of enhanced environmental protection levels. Notably, it emphasised downstream consequences from limited streamflow access driven by increased environmental protection paired with upstream operations. As the catchment has been upgraded to level B (near-natural flows) E-Flows, it will be interesting to explore the ecological and downstream implications of a lower E-Flow category by setting up the model for the entire water management area. This task is left for future research.

However, since the water users in the catchment occupy different sub-areas and have no central abstraction point, the distributed setup posed challenges for conducting a comparative analysis of equitable decisions across socio-economic uses. From the water user perspective, this issue can be justified based on the decentralised nature of water withdrawal in the catchment, where no central storage for all users exists. When interrogating equity, the distributed setup complicates the direct identification of winners and losers emerging from the proposed equitable sharing options. Therefore, a lumped setup is recommended for model applications seeking equitable distribution across the catchment.

7.1.5. Recommendations

Focus on inclusive participation to engrain fair procedures in local decision-making.

The process outlined here highlights the importance of full representation above partial representation in ensuring inclusive and informed decision-making. Unrestricted participation entails respecting the surrounding constraints that influence stakeholders' ability to participate, hence limiting their potential to acquire recognition and group advantages. For example, the modelling process was enriched and contextualised by inviting all stakeholders, independent of economic activity in the catchment. A key point to promoting the use of the tools presented here is securing a buy-in from the Water User Associations.

Improved communication of the alternative scarcity management choices.

Simplify and improve communication of the equitable reallocation strategies in order to increase understanding. Through the game, we discovered that stakeholders, particularly farmers, like realistic and precise details, which were originally strategyd out for game simplicity. The specifics may be revealed by shifting the game to a desktop version, which would be more robust in terms of the effects of scarcity management choices. A computerised game version will also be able to better handle the abstract aspects of the game, such as groundwater abstraction, the impact of upstream water transfer, and dam storage. The Allocation Model outputs encompass most of these specifics but must be transferred to a simplified format.

Model improvements to also show groundwater withdrawal impacts.

Currently, the Allocation Model is limited to surface water reallocation, and groundwater is indirectly included. The effects of groundwater abstraction are considered at the water balance stage (hydrological input) as well as the E-Flow requirements. For the latter, the model uses baseflow parameters to account for E-Flows in the low-flow component. Attention to groundwater dynamics is vital as this hidden source is increasingly withdrawn during dry periods and is a dominant supply source in arid areas.

Focus on holistic impacts to better measure the fairness of outcomes based on underlying vulnerabilities.

Impact or the relative change in socio-economic and environmental outcomes for each user and the community is used as a measure of distributive equity in the game outcomes. Using relative impact is seen as a way of confronting criticisms over the use of inequality metrics such as the Gini coefficient and facilitating a discussion on minimising the emerging socio-economic and environmental costs of scarcity management decisions. Economic sectors operating in countries with robust environmental and water laws are familiar with the holistic impact assessment procedure through sustainability assessments. The same procedures can be adapted to inform the water reallocation process to capture underlying sectorial vulnerability that may further reduce resilience from water deficits. This study took this approach, although not obvious to some involved stakeholders.

Evaluate trade-offs and promote acceptance of winners and losers.

Achieving equity requires flexibility in water allocation planning and an understanding that equitable outcomes will not always translate to winners across society. Therefore, the Water-Sharing Tool outputs and holistic vulnerability assessment approach mentioned above should be leveraged to investigate potential trade-offs between competing uses. Examples of such trade-offs include agriculture vs agriculture or environment vs agriculture, which the model can support from the view of impacts/risk tolerance.

Open access database to reduce uncertainty and maintain consistency.

In many catchments within southern Africa, hydro-climatic monitoring is mainly deficient. Meanwhile, this data is essential to predict the hydrology regime of catchments. As the prospects for region-wide improvement are not promising due to other key infrastructure backlogs and development plans, it is clear that data availability will remain a key limitation in water resource management. An open-access dataset containing citizen-collected data (rainfall, streamflow, soil moisture, groundwater dynamics, and dam levels), model parameters, and simulation outputs could be one way to deal with the growing uncertainty in the region.

Additionally, the absence of dam operation trends made it impossible to validate the simulated dam performance statistically or to propose dam operation strategies realistically. It should be possible to qualitatively validate the dam performance outcomes in a decision-making platform since the model is intended for use in decision support.

Phased introduction of new alternatives and innovations.

One of the main attributions to the failed realisation of the transformative South African National Water Act objectives was the introduction of too many changes in a short time (Schreiner, 2013). A reflective lesson to be learnt from the failure mentioned above is the importance of a phased introduction of new alternatives and innovative tools. Doing so will ensure the stakeholders and decision-makers have the understanding and time to experiment and build on successes. It will also ensure that stakeholders are not overwhelmed by new information.

6.6. Concluding remarks

Although this project did not result in a change in the water-sharing strategy in the catchment, it did expose farmers, residents, NGOs (World Wild Fund-South Africa), representatives from the Department of Agriculture for the Western Cape, and the Department of Water and Sanitation to different ways of equitably managing their surface water. Part of the issue was that the Water User Association in this catchment is run by corporate farmers who were unwilling to engage with the work. This is not the case for all Water User Associations in South Africa, many of which are interested in improving demand management and exploring alternative pathways. The Department of Agriculture in the Western Cape has requested that we present the work to other Water User Associations within the Western Cape (or Olifants-Berg Water Management Area), and they are going to facilitate this process. A non-academic output is being prepared to ensure that the model outputs are more accessible to decision-makers. This will be provided to the Department of Agriculture in the Western Cape who will disseminate and promote the use of the model among Water User Associations. The outputs from this model are assisting the farmers in the catchment to produce a water management plan, which is a requirement of the Department of Water and Sanitation prior to water use authorisation given for a potential new dam. The engagement with the interested farmers, therefore continues.

8. LITERATURE CITED

Abdulla A, Barros VR, Calvo E, Field CB, Moreno JM, Mach KJ, van Aalst MK, Neil Adger W, Arent DJ, Barnett J, Betts RA, Eren Bilir T, Birkmann J, Carmin J, Chadee Trinidad DD, Challinor AJ, Chatterjee USA M, Cramer Germany W, Davidson DJ, Otsuki Estrada USA Y, Gattuso J-P, Hijioka Y, Hoegh-Guldberg O, Aldunce P, Pierre Ometto J, Raholijao N, Yasuhara K, Barros V, Mach K, van Aalst M, Adger W, Arent D, Barnett J, Betts R, Bilir T, Birkmann J, Carmin J, Chadee D, Challinor A, Chatterjee M, Cramer W, Davidson D, Estrada Y, Gattuso J, Hijioka Y, Hoegh-Guldberg O, Huang H, Insarov G, Jones R, Kovats R, Romero-Lankao P, Larsen J, Losada I, Marengo J, McLean R, Mearns L, Mechler R, Morton J, Niang I, Oki T, Olwoch J, Opondo M, Poloczanska E, Pörtner H, Redsteer M, Reisinger A, Revi A, Schmidt D, Shaw M, Solecki W, Stone D, Stone J, Strzepek K, Suarez A, Tschakert P, Valentini R, Vicuña S, Villamizar A, Vincent K, Warren R, White L, Wilbanks T, Wong P, Yohe G, Dokken D, Ebi K, Genova R, Girma B, Kissel E. 2014. *Technical summary. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. *Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK; New York, USA

Abrami G, Ferrand N, Morardet S, Murgue C, Popova A, De Fooij H, Farolfi S, Toit D Du, Aquae-Gaudi W. 2012. Wat-A-Game, a toolkit for building role-playing games about integrated water management. In: Seppelt R, Voinov A., Lange S and Bankamp D (eds) *International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting*. http://www.iemss.org/society/index.php/iemss-2012-proceedings: Leipzig, Germany

Aczél J, Saaty TL. 1983. Procedures for synthesizing ratio judgements. *Journal of Mathematical Psychology* **27**: 93–102. DOI: 10.1016/0022-2496(83)90028-7

Adom RK, Simatele MD. 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

Aerts JCJH, Botzen WJ, Clarke KC, Cutter SL, Hall JW, Merz B, Michel-Kerjan E, Mysiak J, Surminski S, Kunreuther H. 2018. Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change* **8**: 193–199. DOI: 10.1038/s41558-018-0085-1

African Union. 2015. *Goals and priority areas of Agenda 2063*. *The African Union Commission*

Amer M, Daim TU, Jetter A. 2013. A review of scenario planning. *Futures* **46**: 23–40. DOI: 10.1016/J.FUTURES.2012.10.003

Arthington AH, Bhaduri A, Bunn SE, Jackson SE, Tharme RE, Tickner D, Young B, Acreman M, Baker N, Capon S, Horne AC, Kendy E, McClain ME, Poff NLR, Richter BD, Ward S. 2018. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). *Frontiers in Environmental Science* **6**. DOI: 10.3389/FENVS.2018.00045

Arthington AH, Tharme R, Brizga SO, Pusey BJ, Kennard MJ. 2003. Environmental flow assessment with emphasis on holistic methodologies. In: Robin LW and Petr L (eds) *The second international symposium on the management of large rivers for fisheries*. FAO Regional Office for Asia and the Pacific: Bangkok, Thailand, 37–65

Aubert AH, Bauer R, Lienert J. 2018. A review of water-related serious games to specify use in environmental Multi-Criteria Decision Analysis. *Environmental Modelling & Software* **105**: 64–78. DOI: 10.1016/J.ENVSOFT.2018.03.023

Bark RH. 2009. The Arizona Water Settlement Act and urban water supplies. *Irrigation and Drainage Systems* **23**: 79–96. DOI: 10.1007/S10795-009-9075-9

Barnaud C, D’Aquino P, Daré W, Fourage C, Mathevet R, Trébuil G. 2014. Power asymmetries in Companion Modelling processes. *Companion Modelling: A Participatory Approach to Support Sustainable Development*. Springer, Dordrecht, 127–153. DOI: 10.1007/978-94-017-8557-0_6

Barnaud C, van Paassen A. 2013. Equity, power games, and legitimacy: Dilemmas of participatory natural resource management. *Ecology and Society* **18**. DOI: 10.5751/ES-05459-180221

Barreteau O, Bots PWG, Daniell KA. 2010. A framework for clarifying “Participation” in participatory research to prevent its rejection for the wrong reasons. *Ecology and Society* **15**. DOI: 10.5751/es-03186-150201

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**

Barreteau O, Bousquet F, Étienne M, Souchère V, D’Aquino P. 2013. Companion Modelling: A method of adaptive and participatory research. In: Étienne M (ed) *Companion Modelling: A Participatory Approach to Support Sustainable Development*. Springer Netherlands, 13–40. DOI: 10.1007/978-94-017-8557-0_2

Barreteau O, Le Page C, Perez P. 2007. Contribution of simulation and gaming to natural resource management issues: An introduction. *Simulation and Gaming* **38**: 185–194. DOI: 10.1177/1046878107300660

Basco-Carrera L, van Beek E, Jonoski A, Benítez-Ávila C, PJ Guntoro F. 2017a. Collaborative Modelling for Informed Decision Making and Inclusive Water Development. *Water Resources Management* **31**: 2611–2625. DOI: 10.1007/s11269-017-1647-0

Basco-Carrera L, Warren A, van Beek E, Jonoski A, Giardino A. 2017b. Collaborative modelling or participatory modelling? A framework for water resources management. *Environmental Modelling & Software* **91**: 95–110. DOI: 10.1016/J.ENVSOFT.2017.01.014

Bauer C. 2015. Water conflicts and entrenched governance problems in Chile's market model. *Water Alternatives* **8**: 147–172

Beven K. 2006. A manifesto for the equifinality thesis. *Journal of Hydrology* **320**: 18–36. DOI: 10.1016/J.JHYDROL.2005.07.007

Beven K. 2011. I believe in climate change but how precautionary do we need to be in planning for the future? *Hydrological Processes* **25**: 1517–1520. DOI: 10.1002/hyp.7939

Beven K. 2013. So how much of your error is epistemic? Lessons from Japan and Italy. *Hydrological Processes* **27**: 1677–1680. DOI: 10.1002/HYP.9648

Beven K. 2016. Facets of uncertainty: Epistemic uncertainty, non-stationarity, likelihood, hypothesis testing, and communication. *Hydrological Sciences Journal* **61**: 1652–1665. DOI: 10.1080/02626667.2015.1031761

Beven K, Binley A. 2014. GLUE: 20 years on. *Hydrological Processes* **28**: 5897–5918. DOI: 10.1002/HYP.10082

Beven K, Westerberg I. 2011. On red herrings and real herrings: Disinformation and information in hydrological inference. *Hydrological Processes*, 1676–1680. DOI: 10.1002/hyp.7963

Beven KJ, Alcock RE. 2012. Modelling everything everywhere: A new approach to decision-making for water management under uncertainty. *Freshwater Biology* **57**: 124–132. DOI: 10.1111/j.1365-2427.2011.02592.x

Bieger K, Arnold JG, Rathjens H, White MJ, Bosch DD, Allen PM, Volk M, Srinivasan R. 2017. Introduction to SWAT+, a completely restructured version of the soil and water assessment tool. *Wiley Online LibraryK Bieger, JG Arnold, H Rathjens, MJ White, DD Bosch, PM Allen, M Volk, R SrinivasanJAWRA Journal of the American Water Resources Association, 2017•Wiley Online Library* **53**: 115–130. DOI: 10.1111/1752-1688.12482

Biggs R, Clements H, de Vos A, Maciejewski K, Preiser R, Schlüter M (eds). 2021. *The Routledge Handbook of Research Methods for Social-Ecological Systems*. *Taylor and Francis*. Routledge: London. DOI: 10.4324/9781003021339-5

Biggs R, Rhode C, Archibald S, Kunene LM, Mutanga SS, Nkuna N, Ocholla PO, Phanidma LJ. 2015. Strategies for managing complex social-ecological systems in the face of uncertainty: examples from South Africa and beyond. *Ecology and Society* **20**: 52. DOI: 10.5751/ES-07380-200152

Birch S, Brown J, Chihumbiri F, Lize J-B, van Weele G. 2021. *Western Cape Climate Change Response Strategy: Vision 2050*. *Western Cape Government*. Cape Town

Blair P, Buytaert W. 2015. Modelling socio-hydrological systems: A review of concepts, approaches and applications. *Hydrology and Earth System Sciences Discussions* **12**: 8761–8851. DOI: 10.5194/HESSD-12-8761-2015

Blair P, Buytaert W. 2016. Socio-hydrological modelling: A review asking “why, what and how?” *Hydrol. Earth Syst. Sci* **20**: 443–478. DOI: 10.5194/hess-20-443-2016

Blöschl G, Bierkens MFP, Chambel A, Cudennec C, Destouni G, Fiori A, Kirchner JW, McDonnell JJ, Savenije HHG, Sivapalan M, Stumpp C, Toth E, Volpi E, Carr G, Lupton C, Salinas J, Széles B, Viglione A, Aksoy H, Allen ST, Amin A, Andréassian V, Arheimer B, Aryal SK, Baker V, Bardsley E, Barendrecht MH, Bartosova A, Batelaan O, Berghuijs WR, Beven K, Blume T, Bogaard T, Borges de Amorim P, Böttcher ME, Boulet G, Breinl K, Brilly M, Brocca L, Buytaert W, Castellarin A, Castelletti A, Chen X, Chen Y, Chen Y, Chifflard P, Claps P, Clark MP, Collins AL, Croke B, Dathe A, David PC, de Barros FPJ, de Rooij G, Di Baldassarre G, Driscoll JM, Duethmann D, Dwivedi R, Eris E, Farmer WH, Feiccabrino J, Ferguson G, Ferrari E, Ferraris S, Fersch B, Finger D, Foglia L, Fowler K, Gartsman B, Gascoin S, Gaume E, Gelfan A, Geris J, Gharari S, Gleeson T, Glendell M, Gonzalez Bevacqua A, González-Dugo MP, Grimaldi S, Gupta AB, Guse B, Han D, Hannah D, Harpold A, Haun S, Heal K, Helfricht K, Herrnegger M, Hipsey M, Hlaváčiková H, Hohmann C, Holko L, Hopkinson C, Hrachowitz M, Illangasekare TH, Inam A, Innocente C, Istanbulluoglu E, Jarihani B, Kalantari Z, Kalvans A, Khanal S, Khatami S, Kiesel J, Kirkby M, Knoben W, Kochanek K, Kohnová S, Kolechkina A, Krause S, Kreamer D, Kreibich H, Kunstmann H, Lange H, Liberato MLR, Lindquist E, Link T, Liu J, Loucks DP, Luce C, Mahé G, Makarieva O, Malard J, Mashtayeva S, Maskey S, Mas-Pla J, Mavrova-Guirguinova M, Mazzoleni M, Mernild S, Misstear BD, Montanari A, Müller-Thomy H, Nabizadeh A, Nardi F, Neale C, Nesterova N, Nurtaev B, Odongo VO, Panda S, Pande S, Pang Z, Papacharalampous G, Perrin C, Pfister L, Pimentel R, Polo MJ, Post D, Prieto Sierra C, Ramos MH, Renner M, Reynolds JE, Ridolfi E, Rigon R, Riva M, Robertson DE, Rosso R, Roy T, Sá JHM, Salvadori G, Sandells M, Schaefli B, Schumann A, Scolobig A, Seibert J, Servat E, Shafiei M, Sharma A, Sidibe M, Sidle RC, Skaugen T, Smith H, Spiessl SM, Stein L, Steinsland I, Strasser U, Su B, Szolgay J, Tarboton D, Tauro F, Thirel G, Tian F, Tong R, Tussupova K, Tyralis H, Uijlenhoet R, van Beek R, van der Ent RJ, van der Ploeg M, Van Loon AF, van Meerveld I, van Nooijen R, van Oel PR, Vidal JP, von Freyberg J, Vorogushyn S, Wachniew P, Wade AJ, Ward P, Westerberg IK, White C, Wood EF, Woods R, Xu Z, Yilmaz KK, Zhang Y. 2019. Twenty-three unsolved problems in hydrology (UPH) - A community perspective. *Hydrological Sciences Journal* **64**: 1141–1158. DOI: 10.1080/02626667.2019.1620507

Blöschl G, Sivapalan M, Wagener T, Savenije H. 2013. *Runoff prediction in ungauged basins: synthesis across processes, places and scales*.

