The application of a simple decision support system to address water quality contestations in the Vaal Barrage catchment, South Africa

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Abstract

Deteriorating environmental water quality is one of the complex challenges in South Africa that threaten freshwater ecosystem health and functionality. An emerging concern is the contestation of water quality regulatory instruments such as standards in water use licences (WUL), and the resource quality objectives. In the Vaal Barrage catchment where this study was undertaken these contestations were evident, suggesting the need for both technical and social solutions to water quality changes in socio-ecological systems. The Vaal Barrage catchment within the lower section of the Upper Vaal is a highly developed, urbanised, and complex catchment supporting and contributing to the social-economic development of Gauteng Province and the entire country, as the Upper Vaal contribute 20% to the Gross Domestic Product of South Africa.

This study explores the motivations for stakeholders' contestations of water quality regulatory instruments in order to contribute to ways in which water resource users and regulators can collaboratively address water quality challenges in the Vaal Barrage catchment. The study also explores water quality scenarios and their ecological and management implications. Document analysis, participant observations and a semi-structured questionnaire were deployed to explore stakeholders' motivations, values, and perceptions of the water quality regulatory instruments. The results were triangulated to gain better insights into research participants responses. To explore water quality management scenarios, the study applied a water quality systems assessment model Decision Support System (DSS). The DSS was recently developed as part of a bigger project within the Vaal Barrage catchment. Regarding stakeholders' motivation for contesting water quality regulatory instruments in the catchment, the results revealed a perceived lack of scientific credibility and defensibility in the processes used for deriving standards in WUL, a lack of transparent linkage between the WUL and resource quality objectives, and the increased need for stakeholder engagement in the resource quality objective formulation process. Furthermore, the study revealed punitive measures, education and awareness, self-regulation as mechanisms to encourage compliance.

The applied DSS results showed that high nutrient loads, sulphate and total dissolved solids sourced from upstream catchments contribute to water quality deterioration in the Vaal Barrage catchment. The results also showed that the Vaal Barrage catchment could not host additional licence emitters because of TDS, phosphate and nitrate levels, which pose a serious risk to the ecology of the Vaal Barrage catchment, indicating that system had exceeded its assimilative capacity for critical water quality variables. Lastly, the results evidenced the need for collaborative action by the waste emitters within the Vaal Barrage catchment, particularly collaboration between upstream and downstream waste emitters. The study has far-reaching implications for water quality management in South Africa. These include i) the need for transparent and open processes and methods for deriving standards in water use licence, ii) the need for a water quality DSS that recognises catchment hydrological complexity in deriving standards in WUL, and for linking WUL and Resource Quality Objectives (RQOs), iii) collaboration between resources users, and between the resources users and the regulators to bring pollutionto acceptable levels and iv) both social and technical solutions are necessary for managing water quality challenge, particularly in a highly developed catchment such as the Vaal Barragesystem.

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List of Abbreviations

AMD	Acid Mine Drainage
CMA	Catchment Management Authority
CMF	Catchment Management Forum
DSS	Decision Support System
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electric Conductivity
EDSS	Environmental Decision Support System
EIA	Environmental Impact Assessment
ETD	Electronic Thesis and Dissertations
FDC	Flow Duration Curve
FRAI	Fish Response Assessment Index
GA	General Authorisation
GDP	Gross Domestic Product
GGP	Gross Geographic Product
GIS	Geographical Information System
HE	Human Ethic
IBTs	Inter-basin Transfer Schemes
IDSS	Integrated Decision Support System
IUA	Integrated Unit of Analysis
IWR	Institute of Water Research
IWRM	Integrated Water Resource Management
LHWP	Lesotho Highlands Water Project
MIRAI	Macroinvertebrate Response Assessment Index
MC	Management Class
MLR	Multiple Linear Regression
NGO	Non-Governmental Organisation
NPO	Non-Profit Organisation
NWA	National Water Act
NWRS	National Water Resource Strategy
PAI	Physicochemical Assessment Index

PES	Present Ecological State
PPP	Polluter Pay Principle
QUAT	Quaternary
RDM	Resource-directed measures
RDMWQ	Resource-directed management of water quality
RQO	Resource Quality Objectives
RWQO	Resource Water Quality Objectives
SAPPI	South Africa Pulp & Paper Industries
SASS	South African Scoring System
SDC	Source-directed Controls
SES	Socio-ecological systems
SPATSIM	Spatial and Time Series Information Modelling
SOE	State-owned enterprises
SWAT	Soil & Water Assessment Tool
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
VEGRAI	Vegetation Response Assessment Index
WEAP	Water Evaluation and Planning System
WMA	Water Management Area
WRC	Water Research Commission
WRCS	Water Resource Classification System
WQSAM	Water Quality Systems Assessment
WWTW	Wastewater Treatment Works
WReMP	Water resource modelling platform
WRPM	Water Resource Planning Model
WRPYM	Water Resource Yield Modelling
WUAAAs	Water Use Authorisation Assessment Advisory Committees
WUL	Water Use Licence
WULA	Water Use Licence Application

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Chapter 1: General Introduction and Literature Review

1.1 Introduction

Deteriorating environmental water quality is a growing concern and has an impact on freshwater ecosystem health and functionality (Okamura & Feist, 2011). Several water quality stressors threaten freshwater ecosystems: toxic metal pollution, eutrophication, acid mine drainage (AMD), salinisation, sedimentation, and microbial pollution (DWAF, 2004a). The consequences of deteriorating water quality on freshwater ecosystems include altered biotic assemblages, changes in food web dynamics, reported fish mortality (e.g., in the Vaal River system), and the general alteration of ecosystem function, energy and material transfer, as well as organic matter processing (Wepner et al., 2011). In addition, pollution of freshwater resources adversely affects freshwater ecosystem services and livelihoods (Dodds et al., 2013).

Several factors, among them expanding urban developments and industrialisation (Khatri & Tyagi, 2015), have increased the deterioration of freshwater quality. A growing human population, agricultural activities, and substances regarded as emerging water quality concerns such as plastics, pharmaceuticals, and many industrial chemicals also contribute to water quality deterioration (Khatri & Tyagi, 2015). For example, many riverine ecosystems draining urban and industrial landscapes have elevated levels of metals, pathogenic microbial counts, and altered biotic assemblages because of the so-called urban stream syndrome (Khatri & Tyagi, 2015). The Upper Vaal catchment is subject to the environmental consequences of urban development and industrialisation, which calls for water quality management interventions.

The Upper Vaal River drains an urbanised and industrialised catchment in South Africa (Ilunga, 2017). It supports urbanised and industrialised areas such as the Johannesburg, Vereeniging and Vanderbiljpark complex, which are characterised by intense industrial activities (Tempelhoff et al., 2007). The industrial bulk water users in the catchment, such as Eskom, Iscor, Arcelor Mittal and Sasol release waste effluent into the surface water of the catchment (Ochse, 2007). As a result, water quality has become an increasingly severe issue ofconcern within the system and requires urgent water resource management attention.

In the lower section of the Upper Vaal, that is, the Vaal Barrage catchment and associated river systems such as Klip, Leeu-Taaiboschspruit, Blesbokspruit and the Suikerbosrand Rivers, pollution of the water resources is also a significant concern (DWAF, 2004b). Owing to increases in pollution, the Vaal Barrage catchment rivers are seriously impacted by deteriorating water quality, leading to a decline in biotic diversity and general ecosystem functionality (Hopkins et al., 2011). An example of the ecological impacts of deteriorating water quality is the collapse of the Klip Wetland catchment (McCarthy et al., 2007). Wetlands act as a natural filter for pollutants and are vital to improving water quality levels. However, wetlands in the catchments are severely impacted because of overused, poor irrigation practices, urbanisation, and the failure of municipal wastewater treatment works (McCarthy et al., 2007; Ambani & Annegarn, 2015).

Freshwater quality is affected by land use activities emanating from both non-point sourcesand point sources (Borowski & Carroll, 2015). However, identifying the sources of pollution can be complex. Non-point sources are difficult to characterise, as they can emerge from varying sources such as surface runoff agriculture, and irrigation (Ochse, 2007). Point sources are relatively easy to isolate; they include discharges from wastewater treatment plants and stormwater drains, such as the discharge from the South African Pulp & Paper Industries (SAPPI) (Ochse, 2007). Point sources can have a severe impact on a water resource: for instance, the Klip River, which is heavily contaminated by faecal matter from untreated wastewater spills (Makumbe, 2018). To understand water systems in terms of quality and quantity, it is essential to understand land use activities associated with urbanisation, industrial and urban development to identify and manage pollution sources.

Two broad water management strategies are employed in South Africa: resource-directed measures (RDMs) and the source-directed controls (SDCs) (DWAF, 2006). Resource-directed measures are key to achieving water resource protection. They comprise four interlinked processes: the water resource classification system, the classification of every significant water resource, the determination of the Reserve (human and ecological), and the setting of the resource quality objective (RQO) (DWAF, 2016). The water resource classification system prescribes the processes and procedures for allocating a significant water resource to one of three management classes (MC): Class I, Class II and Class III. Class I describes water resources that are minimally impacted, in their near-natural condition; they are accorded high protection priority. Class II describes water resources that are moderately impacted, and protection is not as strict as it is for Class I. Class III refers to water resources that are heavily utilised and are accorded only minimal protection to assure functionality of key ecosystem processes and functions (DWAF, 2011). The management class describes the overall health of the system (DWAF, 2006a). The Reserve encompasses the quantity, quality, and assurance of water supply to meet basic human needs and for the functionality of aquatic ecosystem (DWAF, 2006a).

The resource quality objectives (RQOs) are numerical and/or narrative descriptions that describe desired goals set for the ecosystems to achieve their sustainable utilisation and protection as captured in the management class (DWAF, 2004a). The water quality component of the RQO describes the physicochemical attributes that need to be met to achieve the desired management goal for a water resource (DWAF, 2004a). The RQOs, including the water quality components of the resources, have been determined and gazetted for the water resources of the Upper Vaal catchment, including the Vaal Barrage (DWAF, 2007). The water quality components of the RQOs are thus the desired future state for the rivers within the lower section of the Upper Vaal system (DWAF, 2004a). Source-directed control instruments, such as licences, are imposed on water resource users to achieve the RQOs (DWAF, 2011).

Source-directed controls (SDCs) are measures imposed on water resource users to control water usage and protect water resources. The primary SDC instrument imposed on water resource users in the catchment is compulsory water use licencing (WUL) (DWAF, 2007). Water quality licencing is an SDC instrument used to control and restrict activities likely to impact water quality; the licence usually specifies the water quality standards that users must comply with (DWAF, 2007). A typical water quality licence contains information on waste discharge volume, effluent discharge standards, discharge regime, monitoring frequency, and other specifications. These licence conditions aim to restrict impacts on receiving water resources to ensure sustainable water resources to meet the economic, social, and ecological objectives (DWAF, 2007).

Given the complex water quality challenges in the Vaal Barrage catchment and associated river systems, it is now increasingly recognised that there is a need for technical and social solutions within a socio-ecological system approach (Odume et al., 2018). Participatory modelling is an example of technical and social solutions which suggests combining scientific methods with stakeholder collaboration (Maskrey et al., 2016). Participatory modelling is the practice of integrated water resource management (IWRM). It prompts a bottom-up approach to water quality management, which may be necessary for implementing the RQO and WULs (Odume et al., 2018). For example, in the Vaal Barrage catchment, water resource users contested water quality standards in their water use licences, arguing for a more scientifically defensible and transparent process of setting water quality standards in water use licences linked to the RQOs

(Odume et al., 2018). Both social and technical solutions are needed for the RQOs and SDC to be effective. For instance, the cooperation of water resource users is required to move towards self-compliance, monitoring, and enforcement. Thus, the present study draws on social-ecological system framing to explore the contestations around water quality management in the Vaal Barrage catchment. Secondly, this study applies a newly developed Decision Support System (DSS) to model various scenarios relating to changing standards in WUL on the RQOs. The rest of the chapter is a literature review beginning with an overview of water quality within social-ecological system framework. A detailed review of water quality management instrument in South Africa is provided, followed by water quality challenges and contestations in the Vaal system. The chapter ends with a review of decision support systems in water quality management, rationale for the study, and aim and objectives of the study, and thesis structure.

1.2 Water Quality Management Within the Socio-ecological System Framework

Systems thinking provides a basis for recognising aquatic systems as complex socio-ecological systems (SES) characterised by feedback loops and cross-scale linkages (Glaser & Glaeser, 2014). The SES view of freshwater ecosystems considers that social and ecological components are a coupled, unitary system in which the two parts are in ongoing dynamic, cross-scale interactions, characterised by feedback loops, unpredictability, and complexity (Berkes et al., 2002; Odume & de Wet 2019). Acknowledging the interactions within any SES has enabled resource managers to adopt holistic approaches in addressing environmental problems; for example, resilience, adaptive management, and complexity have emerged as approaches towards conceptualising ecological challenges and their solutions (Cote & Nightingale, 2012).

The resilience theory originates in the field of ecology in the 1960s and early 1970s, defined as the ability of a system to withstand changes that may cause the system to reach a threshold, or its ability to absorb shocks, disturbances, and surprises (Folke, 2006; Domptail et al., 2013).The resilience approach acknowledges that a system can have multiple stability domains, enabling it to absorb shocks without collapsing or reaching a new threshold (Holling, 1987). Resilience thus allows resource managers to understand a system's capabilities and identifies its threshold (Ĉoté & Darling, 2010). In water quality management, the resilience theory provides a basis for investigating the assimilative capacity of the freshwater system and the threshold beyond which further pollution may cause total collapse and possibly regime shift. Thus, it is urged that the gazetted RQOs for any given freshwater system are met to protect vital ecosystem functionality within their limits of resilience.

1.3 Water Quality Management Measures and Instruments

The National Water Act (NWA; Act No. 36 of 1998) provides the legal framework for managing water quality in South Africa. Water quality management instruments can be divided into resource-directed measures (RDM) and those related to source-directed controls (SDC). As mentioned earlier, the RDMs and SDCs are the two strategies envisaged in the National Water Resource Strategy 2 (NWRS; DWAF, 2013) to balance the use and protection of water resources. In addition, the RDMs and SDCs are the two complementary strategies concurrently implemented to ensure that water resources are protected from pollution and other human-induced activities likely to impact water quality in freshwater ecosystems (DWS, 2011).

1.31 Resource Directed Measures

The RDMs are directed at the resource itself, and they include the classification system, the classification of every significant water resource, the Reserve (ecological and human) determination, and the setting of the resource quality objectives (RQOs). The classification comprises a series of methods that define strategies to select the Reserve, specify the resource's water quality characteristics, and determine the land-use activities that must be regulated and aligned with resource protection (DWAF, 2011). The classification of every significant water resource (WRCS) ensures sustainable use of water, defined in Volume 1 of WRCS (DWAF, 2011:3) as follows: "the water resource classification system is defined as a set of guidelines and procedures for determining different classes of water resources". A key component of classification is an "iterative process of evaluating catchment scenarios with stakeholders where economic, social and ecological trade-offs, out of which emerge the allocation schedule, ecological Reserve, RQOs, catchment management strategies and classes" (DWAF, 2011: 4). A seven-step process accompanies the WRCS, which is not presented in this study. However, it is imperative to note that the last seventh step is gazetted as the management classes, Reserve and RQOs (DWAF, 2017). The management class, as earlier presented, is described in Table 1.1.

Table 1. 1: Management classes (MC) and their description from DWAF (2011). The MCs guidethe ecological Reserve and the RQOs. Resources at high environmental categories such as A or B are assigned Class 1, associated with more conservative RQOs and ecological Reserve (DWA, 2011).

Management Class	Description
Class I	Minimally utilised; a minimal impact of humans on water quality; safe for most uses.
Class II	Moderately utilised; human activity has lightly altered water resources from natural status.
Class III	Heavily utilised; human activity has resulted in significant changes to the water resource; however, is still ecologicallystable.

The Reserve determination mentioned earlier comprises two components, the basic human needs Reserve and the ecological Reserve (Kleynhans et al., 2008). The basic human needs Reserve refers to water that is allocated for basic human needs such as water for drinking, food preparation, and personal hygiene (DWAF, 2011). The ecological Reserve defines conditions such as the quality, quantity and amount of water required to sustain the water resource for ecological functionality (van Wyk et al., 2006; Hering & Ingold, 2012). The ecological Reserve considers the interactions between different states of water within the hydrological cycle and, unlike the human Reserve, is difficult to determine owing to the inherent complexity of ecosystems and processes (DWAF, 2006a). Achieving a balanced, sustainable use of water resources requires negotiated trade-offs between ecological needs and human needs (van Wyk et al., 2006; Hering & Ingold, 2012). The ecological Reserve is an essential component of the RQO determination process, as the data produced relates to the environmental objectives that need to be met (DWAF, 2006a). The objectives made through the ecological Reserve process are known as Ecological Specifications, or 'Eco Specs'. The Eco Specs contain measurable descriptions of ecological attributes, such as water quality, flow, and biological integrity, and are used as inputs to the resource class and RQOs. Thus, the Reserve facilitates river management by aiming to meet the resource objectives, such as RQOs, and is given effect through WULs (van Wyk et al., 2006). It needs to be noted that as per the National Water Act, water is allocated to all other uses once the Reserves have been set aside. That is, the Reserves come first and then all other uses.

Resource quality objectives are descriptive and quantitative statements detailing the objectives required to balance resource protection and resource use. Since RQOs are descriptive statements, these help resource managers and users understand the crucial steps to achieve the balance between water resource use and protection (DWAF, 2011). The RQOs are based on acceptable risk to the resource and, therefore, stringent, and sound management is necessary (DWA, 2006b). As part of the RQO determination procedure, two primary tools assist in decision making: the resource unit prioritisation tool, and the resource unit evaluation tool. The resource unit prioritisation tool aids in identifying priority resources for setting the RQOs and their monitoring. The resource unit evaluation tool aids in selecting appropriate indicators to monitor the resource unit (DWAF, 2011). The seven-step process for determining the RQOs has been gazetted (DWAF, 2011), and the seven steps are: i) delineating the integrated unit of analysis, ii) establishing a vision for the catchment and critical elements for the IUAs, iii) prioritising and selecting preliminary resource units for RQO determination, iv) prioritising sub-components for RQO determination, v) selecting the best indicator for monitoring each of the component, vi) developing draft RQOs and numerical limits, agreed with stakeholders, and vii) finalising and gazetting RQOs (DWAF, 2011). The RQO determination procedure takes on an adaptive management cycle; the overall RQO determination procedure touches on defining the resource, setting a vision, setting the RQO and numerical limit. Once gazetted, the next stage leads to implementation, and monitoring (DWAF, 2011). The RQO has a quantity, quality, and biotic components. The water quality component sets the numerical and descriptive objectives for the water quality component of the resource.

Resource quality objectives related water quality and biotic monitoring instruments

Once the RQOs have been gazetted, several instruments exist to monitor whether the water quality and biotic components of the RQOs are met. These instruments include monitoring identified physicochemical variables and biological responses (Kleynhans & Louw, 2008). Physicochemical monitoring is aimed at assessing the physical and chemical condition of the water resource to determine the direction of change in relation to the gazetted RQOs. Variables commonly monitored include temperature, nutrients, dissolved oxygen and electrical conductivity, turbidity, and pH. The national physicochemical monitoring programme (DWAF, 2004) is the official programme for monitoring physicochemical variables of water resources in the country.

The second instrument is biological monitoring, which generates information about the fish, riparian vegetation, and macroinvertebrates in the aquatic ecosystem (Kleynhans & Louw, 2008). The River EcoStatus Monitoring programme uses ecological indices such as the macroinvertebrate response assessment index (MIRAI), the fish response assessment index (FRAI), the riparian vegetation response assessment index (VEGRAI), and the physicochemical driver assessment index (PAI) to generate the ecological data necessary to track whether the RQOs are achieved. Biological responses in an aquatic ecosystem are often used as indicators where the ecosystem function has been compromised to help identify the causes of impairment (Kleynhans & Louw, 2008). The most used biomonitoring tool is the South African Scoring System version 5 (SASS5) (Dickens & Graham 2002). This biomonitoring tool provides an assessment of the ecological integrity of the aquatic ecosystem using macroinvertebrates (Graham & Dickens, 2004). These instruments, used together with SDC-related tools, provide a strong foundation for water resource protection in South Africa.

1.3.2 Source-directed controls (SDC)

The SDCs are instruments used to control and restrict water use to achieve the desired level of protection accorded to a particular water resource (DWAF, 2006c). Source-directed control instruments include general authorisation (GA), existing lawful use, permits, compulsory water use licencing (WUL), and incentives. The National Water Resource Strategy (NWRS) stipulates two types of authorisations for water use: Schedule 1, which permits the use of water in small quantities for domestic use, including non-commercial and stock watering (DWAF, 2002). This type of water use does not require formal registration and authorisation (DWAF, 2006c). General authorisation allows limited but conditional water use. Conditions such as monitoring and reporting requirements are imposed to track the impact of use on water resources (DWAF, 2006d). Existing lawful water use refers to legal water use issued under the previous Water Act (54 of 1956). Compulsory water use licencing is imposed on all water uses that fall outside the scope of GA, existing lawful use, and those identified in Schedule 1 of the Act (DWAF, 2006d). The WUL is important because it is an instrument used to address historical inequality in terms of water access, as well as ensuring water resource protection. Thus, the general purpose of a WUL is twofold: firstly, to facilitate water resource protection to reach management objectives (RQOs) and secondly, to authorise responsible use of water resources (DWAF, 2006d). Water uses requiring WUL are indicated in Section 21 of the NWA (DWAF, 2006d). Of importance to this study is that the discharge of waste into the resource requires WUL. Water use licences are legally enforceable, and compliance on the part of water resource users is desirable.