Bonté B, Therville C, Bousquet F, Simi C, Abrami G, Guerbois C, Fritz H, Barreteau O, Dhenain S, Mathevet R. 2021. Simulating together multiscale and multisectoral adaptations to global change and their impacts: A generic serious game and its implementation in coastal areas in France and South Africa. In: Garbolino E and Canicio C (eds) *Ecosystem and Territorial Resilience: A Geoprospective Approach*. Elsevier: Amsterdam, 247–278. DOI: 10.1016/B978-0-12-818215-4.00009-2

Booker JF, Howitt RE, Michelsen AM, Young RA. 2012. Economics and the modelling of water resources and policies. *Natural Resource Modeling* **25**: 168–218. DOI: 10.1111/J.1939-7445.2011.00105.X

Borowski I, Hare M. 2007. Exploring the gap between water managers and researchers: Difficulties of model-based tools to support practical water management. *Water Resources Management* **21**: 1049–1074. DOI: 10.1007/S11269-006-9098-Z

Bowman BM, Abbott-Donnelly I, Barsoum J-F, Williams P, Hunt DVL, Rogers CDF. 2023. The water pivot: transforming unsustainable consumption to valuing water as a resource for life. *Frontiers in Sustainability* **4**. DOI: 10.3389/frsus.2023.1177574

Brand U, Muraca B, Pineault É, Sahakian M, Schaffartzik A, Novy A, Streissler C, Haberl H, Asara V, Dietz K, Lang M, Kothari A, Smith T, Spash C, Brad A, Pichler M, Plank C, Velegrakis G, Jahn T, Carter A, Huan Q, Kallis G, Martínez Alier J, Riva G, Satgar V, Teran Mantovani E, Williams M, Wissen M, Görg C. 2021. From planetary to societal boundaries: an argument for collectively defined self-limitation. *Sustainability: Science, Practice and Policy* **17**: 265–292. DOI: 10.1080/15487733.2021.1940754

Brent AC, Musango JK, Smit S, Pillay NS, Botha A, Louw R, Roper S, Simelani T, Clifford-Holmes JK, Pretorius L. 2017. Utilization of System Dynamics in southern Africa: A systematic review. *Systems Research and Behavioral Science* **34**: 657–670. DOI: 10.1002/SRES.2401

Brisbois MC, de Loë RC. 2016. Power in collaborative approaches to governance for water: A systematic review. *Society and Natural Resources* **29**: 775–790. DOI: 10.1080/08941920.2015.1080339

Brown J. 2013. Can Participation Change the Geography of Water? Lessons from South Africa. *Annals of the Association of American Geographers* **103**: 271–279. DOI: 10.1080/00045608.2013.754685

Calverley CM, Walther SC. 2022. Drought, water management, and social equity: Analyzing Cape Town, South Africa's water crisis. *Frontiers in Water* **4**. DOI: 10.3389/frwa.2022.910149

Campanhão LMB, Picharillo C, Ranieri VEL, Okawa CMP. 2021. Socioeconomic and environmental impacts of water markets: A literature review. *Desenvolvimento e Meio Ambiente* **56**: 275 – 291. DOI: 10.5380/dma.v56i0.73765

Candido LA, Coêlho GAG, de Moraes MMGA, Florêncio L. 2022. Review of decision support systems and allocation models for integrated water resources management focusing on joint water quantity-quality. *Journal of Water Resources Planning and Management* **148**: 03121001. DOI: 10.1061/(ASCE)WR.1943-5452.0001496

Canfield K, Cato A, Torso K, Mulvaney K. 2023. Waves of change: A preliminary literature review of non-drinkable water and environmental justice research. *Hydrological Sciences Journal* **69**: 120–138. DOI: 10.1080/02626667.2023.2280679

Carr G, Barendrecht MH, Debevec L, Kuil L, Blöschl G. 2020. People and water: Understanding integrated systems needs integrated approaches. *Journal of Water Supply: Research and Technology - AQUA*. DOI: 10.2166/aqua.2020.055

Carr G, Blöschl G, Loucks DP. 2012. Evaluating participation in water resource management: A review. *Water Resources Research* **48**: 11401. DOI: 10.1029/2011WR011662

Cody KC. 2018. Upstream with a shovel or downstream with a water right? Irrigation in a changing climate. *Environmental Science and Policy* **80**: 62–73. DOI: 10.1016/j.envsci.2017.11.010

Colvin J, Ballim F, Chimbuya S, Everard M, Goss J, Klarenberg G, Ndlovu S, Ncala D, Weston D. 2008. Building capacity for co-operative governance as a basis for integrated water resource managing in the Inkomati and Mvoti catchments, South Africa. *Water SA* **34**: 681–690. DOI: 10.4314/WSA.V34I6.183669

Coulibaly M, Becker S. 2007. Spatial interpolation of annual precipitation in South Africa - Comparison and evaluation of methods. *Water International* **32**: 494–502. DOI: 10.1080/02508060708692227

Cowie AL, Orr BJ, Castillo Sanchez VM, Chasek P, Crossman ND, Erlewein A, Louwagie G, Maron M, Metternicht GI, Minelli S, Tengberg AE, Walter S, Welton S. 2018. Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science and Policy* **79**: 25–35. DOI: 10.1016/j.envsci.2017.10.011

Coxon G, Freer J, Westerberg IK, Wagener T, Woods R, Smith PJ. 2015. A novel framework for discharge uncertainty quantification applied to 500 UK gauging stations. *Water Resources Research* **51**: 5531–5546. DOI: 10.1002/2014WR016532

Crespo D, Albiac J, Kahil T, Esteban E, Baccour S. 2019. Tradeoffs between water uses and environmental flows: A hydroeconomic analysis in the Ebro Basin. *Water Resources Management* **33**: 2301–2317. DOI: 10.1007/S11269-019-02254-3

Crutzen PJ. 2002. Geology of mankind. *Nature* **415**: 6867. DOI: 10.1038/415023a

DEADP. 2011. Status quo report: The Olifants/Doorn WMA. *Western Cape IWRM Action Plan*. Cape Town, South Africa, 287–311

DEFF. 2021. *South African National Land Cover 2020 Accuracy Assessment Report*. Pretoria

Delorit JD, Block PJ. 2018. Promoting Competitive Water Resource Use Efficiency at the Water-Market Scale: An Intercooperative Demand Equilibrium-Based Approach to Water Trading. *Water Resources Research* **54**: 5394–5421. DOI: 10.1029/2017WR022323

Denby K, Movik S, Mehta L, Van Koppen B. 2016. The "Trickle Down" of IWRM: A case study of local-level realities in the Inkomati Water Management Area, South Africa. *Water Alternatives* **9**: 473–492

Department of Water Affairs and Forestry. 2013. *Second National Water Resource Strategy (NWRS-2): Water for an equitable and sustainable future*. *Department of Water Affairs and Forestry*. Department of Water Affairs: Pretoria

Department of Water and Sanitation. 2016. *Department of Water and Sanitation schedule classes of water resources and resource quality objectives for catchments of the Lower Vaal in Terms of Section 13 (1)(a) and (B) of the National Water Act (Act No . 36 of 1998)*. *Government Gazette No. 39943*. Pretoria, South Africa, 600–617

Department of Water and Sanitation. 2017. *Proposed reserve determination of water resources for the Olifants-Doorn Catchments (Public Law 356 of 2017)*. *Government Gazette No. 40785*. Department of Water and Sanitation: Pretoria, South Africa

Department of Water and Sanitation. 2022. *National Water Resources Strategy 3*. *Government Gazette No. 47133*. Pretoria, South Africa

Di Baldassarre G, Brandimarte L, Beven K. 2016. The seventh facet of uncertainty: Wrong assumptions, unknowns and surprises in the dynamics of human–water systems. *Hydrological Sciences Journal* **61**: 1748–1758. DOI: 10.1080/02626667.2015.1091460

Di Baldassarre G, Montanari A. 2009. Uncertainty in river discharge observations: A quantitative analysis. *Hydrology and Earth System Sciences* **13**: 913–921. DOI: 10.5194/hess-13-913-2009

Di Baldassarre G, Wanders N, AghaKouchak A, Kuil L, Rangecroft S, Veldkamp TIE, Garcia M, van Oel PR, Breinl K, Van Loon AF. 2018. Water shortages worsened by reservoir effects. *Nature Sustainability 2018 1:11* **1**: 617–622. DOI: 10.1038/s41893-018-0159-0

Dibble C. 2006. Computational Laboratories for Spatial Agent-Based Models. *Handbook of Computational Economics*. Elsevier, 1511–1548. DOI: 10.1016/S1574-0021(05)02031-9

Dinar A, Rosegrant MW, Meinzen-Dick R. 1997. *Water Allocation Mechanisms: Principles and Examples*. *Policy Research Working Papers*. DOI: 10.1596/1813-9450-1779

Dionisio Pérez-Blanco C, Loch A, Mejino-López J, Gil-García L, Adamson D, Saiz-Santiago P, Antonio Ortega J. 2024. Abatement and transaction costs of water reallocation. *Journal of Hydrology* **635**: 131119. DOI: 10.1016/J.JHYDROL.2024.131119

Du Toit D, Pollard S. 2009. Updating public participation in IWRM: A proposal for a focused and structured engagement with catchment management strategies. *Water SA* **34**: 707–714. DOI: 10.4314/wsa.v34i6.183674

Du Toit D, Pollard S, Burt J, von Balkom M. 2013. *The Shared River Initiative Part 1: Collective action for improved water resources management (WRC Report N°TT 572/13)*. *Water Research Commission*. Pretoria

Du Y, Zhao D, Qiu S, Zhou F, Peng J. 2022. How can virtual water trade reshape water stress pattern? A global evaluation based on the metacoupling perspective. *Ecological Indicators* **145**: 109712. DOI: 10.1016/j.ecolind.2022.109712

DWAF. 2005. *Groundwater Resource Assessment II*.

Dzikiti S, Schachtschneider K. 2015. *Technical report: Water stewardship for stone fruit farmers*. *WWF-SA*. Cape Town

EasyData. 2022a. *Employment and compensation, electronic dataset*. *Quantec*

EasyData. 2022b. *International Trade by industry, electronic dataset*. *Quantec*

EasyData. 2022c. *Annual agricultural survey & census of commercial agriculture*. *Quantec*

EasyData. 2022d. *Regional output and GVA at 2015 constant prices, electronic dataset*. *Quantec*

Edmunds D, Wollenberg E. 2001. A strategic approach to multistakeholder negotiations. *Development and Change* **32**: 231–253. DOI: 10.1111/1467-7660.00204

Ellender BR, Wasserman RJ, Chakona A, Skelton PH, Weyl OLF. 2017. A review of the biology and status of Cape Fold Ecoregion freshwater fishes. *Aquatic Conservation: Marine and Freshwater* **27**: 867–879. DOI: 10.1002/aqc.2730

Elleuch MA, Euchi J, Haddar B, Frikha A. 2023. *A Fuzzy Mathematical Model with Group Decision-*

Making to Solve the Water Allocation Problem: Tunisian Case. *Process Integration and Optimization for Sustainability*. Springer Nature Singapore. DOI: 10.1007/s41660-022-00303-w

Elshafei Y, Sivapalan M, Tonts M, Hipsey MR. 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

Étienne M (ed). 2014. *Companion Modelling: A participatory approach to support sustainable development*. Soringer: Dordrecht. DOI: 10.1007/978-94-017-8557-0

Etienne M, Du Toit DR, Pollard S. 2011. ARDI: A co-construction Method for Participatory Modeling in Natural Resources. *Ecology and Society* **16**: 44

Farolfi S, Müller JP, Bonté B. 2010. An iterative construction of multi-agent models to represent water supply and demand dynamics at the catchment level. *Environmental Modelling & Software*, 1130–1148. DOI: 10.1016/j.envsoft.2010.03.018

Farriansyah AM, Juwono PT, Suhartanto E, Dermawan V. 2018. Water allocation computation model for river and multi-reservoir system with sustainability-efficiency-equity criteria. *Water (Switzerland)* **10**. DOI: 10.3390/W10111537

Feuillette S, Bousquet F, Le Goulven P. 2003. SINUSE: A multi-agent model to negotiate water demand management on a free access water table. *Environmental Modelling & Software* **15**: 413–427. DOI: 10.1016/S1364-8152(03)00006-9

Fischhoff B, Davis AL. 2014. Communicating scientific uncertainty. *Proceedings of the National Academy of Sciences* **111**: 13664–13671. DOI: 10.1073/PNAS.1317504111

Fisher MB, Shields KF, Chan TU, Christenson E, Cronk RD, Leker H, Samani D, Apoya P, Lutz A, Bartram J. 2015. Understanding handpump sustainability: Determinants of rural water source functionality in the Greater Afram Plains region of Ghana. *Water Resources Research* **51**: 8431–8449. DOI: 10.1002/2014WR016770

Fletcher SM, Giuliani M, Di Milano P, Gold D, Figueroa AJ. 2022. Equity in water resources planning: A path forward for decision support modelers. *Journal of Water Resources Planning and Management* **148**: 02522005. DOI: 10.1061/(ASCE)WR.1943-5452.0001573

Flörke M, Schneider C, McDonald RI. 2018. Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability 2017 1:1* **1**: 51–58. DOI: 10.1038/s41893-017-0006-8

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK. 2005. Global consequences of land use. *Science* **309**: 570–574. DOI: 10.1126/science.1111772

Ford A. 2010. Modelling the environment: An introduction to system dynamics modelling of environmental systems. *International Journal of Sustainability in Higher Education* **1**. DOI: 10.1108/ijshe.2000.24901aae.002

Forman E, Peniwati K. 1998. Aggregating individual judgments and priorities with the analytic hierarchy process. *European Journal of Operational Research* **108**: 165–169. DOI: 10.1016/S0377-2217(97)00244-0

Fu B, Merritt WS, Croke BFW, Weber TR, Jakeman AJ. 2019. A review of catchment-scale water quality and erosion models and a synthesis of future prospects. *Environmental Science Modelling & Software* **114**: 75--97. DOI: 10.1016/j.envsoft.2018.12.008

Funk C, Peterson P, Landsfeld M, Pedreros D, Verdin J, Shukla S, Husak G, Rowland J, Harrison L, Hoell A, Michaelsen J. 2015. The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Scientific Data* **2**: 150066. DOI: 10.1038/sdata.2015.66

Garrick D, De Stefano L, Yu W, Jorgensen I, O'Donnell E, Turley L, Aguilar-Barajas I, Dai X, de Souza Leão R, Punjabi B, Schreiner B. 2019. Rural water for thirsty cities: A systematic review of water reallocation from rural to urban regions. *Environmental Research Letters* **14**: 043003. DOI: 10.1088/1748-9326/ab0db7

Garrick D, Siebentritt MA, Aylward B, Bauer CJ, Purkey A. 2009. Water markets and freshwater ecosystem services: Policy reform and implementation in the Columbia and Murray-Darling Basins. *Ecological Economics* **69**: 366–379. DOI: 10.1016/J.ECOLECON.2009.08.004

Gleeson B, Low N. 2002. *Justice, Society and Nature*. *Justice, Society and Nature*. Routledge. DOI: 10.4324/9780203006689

Gleick PH, Palaniappan M. 2010. Peak water limits to freshwater withdrawal and use. *Proceedings of* *the National Academy of Sciences of the United States of America* **107**: 11155–11162. DOI: 10.1073/pnas.1004812107

Global Water Partnership. 2024. *IWRM explained*. *IWRM Action Hub*

Gober P. 2014. Decision making under uncertainty: A new paradigm for water resources planning and management. In: Wang L and Yang C (eds) *Modern Water Resources Engineering*. Humana Press Inc., 411–436. DOI: 10.1007/978-1-62703-595-8_8

Gober P, Wheater H. 2015. Debates—Perspectives on socio-hydrology: Modeling flood risk as a public policy problem. *Water Resources Research* **51**: 4782–4788. DOI: 10.1002/2015WR016945

Grey D, Garrick D, Blackmore D, Kelman J, Muller M, Sadoff C. 2013. Water security in one blue planet: Twenty-first century policy challenges for science. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **371**. DOI: 10.1098/rsta.2012.0406

Grošelj P, Zadnik Stirn L. 2012. Acceptable consistency of aggregated comparison matrices in analytic hierarchy process. *European Journal of Operational Research* **223**: 417–420. DOI: 10.1016/J.EJOR.2012.06.016

Gui Z, Zhang C, Li M, Guo P. 2015. Risk analysis methods of the water resources system under uncertainty. *Frontiers of Agricultural Science and Engineering* **2**: 205–215. DOI: 10.15302/J-FASE-2015073

Gupta A, Govindaraju RS. 2023. Uncertainty quantification in watershed hydrology: Which method to use? *Journal of Hydrology* **616**: 128749. DOI: 10.1016/j.jhydrol.2022.128749

Gupta H V, Clark MP, Vrugt JA, Abramowitz G, Ye M. 2012. Towards a comprehensive assessment of model structural adequacy. *Water Resources Research* **48**. DOI: 10.1029/2011WR011044

Gush M, Dzikiti S, van der Laan M, Steyn M, Manamathela S, Pienaar H. 2019. Field quantification of the water footprint of an apple orchard, and extrapolation to watershed scale within a winter rainfall Mediterranean climate zone. *Agricultural and Forest Meteorology* **271**: 135–147. DOI: 10.1016/J.AGRFORMET.2019.02.042

Gwapedza D, Barreteau O, Mantel S, Paxton B, Bonte B, Tholanah R, Xoxo S, Theron S, Mabohlo S, O'Keeffe L, Bradshaw K, Tanner J. 2024a. Engaging stakeholders to address a complex water resource management issue in the Western Cape, South Africa. *Journal of Hydrology* **639**:

131522. DOI: https://doi.org/10.1016/j.jhydrol.2024.131522

Gwapedza D, Mantel S, Mabohlo S, Theron S, Xoxo S, Paxton B, Barreteau O, Tholanah R, Bradshaw K, Bonte B, Tanner JL. 2024b. *A stakeholder driven process to develop a more equitable and sustainable water resource management plan. Project No. C2020/2021-00607*. *Water Reseach Commission*. Pretoria, South Africa

Halbe J, Pahl-Wostl C, Adamowski J. 2018. A methodological framework to support the initiation, design and institutionalization of participatory modeling processes in water resources management. *Journal of Hydrology* **556**: 701–716. DOI: 10.1016/J.JHYDROL.2017.09.024

Hall J, Borgomeo E. 2013. Risk-based principles for defining and managing water security. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **371**. DOI: 10.1098/rsta.2012.0407

Hamada YM. 2017. Effects of Dams and Barrages on River Channels. *The Grand Ethiopian Renaissance Dam, its Impact on Egyptian Agriculture and the Potential for Alleviating Water Scarcity*. Springer, Cham, 59–75. DOI: 10.1007/978-3-319-54439-7_5

Hamann KRS, Reese G. 2020. My Influence on the World (of Others): Goal Efficacy Beliefs and Efficacy Affect Predict Private, Public, and Activist Pro-environmental Behavior. *Journal of Social Issues* **76**: 35–53. DOI: 10.1111/JOSI.12369

Hare M. 2011. Forms of participatory modelling and its potential for widespread adoption in the water sector. *Environmental Policy and Governance* **21**: 386–402. DOI: 10.1002/EET.590

Harris I, Osborn TJ, Jones P, Lister D. 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data* **7**: 1–18. DOI: 10.1038/s41597-020-0453-3

Hellegers P, Leflaive X. 2015. Water allocation reform: what makes it so difficult? *Water International* **40**: 273–285. DOI: 10.1080/02508060.2015.1008266

Hoekstra AY. 2014. Sustainable, efficient, and equitable water use: The three pillars under wise freshwater allocation. *Wiley Interdisciplinary Reviews: Water* **1**: 31–40. DOI: 10.1002/WAT2.1000

Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD. 2012. Global monthly water scarcity: Blue water footprints versus blue water availability. *PLoS ONE* **7**. DOI: 10.1371/journal.pone.0032688

Höllermann B, Evers M. 2017. Perception and handling of uncertainties in water management—A study of practitioners' and scientists' perspectives on uncertainty in their daily decision-making. *Environmental Science and Policy* **71**: 9–18

Höllermann B, Evers M. 2019. Coping with uncertainty in water management: Qualitative system analysis as a vehicle to visualize the plurality of practitioners' uncertainty handling routines. *Journal of Environmental Management* **235**: 213–223. DOI: 10.1016/J.JENVMAN.2019.01.034

Holmes P, Esler K, … BVW-T of the, 2020 U. 2020. Ecological restoration of ecosystems degraded by invasive alien plants in South African Fynbos: Is spontaneous succession a viable strategy? *Transactions of the Royal Society of South Africa* **75**: 111–139. DOI: 10.1080/0035919X.2020.1781291

Hoogesteger J, Wester P. 2015. Intensive groundwater use and (in)equity: Processes and governance challenges. *Environmental Science and Policy* **51**: 117 – 124. DOI: 10.1016/j.envsci.2015.04.004

Horlitz T. 2007. The role of model interfaces for participation in water management. *Water Resources Management* **21**: 1091–1102. DOI: 10.1007/s11269-006-9100-9

Hrachovitz M, Savenije HHG, Blöschl G, McDonnell JJ, Sivapalan M, Pomeroy JW, Arheimer B, Blume T, Clark MP, Ehret U, Fenicia F, Freer JE, Gelfan A, Gupta H V., Hughes DA, Hut RW, Montanari A, Pande S, Tetzlaff D, Troch PA, Uhlenbrook S, Wagener T, Winsemius HC, Woods RA, Zehe E, Cudennec C. 2013. A decade of Predictions in Ungauged Basins (PUB)—A review. *Hydrological Science Journal* **58**: 1198–1255. DOI: 10.1080/02626667.2013.803183

Hughes D. 2010. Hydrological models: Mathematics or science? *Hydrological Processes* **24**: 2199–2201. DOI: 10.1002/hyp.7805

Hughes D. 2012. Hydrological education and training needs in sub-Saharan Africa: requirements, constraints and progress. *Hydrology and Earth System Sciences,* **16**: 861–871. DOI: 10.5194/hess-16-861-2012

Hughes D, Mohobane T, Mallory SJL. 2015. *Implementing uncertainty analysis in water resources assessment and planning (Report No. 2056/1/14)*. Water Research Commission (WRC): Pretoria, South Africa

Hughes DA. 2004. Incorporating groundwater recharge and discharge functions into an existing monthly rainfall-runoff model. *Hydrological Sciences Journal* **49**: 297–312. DOI:

10.1623/hysj.49.2.297.34834

Hughes DA. 2013. A review of 40 years of hydrological science and practice in southern Africa using the Pitman rainfall-runoff model. *Journal of Hydrology* **501**: 111–124. DOI: 10.1016/j.jhydrol.2013.07.043

Hughes DA. 2016. Hydrological modelling, process understanding and uncertainty in a southern African context: lessons from the northern hemisphere. *Hydrolo* **30**: 2419–2431. DOI: 10.1002/hyp.10721

Hughes DA. 2019. Facing a future water resources management crisis in sub-Saharan Africa. *Journal of Hydrology: Regional Studies* **23**: 100600. DOI: 10.1016/J.EJRH.2019.100600

Hughes DA, Desai AY, Birkhead AL, Louw D. 2014a. 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 DA, Farinosi F. 2021. Unpacking some of the linkages between uncertainties in observational data and the simulation of different hydrological processes using the Pitman model in the data scarce Zambezi River basin. *Hydrological Processes* **35**. DOI: 10.1002/HYP.14141

Hughes DA, Kapangaziwiri E, Sawunyama T. 2010. Hydrological model uncertainty assessment in southern Africa. *Journal of Hydrology* **387**: 221–232. DOI: 10.1016/j.jhydrol.2010.04.010

Hughes DA, Mallory SJL. 2009. The importance of operating strategies and assessments of beneficial use in water resource allocation policy and management. *Water Policy* **11**: 731–741. DOI: 10.2166/wp.2009.035

Hughes DA, Mallory SJL, Haasbroek B, Pegram GGS. 2011. Hydrological and stochastic uncertainty: linking hydrological and water resources yield models in an uncertainty framework. *Risk in Water Resources Management (Proceedings of Symposium H03 held during IUGG2011)*. IAHS Publ: Melbourne, Australia, 127–132

Hughes DA, Mantel S, Mohobane T. 2014b. An assessment of the skill of downscaled GCM outputs in simulating historical patterns of rainfall variability in South Africa. *Hydrology Research* **45**: 134–147. DOI: 10.2166/NH.2013.027

Hughes DA, Mantel SK. 2010. Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. *Hydrological Sciences Journal* **55**: 578–592. DOI: 10.1080/02626667.2010.484903

Iftekhar MS, Fogarty J. 2017. Impact of water allocation strategies to manage groundwater resources in Western Australia: Equity and efficiency considerations. *Journal of Hydrology* **548**: 145–156. DOI: 10.1016/j.jhydrol.2017.02.052

Iglesias A, Garrote L. 2015. Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management* **155**: 113–124. DOI: 10.1016/J.AGWAT.2015.03.014

IPCC. 2007. *Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press: Cambridge, UK

IPCC. 2022. Summary for policymakers. In: Pereira J, Revi A, Rose S, Sanchez-Rodriguez R, Lisa Schipper Sweden EF, Schmidt DU, Schoeman D, Shaw R, Singh C, Solecki W and Stringer L (eds) *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK and New York, USA, 3–33. DOI: 10.1017/9781009325844.001

Ison R, Röling N, Watson D. 2007. Challenges to science and society in the sustainable management and use of water: Investigating the role of social learning. *Environmental Science & Policy* **10**: 499–511. DOI: 10.1016/J.ENVSCI.2007.02.008

Jackson S, Barber M. 2013. Recognition of indigenous water values in Australia's Northern Territory: Current progress and ongoing challenges for social justice in water planning. *Planning Theory and Practice* **14**. DOI: 10.1080/14649357.2013.845684

Joy KJ, Kulkarni S, Roth D, Zwarteveen M. 2014. Re-politicising water governance: exploring water re-allocations in terms of justice. *Local Environment* **19**: 954 – 973. DOI: 10.1080/13549839.2013.870542

Kabuya PM, Hughes DA, Tshimanga RM, Trigg MA, Bates P. 2020. Establishing uncertainty ranges of hydrologic indices across climate and physiographic regions of the Congo River Basin. *Journal of Hydrology: Regional Studies* **30**: 100710. DOI: 10.1016/J.EJRH.2020.100710

Kandasamy J, Sounthararajah D, Sivabalan P, Chanan A, Vigneswaran S, Sivapalan M. 2014. Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: A case study from Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences* **18**: 1027–1041. DOI: 10.5194/HESS-18-1027-2014

Kapangaziwiri E, Hughes DA, Wagener T. 2012. Incorporating uncertainty in hydrological predictions for gauged and ungauged basins in southern Africa. *Hydrological Sciences Journal* **57**: 1000–1019. DOI: 10.1080/02626667.2012.690881

Karcher DB, Cvitanovic C, Colvin RM, van Putten IE, Reed MS. 2021. Is this what success looks like? Mismatches between the aims, claims, and evidence used to demonstrate impact from knowledge exchange processes at the interface of environmental science and policy. *Environmental Science and Policy* **125**: 202–218. DOI: 10.1016/j.envsci.2021.08.012

Keeler BL, Derickson KD, Waters H, Walker R. 2020. Advancing water equity demands new approaches to sustainability science. *One Earth* **2**: 211–213. DOI: 10.1016/j.oneear.2020.03.003

Kellner E. 2021. The controversial debate on the role of water reservoirs in reducing water scarcity. *Wiley Interdisciplinary Reviews: Water*. John Wiley and Sons Inc. DOI: 10.1002/wat2.1514

Kelly B, Keeler B, Helm G, Krantzberg G, Lyon T, Mabee W. 2015. Energy as a driver of change in the Great Lakes-St. Lawrence River Basin. *Journal of Great Lakes Research* **41**: 59–68. DOI: 10.1016/j.jglr.2014.11.019

Kelly RA, Jakeman AJ, Barreteau O, Borsuk ME, ElSawah S, Hamilton SH, Henriksen HJ, Kuikka S, Maier HR, Rizzoli AE, van Delden H, Voinov AA. 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

Kemerink JS, Méndez LE, Ahlers R, Wester P, Van Der Zaag P. 2013. The question of inclusion and representation in rural South Africa: Challenging the concept of water user associations as a vehicle for transformation. *Water Policy* **15**: 243–257. DOI: 10.2166/WP.2012.127

Kibler KM, Biswas RK, Lucas AMJ. 2014. Hydrologic data as a human right? Equitable access to information as a resource for disaster risk reduction in transboundary river basins. *Water Policy* **16**: 36 – 58. DOI: 10.2166/wp.2014.307

Kidd M. 2016. Compulsory licensing under South Africa's National Water Act. **41**: 916–927. DOI: 10.1080/02508060.2016.1214776

King J, Brown C, Sabet H. 2003. A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications* **19**: 619–639. DOI: 10.1002/RRA.709

King J, Louw D. 1998. Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. *Aquatic Ecosystem Health & Management* **1**: 109–124. DOI: 10.1080/14634989808656909

Kingsford RT, Biggs HC. 2012. *Strategic adaptive management guidelines for effective conservation of freshwater ecosystems in and around protected areas of the world. IUCN WCPA Freshwater Taskforce*. DOI: 10.1016/j.biocon.2010.09.022

Kingsford RT, Biggs HC, Pollard SR. 2011. Strategic Adaptive Management in freshwater protected areas and their rivers. *Biological Conservation* **144**: 1194–1203. DOI: 10.1016/J.BIOCON.2010.09.022

Kirchhoff CJ, Lemos MC, Engle NL. 2013. What influences climate information use in water management? The role of boundary organizations and governance regimes in Brazil and the U.S. *Environmental Science and Policy* **26**: 6–18. DOI: 10.1016/j.envsci.2012.07.001