The link between WUL and RQOs is crucial in achieving the balance between water resource protection and use. As previously mentioned, the RQOs are a component of the resource-directed measures which focus on meeting water resource needs by setting the appropriate objectives. Once the RQOs are determined, the WUL are the restrictions imposed on the user. The water quality standards set in the WUL are to give effect to RQOs (DWAF, 2006e). Licence conditions are well-defined and developed in a practical manner that enables achievement of and compliance with RQOs. Since the RQOs are narrative descriptors of the water resource based on a particular characteristic, for example, minimising the impact on water quality through reducing the impact of surface runoff, the licence conditions then set out that riparian vegetation should remain intact (DWAF, 2006e). Therefore, reducing the impact of surfacerunoff by not altering riparian vegetation that is responsible to surface water retention (DWAF,2006e). Thus, RQOs inform the licence conditions and ultimately minimise the impact on waterquality.

1.4 Water Quality Challenges in the Vaal Barrage catchment and Associated Tributaries

Catchments within the lower section of the Upper Vaal are highly industrialised and urbanised, with a very high population density (DWAF, 2004; Weideman et al., 2020). As a result, several water quality problems exist because of many pollution sources. Wastewater treatment works (WWTWs) failures are recognised as critical contributors to deteriorating water quality in the Vaal Barrage, releasing both treated and untreated waste waters (Du Plessis, 2017). Mamabolo (2015) indicated that a lack of co-operative governance is one of the challenges facing WWTWs in the Vaal Barrage catchment. Government functions as custodians of WWTWs and is supposed to ensure that treated effluent complies with set standards and regulations. However, on many occasions, local governments are responsible for discharging poorly treated effluent into the rivers. Discharges of poorly treated effluent are mainly due to lack of infrastructure maintenance, WWTWs operating above their design capacity, as well as by poor technical and managerial expertise to oversee their operations (Mamabolo, 2015). A key example is the impact of a breakdown in wastewater treatment facilities such as the overflowing wastewater in the town of Emfuleni, which has contributed to the chronic pollutionin the Vaal Barrage and Vaal River Mamabolo (2015).

Salinity in the Vaal Barrage remains a persistent water quality issue because of anthropogenic activities such as mining, manufacturing, agriculture, wastewater treatment works and dense settlement. Mining in the Upper Vaal is an important economic activity; however, active and defunct mines have led to numerous environmental problems (McCarthy & Pretorius, 2009). Coal mining in the town of Vereening within the area drained by the Vaal Barrage catchment contributes to salinity in the catchment (De klerk, 2012). In the same way, manufacturing industries, such as power stations in the Vaal Triangle and Sasolburg's iron and steel companies, and the manufacture of fertilisers and explosives have led to diffuse salinity in the Vaal Barrage catchment (Seretlo, 2012).

1.5 Contestation of Water Quality Management Processes and Instruments in the Vaal Barrage Catchment Within the Upper Vaal Catchment

A study conducted by Odume et al. (2018) in the lower section of the Upper Vaal revealed that stakeholders were contesting the discharge standards in their WUL. Water resource users in the catchment argued that discharge standards in their WUL conditions did not sufficiently account for social, ecological, and economic imperatives. They further argued that it was not clear how discharged standards in their WUL related to the gazetted water quality component of the RQOs (Odume et al., 2018). Some of the bulk water users in the catchment further arguedthat water quality standards in their WUL were unrealistic, considering the ecological and hydrological dynamics of the systems. The contestation is based on the belief that the catchment is complex, with many water users discharging effluent into the resources, and therefore discharge standards ought to account for effects of upstream waste loads on downstream users (Odume et al., 2018).

In arguing for clarity about the relationship between water quality discharge standards in WUL and the water quality component of the RQOs, water resource users raised concerns about how discharge standards were derived in water resource units without RQOs (Odume et al., 2018). For example, some water resource users wanted to know what informs discharge standards in WUL for emitters situated in sub-catchments without RQOs, and what the thresholds are against which the water quality conditions of such resource units are benchmarked to track the direction of change, whether deteriorating or improving. The present study, then, aims to explore the motivation for and nature of contestation of water quality management instruments in the Vaal Barrage catchment. Another contested area of the regulatory instruments is the scientific credibility of the process underpinning current WULs. Resource users argue that it is necessary to interrogate the science underlying WUL to raise confidence in the entire process. To address this concern, it has been suggested that a participatory Decision Support System (DSS) is a useful tool to link WUL and RQOs in a stakeholder engaged process.

1.6 Decision Support System (DSS) in Relation to Water Quality Management in the Vaal Barrage Catchment

Decision support system (DSS) is a computerised information system, which serves as a decision supporting tool and is designed to enable stakeholder participation and engagement in the decision-making process (Power, 2002; Chan et al., 2017). The term DSS first emerged in the literature in the early 1970s where it was used in the business and financial industries to facilitate decision-making processes for solving structured or unstructured problems (Mysiak et al., 2005). In the 1980s, the purpose of the DSS was to provide management information, select information for analysis, and build simple analytical models (Power, 2002). However, over time, DSSs have seen advanced applications in other disciplines, such as environmental quality management on both land and water resources, with tools such as Environmental Decision Support Systems (EDSS), owing to increased recognition of socio-ecological systems as complex systems (Matthies et al., 2007; Oprea, 2018).

Environmental decision support systems (EDSS) provide information systems concerning complex environmental issues (Swayne et al., 2000). Environmental decision support systems involve a developed software for environmental modelling, simulation scenarios, GIS, databases, and assessment tools containing environmental data that are useful in the process of making decisions about a given problem (Stewart & Purucker, 2011). The EDSS involves scenario analysis to plan strategically for 'what-if' scenarios. The EDSS platforms recognise the complexity of environmental systems, their interconnections, and relationships, and they incorporate the interactions of physical, biological, and chemical factors in the environment (Oprea, 2018). An example of EDSS is MODISM 8.0 developed in 1978 and applied to river basin management to assist in strategic planning for drought management, short-term water management plans, and water rights analysis (Labadie, 2006).

Although, DSSs are widely used in water resource management, the success of their application is mixed. Applied DSS in water resource management can lead to a few advantages, such as sharing of knowledge and transparency in decision making, co-learning amongst stakeholders, and implementing local ecological knowledge. A DSS creates a platform for conflict negotiation and exploratory decision making; for example, a study by Giodano et al. (2007) experimentally applied an Integrated Decision Support System (IDSS) to facilitate decision making concerning the use of wastewater for irrigation purposes in the Apulia Region (southern Italy). The applied IDSS provided a platform for stakeholders to share ideas and perspectives, which increased co-learning among the multi-group with expertise in different fields. Furthermore, the negotiation among the stakeholders created a platform for negotiations around solutions for using treated wastewater for irrigation purposes, and resulted in improved transparency of decision making, ultimately improving the legitimacy of the developed DSS. Lastly, the added value of local ecological knowledge contributes to ensure holistic and fair decision making.

Although a DSS can lead to positive outcomes in the environmental sphere, there are instances where the approach may lead to failure in implementation. Where the DSS does not suit the needs, or is too complex, the intended users may fail to adopt it. Thus, compromising the longevityof the developed DSS (Reed, 2008). The success of a DSS depends on stakeholder participation.

1.7 The Role of Participation in the Decision Support System (DSS) in Water Modellingfor the Vaal Barrage Catchment

In understanding the role of participation, it is imperative to understand the different types of participation. Lynch and Gregor (2004) identify three types of participation: consultative, representative, and consensus. In consultative participation, the needs of the users of the DSS are prioritised during the development process. Representative participation refers to the representation of the affected group in the DSS design team (Lynch & Gregor, 2004). Lastly, consensus involves all users of the DSS and incorporates them into the DSS development process (Lynch & Gregor, 2004). The level of user participation can influence the scope of the design process, from advisory to sign-off. In the current study, stakeholders within the lower section of the Upper Vaal were regularly consulted in designing the DSS for linking WUL to RQOs.

Participation can build trust among the stakeholders and lead to ownership of the developed DSS (Okumah et al., 2020). Where there is trust and a common understanding of the issues, stakeholders can effectively work through the issues with a view to achieving environmental sustainability (Black et al., 2014). The current study follows up on a recent study that developed a simple DSS based on the Water Quality Systems assessment model (WQSAM) (Odume et al., 2021). The developed DSS enables the water quality components of the RQOs in the Vaal Barrage catchment to be linked to water quality discharge standards in WUL. By applying the WQSAM-based DSS, stakeholders can model 'what-if' scenarios.

1.8 Water Quality Systems Assessment Model (WQSAM)-based Decision Support System (DSS) for Linking WUL Standards to RQOs in the Vaal Barrage Catchment

In South Africa, much effort has gone into developing hydrological models for water resource assessment and management. These models include the Pitman model and the water resources modelling platform (WReMP) (Slaughter, 2017). However, it was evident that no water quality model existed for effective decision-making regarding water quality, a situation that led to the development of the WQSAM in response to the identified gaps in managing water quality in South Africa.

The WQSAM is suitable for water quality management thanks to the functions the model provides, such as the ability to translate flow into water quality consequences (Sawunyama & Slaughter, 2018). The WQSAM model is also said to have potential use in water resource management because its strengths lie in its functionalities. First, WQSAM can simulate water quality with limited water quality data (Slaughter, 2017). Second, the model can disaggregate monthly flow into daily cumulative flow. Third, the model applies scenario analysis to facilitate water resource management. WQSAM has previously been applied in the Amatole District in the Eastern Cape and in the Crocodile catchment in Mpumalanga (Slaughter et al., 2012; Sawunyama & Slaughter, 2018). The WQSAM forms the basis of the DSS developed for linking water quality standards in WUL to RQOs in the Vaal Barrage catchment (Odume et al 2021).

As already mentioned, the DSS is beneficial in creating a platform for stakeholder participation in water management. In the current study the WQSAM-based DSS is a calibrated version of the WQSAM and simulates water quality constituents that are of concern in the Vaal Barrage catchment (Odume et al., 2021).

1.9 Rationale of the Study

Given the complexity of managing water quality within the Vaal Barrage catchment, a socio-ecological system framing was adopted (Figure 1.1). An SES approach was adopted as it provides a conceptually sound foundation for addressing the water quality challenges in the Vaal Barrage catchment. Drawing on the SES conceptualisation, social drivers of water quality deterioration, such as contestations of applicable regulatory instruments for managing water quality in the catchment, are addressed. Investigating the motive and values underlying the contestations is important because such investigation could shed light on how resource users and regulators work towards voluntary compliance without regulatory enforcement, thus improving water resource quality.

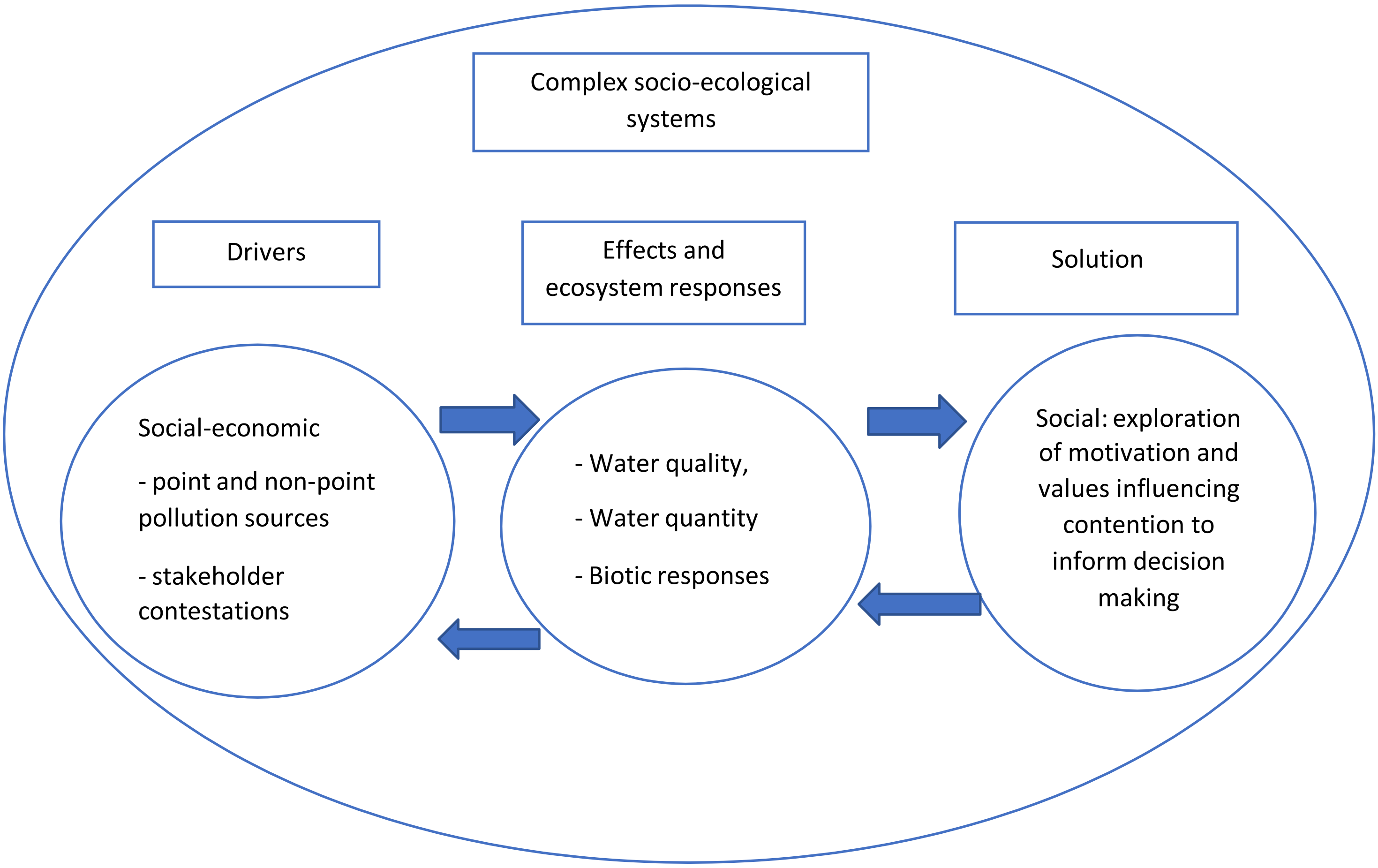


Figure 1.1: Socio-ecological system conceptual framework for assessing the water quality challenges in the Vaal Barrage.

One of the fundamental issues about water quality contestation in the catchment is the scientific defensibility of existing methods of setting water quality standards linked to the water quality components of RQOs. In the present study, a DSS recently developed through stakeholder consultation is applied for scenario modelling to evaluate the consequences of alternative development paths in the catchment. This study thus makes an important contribution to the science and practice of waterquality management in two important ways: i) it acknowledges contestations as critical social drivers of water quality deterioration and then explores solutions by focusing on the values and motivations informing such contestation, and ii) the study uses decision support systems whichclearly link RQOs and WUL to provide insights into the water quality consequences of alternative development paths, and upstream-downstream interactions within the studied riversystems.

1.10 Aim and Objectives

The aim of this study is to integrate stakeholders' perspectives and technical solutions to provide a holistic approach to managing water quality in the Vaal Barrage and associated tributaries.

The objectives of the study are threefold:

I. To explore the motivations and values influencing stakeholders' contestations of water quality use and management instruments in the Vaal Barrage catchment and associated tributaries

II. To model water quality scenarios linked to water quality standards in WUL and RQOs within the Vaal Barrage catchment and associated tributaries.

1.10.1 Limitations of the study

The research study faced two limitations, highlighted below.

Survey limitations

The study had a restricted sample pool for the following reasons. First, most of the participantsfrom the Vaal Barrage catchment and associated tributaries who were contacted for the surveydeclined without providing reasons. A larger pool of responses was achieved by attending thecatchment management forum meeting of the Vaal Barrage's associated rivers. Secondly, someparticipants chose not to participate owing to the sensitivity of contestations to the WUL and RQOs.

Modelling limitations

A limitation was that the model acquired limited water quality data. Ideally, the model shouldhave more data on metal and other nutrients, as metals are a significant water quality concern in the Vaal Barrage. Lastly, the WUL standard for discharge points of specific emitters were not available, which restricted the scope of the second scenario explored.

1.11 Thesis Structure

Chapter One introduces the study and provides a literature review.

Chapter Two provides contextual perspectives on the study area.

Chapter Three presents the investigation of stakeholder contestations on the RQO and WUL conditions. This is the first results chapter and is followed by the second results chapter (Chapter Four).

Chapter Four presents the scenario modelling using WQSAM- DSS.

Chapter Five integrates key results from Chapters Three and Four to inform the general discussion, conclusion, and recommendations made in this study.

Chapter 2: Study Area Description

2.1 General Introduction

The focus of this study is the Vaal Barrage region and its tributaries within the Upper Vaal catchment. The chapter opens with a brief description of the Upper Vaal in terms of biophysical characteristics of the Upper Vaal and Vaal Barrage catchment and socioeconomics and closes with a focus on the key water quality stressors in the lower section of the Upper Vaal, that is, the Vaal Barrage catchments and associated tributaries.

2.2 Biophysical Characteristics of the Upper Vaal Catchment and the Vaal Barrage Catchment

The Vaal River flows from the Drakensburg Mountains in the eastern interior, reaches the confluence with the Orange River to discharge into the Atlantic Ocean on the border between South Africa and Namibia in the west (Mamabolo, 2012;), covering an estimated distance of more than 13 000 km (Tempelhof et al., 2007). The main tributaries of the Vaal River are the Klip River, Little Vaal, Wilge and Waterval (DWA, 1993). The main tributaries of the Vaal Riverdrain from the Drakensburg in the east, the Witwatersrand in the north and the Maluti mountains in the south (Braune & Rogers, 1987). The Vaal River flows through the industrial hub of Gauteng and the surrounding mines of the North West Province and the Northern Cape, earning it the title of the "hardest-working river" in South Africa. The Upper Vaal has three major dams namely, the Vaal Dam, the Grootdraai and the Sterkfontein Dam, and three main sub-areas, the Vaal upstream of the Vaal Dam, Wilge and the area downstream of the Vaal Dam (Vaal Barrage) (DWAF, 2004b). The Vaal Barrage catchment lies within the quaternary C22K catchment as shown in Figure 2.1. The Vaal Barrage catchment falls within the Vaal Triangle in which the towns Vanderbiljpark, Vereening and Sasolburg are situated (Mnisi, 2019). The Vaal Triangle is a hotspot of economic activities that impact the water resources in the Vaal Barrage catchment.

The Vaal Barrage development was completed in 1923 to supply potable water to Johannesburg and the Witwatersrand. This development was initiated by the water board of the time, Rand Water (Tempelhoff, 2009). The supporting tributaries of the Vaal Barrage include the Klip River, Blesbokspruit, Suikerbospruit, Taaibospruit and Leeuspruit as shown in Figure 2.1. The Vaal Barrage extends 63 km from the Vaal Dam, and the surrounding areas include Vereeniging, Sasolburg and Vanderbiljpark. The functions of the Barrage have evolved over the years as industrialisation developed; for instance, the Vaal Barrage now supports 13 600 wet industries, approximately more than 20 wastewater treatment works, and the mining industry (Tempelhof, 2007). The increased industrial and urban development has compromised the water quality of the Vaal Barrage catchment and, as a result, the catchment no longer supplies water to Johannesburg (Mnisi, 2019).

The Vaal Barrage has a highly modified flow owing to the number of inter-basin transfer schemes (IBTs), which transfer water into and out of the catchment. During the 1980s, the Gauteng region experienced its first-ever extended drought period, straining water supplies (Tempelhof et al., 2007). This extended drought prompted environmental managers and the government to consolidate and implement a strategy to tackle the issue. In 1986, the South African government signed an agreement with Lesotho to develop the Lesotho Highlands Water Project (LHWP) to provide economic growth to the Gauteng region (Tempelhof et al., 2007). Since then, several IBTs have been developed in the Vaal Barrage, including the Heyshope, Zaaihoek and Tugela water transfer schemes, which have become instrumental in supplying water to industries within the catchment (DWAF, 2004). The transfer of water into and out the system alters both the water quality and quantity in the Vaal Barrage.

Inter-basin transfer (IBTs) schemes are developments designed to transfer water from one geographical catchment to another river reach or basin (Gupta et al., 2008). These IBTs are primarily developed with the aim of addressing a water supply problem in specific economic heartlands such as the Upper Vaal (Gupta & Zaag, 2008). Understanding the interactions between water quantity and quality in the case of IBTs can help make future predictions of environmental impacts for future developments of IBTs (Das, 2006). The donor stream can alter the receiving stream's water quality by transferring nutrient loads and biological variables such phytoplankton, which may trigger eutrophication leading to algal blooms (Fornarelli & Antenucci, 2011). Inter-basin transfers may also lead to high levels of aridity and salinity in the donor river as more and more water is transferred to the receiving river (Purvis & Dinar, 2020). A study by Woo et al. (2021) evaluated the implications of inter-basin transfer schemes on water quality through scenario modelling using the soil and water assessment tool (SWAT). The results from the scenarios indicated that IBTs can decrease the concentrations of water quality variables of the recipient, such as suspended solids and, nutrients (Woo et al., 2021).