Kirchner JW. 2006. Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research* **42**. DOI: 10.1029/2005WR004362

Knüppe K, Meissner R. 2016. Drivers and barriers towards sustainable water and land management in the Olifants-Doorn Water Management Area, South Africa. *Environmental Development* **20**: 3–14. DOI: 10.1016/J.ENVDEV.2016.09.002

Korteling B, Dessai S, Kapelan Z. 2013. Using Information-Gap Decision Theory for water resources planning under severe uncertainty. *Water Resources Management* **27**: 1149–1172. DOI: 10.1007/s11269-012-0164-4

Kumar P, Avtar R, Dasgupta R, Johnson BA, Mukherjee A, Ahsan MN, Nguyen DCH, Nguyen HQ, Shaw R, Mishra BK. 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

Lane SN. 2014. Acting, predicting and intervening in a socio-hydrological world. *Hydrol. Earth Syst. Sci* **18**: 927–952. DOI: 10.5194/hess-18-927-2014

Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ. 2012. Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustainability Science* **7**: 25–43. DOI: 10.1007/S11625-011-0149-x

Laniak GF, Olchin G, Goodall J, Voinov A, Hill M, Glynn P, Whelan G, Geller G, Quinn N, Blind M, Peckham S, Reaney S, Gaber N, Kennedy R, Hughes A. 2013. Integrated environmental modeling: A vision and roadmap for the future. *Environmental Modelling & Software* **39**: 3–23. DOI: 10.1016/J.ENVSOFT.2012.09.006

Larson KL, Wiek A, Withycombe Keeler L. 2013. A comprehensive sustainability appraisal of water governance in Phoenix, AZ. *Journal of Environmental Management* **116**: 58 – 71. DOI: 10.1016/j.jenvman.2012.11.016

Law EA, Bennett NJ, Ives CD, Friedman R, Davis KJ, Archibald C, Wilson KA. 2018. Equity trade-offs in conservation decision making. *Conservation Biology* **32**: 294–303. DOI: 10.1111/COBI.13008

Le Maître D, Görgens A, Howard G, Walker N. 2019. Impacts of alien plant invasions on water resources and yields from the Western Cape water supply system (WCWSS). *Water SA* **45**: 568–579. DOI: 10.17159/wsa/2019.v45.i4.7538

Le Maître DC, Forsyth GG, Dzikiti S, Gush MB. 2016. Estimates of the impacts of invasive alien plants on water flows in South Africa. *Water SA* **42**: 659–672. DOI: 10.4314/wsa.v42i4.17

Le Maître DC, Kotzee IM, O'Farrell PJ. 2014. Impacts of land-cover change on the water flow regulation ecosystem service: Invasive alien plants, fire and their policy implications. *Land Use Policy* **36**: 171–181. DOI: 10.1016/l.landusepol.2013.07.007

Le Maître DC, Seyler H, Holland M, Smith-Adao L, Nel JL, Maherry A, Witthüser K. 2018. *Identification, delineation and importance of the Strategic Water Source Areas of South Africa, Lesotho and Swaziland for surface water and groundwater (Report No. TT 743/1/18)*. Water Research Commission: Pretoria, South Africa

Leach M, Reyers B, Bai X, Brondizio ES, Cook C, Díaz S, Espindola G, Scobie M, Stafford-Smith M, Subramanian SM. 2018. Equity and sustainability in the anthropocene: A social-ecological systems perspective on their intertwined futures. *Global Sustainability* **1**. DOI: 10.1017/sus.2018.12

Leeuwis C. 2000. Reconceptualising participation for sustainable rural development: Towards a negotiation approach. *Development and Change* **31**: 931–959. DOI: 10.1111/1467-7660.00184

Lempert RJ, Collins MT. 2007. Managing the risk of uncertain threshold responses: Comparison of robust, optimum, and precautionary approaches. *Risk Analysis* **27**: 1009–1026. DOI: 10.1111/J.1539-6924.2007.00940.X

Lerat J, Tomkins K, Shao Q, Peeters L, Yang A, Rassam & D. 2011. *How to quantify uncertainty in water allocation models? An exploratory analysis based on hypothetical case studies*. IAHS Publ

Lesnikowski AC, Ford JD, Berrang-Ford L, Barrera M, Heymann J. 2015. How are we adapting to climate change? A global assessment. *Mitigation and Adaptation Strategies for Global Change* **20**: 277–293. DOI: 10.1007/S11027-013-9491-x

Levy J, Xu Y. 2012. Review: Groundwater management and groundwater/surface-water interaction in the context of South African water policy. *Hydrogeology Journal* **20**: 205–226. DOI: 10.1007/S10040-011-0776-4

Liniger H, Harari N, van Lynden G, Fleiner R, de Leeuw J, Bai Z, Critchley W. 2019. Achieving land degradation neutrality: The role of SLM knowledge in evidence-based decision-making. *Environmental Science & Policy* **94**: 123–134. DOI: 10.1016/J.ENVSCI.2019.01.001

Liu J, Yang H, Gosling SN, Kummu M, Flörke M, Pfister S, Hanasaki N, Wada Y, Zhang X, Zheng C, Alcamo J, Oki T. 2017. Water scarcity assessments in the past, present, and future. *Earth's Future* **5**: 545–559. DOI: 10.1002/2016EF000518

Liu X, Liu W, Liu L, Tang Q, Liu J, Yang H. 2021. Environmental flow requirements largely reshape global surface water scarcity assessment. *Environmental Research Letters* **16**: 104029. DOI: 10.1088/1748-9326/AC27CB

Liu Y, Gupta H V. 2007. Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. *Water Resources Research* **43**: 1–18. DOI: 10.1029/2006WR005756

Loar J, Sale M, Cada G. 1986. Instream flow needs to protect fishery resources (No. CONF-8608120-1). *Oak Ridge National Lab*. Enviornmental Sciences Division: Tennessee, USA

Lockwood M, Davidson J, Curtis A, Stratford E, Griffith R. 2010. Governance Principles for Natural Resource Management. *Society and Natural Resources* **23**: 986–1001. DOI: 10.1080/08941920802178214

Loucks D. 2011. Risk and uncertainty in water resources planning and management: A basic introduction. In: Grafton RQ and Hussey K (eds) *Water resources planning and management.* Cambridge University Press: Cambridge, UK, 230–250. DOI: 10.1017/CBO9780511974304.013

Loucks D. 2015. Debates—Perspectives on socio-hydrology: Simulating hydrologic-human interactions. *Water Resources Research* **51**: 4789–4794. DOI: 10.1002/2015WR017002

Loucks DP, van Beek E. 2017. An introduction to optimization models and methods. *Water Resource Systems Planning and Management*. Springer, Cham, 93–177. DOI: 10.1007/978-3-319-44234-1_4

Louw WJA. 2006. General history of the South African Forest Industry. *Southern African Forestry Journal* **208**: 79–88. DOI: 10.2989/10295920609505264

Lukasiewicz A, Dare M. 2016. When private water rights become a public asset: Stakeholder perspectives on the fairness of environmental water management. *Journal of Hydrology* **536**: 183 – 191. DOI: 10.1016/j.jhydrol.2016.02.045

Ly S, Charles C, Degré A. 2013. Methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at watershed scale: A review. *Biotechnology, Agronomy and Society and Environment* **17**: 392–406

Madigele PK. 2018. Efficiency of common-pool resource institutions: focusing on water users associations in South Africa. *Environment, Development and Sustainability* **20**: 825–840. DOI: 10.1007/S10668-017-9912-1

Mallory SJL, Pashkin J, Ntuli C, Mwaka B. 2013. Reservoir operating strategies across a range of system complexities and degree of operator competencies. **362**

Mallory SJL, van Vuuren SJ, Pashkin EA. 2008. The application of the water resources modeling platform from strategic planning through to operational control. *Physics and Chemistry of the Earth, Parts A/B/C* **33**: 919–925. DOI: 10.1016/J.PCE.2008.06.042

Mantel S, Hughes D, Mantel S, Hughes D. 2023. Farm dams in southern Africa: Balancing environmental and socio-economic sustainability. *Dam Engineering - Design, Construction, and Sustainability [Working Title]*. IntechOpen. DOI: 10.5772/INTECHOPEN.113930

Mantel SK, Hughes DA, Muller NW. 2010. Ecological impacts of small dams on South African rivers Part

1: Drivers of change – water quantity and quality. *Water SA* **36**: 351–360

Mapedza E, van Koppen B, Sithole P, Bourblanc M. 2016. Joint venture schemes in Limpopo Province and their outcomes on smallholder farmers livelihoods. *Physics and Chemistry of the Earth* **92**: 92–98. DOI: 10.1016/J.PCE.2015.10.016

Marston L, Cai X. 2016. An overview of water reallocation and the barriers to its implementation. *WIREs Water* **3**: 658–677. DOI: 10.1002/wat2.1159

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 ES, Woods AM, Harou JJ. 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 KB, Rivington M, Blackstock K, McCrum G, Buchan K, Miller DG. 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

Mayer A, Muñoz-Hernandez A. 2009. Integrated water resources optimization models: An assessment of a multidisciplinary tool for sustainable water resources management strategies. *Geography Compass* **3**: 1776–1195. DOI: 10.1111/j.1749-8198.2009.00239.x

McDermott M, Mahanty S, Schreckenberg K. 2013. Examining equity: A multidimensional framework for assessing equity in payments for ecosystem services. *Environmental Science & Policy* **33**: 416–427. DOI: 10.1016/J.ENVSCI.2012.10.006

McMillan H. 2020. Linking hydrologic signatures to hydrologic processes: A review. *Hydrological Processes* **34**: 1393–1409. DOI: 10.1002/HYP.13632

Mcmillan H, Krueger T, Freer J. 2012. Benchmarking observational uncertainties for hydrology: Rainfall, river discharge and water quality. *Hydrological Processes* **26**: 4078–4111. DOI: 10.1002/HYP.9384

Mcmillan H, Seibert J, Petersen-overleir A, Lang M, White P, Snelder T, Rutherford K, Krueger T, Mason R, Kiang J. 2017. How uncertainty analysis of streamflow data can reduce costs and promote robust decisions in water management applications. *Water Resources Research* **53**: 5220–5228. DOI: 10.1002/2016WR020328

Mehrparvar M, Ahmadi A, Safavi HR. 2016. Social resolution of conflicts over water resources allocation in a river basin using cooperative game theory approaches: A case study. *International Journal of River Basin Management* **14**. DOI: 10.1080/15715124.2015.1081209

Meinzen-Dick R, Ringler C. 2008. Water reallocation: drivers, challenges, threats, and solutions for the poor. *Journal of Human Development* **9**: 47–64. DOI: 10.1080/14649880701811393

Meissner R, Funke N, Nienaber S, Ntombela C. 2013. The status quo of research on South Africa's water resource management institutions. *Water SA* **39**: 721–732. DOI: 10.4314/wsa.v39i5.17

Mekonnen MM, Hoekstra AY. 2016. Four billion people facing severe water scarcity. *Science Advances* **2**: e1500323. DOI: 10.1126/sciadv.1500323

Mendoza GA, Martins H. 2006. Multi-Criteria Decision Analysis in natural resource management: A critical review of methods and new modelling paradigms. *Forest Ecology and Management* **230**: 1–22. DOI: 10.1016/J.FORECO.2006.03.023

Merz L, Yang D, Sustainability VH-, 2020 undefined. 2020. A metacoupling framework for exploring transboundary watershed management. *mdpi.com* **12**. DOI: 10.3390/su12051879

Midgley D., Pitman W., Middleton B. 1994. Volume IV: Drainage regions E, G, H, J, K, L: Appendices - WRC Report N° 298/4.1/94. *Surface water resources of South Africa 1990*. Water Research Commission (WRC)

Midgley SJE, Lötze E. 2011. Climate change in the Western Cape of South Africa: Trends, projections and implications for chill unit accumulation. *Acta Horticulturae* **903**: 1127–1134. DOI: 10.17660/ACTAHORTIC.2011.903.157

Mirchi A, Madani K, Watkins D, Ahmad S. 2012. Synthesis of System Dynamics tools for holistic conceptualization of water resources problems. *Water Resources Management* **26**: 2421–2442. DOI: 10.1007/s11269-012-0024-2

Mirosa O, Harris LM. 2012. Human right to water: Contemporary challenges and contours of a global debate. *Antipode* **44**: 932–949. DOI: 10.1111/J.1467-8330.2011.00929.X

Mirumachi N, Van Wyk E. 2010. Cooperation at different scales: challenges for local and international water resource governance in South Africa. *Geographical Journal* **176**: 25–38. DOI: 10.1111/J.1475-4959.2009.00344.X

Montanari A. 2015. Debates—Perspectives on socio-hydrology: Introduction. . DOI: 10.1002/2015WR017430

Montanari A, Koutsoyiannis D. 2012. A blueprint for process-based modeling of uncertain hydrological systems. *Water Resources Research* **48**. DOI: 10.1029/2011WR011412

Montanari A, Young G, Savenije HHG, Hughes D, Wagener T, Ren LL, Koutsoyiannis D, Cudennec C, Toth E, Grimaldi S, Blöschl G, Sivapalan M, Beven K, Gupta H, Hipsey M, Schaefli B, Arheimer B, Boegh E, Schymanski SJ, Di Baldassarre G, Yu B, Hubert P, Huang Y, Schumann A, Post DA, Srinivasan V, Harman C, Thompson S, Rogger M, Viglione A, McMillan H, Characklis G, Pang Z, Belyaev V. 2013. "Panta Rhei-Everything Flows": Change in hydrology and society-The IAHS Scientific Decade 2013-2022. *Hydrological Sciences Journal* **58**: 1256–1275. DOI: 10.1080/02626667.2013.809088

Mostert E. 2018. An alternative approach for socio-hydrology: Case study research. *Hydrol. Earth Syst. Sci* **22**: 317–329. DOI: 10.5194/hess-22-317-2018

Movik S. 2014. A fair share? Perceptions of justice in South Africa's water allocation reform policy. *Geoforum* **54**: 187–195. DOI: 10.1016/J.GEOFORUM.2013.03.003

Movik S, Mehta L, Van Koppen B, Denby K. 2016. Emergence, Interpretations and Translations of IWRM in South Africa. *Water Alternatives* **9**: 456–472

Müller B, Bohn F, Dreßler G, Groeneveld J, Klassert C, Martin R, Schlüter M, Schulze J, Weise H, Schwarz N. 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software* **48**: 37–48. DOI: 10.1016/J.ENVSOFT.2013.06.003

Munier N, Hontoria E. 2021. Shortcomings of the AHP Method. *Uses and Limitations of the AHP Method: A Non-Mathematical and Rational Analysis*. Springer, Cham, 41–90. DOI: 10.1007/978-3-030-60392-2_5

Ncoyini Z, Savage MJ, Strydom S. 2022. Limited access and use of climate information by small-scale sugarcane farmers in South Africa: A case study. *Climate Services* **26**: 100285. DOI: 10.1016/J.CLISER.2022.100285

Ndzabandzaba C, Hughes DA. 2017. Regional water resources assessments using an uncertain modelling approach: The example of Swaziland. *Journal of Hydrology: Regional Studies* **10**: 47–60. DOI: 10.1016/j.ejrh.2017.01.002

Neal MJ, Lukasiewicz A, Syme GJ. 2014. Why justice matters in water governance: Some ideas for a "water justice framework." *Water Policy* **16**: 1 – 18. DOI: 10.2166/wp.2014.109

Nearing GS, Gupta H V. 2018. Ensembles vs. information theory: supporting science under uncertainty. *Frontiers of Earth Science* **12**: 653–660. DOI: 10.1007/S11707-018-0709-9

Null SE, Olivares MA, Cordera F, Lund JR. 2021. Pareto Optimality and Compromise for Environmental Water Management. *Water Resources Research* **57**: 1–13. DOI: 10.1029/2020WR028296

Null SE, Prudencio L. 2016. Climate change effects on water allocations with season dependent water rights. *Science of the Total Environment* **571**: 943–954. DOI: 10.1016/j.scitotenv.2016.07.081

Nüsser M, Dame J, Kraus B, Baghel R, Schmidt S. 2019. Socio-hydrology of "artificial glaciers" in Ladakh, India: assessing adaptive strategies in a changing cryosphere. *Regional Environmental Change* **19**: 1327–1337. DOI: 10.1007/S10113-018-1372-0

Nyam YS, Kotir JH, Jordaan AJ, Ogundeji AA. 2021. Developing a Conceptual Model for Sustainable water Resource Management and Agricultural Development: the Case of the Breede River Catchment Area, South Africa. *Environmental Management* **67**: 632–647. DOI: 10.1007/S00267-020-01399-X

O'Brien K, Eriksen S, Eriksen S, Schjolden A, Nygaard L. 2004. *What's in a word? Conflicting interpretations of vulnerability in climate change research*. *ICERO Working Paper*. Oslo, Norway

Oftadeh E, Shourian M, Saghafian B. 2017. An Ultimatum Game Theory Based Approach for Basin Scale Water Allocation Conflict Resolution. *Water Resources Management* **31**. DOI: 10.1007/s11269-017-1746-y

Okereke C. 2010. Climate justice and the international regime. *WIREs Climate Change* **1**: 462–474. DOI: 10.1002/wcc.52

Olden JD, Poff NL. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* **19**: 101–121. DOI: 10.1002/RRA.700

Opperman JJ, Kendy E, Tharme RE, Warner AT, Barrios E, Richter BD. 2018. A three-level framework for assessing and implementing environmental flows. *Frontiers in Environmental Science* **6**: 362354. DOI: 10.3389/FENVS.2018.00076

Overton IC, Smith DM, Dalton J, Barchiesi S, Acreman MC, Stromberg JC, Kirby JM. 2014. Implementing environmental flows in integrated water resources management and the ecosystem approach. *Hydrological Sciences Journal* **59**: 860–877. DOI: 10.1080/02626667.2014.897408

Owusu A, Mul M, van der Zaag P, Slinger J. 2022. May the odds be in your favor: Why many attempts to reoperate dams for the environment stall. *Journal of Water Resources Planning and Management* **148**: 04022009. DOI: 10.1061/(ASCE)WR.1943-5452.0001521

Owusu AG, Mul M, van der Zaag P, Slinger J. 2021. Re-operating dams for environmental flows: From recommendation to practice. *River Research and Applications* **37**: 176–186. DOI: 10.1002/RRA.3624

Pahl-Wostl C, Lebel L, Knieper C, Nikitina E. 2012. From applying panaceas to mastering complexity: Toward adaptive water governance in river basins. *Environmental Science & Policy* **23**: 23–34. DOI: 10.1016/j.envsci.2012.07.014

Palmer C, Munnik V, du Toit D, Rogers KH, Pollard S, Hamer N, Weaver M, Retief H, Sahula A, O'keeffe JH. 2018. *Practising Adaptive IWRM (Integrated Water Resources Management) in South Africa*. Pretoria, South Africa

Palmer C, Tanner J, Akanmu J, Alamirew T, Bamutaze Y, Banadda N, Cleaver F, Faye S, Kabenge I, Kane A, Longe E, Nobert J, Nsengimana V, Speight V, Weston S, Winter K, Woldu Z. 2023. The Adaptive Systemic Approach: Catalysing more just and sustainable outcomes from sustainability and natural resources development research. *River Research and Applications*. DOI: 10.1002/RRA.4178

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

Pande S, Savenije H. 2016. A sociohydrological model for smallholder farmers in Maharashtra, India. *Water Resources Research* **52**: 1923–1947. DOI: 10.1002/2015WR017841

Pandolfelli L, Meinzen-Dick R, Dohrn S. 2008. Gender and collective action: Motivations, effectiveness and impact. *Journal of International Development* **20**: 1–11. DOI: 10.1002/jid.1424

Pappenberger F, Beven KJ. 2006. Ignorance is bliss: Or seven reasons not to use uncertainty analysis. *Water Resources Research* **42**: W05302. DOI: 10.1029/2005WR004820

Parkoo EN, Thiam S, Adjonou K, Kokou K, Verleysdonk S, Adounkpe JG, Villamor GB. 2022. Comparing expert and local community perspectives on flood management in the Lower Mono River Catchment, Togo and Benin. *Water 2022, Vol. 14, Page 1536* **14**: 1536. DOI: 10.3390/W14101536

Partzsch L. 2017. "Power with" and "power to" in environmental politics and the transition to sustainability. *Environmental Politics* **26**: 193–211. DOI: 10.1080/09644016.2016.1256961

Pascual U, Balvanera P, Anderson CB, Chaplin-Kramer R, Christie M, González-Jiménez D, Martin A, Raymond CM, Termansen M, Vatn A, Athayde S, Baptiste B, Barton DN, Jacobs S, Kelemen E, Kumar R, Lazos E, Mwampamba TH, Nakangu B, OFarrell P, Subramanian SM, Noordwijk M, Ahn S, Amaruzaman S, Amin AM, Arias-Arévalo P, Arroyo-Robles G, Cantú-Fernández M, Castro AJ, Contreras V, Vos A, Dendoncker N, Engel S, Eser U, Faith DP, Filyushkina A, Ghazi H, Gómez-Baggethun E, Gould RK, Guibrunet L, Gundimeda H, Hahn T, Harmáčková Z V, Hernández-Blanco M, Horcea-Milcu A-I, Huambachano M, Lutti Hummel Wicher N, İskender Aydın C, Islar M, Koessler A-K, Kenter JO, Kosmus M, Lee H, Leimona B, Lele S, Lenzi D, Lliso B, Mannetti LM, Merçon J, Sofía Monroy-Sais A, Mukherjee N, Muraca B, Muradian R, Murali R, Nelson SH, Nemogá-Soto GR, Ngouhouo-Poufoun J, Niamir A, Nuesiri E, Nyumba TO, Özkaynak B, Palomo I, Pandit R, Pawłowska-Mainville A, Porter-Bolland L, Quaas M, Rode J, Rozzi R, Sachdeva S, Samakov A, Schaafsma M, Sitas N, Ungar P, Yiu E, Yoshida Y, Zent E. 2023. Diverse values of nature for sustainability. *Nature* **620**: 813–823. DOI: 10.1038/s41586-023-06406-9

Pascual U, Balvanera P, Díaz S, Pataki G, Roth E, Stenseke M, Watson RT, Başak Dessane E, Islar M, Kelemen E, Maris V, Quaas M, Subramanian SM, Wittmer H, Adlan A, Ahn SE, Al-Hafedh YS, Amankwah E, Asah ST, Berry P, Bilgin A, Breslow SJ, Bullock C, Cáceres D, Daly-Hassen H, Figueroa E, Golden CD, Gómez-Baggethun E, González-Jiménez D, Houdet J, Keune H, Kumar R, Ma K, May PH, Mead A, O'Farrell P, Pandit R, Pengue W, Pichis-Madruga R, Popa F, Preston S, Pacheco-Balanza D, Saarikoski H, Strassburg BB, van den Belt M, Verma M, Wickson F, Yagi N. 2017. Valuing nature's contributions to people: the IPBES approach. *Current Opinion in Environmental Sustainability* **26**–**27**: 7–16. DOI: 10.1016/j.cosust.2016.12.006

Pastor A V, Ludwig F, Biemans H, Hoff H, Kabat P. 2014. Accounting for environmental flow requirements in global water assessments. *Hydrol. Earth Syst. Sci* **18**: 5041–5059. DOI: 10.5194/hess-18-5041-2014

Patrick MP. 2014. The cycles and spirals of justice in water-allocation decision making. *Water International* **39**: 63–80. DOI: 10.1080/02508060.2013.863646

Paxton B, Dobison L, Kleynhans M, Howard G. 2017. *Developing an elementary tool for Ecological Reserve monitoring in South Africa's Freshwater Ecosystem Priority Areas (FEPAs): A Pilot study in the Koue Bokkeveld (WRC Report No. 2340/1/16)*. Water Research Commission: Pretoria

Department of Water and Sanitation, 2022. National Water Resources Strategy 3, Government Gazette No. 47133. Pretoria, South Africa.

Nel, J., Colvin, C., Maitre, D. Le, Smith, J., Haines, I., 2013. Defining South Africa's Water Source Areas 1–30.

Paxton, B., Walker, J., 2018. Appendix A—Synthesis Report., Freshwater Research Center. Cape Town, South Africa.

Stein, R., 2006. Water law in a democratic South Africa: A country case study examining the introduction of a public rights system. South African Journal of Environmnental Law and Policytal Law and Policy 13, 181–195. https://doi.org/10.10520/AJA10231765_181

Tewari, D.D., 2009. A detailed analysis of evolution of water rights in South Africa: An account of three and a half centuries from 1652 AD to present. Water SA 35, 693–710. https://doi.org/10.4314/wsa.v35i5.49196

Penny G, Srinivasan V, Apoorva R, Jeremiah K, Peschel J, Young S, Thompson S. 2020. A process-based approach to attribution of historical streamflow decline in a data-scarce and human-dominated watershed. *Hydrological Processes* **34**: 1981–1995. DOI: 10.1002/hyp.13707

Pérez-Blanco CD, Gil-García L, Saiz-Santiago P. 2021. An actionable hydroeconomic Decision Support System for the assessment of water reallocations in irrigated agriculture. A study of minimum environmental flows in the Douro River Basin, Spain. *Journal of Environmental Management* **298**: 113432. DOI: 10.1016/J.JENVMAN.2021.113432

Perez P, Aubert S, Daré W, Ducrot R, Jones N, Queste J, Trébuil G, Van Paassen A. 2013. Assessment and monitoring of the effects of the commod approach. *Companion Modelling: A Participatory Approach to Support Sustainable Development* **9789401785**: 155–187. DOI: 10.1007/978-94-

017-8557-0_7

Perrotton A, Garine-Wichatitsky M de, … HV-F-E and, 2017 U. 2017. My cattle and your park: codesigning a role-playing game with rural communities to promote multistakeholder dialogue at the edge of protected areas. *Ecology and Society* **22**: 35. DOI: 10.5751/ES-08962-220135

Petersen-Perlman JD, Veilleux JC, Wolf AT. 2017. International water conflict and cooperation: challenges and opportunities. *Water International* **42**: 105–120. DOI: 10.1080/02508060.2017.1276041

Pfaff A, Velez MA, Taddei R, Broad K. 2013. Unequal information, unequal allocation: Bargaining field experiments in NE Brazil. *Environmental Science & Policy* **26**: 90–101. DOI: 10.1016/J.ENVSCI.2012.07.002

Pienaar GJ, Van Der Schyff E. 2007. The reform of water rights in South Africa. *Law Environment and Development* **3**: 181–194

Pienaar GW, Hughes DA. 2017. Linking hydrological uncertainty with equitable allocation for water resources decision-making. *Water Resources Management* **31**: 269–282. DOI: 10.1007/s11269-016-1523-3

Pienaar L, Boonzaaier J. 2018. *Drought policy brief Western Cape Agriculture*. *Bureau for Food and Agricultural Policy*

Poff NLR, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: A paradigm for river conservation and restoration. *BioScience* **47**: 769–784. DOI: 10.2307/1313099

Poff NLR, Matthews JH. 2013. Environmental flows in the Anthropocence: Past progress and future prospects. *Current Opinion in Environmental Sustainability* **5**: 667–675. DOI: 10.1016/j.cosust.2013.11.006

Polk E, Diver S. 2020. Situating the scientist: Creating inclusive science communication through equity framing and environmental justice. *Frontiers in Communication* **5**: 489377. DOI: 10.3389/FCOMM.2020.00006/BIBTEX

Pollard S, du Toit D. 2011. Towards Adaptive Integrated Water Resources Management in southern Africa: The role of self-organisation and multi-scale feedbacks for learning and responsiveness in the Letaba and Crocodile Catchments. *Water Resources Management* **25**: 4019–4035. DOI: 10.1007/s11269-011-9904-0

Prasad KC, van Koppen B, Strzepek K. 2006. Equity and productivity assessments in the Olifants River basin, South Africa. *Natural Resources Forum* **30**: 63–75. DOI: 10.1111/J.1477-8947.2006.00158.X

Preiser R, Biggs R, De Vos A, Folke C. 2018. Social-ecological systems as complex adaptive systems: Organizing principles for advancing research methods and approaches. *Ecology and Society* **23**. DOI: 10.5751/ES-10558-230446

Prieto M. 2021. Equity vs. Efficiency and the human right to water. *Water (Switzerland)* **13**. DOI: 10.3390/w13030278

R Core Team. 2020. *R: The R Project for Statistical Computing*. *https://www.r-project.org/*

Ralekhetla MM. 2018. Investigating epistemic justice in an adaptive planning process: Towards developing a local catchment management strategy (Master's thesis, Faculty of Science). Rhodes University.

Rawlins J. 2019. Political economy of water reallocation in South Africa: Insights from the Western Cape water crisis. *Water Security* **6**: 100029. DOI: 10.1016/j.wasec.2019.100029

Rebelo AG, Boucher C, Helme N, Mucina L, Rutherford M. 2006. Fynbos Biome. *he Vegetation of South Africa, Lesotho and Swaziland*. Strelitzia 19, 53–206

Reddy VR, Syme GJ. 2014. Social sciences and hydrology: An introduction. *Journal of Hydrology* **518**: 1–4. DOI: 10.1016/J.JHYDROL.2014.06.022

Reed MS. 2008. Stakeholder participation for environmental management: A literature review. *Biological Conservation* **141**: 2417–2431. DOI: 10.1016/J.BIOCON.2008.07.014

Reed MS, Graves A, Dandy N, Posthumus H, Hubacek K, Morris J, Prell C, Quinn CH, Stringer LC. 2009. Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management* **90**: 1933–1949. DOI: 10.1016/j.jenvman.2009.01.001

Reed MS, Vella S, Challies E, de Vente J, Frewer L, Hohenwallner-Ries D, Huber T, Neumann RK, Oughton EA, Sidoli del Ceno J, van Delden H. 2018. A theory of participation: what makes stakeholder and public engagement in environmental management work? *Restoration Ecology* **26**: S7–S17. DOI: 10.1111/REC.12541

Reichert P, Ammann L, Fenicia F. 2021. Potential and challenges of investigating intrinsic uncertainty of hydrological models with stochastic, time-dependent parameters. *Water Resources Research* **57**: 1–28. DOI: 10.1029/2020WR028400

Rezaee A, Bozorg-Haddad O, Chu X. 2021. Reallocation of water resources according to social, economic, and environmental parameters. *Scientific Reports* **11**: 1–13. DOI: 10.1038/s41598-021-96680-2

Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, Drüke M, Fetzer I, Bala G, von Bloh W, Feulner G, Fiedler S, Gerten D, Gleeson T, Hofmann M, Huiskamp W, Kummu M, Mohan C, Nogués-Bravo D, Petri S, Porkka M, Rahmstorf S, Schaphoff S, Thonicke K, Tobian A, Virkki V, Wang-Erlandsson L, Weber L, Rockström J. 2023. Earth beyond six of nine planetary boundaries. *Science Advances* **9**: 1–16. DOI: 10.1126/sciadv.adh2458

Roa-García MC. 2014. Equity, efficiency and sustainability in water allocation in the andes: Trade-offs in a full world. *Water Alternatives* **7**: 298–319

Rockström J, Bai X, Devries B. 2018. Global sustainability: The challenge ahead. *Global Sustainability* **1**: 14–16. DOI: 10.1017/sus.2018.8

Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D. 2009a. Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research* **45**. DOI: 10.1029/2007WR006767

Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA. 2009b. A safe operating space for humanity. *Nature* **461**: 472–475. DOI: 10.1038/461472a

Rodina L, Baker LA, Galvin M, Goldin J, Harris LM, Manungufala T, Musemwa M, Sutherland C, Ziervogel G. 2017. Water, equity and resilience in Southern Africa: future directions for research and practice. *Current Opinion in Environmental Sustainability* **26**–**27**: 143–151. DOI: 10.1016/J.COSUST.2017.09.001

Roemer JE. 2010. Kantian Equilibrium. *Scandinavian Journal of Economics* **112**: 1–24. DOI: 10.1111/J.1467-9442.2009.01592.X

Rogers K, Luton R. 2011. *Strategic adaptive management as a framework for implementing integrated water resource management in South Africa (WRC Report No. KV 245/10)*. *Water Research Commission*