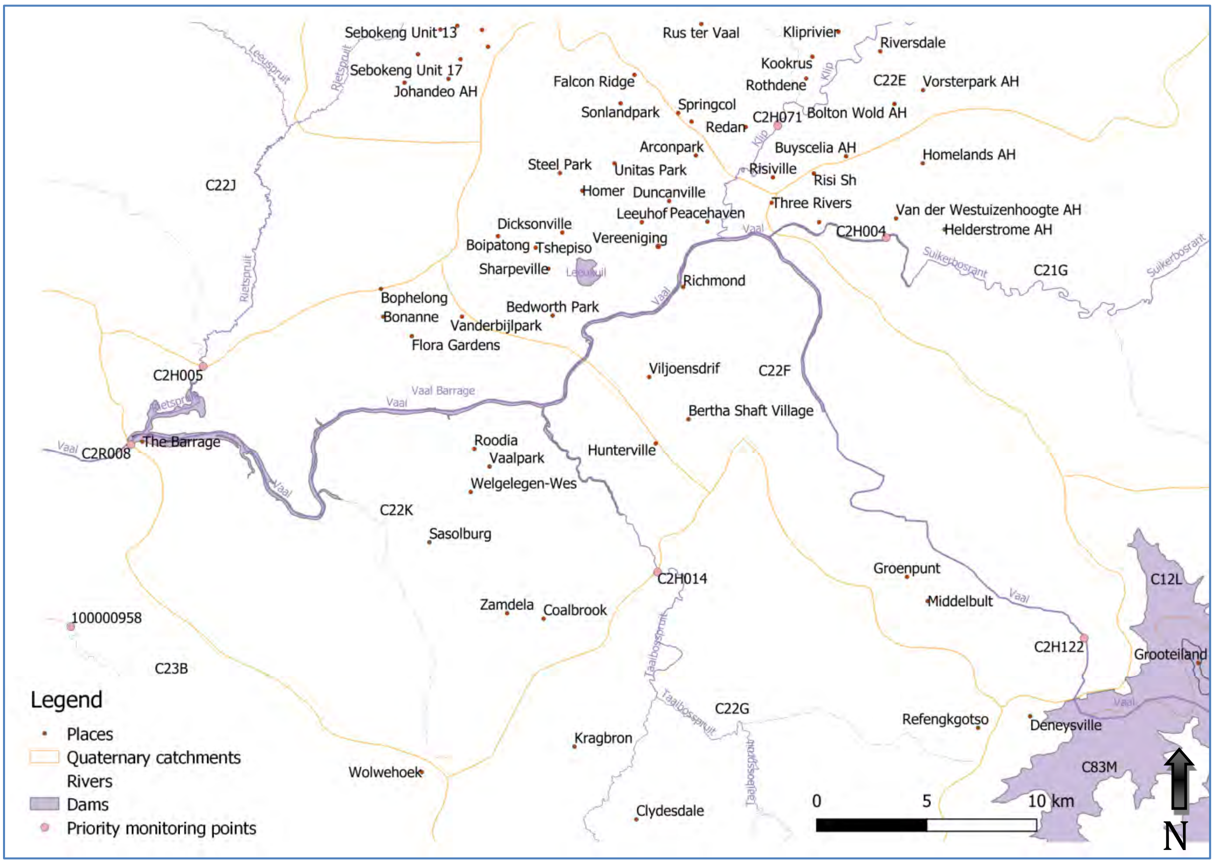


Figure 2.1: The Vaal Barrage and associated rivers (Source: Odume et al., 2021).

2.2.1 Vegetation in the Upper Vaal River catchment

The Upper Vaal catchment is characterised by temperate and transitional forest and shrub, while the northern parts are dominated by grassland vegetation (DWA, 2004). The vegetation in the Vaal Barrage catchment is predominately Cymbopogon-Themeda veld (Ochse, 2007). The dominant species of alien vegetation in the catchment are *Acacia*, *Pinus* (Pines),*Eucalyptus*, *Prosopis* species and *Melia azedarach* (Chinaberry) (Ochse, 2007; DWA, 2002).

2.2.2. Topography of the Upper Vaal River catchment

The slope of the catchment descends gently from 1800 m in the east to 1450 m in the west close to the Vaal Barrage (Ochse, 2007). The water flows from the Upper Vaal catchment past the Middle Vaal and then into the Lower Vaal (DWA, 2004).

The Upper Vaal River catchment is made up of a variety of geological formations, 80% of which is Karoo system. The northern part of the catchment consists of igneous and metamorphic rocks, and the central part of dolomitic exposures (DWA, 2004). The Upper Vaal is mineral-rich, with gold, uranium, and base metals being predominant.

The dominant soils in the Upper Vaal include sandy loam, clay loam and clay soil. Sandy loam dominates the upper reaches of the Vaal and Wilge catchment. Clay loam is dominant in the Klip and Suikerbosrand catchment, and clay soil in the middle and lower catchments of the Wilge, and upstream of the Vaal Dam (DWA, 2004). The Vaal Barrage soil is predominantly clay loam, with dominant lithologies of dolomite and sedimentary strata (Mnisi, 2019).

2.2.3Climate of the Upper Vaal River catchment

The mean annual temperature in the Upper Vaal ranges from 16 °C in the west to 12 °C in the east, withan average of 15 °C across the entire catchment, and an average daily temperature range of approximately 16 °C to 29 °C in January and 1°C to 20 °C in July (DWAF, 2004). he area experiences strong seasonal rain in summer, with the maximum temperature experienced in January and the minimum temperature in July (DWAF, 2004). The Vaal Barrage receives an average rainfall of between 600 mm and 800 mm per year (Mnisi, 2019).

2.3 Socio-economic Context of the Upper Vaal and Vaal Barrage Catchment

The demography in the Upper Vaal catchment has been extensively influenced by economic activities over the years, especially the downstream catchment, where the Vaal Barrage is situated. The completion of the Vaal Barrage stimulated employment and economic opportunities that led to the beginning of urban development and, ultimately, to an increased population that is now estimated at 10 million people (DWA, 2004). The Vaal Barrage catchment falls under the Emfuleni local municipality, Sedibeng District, Gauteng (Mnisi, 2019) which is responsible for providing wastewater treatment services in the local community. However, the municipality has experienced challenges that hinder provision of clean and reliable water and the removal of waste in the surrounding area (Iloms et al., 2019; Mnisi, 2019; Du Plessis, 2021).

The development of the Vaal Barrage in the former Vaal Triangle has led to urban sprawl (Mnisi, 2019; Pieterse, 2021); for example, the population of the coal mining town, Vereening, numbered 2000 people in 1911, had risen to 5442 in 1921, and by 2015, numbered 115 947 residents (Mnisi, 2019). Urbanisation in the Vaal Barrage catchment coincided with the growth of economic activities, local commerce, industrial activities, and farming (Mnisi, 2019). The dominant economic and land-use activities were manufacturing. Community services and strategic electricity with major industries such as AMSA (ISCOR) in the Vanderbiljpark, Sasol (iron and steel production) and Mnisi, 2019; DWA,2009) also developed. Land-use activities in the Upper Vaal catchment and the Vaal Barrage region include agriculture, mining, electricity (power stations), and bulk water supply (DWA, 2004). The Upper Vaal River supports massive economic developments within the Gauteng Province, which contribute 20% of South Africa's GDP (DWS, 2014). Figure 2.2 indicates the individual contribution of the economic activities in the Upper Vaal catchment to the overall gross geographic product (GGP) of the Gauteng region.

The Vaal Barrage supplies water to the Witwatersrand to support the growing population and industries (Mnisi, 2019) of which coal and gold mining are among the leading industrial activities in the Upper Vaal catchment (DWAF, 2004b). The Witwatersrand is characterised by gold mining that started in the 1880s, which has gradually become a leading source of pollution (DWA 2011). By 1997, gold mining activities were producing 221 million tonnes of mineral waste in the Witwatersrand region (DWA 2011). Figure 2.2 shows the contribution of various economic activities to the GGP of the Upper Vaal catchment area.

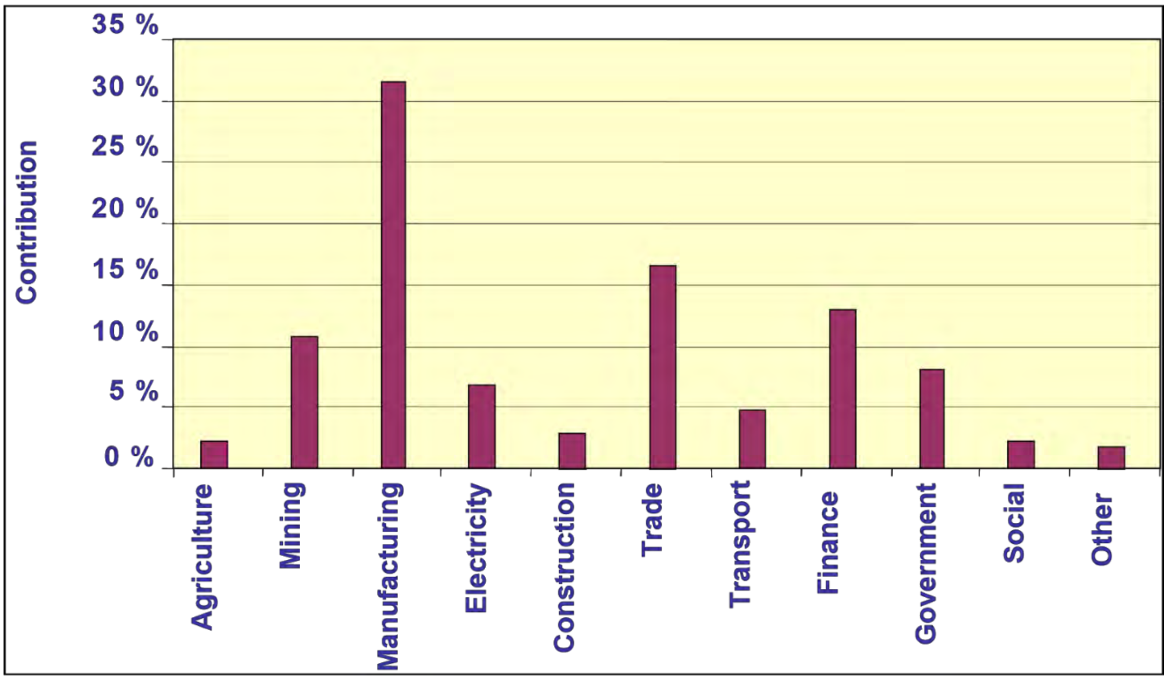


Figure 2.2: Contribution of different economic activities to the GGP in the Upper Vaal. (Source: DWAF,2004).

Water Quality in the Vaal Barrage and Associated Rivers

2.3.1 Sources of pollution

Point source pollution

The Vaal Barrage catchment and the associated rivers are subject to multiple diffuse and point pollution sources. Point sources are easier to detect because they include wastewater treatment works (WWTWs) and direct discharges from industrial plants or factories. Because the Vaal Barrage catchment falls within the Vaal Triangle, which is dominated by industrial activities, the Barrage and its associated tributaries are subjected to direct discharge from industrial effluent (Iloms et al., 2019). Improperly managed industrial wastewater threatens the quality of water resources. According to Pieterse (2021), the Vaal Barrage catchment receives contaminated water from industries in Mayerton and Johannesburg, and Du Plessis (2017) indicated that the increase of industrial effluent in the Vaal Barrage catchment has resulted in the increase of specific water quality constituents, such as total dissolved solids (TDS), total suspended solids (TSS), toxic metals such as cadmium, chromium and nickel, and faecal coliforms. Identifying point source pollution is critical in controlling pollution as such identification enables the implementation of standards and systematic laws (Wang et al., 2018).

A further threat via point source pollution is wastewater and sewage effluent from treatment plants to water resources in the Vaal Barrage catchment. The Vaal Barrage catchment and associated tributaries are severely affected by the wastewater treatment plants in the Emfuleni and Leeukwuil in Vereeninging (Mambolo, 2012). Mamabolo's (2012) study demonstrated that non-compliance with the water quality standards and conditions remains an issue in the Upper Vaal and Vaal Barrage catchment and implies that pollutant discharges exceed the licence conditions and that direct discharges from improperly managed wastewater treatment plants pose a risk to the water resources in the Vaal Barrage because they lead to nutrient enrichment conditions which may have an impact on economic growth as costs are incurred totreat the issue.

Non-point sources

Non-point sources, also known as diffuse sources, are influenced by rainfall-runoff events, and transport of pollutants from land into river systems (Wu & Chen 2012; Patterson et al., 2013). Non-point sources are often challenging to manage owing to their diffuse nature (Patterson et al., 2013). The recognised major diffuse sources in the Vaal Barrage catchment include urban and stormwater runoff and agricultural runoff. The Vaal Barrage catchment is highly influenced by the surrounding tributaries; for example, the Klip River contributes pollution loads to the Vaal Barrage. The pollution from the Klip River is a result of mining activities, and industrial and agricultural activities (Seretlo, 2012). The Klip River catchment is characterised by agricultural activities, which contribute to pollution in the catchment, which is then transported to the Vaal Barrage catchment. The surrounding settlements, such as Vereeninging, have seen an increase of informal settlements and a consequent increase in the individual use of water for domestic purposes (Seretlo, 2012). Domestic water uses results in the poor condition of water resources in the Klip River and is another prime example of a diffuse source that alters water quality in the Vaal Barrage catchment.

2.3.2 Water quality stressors in the Vaal Barrage catchment and associated tributaries

Salinity

Globally, salinisation is among the most consistent water quality stressor of freshwater ecosystems (DWA, 2004; Ochse, 2007; Shortle & Horan, 2013). Historically, salinity has been one of the significant water quality stressors in the Vaal Barrage although dilution measures from the Vaal Dam aim to keep salinity levels at TDS of 600 mg/l (Odume et al., 2021). Salinity drivers are either natural or human-induced. In the lower section of the Upper Vaal, mainly the Vaal Barrage and Blesbokspruit, the primary contributors of salinity are human-induced activities such as mining, discharges from municipal wastewater treatment works, irrigation, and stormwater return flow (DWAF, 2004).

The Grootvlei mine operates underground mining activities by pumping water from underground and releasing it into the Blesbokspruit River (Thorius, 2004), causing water quality levels to deteriorate. Thorius (2004) investigated the impact of the Grootvlei mine pumping on the water quality in the Blesbokspruit by analysing the selected variables of pH, magnesium, EC, and sulphate. The results of the study revealed significant deterioration of water quality and severe impacts on the wetland that is critical to purifying water in the Blesbokspruit (Thorius, 2004). The upstream activities in the lower section of the Upper Vaal have implications for the ability of the downstream catchment to meet WULs' conditions, and the Vaal Barrage currently exceeds required salinity levels.To manage salinity, it is important to understand the external and internal sources of salinity such as water transfers, abstraction, mine dewatering, effluent flows, and catchment wash-off(DWAF, 2009). Water transfers, such as IBTs, into and out of the catchment influence salinity by transferring dissolved salts (DWAF, 2009). Mine-water discharges are one of the major contributors to salinity in the Vaal Barrage catchment (DWAF, 2009). Effluents from wastewater treatment and industrial complexes also contribute to salinity in the Upper Vaal River system (DWAF, 2009).

Nutrients

The average phosphorus concentration in the Vaal Barrage catchment exceeds the water quality components of the RQOs (Rademeyer et al., 2009). The major sources of nutrient enrichment in the catchment are poorly managed municipal wastewater treatment works (Rademeyer et al., 2009) that result in elevated concentrations of nitrate and phosphate, as have been recorded in the Klip River. The resulting nutrient enrichment is a well-known problem in the Vaal Barrage and Klip River catchment (McCarthy, 2007) where the increased nitrogen and phosphorus have caused eutrophication. Eutrophication impacts the composition and function of an aquatic ecosystem by increasing incidents of harmful algal blooms. These algal blooms increase organic matter, leading to anoxic conditions that threaten aquatic biota (Marara & Palamuleni, 2019).

Microbial pollution

The Vaal Barrage catchment is a complex catchment not only because of industrial activities and urbanisation, but also because of the impact of the tributaries that flow into the catchment that contain mineralised, enriched, and severely microbiologically contaminated water (Swanepoel, 2009). The Blesbokspruit River tributary carries microbial contamination from informal settlement sewage, cattle farms along the Blesbokspruit, and the stormwater runoff from both residential and agricultural areas, affecting the microbial levels of the Vaal Barrage catchment (Quinn et al., 2009). Microbial pollution is of critical importance because of the harmful implications for human health, such as an increase in waterborne diseases, which are particularly problematic for residents in the informal settlement; an outbreak of waterborne diseases indicates that the water supply is not reliable and clean for use by the residents

Chapter 3: Exploring the Motivation and Values Influencing Stakeholders' Contestations of Water Quality Use and Management in the Vaal Barrage Catchment

3.1 Introduction

The Vaal Barrage catchment is among the most utilised catchment in South Africa because of its situation in an economic heartland of South Africa (DWA, 2004). Activities such as the expanding industrial footprint, a growing human population, increasing agriculture, mining and informal settlements impact the Vaal Barrage catchment (DWA, 2004). These activities have led to reports of high levels of chemical and microbial pollutants in the system (McCarthy, 2007). Pollution poses a threat to both human health and further economic growth as well as threatening ecological integrity, and the sustainability of the ecosystems upon which humans rely (Richter et al., 2003; Schwarzenbach et al., 2010).

In South Africa, water pollution is controlled through environmental policies and regulatory instruments such as the South African national water quality policy and strategy (DWA, 2014), as well as water quality licencing, which is an important water quality regulatory instrument (DWS, 2014). Examples of other regulatory instruments used to manage water quality and pollution in South Africa include general authorisation, water quality guidelines, a waste discharge charge system, the Green Drop programme, and environmental impact assessments (Odume et al., 2018). These instruments are collectively referred to as source-directed control (SDC) measures (DWA, 2004). Also important are the resource quality objectives (RQOs), Reserve determination, the national classification system, and water resources classification of significant water resources, all of which aim to protect water resources. They are collectively referred to as resource-directed measures (RDM) (DWA, 2004)

Odume et al. (2018; 2020) have shown that water users in the Vaal Barrage catchment contested applicable water quality regulatory instruments such as discharge standards in their water use licencing (WUL). A study carried out by Odume et al. (2021) noted a number of points of contestation: the scientific defensibility of the standards in WULs; the relationship between RQOs and WUL; the relationship between upstream waste loads and downstream users; the relationship between flows and water quality reflected in their licences, and the relationship between diffuse and point source pollution in WUL standards. These contestations led to tension between water resources users and regulators in the catchment. In addition, these contestations present themselves as challenges to achieving water resource protection and use in the Vaal Barrage catchment.

Contestation may also be driven by water resource users' diverse values, perceptions and motivations for water use and for compliance with regulatory instruments. Reser and Bentlupperbaumer (2005) and Jones et al. (2016) define values as more strongly held than attitudes underpinning decisions and behaviour. Perceptions refer to how an individual organises and interprets information in a meaningful way (Lindsay & Norman, 1997; Pickens, 2005). Motivation, as defined by Susan (1995), is the force that drives the persistence of a particular behaviour. For example, in the lower section of the Upper Vaal system, stakeholders have various reasons for water resource use, such as industrial use, mining, agriculture, all of which are uses often driven by economic benefits. The multiple motivations for water use may contribute to the contestation of the applicable regulatory instrument, particularly if water resource users perceive that such instruments may impact the sustainability of their businesses and overall interests (Yoder & Chowdury, 2018). Understanding the social dimension of environmental problems, such as values and human behaviour, is fundamental to understanding how stakeholders perceive and interpret regulatory instruments (Steg, 2016). Overall, motivations in this study describe the 'why' stakeholders choose to contest the water quality instruments, particularly the discharge standards in WUL, the way such discharge standards are derived, and the relationship between discharge standards in WUL and the water quality component of the RQOs.

Given the highly industrialised nature of the Vaal Barrage catchment, a critical area of contestation of the water quality standards in WUL is the relationship between upstream waste loads and downstream users (Odume et al., 2018; 2021). For example, upstream users may release more pollutants into the stream systems, with negative implications for the downstream users (Hou et al., 2020). The upstream water users may have better environmental conditions, such as water quality. Nevertheless, the polluted discharges cause downstream users to suffer high levels of pollution, and thus they require more stringent water quality standards in their WUL. Thus, water users downstream have requested the regulatory authority to clarify how waste loads are generated by upstream users are calculated when deriving the standards for WUL. Furthermore, downstream users in the Vaal Barrage catchment within the lower section of the Upper Vaal system have emphasised the need for stringent standards and targets for upstream users to control water quality impact and to meet the resource quality objectives.

What is clear from these sources of contestation of water quality in the lower section of the Upper Vaal system is the necessity to depart from a command-and-control approach to an approach that considers the interest and values of diverse stakeholders within a catchment (Hou et al., 2020). Stakeholder engagement can assist in addressing the water quality challenges, and gain community support, trust, and buy-in from the stakeholders. Despite the identified contestation of water quality use and regulatory instruments in the lower section of the Upper Vaal (Odume et al., 2018; 2021), no study has explored the perception and motivations underlying these contestations. This study intends to fill this gap as a contribution to the scientific understanding of water quality management and its complexity in a highly industrialised and complex social-ecological system. The objective of this chapter fulfils Objective One of this study (See Chapter 1) in exploring the perceptions and motivations influencing stakeholders' contestations of water quality, and management instruments in the Vaal Barrage catchment within the lower section of the Upper Vaal River system.

3.2 Methods and Materials

3.2.1 Conceptual framing

A conceptual framework is a tool that is used to visually represent the context of the project, and the factors that influence the phenomenon. It is a useful tool that helps determine what is to be measured and evaluated (Margolouis et al., 2008). Water quality management seen through the lens of socio-ecological systems acknowledges the interactions between social, economic, technical, environmental, and institutional considerations. The implication is that attention needs be paid to all dimensions such as trust-building, effective institutions, and transparency, including the environmental elements such as ecosystem functionality.