Roobavannan M, Kandasamy J, Pande S, Vigneswaran S, Sivapalan M. 2017. Allocating environmental water and impact on basin unemployment: Role of a diversified economy. *Ecological Economics* **136**: 178–188. DOI: 10.1016/J.ECOLECON.2017.02.006

Rosner A, Vogel RM, Kirshen PH. 2014. A risk-based approach to flood management decisions in a nonstationary world. *Water Resources Research* **50**: 1928–1942. DOI: 10.1002/2013WR014561

Roux DJ, Foxcroft LC. 2011. The development and application of strategic adaptive management within South African National Parks. *Koedoe* **53**: 5. DOI: 10.10520/EJC132247

Roux DJ, Novellie P, Smit IPJ, de Kraker J, Culloch-Jones SM, Dziba LE, Freitag S, Pienaar DJ. 2022. Appraising strategic adaptive management as a process of organizational learning. *Journal of Environmental Management* **301**: 113920. DOI: 10.1016/J.JENVMAN.2021.113920

RSA. 1998a. The National Water Act (No. 36 of 1998): Government Gazette No: 19182. *Government Communication & Information System*. Office of the President: Pretoria, 101

RSA. 1998b. *National Environmnetal Management Act (Act 107 of 1998)*. *Government Gazette No. 19519*. Republic of South Africa (RSA): South Africa, 318–338. DOI: 10.4324/9781315664262-18

Saaty RW. 1987. The Analytic Hierachy Process- What it is and how it is used. *Mathemetical modelling* **9**: 161–176

Saaty T. 2000. *Fundamentals of decision making and priority theory with the analytic hierarchy process: Analytic Hierarchy Process Series, Vol. 6*. RWS Publications: Pittsburgh

Saaty TL. 2013. The modern science of Multicriteria Decision Making and its practical applications: The AHP/ANP approach. *Operations Research* **61**: 1101–1118. DOI: 10.1287/opre.2013.1197

Sabbaghian RJ, Nejadhashemi AP. 2020. Developing a risk-based consensus-based decision-support system model for selection of the desirable urban water strategy: Kashafroud watershed study. *Water (Switzerland)* **12**. DOI: 10.3390/W12051305

Sachs J, Schmidt-Traub G, Lafortune G. 2020. Speaking truth to power about the SDGs. *Nature* **584**: 344. DOI: 10.1038/D41586-020-02373-7

Sachs JD, Lafortune G, Fuller G, Drumm E. 2023. *Sustainable Development Report 2023 (with indicators)*.

SANBI. 2012. *National vegetation map GIS metadata*. https://bgis.sanbi.org: Pretoria, South Africa

Sand PH. 2004. Sovereignty bounded: Public trusteeship for common pool resources? *Global Environmental Politics* **4**: 47–71. DOI: 10.1162/152638004773730211

Savenije H, Sivapalan M. 2013. PUB in Practise: Case studies. In: Blöschl GS, Sivapalan M, Wagener T, Viglione A and Savenije H (eds) *Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales*. Cambridge University Press, 271–272

Scheierling SM. 2011. *Assessing the direct economic effects of reallocating irrigation water to alternative uses: Concepts and an application*. *World Bank Policy research working paper*

Schlüter M, McAllister RRJ, Arlinghaus R, Bunnefeld N, Eisenack K, Hölker F, Milner-Gulland EJ, Müller B, Nicholson E, Quaas M, Stöven M. 2012. New horizons for managing the environment: A review of coupled social-ecological systems modeling. *Natural Resource Modeling* **25**: 219–272. DOI: 10.1111/j.1939-7445.2011.00108.x

Schreiner B. 2013. Viewpoint-Why Has the South African National Water Act Been so Difficult to Implement? *Water Alternatives* **6**: 2399–245

Schulze RE. 2011. Approaches towards practical adaptive management options for selected water-related sectors in South Africa in a context of climate change. *Water SA* **37**: 621–646. DOI: 10.4314/wsa.v37i5.1

Seidl R, Barthel R. 2017. Linking scientific disciplines: Hydrology and social sciences. *Journal of Hydrology* **550**: 441–452. DOI: 10.1016/j.jhydrol.2017.05.008

Seigerman CK, McKay SK, Basilio R, Biesel SA, Hallemeier J, Mansur A V., Piercy C, Rowan S, Ubiali B, Yeates E, Nelson DR. 2022. Operationalizing equity for integrated water resources management. *Journal of the American Water Resources Association* **00**: 1–18. DOI: 10.1111/1752-1688.13086

Siddiqi A, Wescoat JL, Muhammad A. 2018. Socio-hydrological assessment of water security in canal irrigation systems: A conjoint quantitative analysis of equity and reliability. *Water Sec* **4**–**5**: 44–

45. DOI: 10.1016/j.wasec.2018.11.001

Sivakumar B. 2012. Socio-hydrology: not a new science, but a recycled and re-worded hydrosociology. *Hydrological Processes* **26**: 3788–3790. DOI: 10.1002/HYP.9511

Sivapalan M. 2015. Debates—Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"—Socio-hydrology. *Water Resources Research* **51**: 4795–4805. DOI: 10.1002/2015WR017080

Sivapalan M, Blöschl G. 2015. Time scale interactions and the coevolution of humans and water. *Water Resources Research* **51**: 6988–7022. DOI: 10.1002/2015WR017896

Sivapalan M, Konar M, Srinivasan V, Chhatre A, Wutich A, Scott CA, Wescoat JL, Rodríguez-Iturbe I. 2014. Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future* **2**: 225–230. DOI: 10.1002/2013EF000164

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

Skowno AL, Raimondo DC, Poole CJ, Fizziotti B, Slingsby JA. 2019. *South African National Biodiversity Assessment 2018 Technical Report Volume 1: Terrestrial realm*. South African National Biodiversity Institute, an entity of the Department of Environment, Forestry and Fisheries: Pretoria

Skurray JH, Pandit R, Pannell DJ. 2013. Institutional impediments to groundwater trading: The case of the Gnangara groundwater system of Western Australia. *Journal of Environmental Planning and Management* **56**: 1046–1072. DOI: 10.1080/09640568.2012.716368

Smakhtin VU, Shilpakar RL, Hughes DA. 2006. Hydrology-based assessment of environmental flows: an example from Nepal. *Taylor & Francis* **51**: 207–222. DOI: 10.1623/hysj.51.2.207

Sohns A, Ford JD, Adamowski J, Robinson BE. 2021. Participatory Modeling of Water Vulnerability in Remote Alaskan Households Using Causal Loop Diagrams. *Environmental Management* **67**: 26–42. DOI: 10.1007/S00267-020-01387-1

Srinivasan V. 2013. Coevolution of water security in a developing city. *Hydrology and Earth Science Discussion* **10**: 1–27. DOI: 10.5194/HESSD-10-13265-2013

Stein R. 2006. Water law in a democratic South Africa: A country case study examining the introduction of a public rights system. *South African Journal of Environmnental Law and Policytal Law and Policy* **13**: 181–195. DOI: 10.10520/AJA10231765_181

Stewart B. 2015. Measuring what we manage–the importance of hydrological data to water resources management. *Proceedings of the International Association of Hydrological Sciences*. IAHS Publication: Paris, France, 80–85. DOI: 10.5194/piahs-366-80-2015

Strauß S. 2011. Water conflicts among different user groups in South Bali, Indonesia. *Human Ecology* **39**: 69–79. DOI: 10.1007/S10745-011-9381-3

Streefkerk IN, de Bruijn J, Haer T, Van Loon AF, Quichimbo EA, Wens M, Hassaballah K, Aerts JCJH. 2023. A coupled agent-based model to analyse human-drought feedbacks for agropastoralists in dryland regions. *Frontiers in Water* **4**. DOI: 10.3389/frwa.2022.1037971

Sun F, Roderick ML, Farquhar GD. 2018. Rainfall statistics, stationarity, and climate change. *Proceedings of the National Academy of Sciences of the United States of America* **115**: 2305–2310. DOI: 10.1073/pnas.1705349115

Syme GJ. 2013. Acceptable risk and social values: struggling with uncertainty in Australian water allocation. *Stochastic Environmental Research and Risk Assessment* **28**: 113–121. DOI: 10.1007/s00477-013-0694-1

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**: 143. DOI: 10.3389/FRWA.2022.949901

Tanner JL, Hughes DA. 2015. Surface water–groundwater interactions in catchment scale water resources assessments—understanding and hypothesis testing with a hydrological model. *Hydrological Sciences Journal* **60**: 1880–1895. DOI: 10.1080/02626667.2015.1052453

Tempelhoff J. 2017. The Water Act (No. 54 of 1956) and the first phase of apartheid in South Africa (1948–1960). *Water History* **9**: 189–213. DOI: 10.1007/S12685-016-0181-Y

Tewari DD. 2009. A detailed analysis of evolution of water rights in South Africa: An account of three and a half centuries from 1652 AD to present. *Water SA* **35**: 693–710. DOI: 10.4314/wsa.v35i5.49196

Teweldebrihan MD, Lyu H, Pande S, McClain ME. 2021. Smallholder Farmer's Adaptability to

Anthropogenic and Climate-Induced Variability in the Dhidhessa River Sub-basin, Ethiopia. *Frontiers in Water* **3**. DOI: 10.3389/FRWA.2021.735004

Tharme RE. 2003. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**: 397–441. DOI: 10.1002/RRA.736

The Brisbane Declaration Environmental. 2007. *Environmental flows are essential for freshwater ecosystem health and human well-being. https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ ELOHA/Pages/Brisbane-Declaration.aspx*

Theron SN, Midgley S, Hochrainer-Stigler S, Archer E, Tramberand S, Walker · Sue, Choi W, Walker S, Za WA. 2023. Agricultural resilience and adaptive capacity during severe drought in the Western Cape, South Africa. *Regional Environmental Change* **1**: 23–98. DOI: 10.1007/s10113-023-02091-6

Thompson SE, Sivapalan M, Harman CJ, Srinivasan V, Hipsey MR, Reed P, Montanari A, Blöschl G. 2013. Developing predictive insight into changing water systems: Use-inspired hydrologic science for the anthropocene. *Hydrology and Earth System Sciences* **17**: 5013–5039. DOI: 10.5194/HESS-17-5013-2013

Tian J, Guo S, Liu D, Pan Z, Hong X. 2019. A fair approach for multi-objective water resources allocation. *Water Resources Management* **33**: 3633–3653. DOI: 10.1007/s11269-019-02325-5

Tranmer AW, Weigel D, Marti CL, Vidergar D, Benjankar R, Tonina D, Goodwin P, Imberger J. 2020. Coupled reservoir-river systems: Lessons from an integrated aquatic ecosystem assessment. *Journal of Environmental Management* **260**. DOI: 10.1016/j.jenvman.2020.110107

Troy TJ, Pavao-Zuckerman M, Evans TP. 2015. Debates—Perspectives on socio-hydrology: Socio-hydrologic modeling: Tradeoffs, hypothesis testing, and validation. *Water Resources Research* **51**: 4806–4814. DOI: 10.1002/2015WR017046

Tumbo M, Hughes DA. 2015. Uncertain hydrological modelling: application of the Pitman model in the Great Ruaha River basin,Tanzania. *Hydrological Sciences Journal* **60**: 2047–2061. DOI: 10.1080/02626667.2015.1016948

Turner BL. 2010. Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science? *Global Environmental Change* **20**: 570–576. DOI: 10.1016/J.GLOENVCHA.2010.07.003

Turner BL, Tidwell V, Fernald A, Rivera JA, Rodriguez S, Guldan S, Ochoa C, Hurd B, Boykin K, Cibils A. 2016. Modeling Acequia Irrigation Systems using system dynamics: Model development, evaluation, and sensitivity analyses to investigate effects of socio-economic and biophysical feedbacks. *Sustainability (Switzerland)* **8**: 1019. DOI: 10.3390/SU8101019

UN-Water. 2019. *Step-by-step monitoring methodology for indicator 6.4.2 on water stress*. *https://www.unwater.org/publications/step-step-methodology-monitoring-water-stress-642*

UN. 1997. *The UN Convention on the Law of the Non-Navigational Uses of International Watercourses: Prospects and Pitfalls*. *World Bank Technical Paper*

UN Water. 2024. *The United Nations world water development report 2024: Water for prosperity and peace*. *Water for Prosperity and Development*. UNESCO (United Nations Educational, Scientific and Cultural Organization): Paris, France

Union of South Africa. 1956. *The Water Act*. https://leap.unep.org/countries/za/national-legislation/water-act-no-54-1956

United Nations. 2015. *Transforming our world: The 2030 Agenda for Sustainable Development. United Nations sustainable knowledge platform*. *Sustainable Development Goals*. New York

United Nations. 2017. *Bellagio Principles on valuing water*.

Uusitalo L, Lehikoinen A, Helle I, Myrberg K. 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. *Environmental Modelling & Software* **63**: 24–31. DOI: 10.1016/J.ENVSOFT.2014.09.017

Valipour E, Ketabchi H, Shali RS, Morid S. 2024. Water resources allocation: Interactions between equity/justice and allocation strategies. *Water Resources Management* **38**: 505–535. DOI: 10.1007/S11269-023-03682

van Duinen R, Filatova T, Geurts P, van der Veen A. 2015. Empirical Analysis of Farmers' Drought Risk Perception: Objective Factors, Personal Circumstances, and Social Influence. *Risk Analysis* **35**. DOI: 10.1111/risa.12299

van Emmerik THM, Li Z, Sivapalan M, Pande S, Kandasamy J, Savenije HHG, Chanan A, Vigneswaran S. 2014. Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences* **18**: 4239–4259. DOI: 10.5194/HESS-18-4239-2014

van Loon AF, Laaha G. 2015. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology* **526**: 3–14. DOI: 10.1016/J.JHYDROL.2014.10.059

Van Loon AF, Rangecroft S, Coxon G, Werner M, Wanders N, Di Baldassarre G, Tijdeman E, Bosman M, Gleeson T, Nauditt A, Aghakouchak A, Breña-Naranjo JA, Cenobio-Cruz O, Costa AC, Fendekova M, Jewitt G, Kingston DG, Loft J, Mager SM, Mallakpour I, Masih I, Maureira-Cortés H, Toth E, Van Oel P, Van Ogtrop F, Verbist K, Vidal JP, Wen L, Yu M, Yuan X, Zhang M, Van Lanen HAJ. 2022. Streamflow droughts aggravated by human activities despite management. *Environmental Research Letters* **17**: 044059. DOI: 10.1088/1748-9326/AC5DEF

Van Niekerk A. 2001. Western Cape Digital Elevation Model: Product description. Centre for Geographical Analysis, Stellenbosch University.: Stellenbosch

van Vliet MTH, Jones ER, Flörke M, Franssen WHP, Hanasaki N, Wada Y, Yearsley JR. 2021. Global water scarcity including surface water quality and expansions of clean water technologies. *Environmental Research Letters* **16**: 024020. DOI: 10.1088/1748-9326/ABBFC3

van Wilgen BW, Forsyth GG, de Klerk H, Das S, Khuluse S, Schmitz P. 2010. Fire management in Mediterranean-climate shrublands: a case study from the Cape fynbos, South Africa. *Journal of Applied Ecology* **47**: 631–638. DOI: 10.1111/J.1365-2664.2010.01800.X

Vanham D, Hoekstra AY, Wada Y, Bouraoui F, de Roo A, Mekonnen MM, van de Bund WJ, Batelaan O, Pavelic P, Bastiaanssen WGM, Kummu M, Rockström J, Liu J, Bisselink B, Ronco P, Pistocchi A, Bidoglio G. 2018. Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 “Level of water stress.” *Science of The Total Environment* **613–614**: 218–232. DOI: 10.1016/j.scitotenv.2017.09.056

Vaux HJ. 2012. Water for agriculture and the environment: The ultimate trade-off. *Water Policy* **14**: 136–146. DOI: 10.2166/wp.2012.209

Voinov A, Bousquet F. 2010. Modelling with stakeholders. *Environmental Modelling & Software* **25**: 1268–1281. DOI: 10.1016/J.ENVSOFT.2010.03.007

Voinov A, Kolagani N, McCall MK, Glynn PD, Kragt ME, Ostermann FO, Pierce SA, Ramu P. 2016. Modelling with stakeholders – Next generation. *Environmental Modelling & Software* **77**: 196–

220. DOI: 10.1016/J.ENVSOFT.2015.11.016

von Maltitz GP, Gambiza J, Kellner K, Rambau T, Lindeque L, Kgope B. 2019. Experiences from the South African land degradation neutrality target setting process. *Environmental Science and Policy* **101**: 54–62. DOI: 10.1016/j.envsci.2019.07.003

Vörösmarty CJ, Leveque C, Revenga C, Bos R, Caudill C, Chilton J, Douglas EM, Meybeck M, Prager D, Balvanera P, Barker S, Maas M, Nilsson C, Oki T, Reidy CA. 2005. Freshwater drowning and near-drowning-an update. *Millennium Ecosystem Assessment*. Island Press: Washington, D.C., 165–207. DOI: 10.1007/BF03007034

Wang L, Fang L, Hipel KW. 2008. Basin-wide cooperative water resources allocation. *European Journal of Operational Research* **190**: 798–817. DOI: 10.1016/J.EJOR.2007.06.045

Water for Africa. 2008. *Principles of a process to esstimate and/or extrapolate environmental flow requirements (WRC Report No KV 210/08)*. *Water Research Commission*. Pretoria, South Africa

Weaver MJT, O'Keeffe J, Hamer N, Palmer CG. 2019. A civil society organisation response to water service delivery issues in South Africa drives transformative praxis. Part 1: Emergence and practice. *Geoforum* **107**: 1–13. DOI: 10.1016/j.geoforum.2019.08.020

Wens M, Veldkamp TIE, Mwangi M, Johnson JM, Lasage R, Haer T, Aerts JCJH. 2020. Simulating small-scale agricultural adaptation decisions in response to drought Risk: An empirical Agent-Based Model for semi-arid Kenya. *Frontiers in Water* **2**: 15. DOI: 10.3389/frwa.2020.00015

Westerberg IK, Di Baldassarre G, Beven KJ, Coxon G, Krueger T. 2017. Perceptual models of uncertainty for socio-hydrological systems: A flood risk change example. *Hydrological Sciences Journal* **62**: 1705–1713. DOI: 10.1080/02626667.2017.1356926

Westerberg IK, McMillan HK. 2015. Uncertainty in hydrological signatures. *Hydrology and Earth System Sciences* **19**: 3951–3968. DOI: 10.5194/HESS-19-3951-2015

Western Cape Government Department of Agriculture. 2023. *Cape Farm Mapper 3 User Manual*. *Western Cape Government*

Wiek A, Larson KL. 2012. Water, people, and sustainability—A Systems framework for analyzing and assessing water governance regimes. *Water Resources Management* **26**: 3153–3171. DOI: 10.1007/S11269-012-0065-6

Witzenberg Municipality. 2019. *Annual Report 2019/20*. Ceres

Wolff MG, Cockburn JJ, De Wet C, Bezerra JC, Weaver MJT, Finca A, De Vos A, Ralekhetla MM, Libala N, Mkabile QB, Odume ON, Palmer CG. 2019. Exploring and expanding transdisciplinary research for sustainable and just natural resource management. *Ecology and Society* **24**: 14. DOI: 10.5751/ES-11077-240414

Woodhouse P, Muller M. 2017. Water Governance—An historical perspective on current debates. *World Development* **92**: 225–241. DOI: 10.1016/J.WORLDDEV.2016.11.014

Wurl J, Gámez AE, Ivanova A, Imaz Lamadrid MA, Hernández-Morales P. 2018. Socio-hydrological resilience of an arid aquifer system, subject to changing climate and inadequate agricultural management: A case study from the Valley of Santo Domingo, Mexico. *Journal of Hydrology* **559**: 486–498. DOI: 10.1016/J.JHYDROL.2018.02.050

Wutich A, York AM, Brewis A, Stotts R, Roberts CM. 2012. Shared cultural norms for justice in water institutions: Results from Fiji, Ecuador, Paraguay, New Zealand, and the U.S. *Journal of Environmental Management* **113**: 370–376. DOI: 10.1016/j.jenvman.2012.09.010

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. In: Liu S, Zaraté P, Kamissoko D, Linden I and Papathanasiou J (eds) *Lecture Notes in Business Information Processing*. Springer Nature: Albi, France, 137–155. DOI: 10.1007/978-3-031-32534-2_11

Yadav M, Wagener T, Gupta H. 2007. Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins. *Advances in Water Resources* **30**: 1756–1774. DOI: 10.1016/J.ADVWATRES.2007.01.005

Yang G, Giuliani M, Castelletti A. 2023. Operationalizing equity in multipurpose water systems. *Hydrology and Earth System Sciences* **27**: 69 – 81. DOI: 10.5194/hess-27-69-2023

Yates D, Sieber J, Purkey D, Huber-Lee A. 2005. WEAP21 - A demand-, priority-, and preference-driven water planning model. Part 1: Model characteristics. *Water International* **30**: 487–500. DOI: 10.1080/02508060508691893

Zahir S. 1999. Clusters in a group: Decision making in the vector space formulation of the analytic hierarchy process. *European Journal of Operational Research* **112**: 620–634. DOI: 10.1016/S0377-2217(98)00021-6

Zuo A, Wheeler SA. 2024. The Australian public's preferences for further environmental and cultural water recovery options in the Murray-Darling Basin. *Journal of Hydrology* **633**: 130983. DOI: 10.1016/J.JHYDROL.2024.130983

9. APPENDICES

9.1. Chapter 3 Appendices

9.1.1. Appendix 3.2: Workshop invitations.

Supporting and enhancing water resources management in the KBV

Stakeholder Workshop Two

Thursday 24, November 2022

09.00 – 13.00

PURPOSE:

- To validate prototype model representations.
- To gather stakeholder feedback.
- To gather additional data.

Time	Item
09.00	WELCOME & INTRODUCTIONS
09.10	SCENE SETTING AND VISION
09.40	HYDROLOGY MODEL PRESENTATION & FEEDBACK
10.00	FROM ARDI TO ABM
10.30	TEA
11.00	ABM PROTOTYPE PRESENTATION & FEEDBACK
12.00	COMMUNITY WEIGHTS PRESANTATION & FEEDBACK
12.45	FINAL REFLECTIONS & CLOSE
13.00	LUNCH

9.1.2. Table A-4.1: Shared-Catchment Vision (2050) and contributing values established using the Adaptive Planning Process in May 2022.

Current Concerns	Aspirational Goals	2050 Vision
Socio-cultural		Achieve sustainable catchment management. Effective cooperation between all stakeholders for water use on a basis which benefits all landowners and the environment Fair water usage that ensures dry season flows and healthy riverine systems.
Inequity Human impact	Ways of working together Social value creation	
Technical		
Monitoring Inadequate water storage Increasing water abstraction	Use of science & technology Improved water management Reduced input costs	
Economic		
Ignorance on the economic value of agriculture Land valuation linked to water availability Downstream impacts of upstream activities	Develop within sustainable limits	
Environmental		
Encroachment of riparian vegetation Impacted natural flow Deteriorating water quality Climate extremes Poor soil quality	Invest in ecosystem health	
Political		
Poor compliance	Move towards cooperative governance	

9.1.3. Workshop reflections

Table A-4.1: Stakeholder feedback summary for the workshop that included the adaptive planning process (APP) and actors, resources, dynamics, and interactions.

Q1. How satisfied were you with the communication you received about the purpose and content of the workshop?				
Not satisfied at all	Slightly satisfied	Moderately satisfied	Very satisfied	Extremely satisfied
0	0	4	4	0
Q2. How satisfied were you with the information you received before the session about logistical arrangements?				
0	0	2	3	3
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.)				
0	0	1	6	1
Q4. How valuable did you find the workshop today?				
0	1	1	5	1

9.2. Chapter 5 Appendices

9.2.1. Table A-5.1: Reference evapotranspiration (A-Pan WR90), monthly crop coefficient factors, and monthly irrigation demand for citrus, deciduous fruit, onions, and potatoes in the Koue Bokkeveld region (River E21).

Month	PET A-Pan (mm/month)	Crop Factor Citrus	Crop Factor Deciduous	Crop Factor Onions	Crop Factor Pasture	Crop Factor Potatoes
10	144.79	0.8	0.24	0.70	0.70	0.60
11	213.76	0.52	0.27	0.80	0.80	0.60
12	247.66	0.54	0.36	0.00	0.80	0.60
1	252.00	0.45	0.45	0.00	0.80	0.60
2	207.92	0.52	0.57	0.00	0.80	0.55
3	192.22	0.65	0.48	0.00	0.80	0.55
4	117.90	0.69	0.20	0.15	0.70	0.55
5	66.80	0.96	0.20	0.32	0.60	0.45
6	43.75	0.91	0.20	0.40	0.50	0.40
7	42.59	0.91	0.20	0.57	0.50	0.20
8	59.62	0.59	0.20	0.66	0.50	0.35
9	93.02	0.70	0.20	0.70	0.60	0.50
Irrigation Demand based on 65% effective rainfall						
Month	Rainfall (mm/month)	Citrus (mm)	Deciduous (mm)	Onions (mm)	Pasture (mm)	Potatoes (mm)
10	27.15	98.18	17.10	83.70	83.70	69.23
11	23.51	95.87	42.43	155.73	155.73	112.97
12	12.10	125.87	81.29	0.00	190.26	140.73
1	14.80	103.78	103.78	0.00	191.98	141.58
2	6.62	103.81	114.21	0.00	162.03	110.05
3	15.24	115.04	82.36	0.00	143.87	95.81
4	32.96	59.93	2.16	0.00	61.11	43.42
5	78.16	13.32	0.00	0.00	0.00	0.00
6	184.66	0.00	0.00	0.00	0.00	0.00
7	140.00	0.00	0.00	0.00	0.00	0.00
8	124.85	0.00	0.00	0.00	0.00	0.00
9	61.59	25.08	0.00	25.08	15.78	6.48
Total	721.64	740.89	443.33	264.51	1,004.46	720.28

9.2.2. Table A-5.3: Input parameters used for each water user

Water Users	Riverbanks	Corporate Farms	Family Commercial	Downstream Farmers	Lifestyle Farmers
Community weighting	34	21	20	25	10
Deficit-Impact index	Med. (53%)	V. low (14%)	Med. (39%)	High (64%)	Med. (50%)
Normal Year Demand (m^3)	116,000	140,484	89,717	36,012	2,519
Split-thE-Bill @ Level D	39,900	88,504.9	56,521.7	22,687.6	1,587.0
Split-thE-Bill @ Level B	60,900	77,266.2	49,344.4	19,806.6	1,385.5
Pizza Slices @ Level D	39,900.0	66,027.5	65,493.4	36,012.0	2,519.0
Pizza Slices @ Level B	60,900.0	77,944.0	49,777.0	19,980.0	1,398.0
Equal impact @ Level B	60,900.0	48,228.0	30,800.0	12,363.0	865.0

Community weighting denotes a community-derived user priority for supply in dry periods (detailed in Chapter 3). Deficit-Impact index represents relative residual vulnerability after all adaptation options have been exhausted (also detailed in Chapter 3). Entitlement relates to three scenarios, (i) a normal year with a catchment yield of 400,000 cumecs, (ii) a severe drought year with a modified instream environment (E-Flows at level D), and (iii) a severe drought year with high environmental protection (E-Flows level B).

9.2.3. Appendix A-5.1: Role Playing game manual

FAIR PLAY

A game to advance fairness and explore water-use decision-planning for dry periods

Overview

A serious game played by students, water users, decision-makers, and policymakers play a game to explore equitable decision-making for water reallocation in periods of scarcity. Players are encouraged to consider the social-economic vs environmental well-being when making their decisions. Decisions are based on different restriction mechanisms and in-game discussions.

Realising Equity

Individual preferences or ambitions may clash with or oppose those of other actors. For instance, although some may believe that everyone should be treated equally, others may believe that less capable people should be given a higher priority. Knowing others' preferences and limitations is crucial for well-being, transparency, and trust.

The game aims to:

Introduce plausible water-sharing options to cope with water gaps.

Use dialogue, cooperation, and engagement, to increase transparency and trust.

Promote repercussions awareness of water management.

PROCEDURE

Fair Play can be played by individuals or teams of 2, with four different water users/groups.

Each player manages his/her farm and can talk to neighbours.

The "Water User's Association" will introduce an operation rule using narrative cards.

Players meet their water needs by extracting from a shared river with endemic fish.

Too much extraction kills the fish, and the tourism sector and harms the estuary downstream (not shown).

All water users respond by complying or neglecting the restriction

If a player chooses or is compelled to comply with a restriction, the player needs to demonstrate the impact of the restriction on their business.

When it's your turn to play, you can sacrifice a crop, irrigate from an alternative source, or ask a neighbour to help.

If the reserve requirements are not satisfied, endemic fish species will begin to die, tourism may be restricted, and downstream consumers will have limited access to water

Since the game is meant to be interactive and fun, discussion is highly recommended

After each round, the moderator will collect the key indicators (change in land use and water use)

The Technical Assistant will use them to provide the Water Users Association with information about the effects of the restrictions

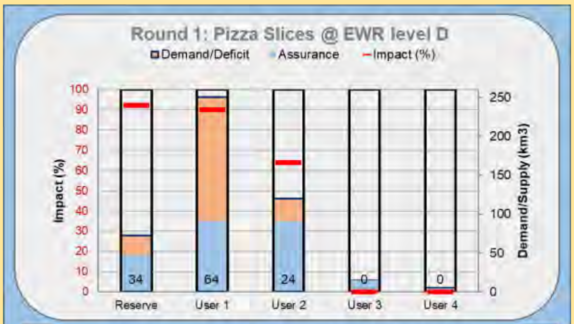
Thereafter a new rule will be introduced…

The game continues until all four policy options have been explored

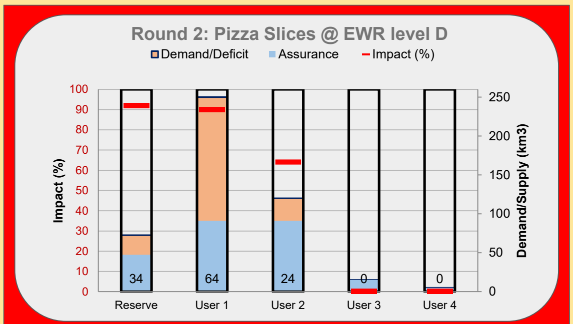
After each round, impact reports will be given to players for consideration.

REMEMBER TO HAVE FUN AND BE CREATIVE.

9.2.4. Appendix A-5.2: Fair Play narrative card format showing an example of narrative cards for game Tables 1 and 2.

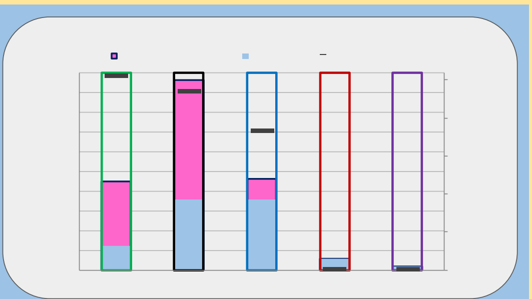


To mitigate the drought situation, the WUA imposes restrictions:
Consortium - 64% (-26)
Family - 24% (0)
Decide how much you want to take from the reserve to lessen the impact.

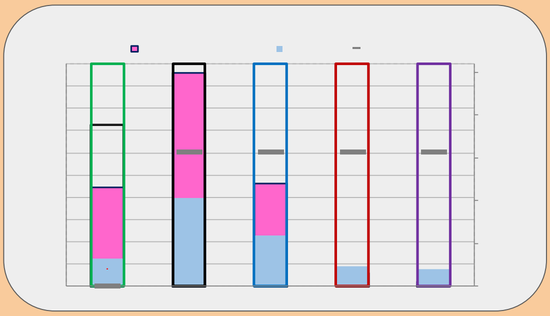


RED ALERT: EWR satisfaction is behind schedule
The environmental impact is very concerning, this is a good time to do something about that or further releases/ restrictions will be imposed.