The present study uses the conceptual framing developed by Odume et al. (2018) of possible sources of water quality contestation in the lower section of the Upper Vaal River catchments as a framework to better understand water quality contestation, and thus to explore perception and motivation (Figures 3.1a-d). Figure 3.1a provides a diagram of the ideal environmental (water) management cycle. As shown in the figure, if a discrepancy occurs between the present ecological state (PES) and the desired goals for the system, the users may take permissible voluntary actions and/or comply with applicable legal instruments. These actions ensure that PES meet the desired goals. In this cycle, both water resource users and the regulators have a common understanding of the system. The second possible cycle is the trust cycle (Figure 3.1b).

In this cycle there is effective management of the aquatic system based on the increased trust between stakeholders and the regulator regarding the scientific defensibility of the methods, institutional efficiency and effectiveness of enforcement and sanctions. Within this cycle, there is a reduction of non-permissible actions that have negative effects on the aquaticecosystem.

The third cycle pertains to contestation of the instream goals expressed as RQOs (Figure 3.1c.) Although contesting the goals is possible, once they are gazetted, they assume the status of law and therefore re-formulating them becomes increasingly difficult and time consuming. The fourth cycle pertains to contesting applicable SDC instruments such as WUL, permit, waste discharge charge system, and so on (Figure 3.1d). As shown in this cycle, contestation may lead to mediation, or application of sanctions and enforcement mechanisms on the part of the regulator. However, when contestation arises, it may lead to a trust-deficit environment, impacting transparency, and undermining the credibility of the system, the examination of which is the thrust of the current study.

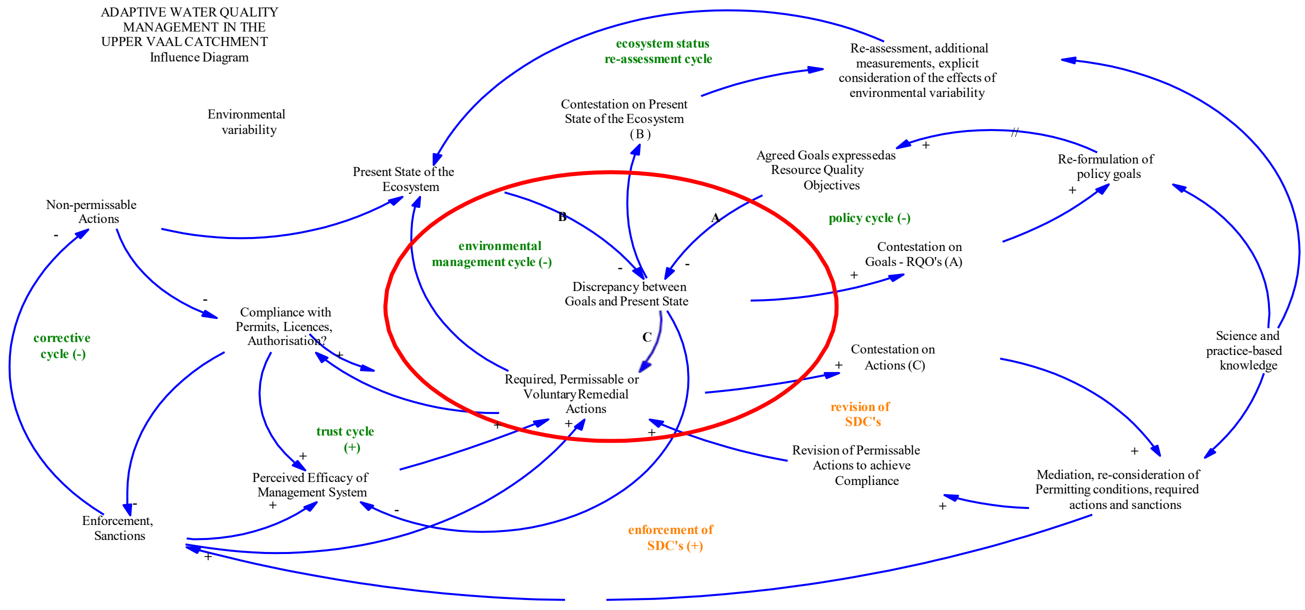


Figure 3.1a: The ideal environmental management cycle (area within red ellipse). (Source: Odume et al., 2018).

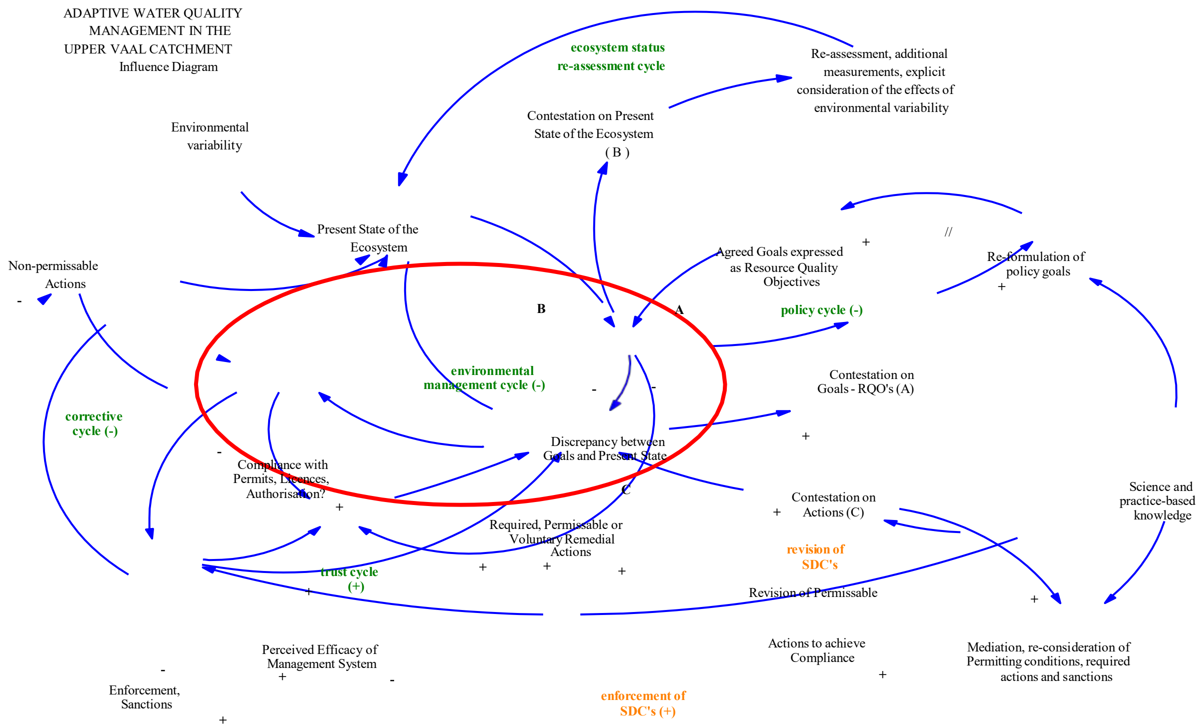


Figure 3.1.b: Adaptive water quality management cycle showing trust in the water quality regulatory instruments and systems (area within redellipse). (Source: Odume et al., 2018).

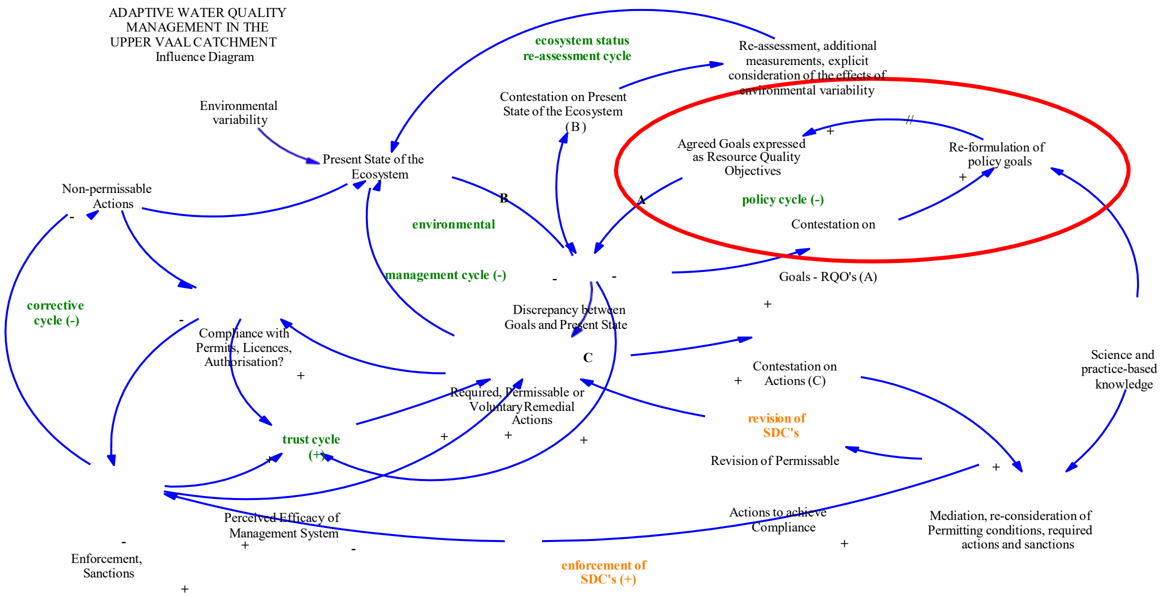


Figure 3.1c: Adaptive water quality management cycle indicating possible contestation of the instream goals (RQOs) (area within red ellipse). (Source: Odume et al., 2018).

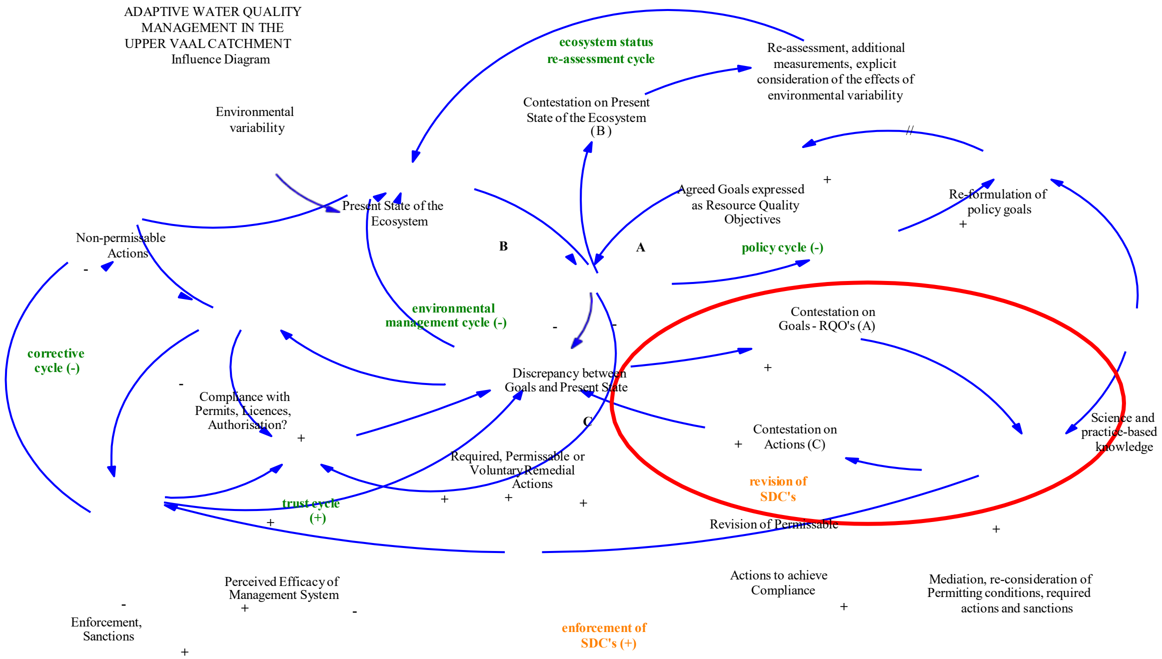


Figure 3.1d: Adaptive water quality management cycle indicating contestation of the SDC instruments/actions (area within red ellipse). (Source: Odume et al., 2020).

3.2.2 Sampling strategy

Purposive sampling

The study purposefully sampled participants from the catchment management forums (CMFs) within the lower section of the Upper Vaal catchment. Purposive sampling, also known as judgement sampling, is a non-random tool in which the researcher deliberately selects the participants based on their experiences and the knowledge they possess concerning the phenomenon of interest (Palinkas et al., 2013). For example, the 19 participants in this study were selected based on their area of interest and speciality, and they represented industry, government, communities, non-governmental organisations (NGOs), and state-owned enterprises (SOEs). The participants were all members of the Leeu-Taaiboschspruit forum. These participants were selected on the basis of their field of expertise in water quality management, which would provide a substantial insight to the contestations surrounding WUL and RQOs in the Vaal Barrage catchment. Secondly, the selection of participants was based on the study by Odume et al. (2018) funded by Water Research Commission (WRC), the relevant stakeholders from the Vaal Barrage catchment had raised concerns regarding the WUL conditions and how they relate to achieving the RQOs.

An essential aspect of the purposive approach is the willingness of participants to make an in-depth contribution, so this strategy is suitable for rich and detailed case studies (Etikans et al., 2016). Purposive sampling provides insightful information and understanding of the research problem. The in-depth nature of information provided through the strategy often compensates for the low number of participants, in contrast to the approach emphasised in the random sampling approach. For example, Libala (2019) used purposive sampling to engage with livestock owners to gain an understanding of the livestock practices in the Tsitsa River catchment in the Eastern Cape.

3.2.3 Data collection

To gain insight into the motivations, perceptions and values underpinning water quality contestation in the study area, participant observation, semi-structured interviews and document analysis were undertaken. Data from all the three methods were then triangulated to obtain in-depth insights into the contestation of water quality instruments in the study area.

Semi-structured interview development

A semi-structured questionnaire is a mixed method approach which encompasses both open-ended and closed questions (Newcomer et al., 2015). Open-ended questions provide depth into the study as the researcher can identify emerging themes and group them according to their similarities. On the other hand, closed questions provide breadth, but limit the participant responses to those that have been predetermined by the researcher (Palinkas et al., 2013). In this study, the semi-structured questionnaire was selected as the appropriate tool, providing both depth and breadth. The semi-structured questionnaire used for this study is provided in Appendix A.

The questionnaire consisted of six sections highlighting the various points of interest that feed into the study and was structured into four themed headings to help to contextualise the research. The first section investigated perceptions of the importance of water resources in the Vaal Barrage catchment; the second section focused on the water quality challenges faced in the system; section three focused on perceptions of RQOs and their achievement, and the fourth section posed questions to elicit stakeholder perceptions and motivations underpinning the contestation of WUL conditions in the study area, as well as basic demographic information. The questionnaire was completed online using Google forms which were sent out through email communication so the key stakeholders could access the link. Email follow-ups were done, reminding stakeholders to participate in the survey, throughout the first year of the study.The questionnaire was also administered at a meeting of the Leeu-Taaiboschspruit forum workshop, held on 14 February 2020.

Document analysis

Document analysis is a systematic technique of reviewing documents with the aim of understanding the targeted phenomenon (Bowen, 2009). Knowledge is gained through documents such as published articles, textbooks, and minutes of meetings (Bowen, 2009). Document analysis provides supplementary information and, in some cases, shapes the direction of the study. Such analysis is often triangulated with other sources of data analysis enabling the researcher to gain evidence to build the credibility and validity of the data (Bowen, 2009).

In the present study, the key documents analysed were published papers and research reports, minutes and research proposals. For example, the Water Research Commission-funded project provided insight to contestations in the Upper Vaal (Odume et al., 2018; 2021), while published papers such as DWAF (2004;2006;2009) Este Ochse (2007) and Tempelhof (2007;2009) provided perspectives into water quality deterioration in the catchment. A full list of all the documents analysed for the study is provided in Appendix B.

Participant observation

Participant observation an essential tool in qualitative research, in which the researcher takes on a voyeur's role (Balsiger & Lambelet, 2014). Marshall and Rossman (1989:79) define participant observation as "the systematic description of events, behaviours and artefacts in the setting chosen for study" (Kawulich, 2005). The researcher takes on the role of a participant observer, collecting data either using field notes, audiotapes, or even photographs, and translating the data into interpretations related to the underpinning theories of the study. In this case study, participant observation was undertaken by attending the Leeu-Taaiboschspruit forums on 12 February 2020 and 14 November 2020 in Sasol Kliplapa, Gauteng. These field notes describe how the forum functioned, the conversations that happened between thedifferent stakeholders and the issues that emerged. Participant observation has proved to be beneficial to researchers as it can increase the validity of evidence supporting the phenomenonand provide a better understanding of it. This tool of data collection, used in conjunction with semi-structured questionnaires and document analysis, strengthened the depth of the present study.

The observation was guided by a set of predefined questions which probed the main concerns of the stakeholders during the meeting, the key areas of contestation (if any), the meeting format, the main challenges in the catchment and solutions (if applicable), as well as participant attitudes towards the regulators and regulatory instruments for water quality management.

3.2.4 Ethical consideration

As the research required engagement with the stakeholders through a semi-structured interview, institutional ethics clearance was mandatory. Ethical clearance was obtained from the Rhodes University Ethics Committee with the approval number 2019-0288-693 that allowed the researchers to survey and communicate with the participants.

3.2.5 Data analysis

Descriptive statistics

The descriptive statistics used in this study include frequencies and percentages. The results are visually presented in the form of graphs and tables.

Thematic analysis

The primary purpose of qualitative analysis is to appropriately communicate data that have been collected by turning diverse data into a succinct structure (Creswell, 2013). The presented data should indicate a clear relationship with the research objectives. A critical part of qualitative analysis is developing a strategy that encompasses the management and classification of data, visualisation and interpretation of the data, and the representation and reporting of the data.

Thematic analysis is regarded as a useful method applied to identifying, analysing, and recognising patterns in data (Braune & Clarke, 2006). The themes emerge through analysing the responses from interviews, surveys, and questionnaires, such that the researcher can identify emerging themes. An essential component of the thematic analysis process is reflexivity, making the researcher aware of his/her influence on the research.

The thematic analysis incorporates several approaches that researchers select to align with the objectives of the study, such as phenomenological, narrative, grounded theory, and the case study approach. The case study approach is used to create an in-depth picture of the cases and to represent data as narratives, presenting emerging themes (Creswell, 2013). Since there are various ways of presenting the analysed data, the case study approach was selected for this study, as the most appropriate because of the current contestation of the water quality instruments in the Vaal Barrage catchment and associated tributaries, which represent a particular case.

The thematic analysis was conducted using the framework developed by Creswell (2013). The first step of thematic analysis involves familiarising oneself with the data by reading and taking notes of the initial ideas. Step two involves generating initial codes and key concepts to organise the data. The third step is the process of collating the categories and gathering the relevant data under a potential theme. This process was also the initial process of developing a detailed description of the potential themes. In step four the themes were established and checked against the coded extracts and the entire dataset. Step five involved the ongoing evaluation of the established themes, refining them and fitting them to the overall narrative of the study. All five steps were carried out in this study. Through this process, four main themes and 15 sub-themes were identified. The four main themes are i) the perceptions regarding the RQOs in the catchment within the lower section of the Upper Vaal, ii) perceptions of water quality licence standards and conditions in the catchment, iii) the seriousness and sources of water quality threats in the Vaal Barrage catchment and associated tributaries, and iv) the perceived importance of water resources in the Vaal Barrage catchment and associated tributaries.

3.3 Results

3.3.1 Participant demographics

A total of 19 respondents were interviewed for this study. Approximately 74% of the participants work in the public sector, that is, government departments across jurisdictional approaches and scale, 15% of the participants were in non- profit organisation (NPOs), and 11% in the private sector. Participants' interest in the water sector ranged from water resource management (37%), integrated water quality management (11%), environmental policy implementation (5%), environmental toxicology (11%), environmental protection (16%) and activist/ social injustice advocacy (5%). Participants’ level of education and qualifications were Bachelor of Science (15%), Honours degree (5%), Master of Science (57%) and Doctor of Philosophy (21%). The participants’ specialisations included ecology, hydrogeology, hydrology, chemistry, toxicology, as shown in Figure 3.2. The sectors of organisation of participants are shown in Figure 3.3 were diverse, ranging from research to energy, through water and analytical monitoring.

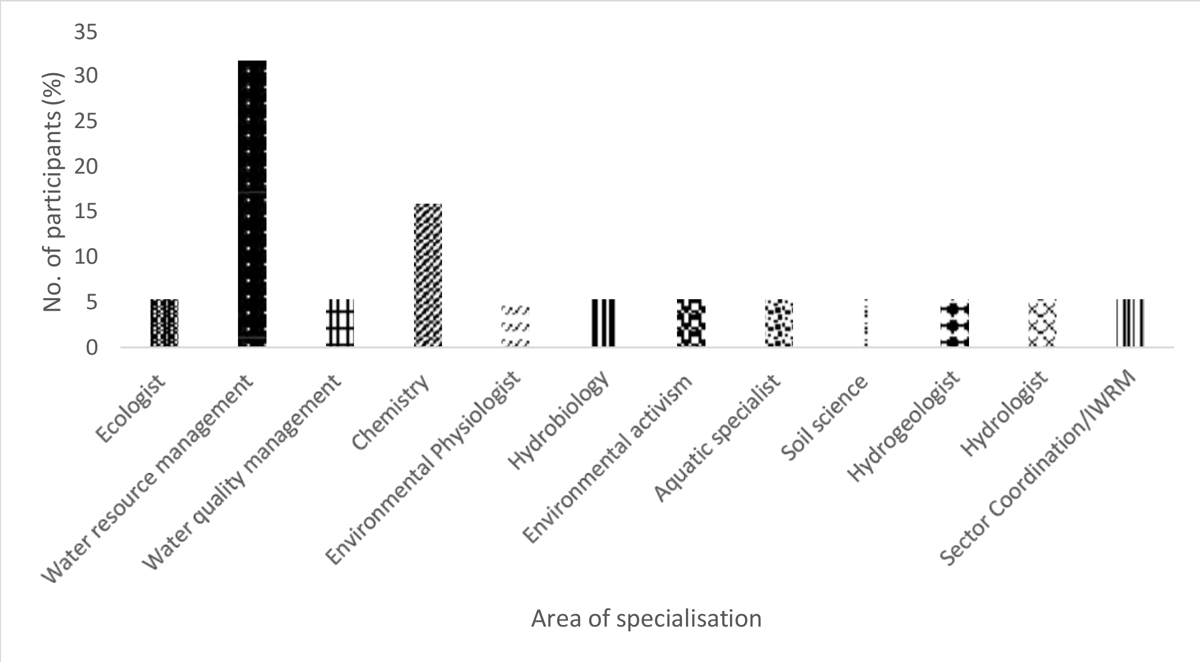


Figure 3.2: Specialisations of research participants interviewed in this study.

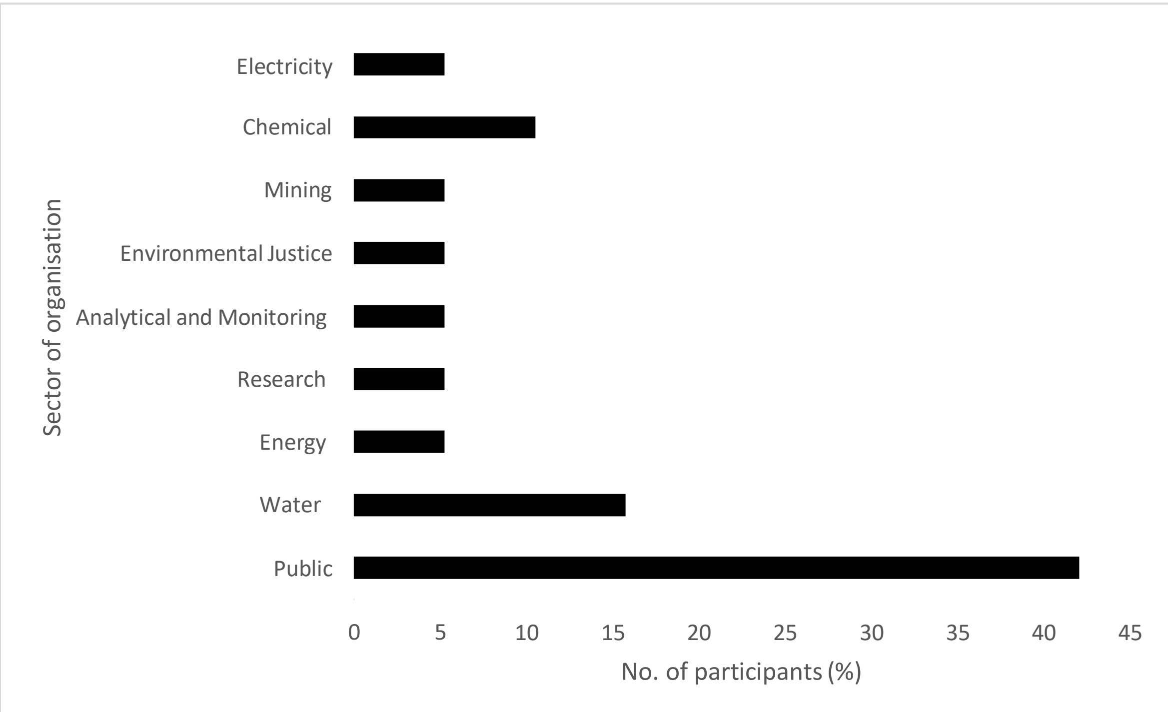


Figure 3.3: Groups from which participants were drawn for the interviews.

3.3.2 Perceptions regarding the resource quality objectives (RQOs) in the Vaal Barrage catchment and associated tributaries.

From the data, three main themes emerged on perceptions regarding the RQOs: i) unrealistic RQOs and the implications thereof, ii) poor institutional capacity, and iii) solutions to RQOs disputes/contestations. These sub-themes are presented and discussed.

Unrealistic RQOs and the implications thereof

When participants were asked whether the gazetted RQOs (see Appendix A) for water resources in the Vaal Barrage catchments were realistic, more than a third of them (37%) found the RQOs to be realistic. About 26% of the participants found the RQOs unrealistic and 5% regarded them as "very unrealistic".

Participants who found the RQOs unrealistic provided reasons such as:

> *"I am not convinced that the resource water quality objectives have a proper scientific basis. If the objectives are too lenient, we may not see any benefit of setting parameters as per WUL."*
>
> *"Some levels are too lenient, but others are too strict."*

Approximately 5% of the participants were unaware of the gazetted RQOs, indicating a lack of awareness on the part of the water resource users. About 26% of the participants were not sure whether the RQOs were realistic or not, as shown in Figure 3.4. The participants that indicated that the RQOs were realistic gave different reasons; one of the participants indicated the availability of historical data as the basis for the necessity for realistic RQOs:

> *"[There isenough historical data available to base RQO on, so they should be achievable."*
>
> *"The RQOs in most catchments have been determined scientifically so they should be realistic, but mines/industries have to be more willing to try to comply."*

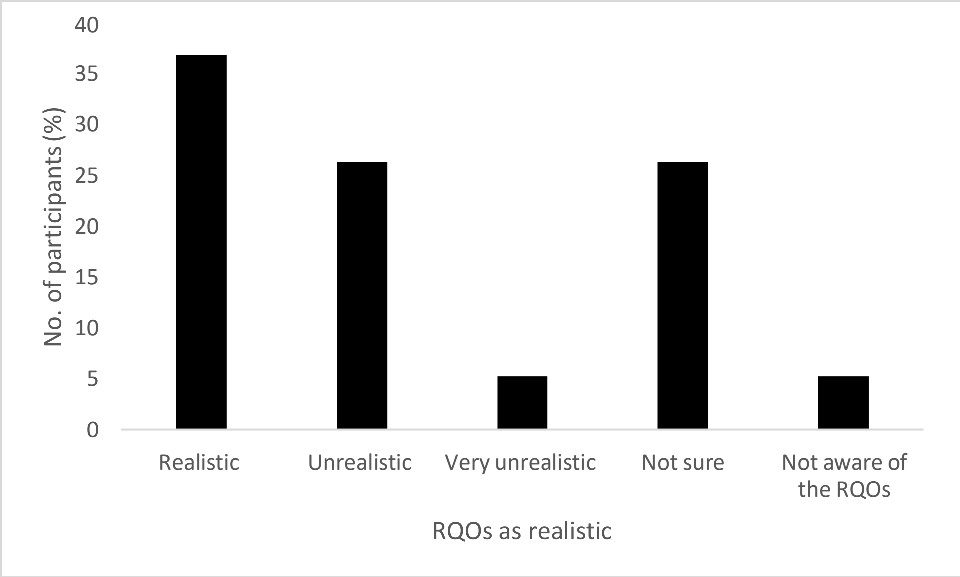


Figure 3.4: Participants' responses to whether the RQOs were realistic or not

Within the RQO formulation process, stakeholder involvement is a critical process that informs the RQOs. In the present study, participants were asked whether the RQO process was indeed consultive and involved stakeholders. Interestingly, about 21% agreed and 21% strongly agreed that the RQO process was consultive and stakeholders were involved, as shown in Figure 3.5. However, 21% disagreed and 5% of the respondents strongly disagreed that RQO involved stakeholders. The results also indicated that 21% of the participants were neutral.

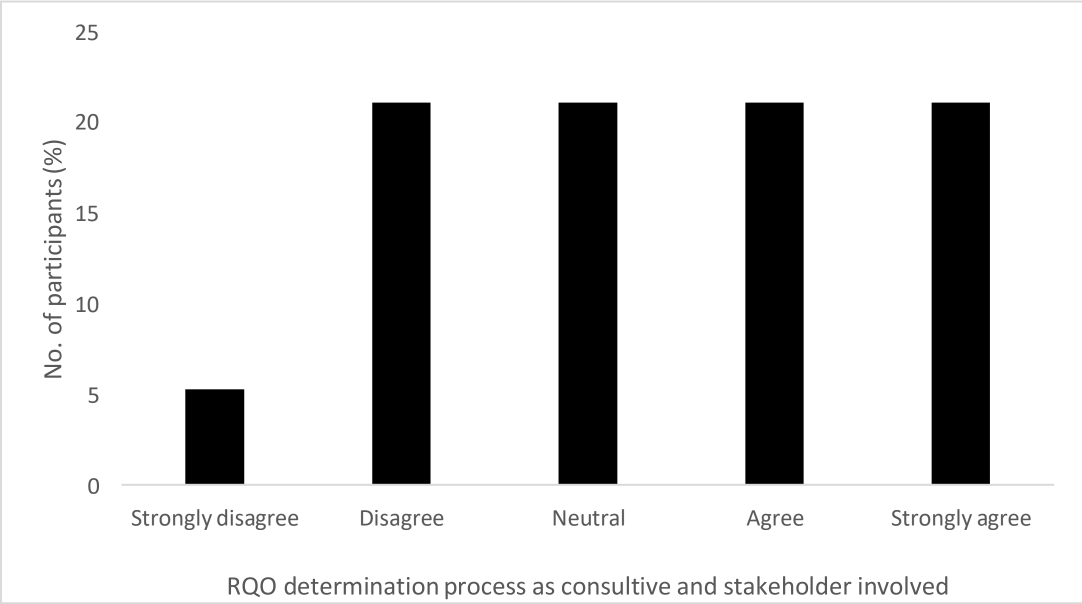


Figure 3.5: Participant response to whether the RQO determination process is consultive and involves stakeholders.

Participants were asked what the most likely serious consequences were of not meeting the gazetted water quality component of the RQOs. About 63% of the participants agreed that degraded ecosystems and impaired functionality would be a serious consequence of not meeting the RQOs (Table 3.1). Twenty-six percent (26%) of the participants perceived the risk of human infections and diseases due to impaired water quality as a serious consequence of not meeting the RQOs. Water quality stressors, in particular microbial pollution, is known to be a threat to human health, causing waterborne diseases such as cholera. About 11% of the participants considered job losses due to increased operational costs related to treating raw water as a serious consequence of not meeting the RQOs.

Table 3. 1: Perceived seriousness of the consequences of not meeting the water quality component of the RQOs.

Consequences of not meeting the RQOs	**N= Frequency**	**N= % frequency**
Degraded ecosystems and impaired ecosystem functionality	12	63
Job losses due to increased operational costs related to treated raw water	2	11
Risk of human infections and diseases due to impaired water quality	5	26
Business profitability due to increased operational costs	0	0
Impact on water quality-sensitive crops and general agricultural productivity	0	0
Aesthetic value of the water resources within the catchment	0	0

Participants were asked to rank the necessary actions required to control water use activities within the Vaal Barrage catchment on a scale of 1-5, where 1 was the least important and 5 the most important required to meet the RQOs. About 74% of the participants indicated statutory enforcement and compliance monitoring of water use activities; 53% felt raising awareness, education and continuous stakeholder engagement were important, and 58% indicated that the "polluter pay" principle would be the most important way to control and regulate activities within the catchment, as shown in Figure 3.6. Interestingly, participants ranked voluntary self-regulation, for example, through ISO and incentive/reward to water users for perceived good behaviour, to be the least important method of meeting the RQOs. Only 11% of the participants ranked self-regulation higher, and only 16% of the respondents' ranked incentives for good behaviour high.

Poor institutional capacity

Institutional capacity to deliver on mandate has been identified as critical in the South African water sector (DWA, 2011). The participants in the present study identified institutional capacity as the primary reason why the RQOs might not be achieved. When the participants were asked whether the RQOs in the catchment were achievable, approximately 68% of them indicated that it was either unlikely or highly unlikely that RQOs, given the current management trajectory, would be achieved. These participants stressed that institutional capacity was necessary to meet the gazetted RQOs and the relevant water quality instruments. One of the participants indicated:

> *"There is lack of commitment from the Department (DWS) in bringing all the role players in the CMFs so to achieve RQOs purposes."*

Participants emphasised the role of each resource manager and of catchment management agencies to meet the RQOs:

> *"Once the RQOs are set, they are binding to all who use the resource. RQOs are set for the resource and not for the users (licence conditions). It becomes the responsibility of [the] CMA and regional people to implement the monitoring of the set RQO."*

Even though most participants were of the view that the RQOs cannot be met, 11% (highly likely) and 5% (likely) of them felt that the RQOs were likely to be met. One of the participants opined that it was likely that the RQOs could be met, given that the implementation and assessment plans reflect the current local conditions of the catchment. Interestingly, one participant challenged the notion of the RQO, and focused on whether the objectives would result in promoting sustainable resource management within the catchment:

> *"Honestly it would vary per catchment; many objectives are not stringent at all, and in fact, if they were met, would result in an unsustainable catchment management situation. An example is the manganese limit set for the Mooirivier, which results in acute toxicity to the receiving environment. While on the other side, there are other objectives that have been set that can never be met, or have no reasonable scientific basis for why they were included, such as the uranium limit in some catchments (with known uranium sources) of 15 ug/L as opposed to drinking water quality requirements as per SANS and WHO of 30 ug/L, not to mention the higher qualities that can be tolerated by the receiving environment, as supported by literature. Therefore, the question is less about the likelihood of achieving these objectives and more about whether these objectives would result in the improvement in the catchment management we really need to see occurring in order to ensure sustainable catchment management for present and future water users (includes the environment)."*

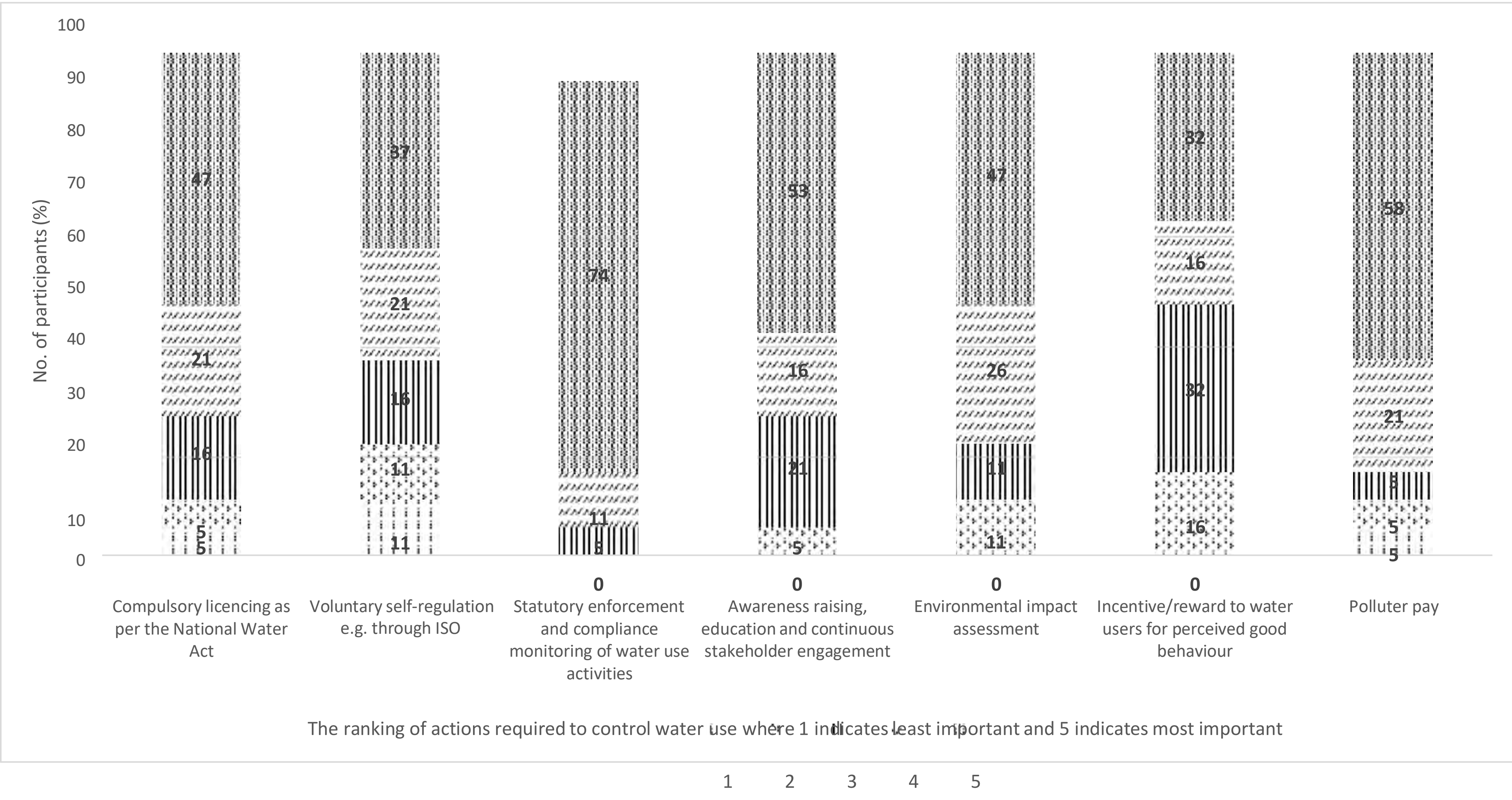
"It is highly likely that the gazetted RQOs would be met, provided that appropriate implementation and assessment plans which reflect current local conditions of the catchment are made available or put in place."

As shown in Figure 3.6, participants ranked statutory enforcement and compliance monitoring of water use activities as the most important actions required to control water use activities in the Vaal Barrage catchment. This was followed by a "polluter pay" principle and awareness-raising, education, and continuous stakeholder engagement. The participants were of the view that licencing, monitoring, and the "polluter pay" principle would ensure that water quality was taken seriously within the catchment. One of the participants reflected:

"Compulsory licencing, compulsory monitoring and enforcement and polluter pay principles when implemented and evaluated will ensure that water quality is taken seriously and that will assist meeting the RQOs."

The participants also felt that creating awareness and educating stakeholders on how their behaviour influences water resources could contribute to water quality management. The participants in this category based their argument on the fact that the statutory measures can take time and that, given government incapacity to enforce statutory instruments, education and awareness-raising on detrimental behaviour can accelerate solutions to contestations around the RQOs:

"Also due to the state of the government, it can take years to achieve; therefore, water users taking the initiative to be responsible and being educated to do so would be more beneficial, while the government can then play a regulatory and advisory oversight."



No. of participants (%)
Compulsory licencing as per the National Water Act
Voluntary self-regulation e.g. through ISO
Statutory enforcement and compliance monitoring of water use activities
Awareness raising, education and continuous stakeholder engagement
Environmental impact assessment
Incentive/reward to water users for perceived good behaviour
Polluter pay
The ranking of actions required to control water use where 1 indicates least important and 5 indicates most important
1
2
3
4
5

Figure 3.6: Participant response to the necessary actions required to control water use activities in the Vaal Barrage catchment.

3.3.3 Perceptions regarding water quality standards in water use licences (WUL)

Water quality licencing is an important statutory instrument for reducing pollution (DWAF, 2007). Compliance with standards in water quality licences can be enhanced if water resource users view such standards as credible, scientifically defensible, and the process of their derivation as fair and transparent (Odume et al., 2021). In the current study, when participants were asked about the key challenges of water quality licencing in the Vaal Barrage catchment and associated tributaries, participants ranked scientific credibility and defensibility of methods for deriving water quality standards in WUL as top (Table 3.2). Other key challenges identified as priorities for WUL were clarity regarding the relationship between RQOs and water quality licencing, as well as institutional capacity, including expert knowledge. Some of the participants, particularly industry representatives, were of the view that the lack of scientific expertise, specifically from regulators, added to the uncertainty regarding scientific defensibility and credibility of the WUL in the catchment. These participants argued that such uncertainties could lead to the licence conditions being unrealistic. The clarity between RQOs and licencing conditions also featured prominently; the participants were of the view that transparency was imperative as users do not understand the linkage between the two water quality management instruments and whether these can replace one another. For example, a participant from the public sector opined that:

> *"That is why the concept of RDM, including clarity regarding the relationship between RQOs and water quality licencing, seems not easy to understand by many of us."*

Participants also referred to institutional capacity in government structures responsible for monitoring the water quality instruments, and the lack of financial resources that are necessary for licencing procedures as factors that impede finalising the licencing process. These issues were captured in one of the participant responses as follows:

> *"The Regulator is HIGHLY ineffective due to the lack of funding, multiple layers of poor senior managers, enormous bureaucratic and administrative burden, distrust, centralised decision making, disempowered middle managers and junior staff, rigid work environment that is not conducive to innovation, etc."*

Table 3. 2: Frequency of the top water quality licencing challenges in the Vaal Barrage catchment and associated tributaries. Note that one participant could indicate more than one challenge as a top priority.