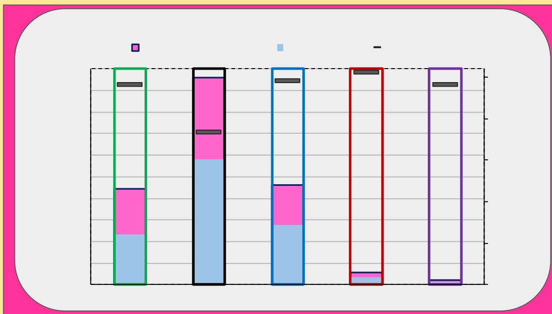
Meanwhile, tourists have to stay away.



Round 3:
As a community, you decided that environmental protection is important. Meaning, fish populations CANNOT decline. To ensure compliance:
User 1: - 60%
User 2: - 20%
How do you respond?

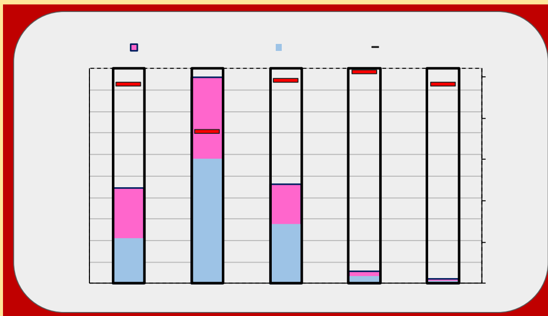


Experience from previous droughts indicates that some users suffered more.
Governance is weakened but to be fair while maintaining system stability, water can be cut to ensure a similar impact at 60%.



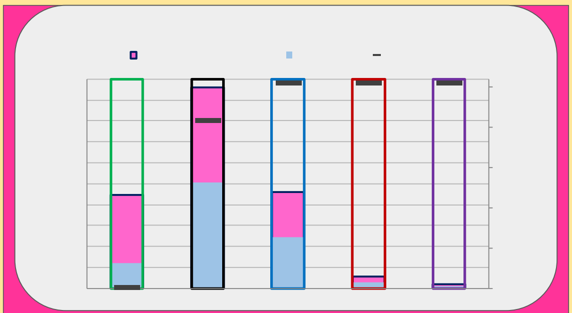
It's the year 2000, and a newly formed WUA isfaced with helping water users cope with a severe drought.

A decision is reached to cut water supply across users by 40%

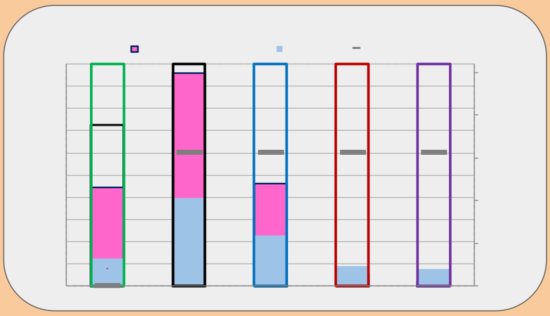


RED ALERT: Environmental dissatisfaction

The environmental impact is very concerning, this is a good time to do something about that or further releases/ restrictions will be imposed.
Meanwhile, tourists must stay away.



Indigenous fish species in the river were detected and require more water than previously thought (29% of MAR/a from 119%). Urbandevelopment downstream also adds pressure.
As the drought continues, the regulator imposes further cuts. Users must now reduce their river usage by half.



Experience from previous droughts indicates that some users suffered more.
Governance is weakened but to be fair while maintaining system stability, water can be cut to ensure a similar impact at 60%.

9.3. Appendices

9.3.1. Table A-6.2: Final input naturalised flow parameter ensembles (minimum and maximum) for uncertain parameters, and only average values for parameters not set to uncertain.

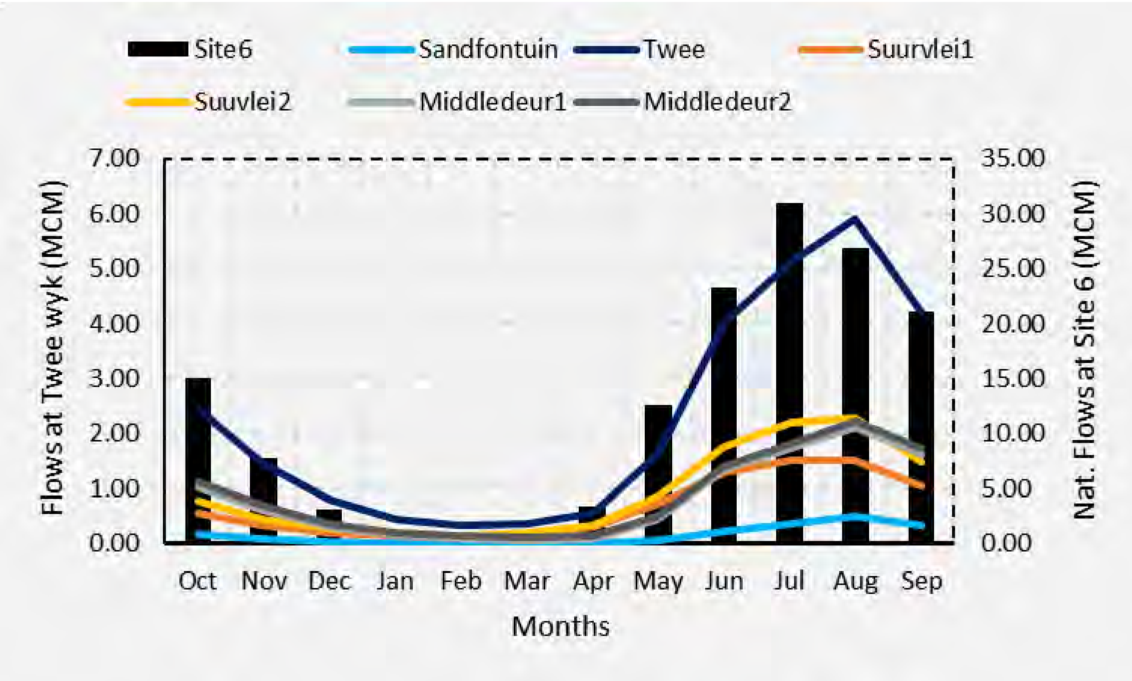
* Dark green cells represent parameters responsible for surface discharge; light green cells show parameters responsible for the sub-surface process; and blue cells depict parameters responsible for groundwater recharge and discharge. Water-use parameters (n=11) have been excluded from the list.

Array parameter	Twee (Out)	Sandfontuin	Middeldeur (out)	Middeldeur (up)	Suurvlei (out)	Suurvlei (up)
1. Rain Distribution Factor	1.28	1.28	1.28	1.28	1.28	
2. Proportion of impervious area AI	0	0	0	0	0	0.25
3. Summer intercept cap.(Veg1) PI1s	1.5	1.5	1.5	1.5	1.5	1.5
4. Winter intercept cap.(Veg1) PI1w	1.5	1.5	1.5	1.5	1.5	1.5
5. Summer intercept cap.(Veg2) PI2s	4	4	4	4	4	4
6. Winter intercept cap.(Veg2) PI2w	4	4	4	4	4	4
7. % Area of Veg2 AFOR	0	0	0	0	0	0
8. Veg2/Veg1 Pot. Evap. Ratio FF	1.4	1.4	1.4	1.4	1.4	1.4
9. ST fraction for sat. excess runoff	0.8 to1	0.8 to 1	0.4 to 0.65	0.7 to 1	0.8 to 1	1
10. Annual Pan Evaporation (mm) PEVAP	1667 to1802	1670	1670	1670	1667 to 1802	1670
11. Summer min.abs.rate (mm/mth) ZMINs	0 to10	11 to 18	10 to 20	10 to 25	5 to 25	10 to 30
12. Winter min.abs.rate (mm/mth) ZMINw	0 to10	11 to 18	10 to 20	10 to 25	5 to 25	10 to 30
13. Mean absorption fraction	0.5	0.5	0.5	0.5	0.5	0.5
14. Maximum abs.rate (mm/mth) ZMAX	250 to350	250 to 300	300 to 350	300 to 450	180 to 250	160 to 210
15. Maximum storage capacity	235 to 345	250 to 280	100 to 200	250 to 350	125 to 225	125 to145
16. No recharge below storage	0	0	0	0	0	0
17. Power : storage-runoff curve POW	1.5 to 2.5	1.8 to 2	2.5 to 3	1.8 to 2.5	1.8 to 2.5	1.8 to 3
18. Runoff rate at ST (mm/mth) FT	15 to23	15 to 20	0 to 5	15 to 25	30 to 50	15 to 20
19. Max. Recharge rate (mm/month) GW	5.5 to10	5 to 10	15 to 20	10 to 15	15 to 25	10 to15
20. Evaporation-storage coefficient R	0.55 to 0.65	0.4 to 0.65	0.2 to 035	0.6 to 0.85	0.6 to 1	0.2 to 0.4
21. Sub-area Routing Coeff. (mnths) TL	0.225	0.225	0.225	0.225	0.25	0.25
22. Channel Routing Coeff (mnths). CL	0	0	0	0	0	0
32. Channel Loss TLGMax(mm)	2	0	0	2	0.1	0

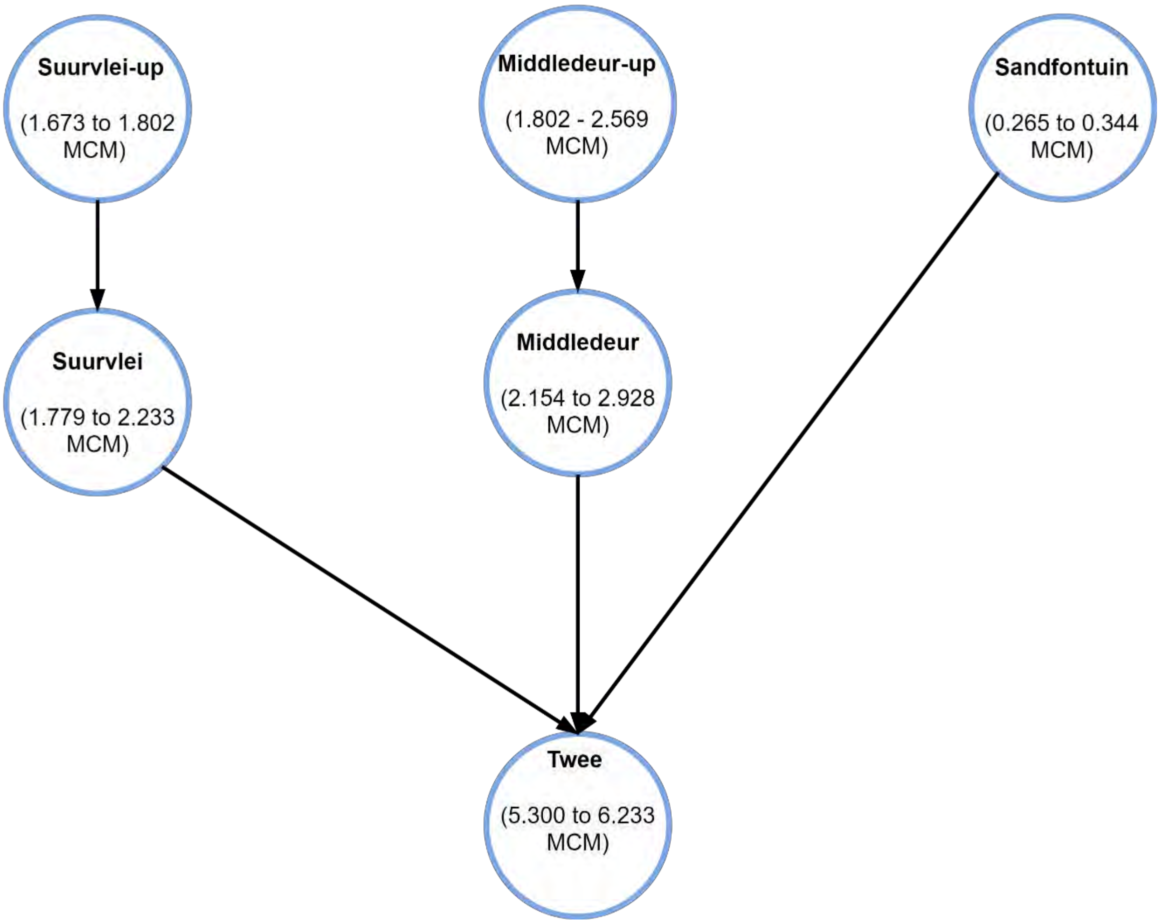
33. Power : Storage-Recharge curve GPOW	2.5:3.5	2.5: 3.5	2.5: 3	3: 3.5	3:3.5	2.5: 4
34. Drainage density	0.4	0.2	0.2	0.2	0.001	0.1: 0.4
35. Transmissivity (m^2/day)	20.7	28.5	20.7	28.5	0.01	22.55
36. Storativity	0.001	0.003	0.003	0.001	0.001	0.001

9.3.2. Figure A-6.2: Seasonal distribution of 1 in 2-year naturalised flows (50th Ensemble in MCM) for the Twee wyk, alongside average naturalised flows for E-Flow Site 6.

Figure A-6.2 presents the results of the median hydrological simulation output conducted over a 28-year period from October to September. The average monthly streamflow at various Twee Wyk sub-basins ranges from 0.000 to 7.00 $*10^6$ $m^3.y^{-1}$ and 0.000 to 35.00 $*10^6$ $m^3.y^{-1}$ at E-Flow Site 6.

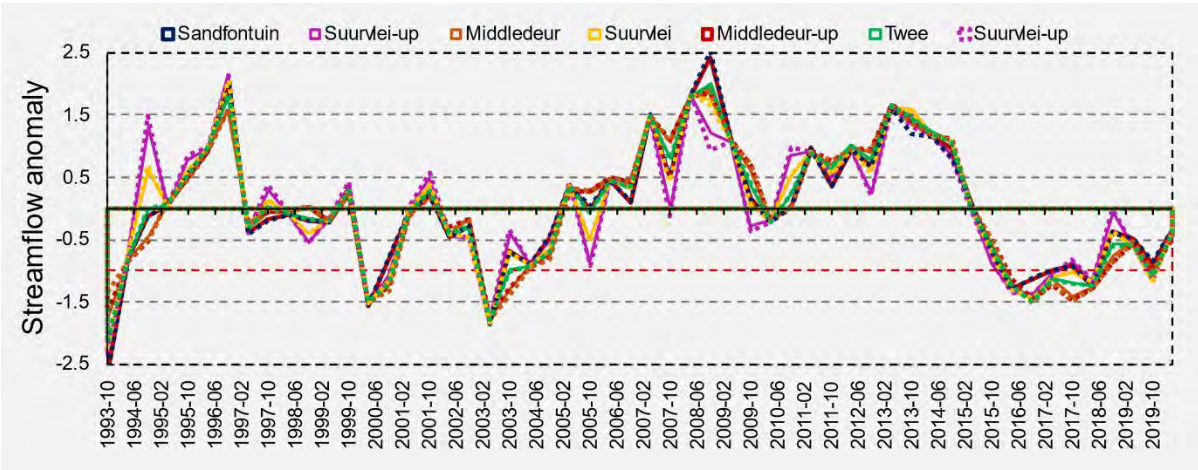


9.3.3. Figure A-6.3: Figure A-9.1: Cumulative dry season (October to March) natural streamflow estimates showing simulations within the 90% confidence interval between 1993 and 2021.



9.3.4. Figure A-6.4: Streamflow anomalies in the Wyk showing drought/flood events over time. The analysis is based on a standardised streamflow index (n=6 months) both for the 5th (solid lines) and 95th (dashed lines) ensembles of streamflow. The red horizontal line shows severe droughts (Standardised Streamflow Index ≤1).

The analysis reveals poor predictability and no universal patterns in streamflow anomalies, with considerable temporal variability and slight differences between ensembles.



9.3.5. Figure A-6.5: Screenshots of reservoir performance analysis for a lumped storage of reservoirs in the upstream sub-basins of the Twee Wyk. The time series plots illustrate monthly reservoir performance using Box and Whisker plots that represent the mean and standard deviations of storage levels.