Top water quality licensing challenges	**N=Frequency**	**N=% Frequency**
Scientific credibility and defensibility of methods for deriving water quality standards in licence conditions	12	63
Institutional capacity, including expert knowledge, to deal with water quality licencing	11	58
Clarity regarding the relationship between RQOs and water quality licencing	11	58
Institutional efficiency and effectiveness in issuing water quality licences	10	53
Perceived fairness in enforcement, compliance monitoring and sanctions	7	37
Backlog of licence applications	7	37
Lack of transparency in the way licence conditions are derived	6	32
Over-stretched regulators who are unable to cope with new applicants	5	26

Participants were asked whether the process of deriving water quality standards in water use licence conditions was consultative and involved the stakeholders. Approximately 32% of the participants disagreed, with 11% strongly disagreeing that the process for deriving WUL standards was consultative. About 26% chose to be neutral and 26% of the participants agreed that the process was consultative, as shown in Figure 3.7.

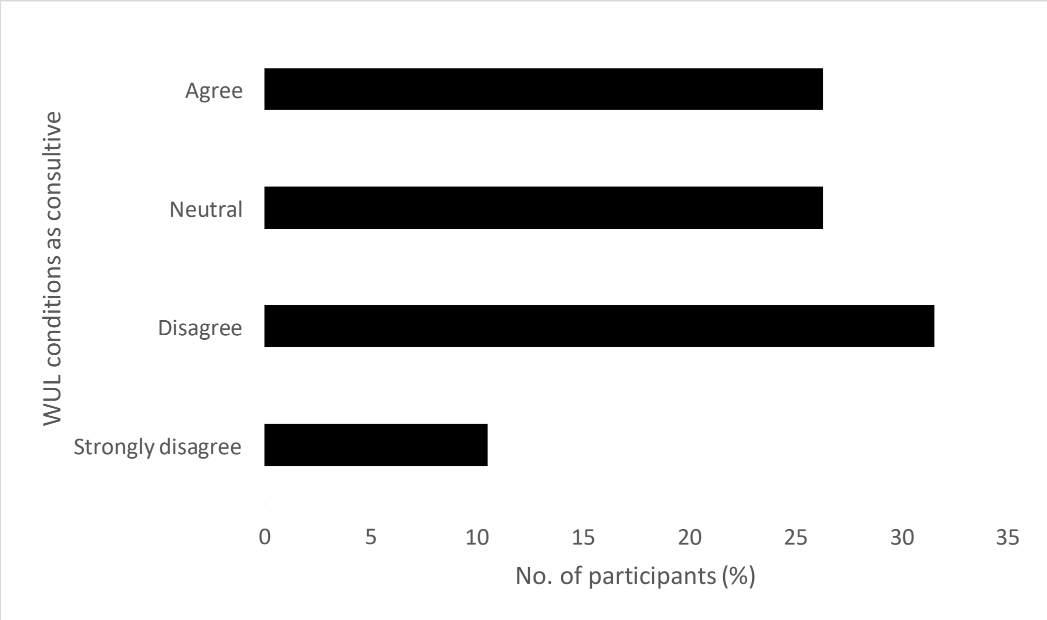


Figure 3.7**:** Participants' responses to whether the process for deriving water quality standards in water use licence conditions was consultative and involved stakeholders.

Self-regulation and voluntary monitoring of water quality licence standards

Participants were asked about the actions necessary to stimulate the spirit of self-regulation and compliance with water quality licencing conditions. Interestingly, severe punishment for sustained bad behaviour by water users, as well as scientific credibility and defensibility of methods of deriving water quality licence standards were top for the participants (Figure 3.8). Most of the participants indicated these two measures were the most important, each scoring 32%. Participants also viewed institutional efficiency and their effectiveness in dealing with water quality licensing issues as important (16%). Although incentives as a means of promoting compliance have been promoted in the sector via the Green Drop Programme (Olawale & Olanrewaju, 2011), this aspect did not receive much attention as only 11% of the participants thought that incentives for sustained good behaviour could lead to self-regulation and compliance. Self-regulation can be seen as a reflection of human behaviour driven by various motives.

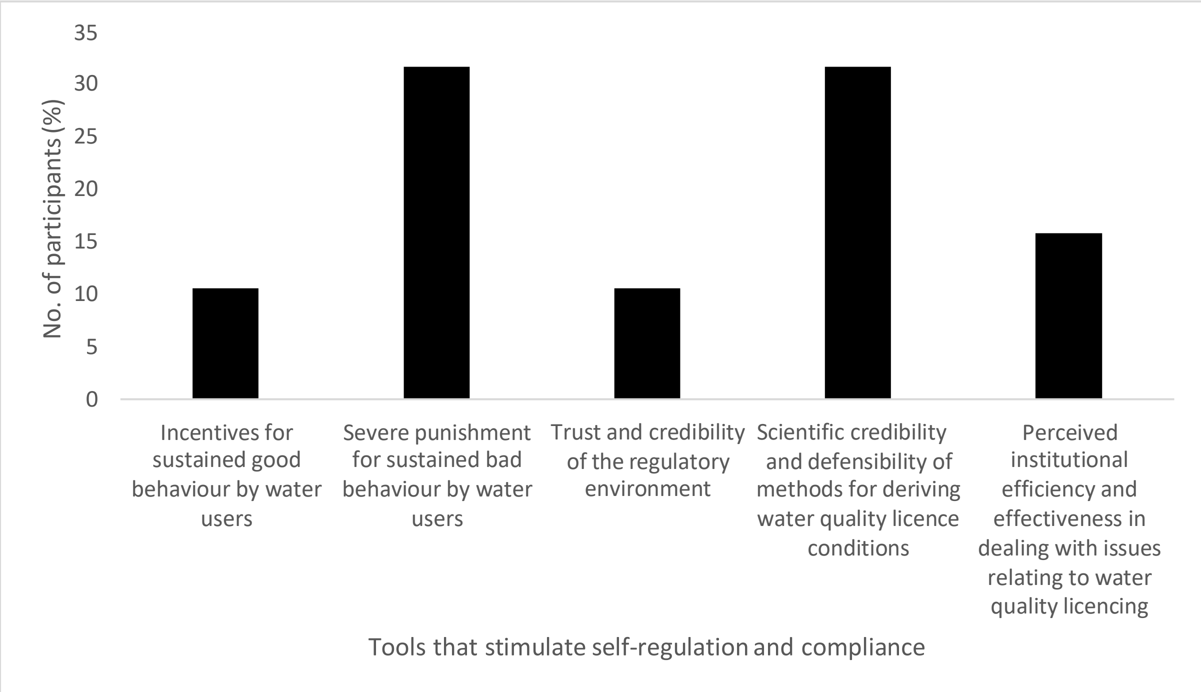


Figure 3.8: Participant responses to actions necessary to stimulate self-regulation and compliance with water quality standards in WUL.

Participants were asked the likelihood of water users engaging in self-regulation, voluntary monitoring, and compliance (Figure 3.9). About 63% of the participants found it likely that water users would engage in self-regulation and voluntary monitoring, whereas 26% of the respondents thought it was highly likely. Of the participants, 5% found self-regulation and voluntary monitoring unlikely, and 5% of them, highly unlikely.

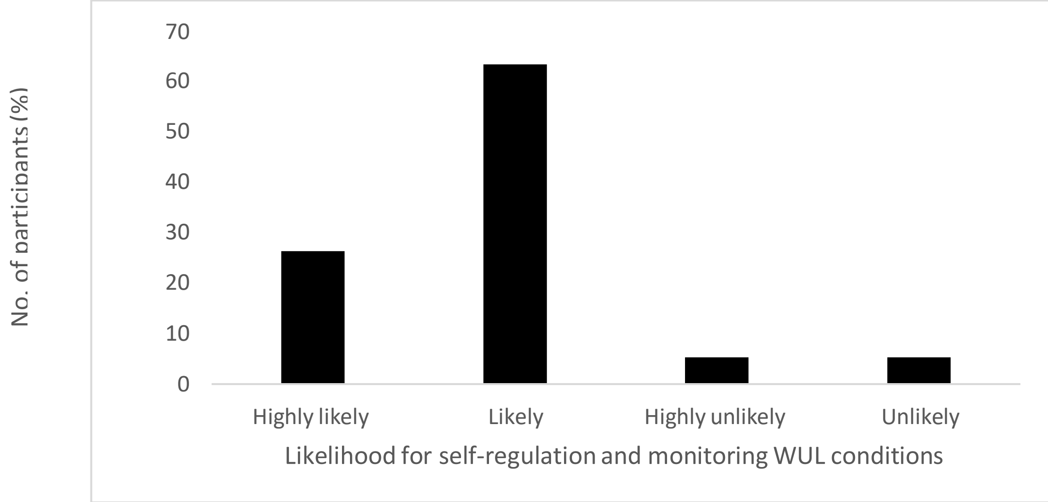


Figure 3.9: Participants response to the likelihood of water users engaging in self-regulation, voluntary monitoring, and compliance to the provision of water quality regulatory instruments such as WUL.

Participants were asked to rank the objectives of issuing water quality licences as one of the instruments for controlling water use on a scale of 1–5, where 1 was the least important and 5 the most important (Figure 3.10). Participants ranked 'water resources are protected for future generation' (84%) and 'maintain ecological health and integrity' (84%) as the most important objectives for issuing WUL, while 32% of participants ranked to 'prevent job losses due to increased operational costs that may arise from impaired source water quality' as the most important.

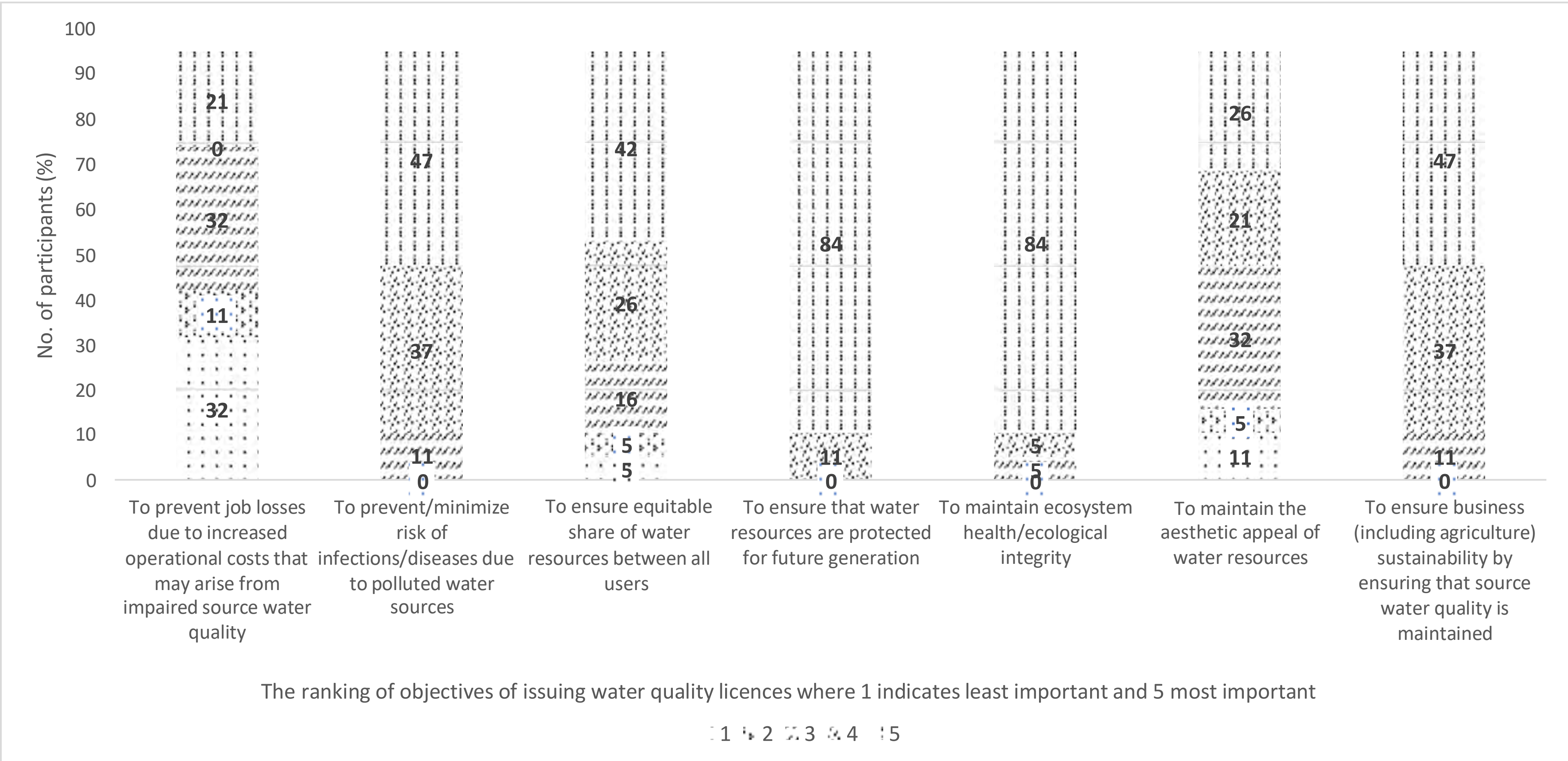


Figure 3.10: Participants' responses to the objectives of issuing water licences as an instrument to control water use.

Participants were asked to rank the actions taken to address disputes regarding licence conditions, on a scale of 1 to 5, where 1 represents the lowest priority and 5 is the highest priority (Figure 3.11). Participants (53%) ranked negation between parties as the highest priority, followed by (32%) reconsideration and reformulation of licence conditions. About 26% of the participants ranked a legal challenge in the court of law as the lowest priority, and 11% of the participants ranked an appeal for the licence condition as the lowest priority.

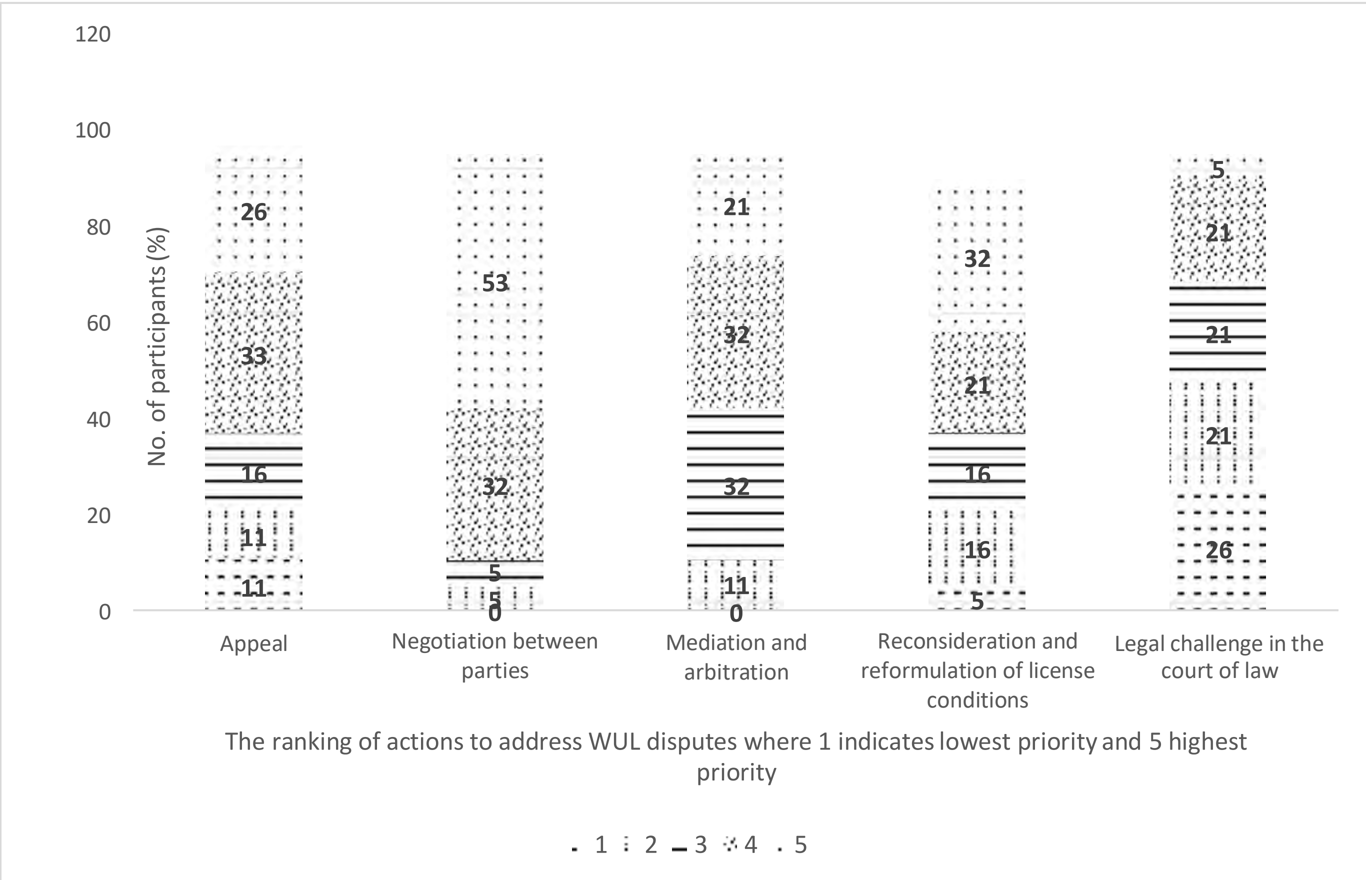


Figure 3.11: Participants' responses to the actions required to address WUL disputes.

3.3.4 The seriousness of pollution and sources of water quality threats in the Vaal Barrage.

When participants were asked to indicate how serious pollution was in the catchment, approximately 93% of participants indicated that pollution was a very serious issue (Figure 3.12). Only 7% of participants indicated that pollution was a mild issue. To reflect the seriousness of pollution within the system, one participant representing the private sector, specifically the mining industry, indicated the various sources that contribute to the seriousness of water pollution experienced in the Vaal Barrage catchment, such as the unregulated waste discharges, inertia on the part of the government in treating the issue of pollution as serious, and a lack of monitoring water quality. This participant offered the following opinion:

> *"Where to begin... Many uses and discharges go completely unregulated, so there is not only a lack of control, but also a lack of data to understand the extent of the issues and how they can be mitigated. The most basic of water treatment issues, sewage treatment, has completely failed, and yet government is reluctant to take the necessary action to address the situation. Further to this, the state of our watercourses in terms of its [sic] ability to serve the necessary functions in terms of all water users within the catchment (this includes the environment) has only recently started to again be assessed, and unfortunately, these assessments have big gaps and limited alignment."*

Regarding the sources of pollution and their seriousness, the participants accounted for several sources in the catchment, such as the historical impacts of unregulated activities. One participant mentioned the historical implications of untreated sewer sludge on Loch Vaal, which has led to unfavourable conditions for the catchment, and has impacted on ecosystem services relied upon by people. Another example of an unregulated system indicated by one of the research participants is a private hospital that dumped medical waste into the Blesbokspruit catchment, which has impacted the catchment negatively:

> *"Private businesses have turned to dump their solid waste inside the water weirs in the catchment, that is, in the Blesbokspruit Catchment Management Forum I learned there used to be a private hospital that dumped medical waste; this was picked up and reported by one of our counterparts working as a Traditional Health Practitioner."*

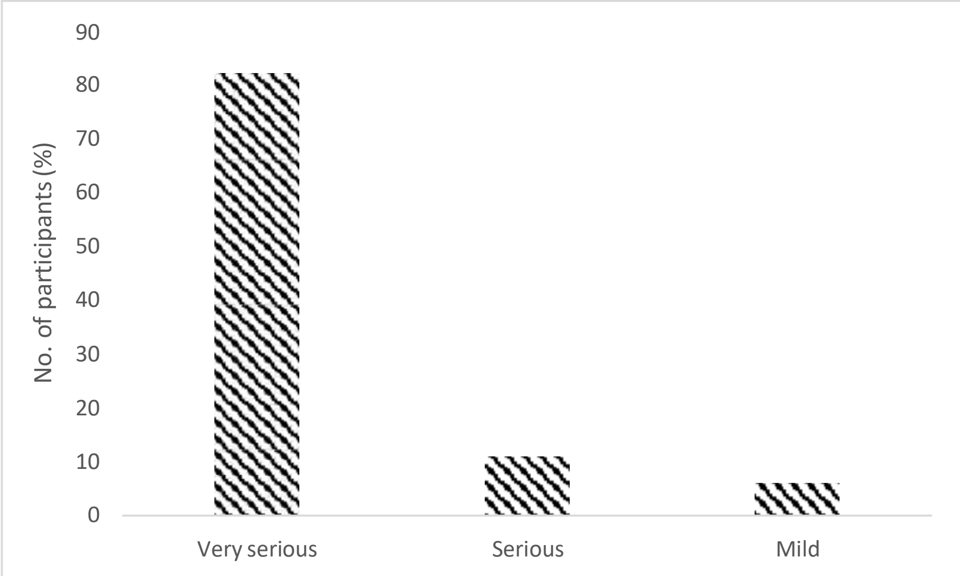


Figure 3.12: Participants' responses to the seriousness of the threat posed by deteriorating water quality to the ecological integrity of the Vaal Barrage catchment.

Participants were asked to rank the degree of seriousness of the threat the various activities posed to the water resources within the catchment on a scale of 1–5, where 1 indicates least serious and 5 most serious. Participants ranked effluent from wastewater treatment works (84%), mining (63%) and a growing human population (53%) as the most serious factors contributing to unsustainable utilisation of water resources within the catchment. Dams (11%), large-scale irrigation schemes (11%) and bulk water supplies (5%) were considered as the least serious threats (Figure 3.13).

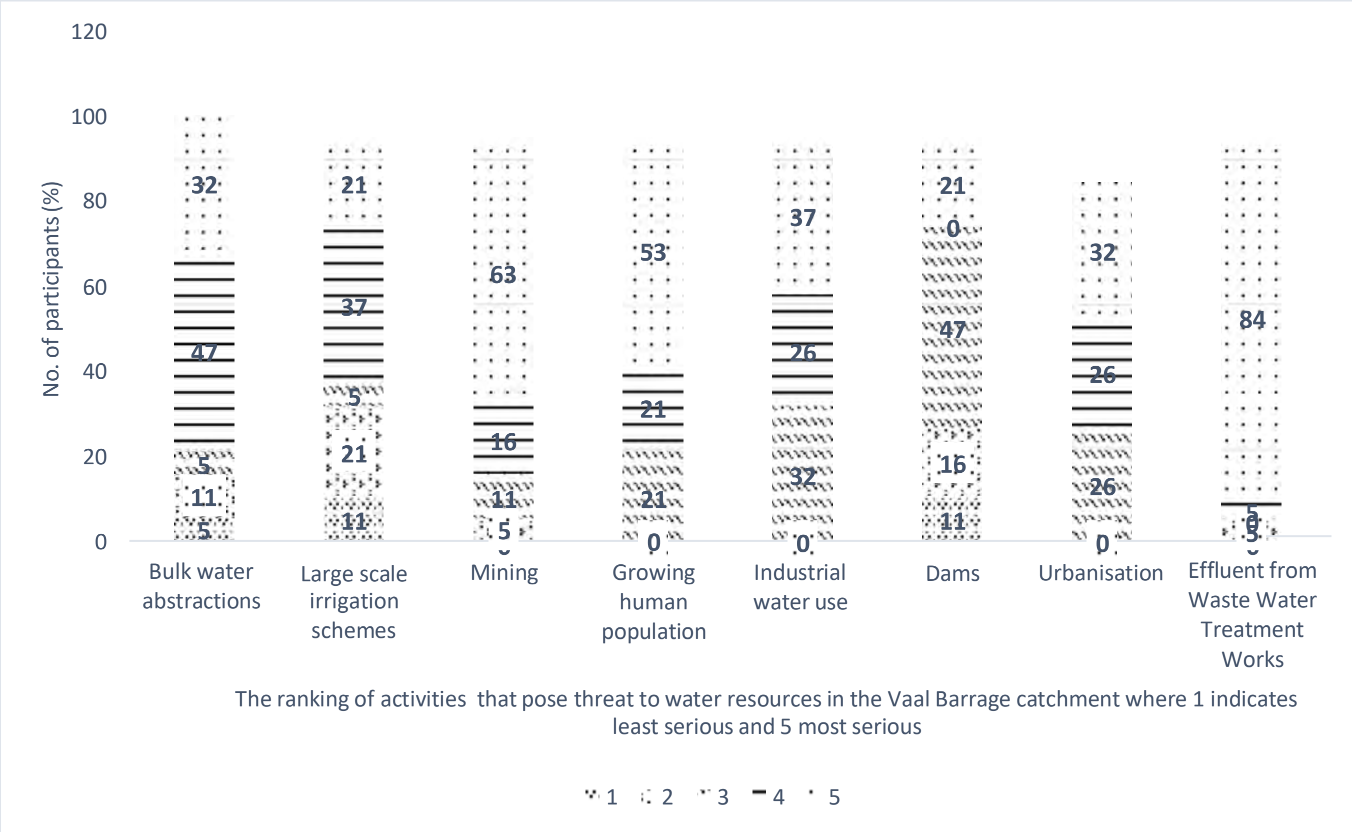


Figure 3.13: Participant's responses to the seriousness of the threat the various activities pose to water resources in the Vaal Barrage catchment.

Participants were asked to rank the seriousness of threats posed to the quality of water resources in the Vaal Barrage on a scale of 1–5, where 1 indicates the least serious and 5 most serious threat. About 79% of the participants ranked discharges of treated and inadequately treated effluents from municipal WWTW as most serious (Figure 3.14), while recreational, spiritual, and cultural activities (21%), runoff from agricultural farmlands (26%) posed the least serious effects on water resources.

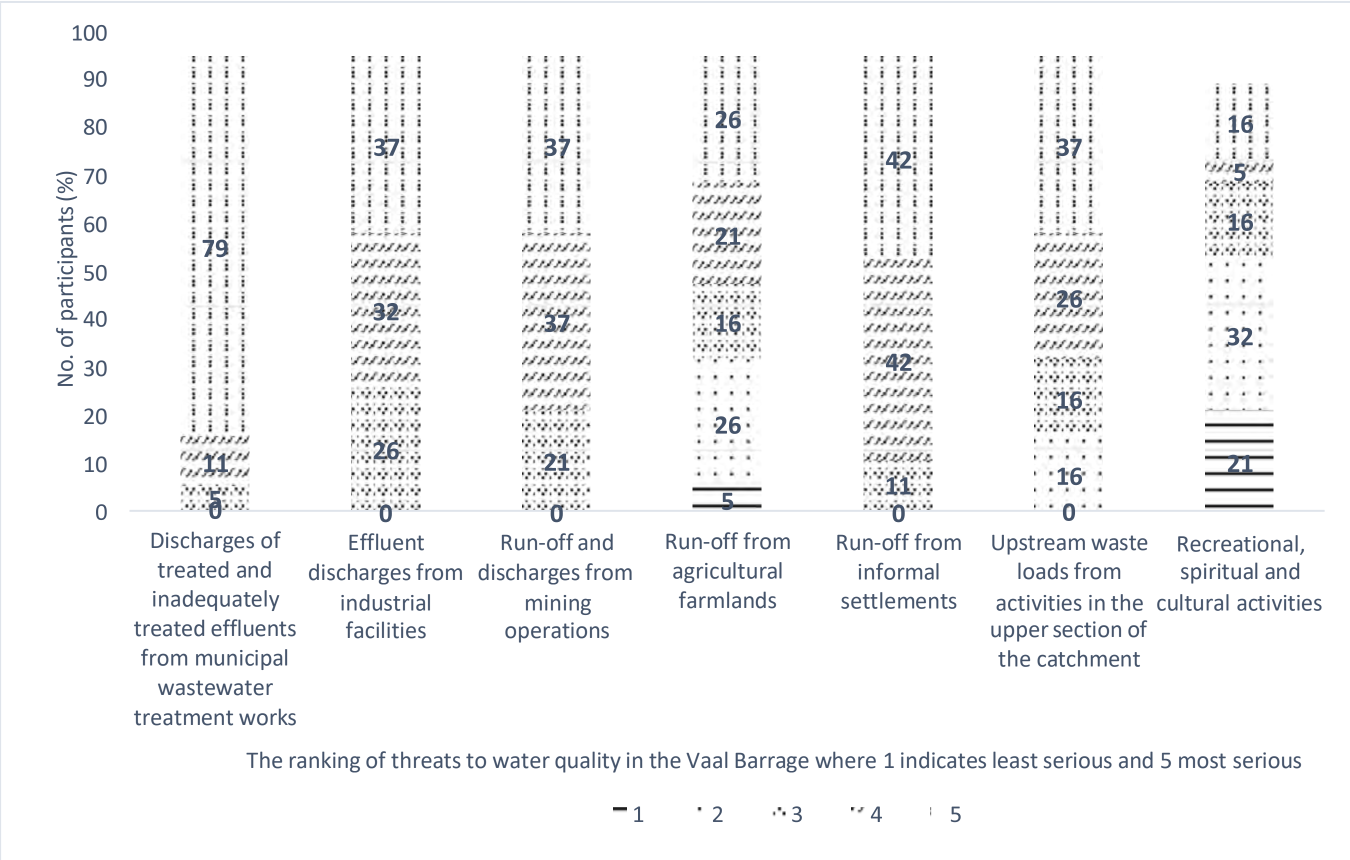


Figure 3.14: Participants' responses to the threats to the quality of water resources in the Vaal Barrage catchment.

In relation to business profitability, approximately 52% of the participants agreed that pollution in the Barrage impacted raw water-dependent business, while 20% of the participants disagreed that pollution impacted negatively on business profitability, and about 7% of the participants were neutral on the position that pollution had a significant impact on business profitability in the Vaal Barrage catchment (Figure 3.15). The responses indicate the consequences of not meeting the water quality conditions, leading to the deteriorating water quality and its impact on industries. The deteriorating water quality may lead to industries bearing costs for water quality treatment.

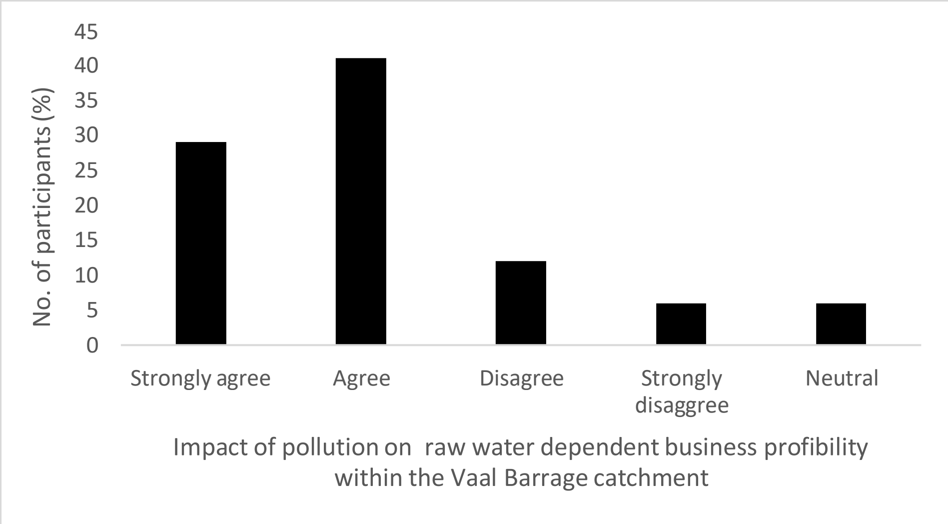


Figure 3.15: Participants' responses to the question whether pollution of water resources in the Vaal Barrage catchment significantly impact raw water-dependent business within the catchment.

3.3.5 Perceived importance of water resources in the Vaal Barrage catchment and Upper Vaal catchment

When asked about the importance of water resources of the catchment, 100% of the participants agreed that the water resources were very important. Analysis of the data showed that participants recognised three primary aspects of importance of the water resources of the Vaal Barrage catchment: economic importance, social importance, and ecological fragility.

Economic importance

The economic value of the Vaal Barrage catchment reflects the economic benefits that stakeholders draw from the ecosystem. All participants agreed that water resources in the lower section of the Upper Vaal were essential, indicating that water resources within the study area contribute significantly towards the economy in Gauteng Province and the entire South Africa. One participant suggested that the Upper Vaal water management area contributes 20% of the Gross Domestic Product (GDP) of the country:

> *"This water management area (WMA)[is] economically one of the most important in the country and nearly 20% of the GDP of South Africa originates from the Upper Vaal WMA."*

One participant gave a broader perspective of the implications of economic development and urban development inducing population growth and therefore impacting water demand and supply:

> *"Trend[s] in the Johannesburg-Vanderbijlpark-Vereeniging area lean toward concentration of economic development, which means increased urbanisation with subsequent strong demand for water."*

These views were supported by results of document analysis. For example, the Upper Vaal is known to contribute more than 20% of the GDP of South Africa, implying that it forms one of the mainstays of the country's economy (DWA, 2006).

Social importance, including intergeneration equity

The water resources within the lower section of the Upper Vaal catchment have long been recognised as contributing to water security and supporting the livelihoods of communities and the urban population within the catchment (Ochse, 2007). Participants agreed that the Upper Vaal catchment and the Vaal Barrage catchment contribute to the livelihoods of the population in the urban area. For example, they were of the view that the Vaal Barrage catchment provides water security and contributes to their livelihoods. Although this theme did not feature prominently among the participants' responses, it indicates the significance of the catchment in terms of water security, in this context defined as the provisioning of water to the Gauteng Province and Vaal Triangle. Further insight was provided by one participant highlighting the linkage between water quantity and quality:

> "*All catchments are important to the livelihood of all."*

> "*Water quality and quantity of the Vaal Barrage is imperative for the security of drinking water supply for Gauteng."*

Participants also emphasised intergenerational equity as one of the reasons why the water resources must be protected. One participant provided insights regarding intergeneration equity as follows:

"For the protection of both present and future water users, the management of the water resources, including its tributaries, needs to be carefully managed."

Ecological importance and fragility of the system

The South African National Water Act places a premium on ecosystem protection through the notion of the ecological Reserve (DWAF, 2011). Participants described the Vaal Barrage catchment as a fragile system owing to the impacts of effluent discharges from sources such as industries, WWTWs and agriculture. Most of the participants were of the view that the release of effluents from these sources contributes to and accelerates deterioration of the overall catchment, and then emphasised the importance of ecosystem protection. One of the participants put it this way:

"Water resources are important, not only for the health of the communities, but also for aquatic ecosystems. Resources are not being protected as it [sic] used to be."

"…very fragile due to upstream impacts from mine water, industrial chemical effluent, untreated sewage, agricultural phosphates, and domestic pollution runoff. The downstream users of the Upper Vaal stand the compromised [sic] of prolonged degradation in the catchment."

3.4 Discussion

The aim of the study was to unpack the motivations underpinning the stakeholder contestations of the water quality regulatory instruments such as RQOs and WUL conditions. The water quality components of the RQO are measurable qualitative and quantitative goals that must be met to protect the ecosystems at a desired level of protection (DWA, 2006). The present study explores reasons why stakeholders within the catchment may contest the RQOs. Most participants in the present study regarded the RQOs as realistic; however, some of the participants were of the view that the RQOs were either unrealistic or very unrealistic. These views may have arisen because i) the catchment is complex and the RQOs may not reflect this complexity in terms of the multiple point and diffuse sources of pollution (Odume et al., 2018); ii) the historical pollution in the catchment could mean that the RQOs do not reflect an appropriate baseline, and iii) the RQOs may be too lax for some water quality variables, yet too stringent for others. Whatever the case may be, the perception that the RQOs are unrealistic implies that stakeholders are less likely to embark on activities that ensure that the RQOs are met, which may be detrimental to their long-term economic and social well-being as well as the ecological integrity of the socio-ecological systems within the catchment.

The RQOs are usually formulated through a consultative process in which stakeholders are encouraged to participate and make input (DWAF, 2011). What the results of the present study suggest is the need to broaden and strengthen the participation process to take forward more of local and catchment-embedded knowledge in the formulation of the RQOs. If the RQOs reflect more of the local knowledge of the catchment, feelings about whether the RQOs are unrealistic may be diminished, so encouraging stakeholders to embark on activities that reduce pollution, and thus water quality deterioration. The National Water Act does not make provision for revising the RQOs after they have been gazetted (DWAF, 2011) so contesting gazetted RQOs becomes difficult in terms of whether they can be revisited and revised. The fact that the NWA does not make provision for revising of gazetted RQOs is a weakness that has been identified in the Act.

Scientific credibility improves the legitimacy and reliability of the regulatory instruments (Heink et al., 2015), and refers to information perceived to meet the scientific standards and technical adequacy (Cash et al., 2003). Legitimacy refers to the perceived fairness of process, such as the enforcement of WULs. Credible scientific measurement is essential to environmental decisions and policies and must be trustworthy to avoid running the risk of basing policy on disreputable information and data (Dunn & Laing, 2017). A study by Odume et al. (2018) showed that one of the contested issues associated with the water quality regulatory instruments is the perceived lack of scientific credibility and defensibility of the standards in the WULs. The present study seeks to deepen and widen the understanding behind these contestations by looking at the perceptions and motivations underpinning them. Stakeholders felt that the scientific credibility of methods of deriving standards was the most crucial challenge for contesting the WUL. In this study, the participants advanced several reasons why they dispute the scientific credibility of the process of deriving water quality standards in WUL. For example, the participants argued that the links between WUL and RQOs were not clear, and that the implications of upstream waste loads on the standards for downstream resources users were also unclear. Given these reasons, it is important that the regulator embark on an open, transparent process that reassures all resource users and stakeholders of the scientific credibility of the methods and processes to ensure maximum compliance to standards in WUL.

For example, a study by Lemos and Morehouse (2005) indicated that keys to a successful implementation of policies is the combination of interdisciplinary approaches (multiple disciplines working together), engagement with stakeholders, and credible science. What this implies is that perceived scientific credibility can enhance effective implementation of regulatory instruments and user compliance.

Compliance with regulatory instruments is necessary to achieve a balance between resource protection and use. Effective compliance could lead to equitable water allocation, improved upstream and downstream relationships, and a reduction in illegal water use that threatens the ecosystems (Holley & Sinclair, 2012). Within the water sector in South Africa, compliance monitoring is done by regulatory institutions such as the DWS, Catchment Management Agencies (CMAs) and regional offices of the DWS. To ensure compliance, a study conducted by Hugo (2014) reported the need for a structured criminal penalty system for environmental violations in terms of the National Water Act, Act No. 36 of 1998 (RSA 1998). An effective administrative penalty system may be a possible solution for ensuring that water users comply with the provision of their WUL (Hugo, 2014). As argued by Hugo (2014), such an administrative penalty system for environmental violations would implement punitive measures in the case of non-compliance and provide incentives to encourage compliance. An example of punitive measure is the 'polluter pay' principle (PPP) (Nabileyo, 2009).

Punitive measures to motivate compliance are recognised as calculated motivation (Winter & May 2001). Calculated motives refer to resource user compliance motivated by the likelihood of fines that are imposed upon violation of the water quality standards in the WUL (Winter & May, 2001). A study by Winter and May (2001) revealed that the likelihood of detection, the likelihood of a fine, and the cost of compliance are important factors that may influence a resource user's decision to comply with the provision of WUL. The likelihood of detection refers to the frequency of inspection, which may lead to the detection of violation, whereas the likelihood of a fine may influence the resource users to comply, particularly if the costs of the fine far exceed that of compliance in the ordinary course of business operation (Winter & May, 2001). The present study indicates that compliance with the WUL conditions by industries is motivated by statutory enforcement, which suggests the importance of strong regulatory institutions.

Apart from punitive measures, other mechanisms exist for facilitating and encouraging compliance, such as incentives to encourage compliance, education and awareness-raising, self-regulation through ISO, as well as building trust and credibility within the regulatory system to encourage voluntary monitoring and compliance (Heink et al., 2015). The research participants indicated that education and raising awareness can encourage compliance with the water quality standards in the WUL. Studies such as that undertaken by Okumah et al. (2018) have indicated that scientific evidence and raising awareness can influence resource users' actions towards meeting regulatory standards. The study suggests that active awareness-raising and education can result in stakeholders making better, informed decisions (Okumah et al., 2018).

Research participants expressed concerns about the lack of institutional capacity in the context of water quality management. Financial resources, poor technical skills, and government response time were highlighted as the main challenges in water quality management. Financial resources play a key role in the licensing procedure from the stakeholder completing the licence application and the regulator conducting the monitoring of water quality levels (DWAF, 2006). A study by Koppen and Schreiner (2014) indicated the institutional capacity challenges associated with licence applications, such as the lack of administrative capacity. Administrative capacity results in an administrative burden that has an impact on the processing of licences. The Koppen and Schreiner (2014) study also mentioned the impact of finances on the licence processes which can be costly and therefore inaccessible to many resource users.

3.5 Conclusion

In this chapter, the motivation underpinning water use, and the contestation of relevant regulatory instruments were explored. Perceived unrealistic RQOs, perceived lack of scientific credibility of the methods for deriving water quality standards in WUL, as well as poor institutional capacity were identified as the top motivations for contesting applicable regulatory instruments in the catchment. However, the research participants recognised the importance of water resources within the catchment, and the need to heighten compliance levels to protect the water resources. Punitive measures, and education and awareness-raising were identified as key to accelerating compliance. The general implications of the findings in this chapter are that i) there is a need for a multi-pronged approach to increase compliance, ii) there is a need for trust within the regulatory system to increase confidence in the system, iii) transparent, open processes and methods are needed for deriving standards in WUL to assure their credibility and defensibility. Overall, this chapter contributes to our general understanding of the intricacies of water quality management within a contested space.

Chapter 4: Scenario Modelling Using the WQSAM Decision Support System (DSS) that Links the Resource Quality Objectives (RQOs) to the Water Use Licence (WUL) Standards in the Vaal Barrage Catchment and Associated Tributaries

4.1 Introduction

Decision support systems (DSSs) facilitate Integrated Water Resource Management (IWRM) through stakeholder participation (Anzaldi et al., 2014). Stakeholder participation in IWRM encourages dialogue between resource users and regulators, providing a platform for negotiation (Carerra et al., 2017). A DSS can strengthen and deepen stakeholder involvement in water resource management, allowing both resource users and regulators to co-explore environmental challenges and solutions (Luyet et al., 2012). Decision support systems are useful for exploring the implications and consequences of management decisions on complex systems such as water resources (Jao, 2011) and, for this reason, the systems have been developed and used widely, for example, in north-east Italy (Mysiak et al., 2002), where a DSS was used to select the appropriate action for the improvement of Vela's catchment water quality. In Athens, Greece (Mamassis & Koutsoyiannis, 2004), a DSS was used to explore alternative solutions for the operations in the water resource system and north-western China a DSS was developed to aid in decision processes regarding water allocation and water supply (Ge et al., 2013). However, in South Africa, few studies have applied a DSS based on water quality in managing water resources.

The Water Quality Systems Assessment Model (WQSAM) is a water quality model explicitly designed for use in data-scarce southern African catchments (Slaughter et al., 2007). The model uses the concept of requisite simplicity; that is, representing only the water quality processes that explain most of the variation in observed water quality data, to maintain a relatively simple structure with low data requirements (Slaughter et al., 2017). The WQSAM integrates hydrological and water management models routinely used in South Africa with the simulated flow of these models driving water quality simulations in WQSAM (Slaughter et al., 2017). The WQSAM represents water quality simulations as frequency distributions that indicate how often certain water quality thresholds are exceeded (Slaughter et al., 2017). The thresholds can, for example, be water quality guidelines or resource quality objectives (RQOs). The WQSAM is suitable since the RQOs represent the water quality threshold and contain a risk threshold that is likely to trigger management action when exceeded. The WQSAM can express the risk associated with the water quality threshold by plotting long-term water quality data as frequency distribution, incorporating wet, dry, and normal hydrological periods. By plotting water quality as a frequency distribution, the risk of a threshold being exceeded is essentially the point on the x-axis for any chosen threshold on the y-axis.

The WQSAM fulfils a useful role in water resource management because it can provide an integrated understanding of the processes driving water quality in a catchment as well as the spatial discretisation of pollutant loads impacting a river system (Slaughter, 2017). The WQSAM is also useful for simulating and exploring the impacts on water quality of different water management scenarios (Odume et al., 2021) and has previously been applied to the Buffalo River, the Crocodile River, and the Upper Olifants River catchments (Slaughter et al., 2019). In response to the call to address water quality contestation in the Vaal Barrage catchment, Odume et al. (2021) developed the WQSAM DSS to simulate water quality in relation to WUL standards. The intention was to develop a DSS that was scientifically defensible, transparent, and easy to use with a wide degree of flexibility. The DSS was developed to address identified challenges regarding water quality contestations. The challenges include: i) estimating the risk posed by individual emitters on water quality exceeding the RQOs; ii) simulating effects of upstream emitters on downstream users and their WULs; iii) simulating the relative contributions of non-point and point sources of pollution to instream pollution loads in the Vaal Barrage catchments, and iv) simulating both conservative and non-conservative water quality variables (Odume et al., 2021).

The development of the DSS adopted some of the principles of participatory modelling to address water quality contestations in the Vaal Barrage. Participatory modelling is an approach that involves stakeholders in the modelling process (Carerrer et al., 2017). Stakeholder engagement is one of the principles used to achieve successful participatory modelling and was adopted in the development of DSS (Odume et al., 2021). Stakeholder engagement can improve resource users' understanding of the complexities of water quality allocation and licencing (Kotir et al., 2015). Interactions between stakeholders, scientists, and resource regulators may encourage collaborative action towards managing water quality issues, as was evident during the development of the WQSAM DSS, which links RQOs to WUL standards for the Vaal Barrage system (Kotir et al., 2015; Odume et al., 2021). During the first phase of the development of the WQSAM DSS, stakeholders were given the opportunity to define the problem and identify possible management options, thereby reinforcing transparency within the entire management process (Kotir et al., 2015; Odume et al. 2021).

Resource quality objectives are set on the premise of acceptable risks, considering catchment sensitivity, and are used to inform WUL conditions (DWAF, 2011). Acceptable risk refers to the risk to a water resource that both users and regulators may be willing to accept on the premise that critical functionalities of the systems are not severely impacted. The acceptable risk is a trade-off between the needs of stakeholders to exploit the resource and the protection needed to maintain the ecological integrity of the resource (DWAF, 2011). Measures to protect the resource are often captured in source-directed control (SDC) instruments, such as water use licences (WUL). Since stakeholders were contesting the scientific defensibility of standards in their WUL, and the links between RQOs and WUL, the WQSAM DSS was developed to address these contestations. Thus, the objective of this chapter was to apply the newly developed WQSAM DSS through scenario modelling in the Vaal Barrage system. Modelled scenarios were jointly identified with key catchment stakeholders (regulators and resource users) during the development process of the DSS. This chapter fulfils Objective 2 of this study.

4.2 Materials and Methods

4.2.1 Brief description of WQSAM

A team of researchers within the Institute for Water Research at Rhodes University developed the WQSAM DSS. More details on the DSS can be found in the Water Research Commission (WRC) report of project K5/2910 (Odume et al., 2021). This section provides a brief description of the DSS and the process it represents to provide insight into the functions of the model. The DSS can be regarded as a version of the WQSAM with some functionality removed, that is, the users cannot edit parameters in the model that are not directly related to pollutant loads. On the other hand, the DSS provides some specialist functionality not availablein the WQSAM about its core function of exploring WULs in relation to the RQOs. These functionalities include inputting RQOs for different parts of the catchment and visually interpreting water quality with the RQOs.

It is practical to first briefly describe the WQSAM on which the DSS is based. The WQSAM is accessed through the Spatial and Time series Information Modelling (SPATSIM) framework (Hughes, 2005; Hughes et al., 2014) which is a geo-referenced hydrological modelling platform (Hughes, 2005; Hughes et al., 2014). Figure 4.1 represents the conceptual tiered structure of WQSAM (Hughes et al., 2014; Slaughter et al., 2017). Water quality simulations in the WQSAM are driven by flow, and the model is designed to integrate closely with routinely used water management models in South Africa, such as the Water Resources Yield Model (WRYM) (Basson et al., 1994; Slaughter et al., 2017). The first tier (A) in Figure 4.1 represents the functionality of the model to bring in flows from the yield model, with the node-link structure of the WQSAM following that of the yield model (Hughes et al., 2014; Slaughter et al., 2017).

Since the yield model flows are monthly data and WQSAM requires daily flows to reasonably represent the variability of water quality data, the monthly yield flow data are disaggregated to daily using a monthly-daily disaggregation method (B) (Hughes et al., 2014; Slaughter et al., 2017). The WQSAM then separates incremental flows into the flow fractions, surface flow, interflow and groundwater flow using a baseflow separation method (C) (Hughes et al., 2014; Slaughter et al., 2017). This baseflow separation method is important as these flow fractions are assigned water quality signatures in the model to represent non-point inputs of pollutants (Hughes et al., 2014; Slaughter et al., 2017; Slaughter, 2017). Within D, the other forms of modified flows, such as abstractions and return flows, are disaggregated from monthly to daily (Hughes et al., 2014; Slaughter et al., 2017). Finally, within E, the WQSAM provides facilities to simulate water temperature, conservative (salts) and non-conservative (nutrients) water quality variables (Hughes et al., 2014; Slaughter et al., 2017).

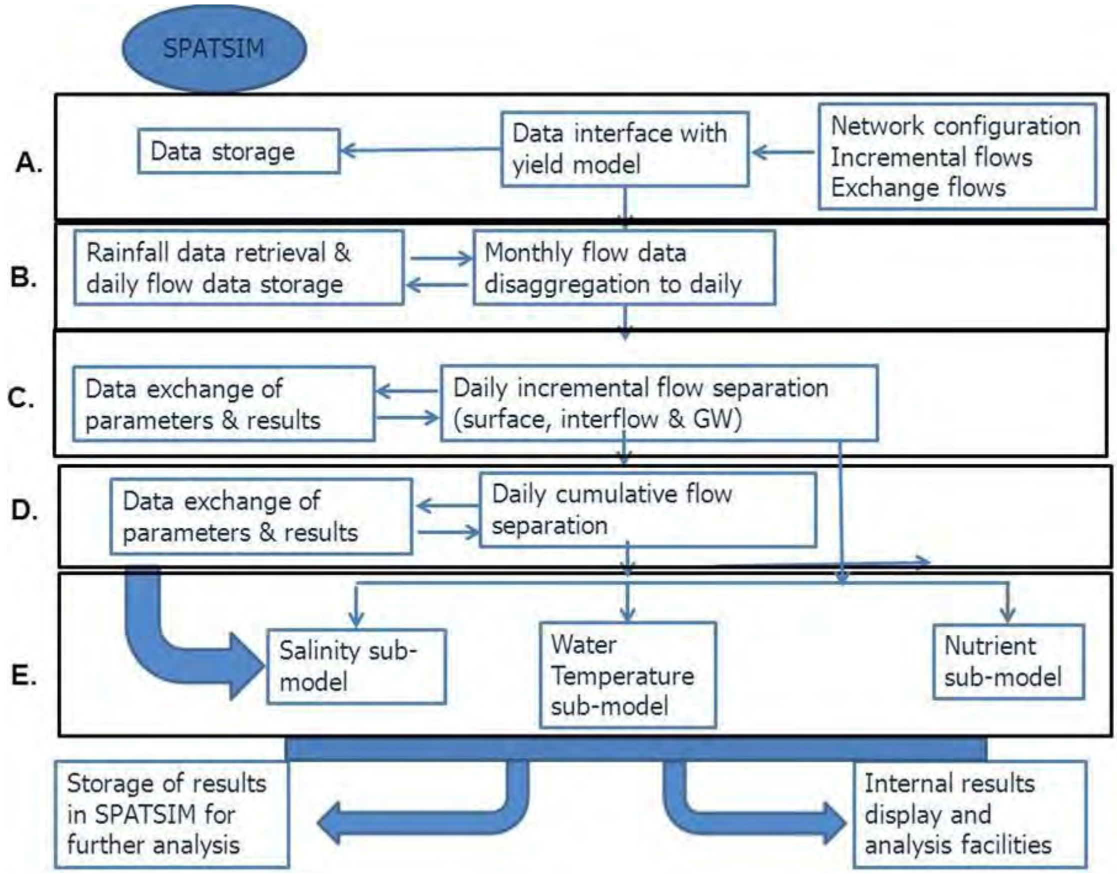


Figure 4.1: Conceptual representation of the model components in the Water Quality Systems Assessment Model (WQSAM): A) input of water quantity model output data and storage to the modelling framework Spatial Time Series and Information Modelling (SPATSIM) system, and replication of the nodal structure of the water quantity model to WQSAM and SPATSIM; B) disaggregation of simulated monthly incremental flow to daily and storage to SPATSIM; C) baseflow separation of simulated daily incremental flow to the flow components: surface water flow, interflow and ground water; D) disaggregation of monthly cumulative flows to daily; E) water quality modelling components for salinity, water temperature and nutrients (Source: Slaughter et al., 2017; Odume et al., 2021).

Disaggregation of monthly to daily simulated flow

An important element of WQSAM is that it operates on a daily time scale to sufficiently represent the variability in water quality variables because water quality variables show variability over short time scales. However, since established water quantity models in South Africa operate on a monthly time scale, the WQSAM needs to disaggregate monthly flows to daily flows (Slaughter et al., 2015; Hughes & Slaughter, 2016). The monthly disaggregation method adopted the Flow Duration Curve (FDC) principle that converts three-time series of daily rainfall to antecedent rainfall distribution (Slaughter et al., 2015; Hughes & Slaughter, 2016). Antecedent rainfall distribution then finds a representative flow for percentage exceedance on daily FDC to generate time series of daily flow (Slaughter et al., 2015; Hughes & Slaughter, 2016).

Disaggregation of flow into surface flow, interflow, and groundwater flow

Natural flow runoff generally enters a river through three distinct pathways or flow components: surface runoff, interflow, and groundwater flow (Slaughter, 2017). The different flow components have different water quality signatures. For example, groundwater in South Africa tends to have higher salinity levels than surface flow due to the leaching of minerals and salts from the geology of the catchment (Slaughter, 2017). In contrast, surface flow is affected by land use to a greater extent than groundwater flow, with land use such as agriculture and informal settlements often leading to high nutrient concentrations in surface flow. The different flow components are incorporated in the model and represent non-point sources of pollutant load integral to water quality modelling. The study adopted a baseflow disaggregation model to achieve the separation of these components (Slaughter, 2017). The baseflow disaggregation model is a method of separating surface runoff (also known as quick flow) from groundwater (Schwartz, 2007).

Simulation of water temperature

Water temperature is an essential determinant of rates of processes driving water quality. For example, decomposition and nitrification rates are accelerated under increased water temperature (Chapre, 1997; Slaughter et al., 2017). Therefore, water temperature is vital to consider when simulating water quality. A multiple linear regression model (MLR) approach was used in the WQSAM to simulate water temperature. The independent variables were the mean and minimum daily air temperature (Slaughter et al., 2017). The MLR was adopted from Rivers-Moore et al. (2018) who used daily air temperature (mean and minimum temperature) in linear regressions to simulate water temperature (Slaughter et al., 2017).

Simulation of conservative water quality variables

Conservative water quality variables do not change chemical form within their life cycle. Some important conservative water quality variables simulated by the WQSAM include total dissolved solids (TDS), sulphate, calcium, magnesium, and sodium. The WQSAM models conservative water quality variables using a simple mass-balance approach considering their inputs through point and non-point sources, evaporation, extraction, and dilution (Venkatesharaju et al., 2010; Odume et al., 2021). Levels of TDS are modelled in the WQSAM as a generic measure of salinity.

Simulation of non-conservative water quality variables

Non-conservative water quality variables can change chemical form through their life cycle through physical, chemical, and biological processes (Hoke, 2006), making them more difficult to simulate within water quality models. Examples of non-conservative water quality variables simulated in WQSAM include nitrates + nitrites, ammonium, and phosphates. The WQSAM represents these variables through the processes used to describe conservative water quality variables and additional processes affecting the chemical forms of these variables, such as decomposition, uptake by algae and nitrification/denitrification (Slaughter et al., 2017). Figures 4.2a and 4.2b show the interlinkages in the processes affecting the non-conservative water quality variables within WQSAM, with Figure 4.2a representing the water quality processes affecting the non-conservative variables in the river nodes in WQSAM. Figure 4.2b is a representation of the complex process affecting the non-conservative variables in river nodes and interactions with macrophytes such as hyacinth and organic sediment (Slaughter et al., 2017; Odume et al., 2021).

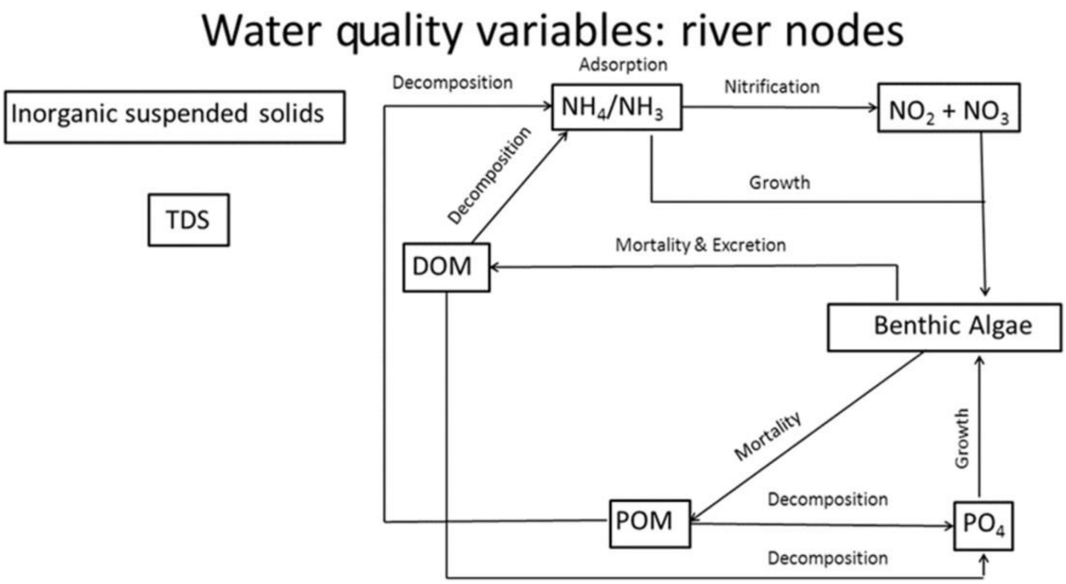


Figure 4.2a: Conceptual representation of the non-conservative water quality constituents in WQSAM. (Source: Slaughter et al., 2017)

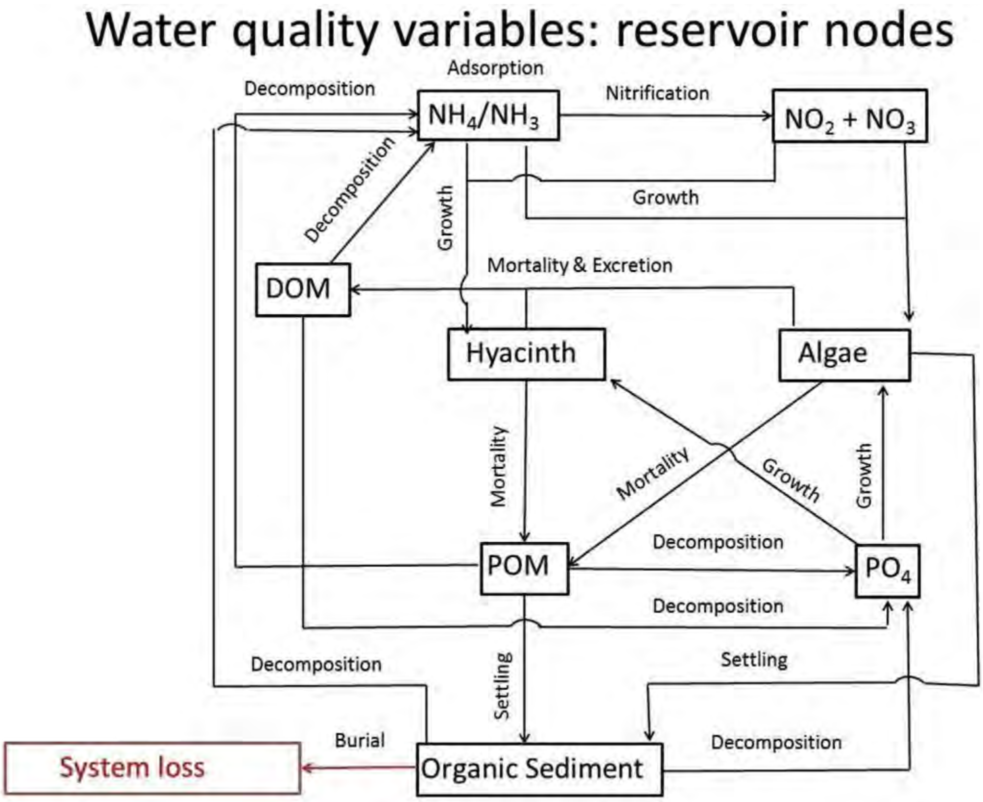


Figure 4.2b: Conceptual framework for simulation of the non-conservative water quality variables within WQSAM. (Source: Slaughter et al., 2017).

Simulation of point and non-point sources

Point sources were represented in WQSAM since they represent one of the input pathways of pollutants into water resources (Odume et al., 2021). The parameters for point sources in the WQSAM can either be set directly by the user for effluent flows from industry and wastewater treatment works (WWTW), or indirectly as a calibration exercise in the model when matching simulated water quality data to observed water quality data (Odume et al., 2021).

Non-point sources represent the other major pathway of pollutants into water resources. Non-point sources are often difficult to represent in a model relative to point sources as they show high spatio-temporal variation and have complex relationships with other catchment processes (Odume et al., 2021). As previously stated, non-point sources are represented as water quality signatures assigned to the flow components (surface flow, interflow, and groundwater flow) of the incremental (natural) flow.

Simulation in nodes

The WQSAM is a node-link model as it is designed to integrate closely with the Water Resources Yield Model, which also has a node-link structure (Slaughter, 2017). The Water Resources Yield Model function is to perform water mass-balance (Hughes et al., 2014). Nodes represent a point in the catchment where water can be added, extracted, stored, and recorded. Nodes within SPATISM represent a spatial element that contains linked attributes such as model parameter data, observed and simulated water quality, flow data, and rainfall data (Hughes et al., 2014). The nodes can simulate non-point sources if the node is positioned near agricultural land or urban land, and/or point sources as, for example, discharges from industries and WWTW (Slaughter, 2017). Some nodes also represent reservoirs and include more complex water quality processes.

Simulation of metals

Metals have been identified as one of the important water quality stressors in the Vaal Barrage catchment; therefore, simple initial capabilities were added to the WQSAM to simulate metals. However, simulations of metals for South African water resources, including for the Vaal Barrage, are uncertain since there are very few observed data against which the model simulations can be benchmarked (calibrated) (Odume et al., 2020). Uncertainty in simulations can lead to inaccurate predictions from the model.

4.2.2 Brief description of the Decision Support System

The DSS can be described as a version of WQSAM with some key differences. Firstly, some users may not feel comfortable using SPATSIM as the framework requires some training and experience to navigate (Odume et al., 2021). However, the DSS can be run from the outside of SPATSIM as a separate executable programme (Odume et al., 2021). Unlike the WQSAM that requires expertise and experience to work with the water quality parameters, the DSS has a user-friendly interface that enables the user to explore various WUL scenarios. The WQSAM also has numerous water quality parameters that would not be relevant when investigating the relationship between WULs and RQOs, such as water temperature modelling parameters and parameters related to some key processes affecting non-conservative water quality variables, such as nitrification rates (Hughes et al., 2017). The DSS is a version of WQSAM in which all these parameters have been calibrated against observed data, and the DSS does not allow users to change these parameters (Odume et al., 2021). The DSS does, however, allow users to change parameters that are directly related to inputs of water quality loads in the system, namely point and non-point loads, with the former related directly to the WULs.

The other difference between WQSAM and the DSS is that the DSS provides functionality related to its core function: to allow an investigation of the relationship between WULs and RQOs in a modelled catchment. In this respect, the DSS allows users to input RQOs (values for both the 95th percentile and numerical limit) and the DSS allows a visual representation of that relationship (Figure 4.3).

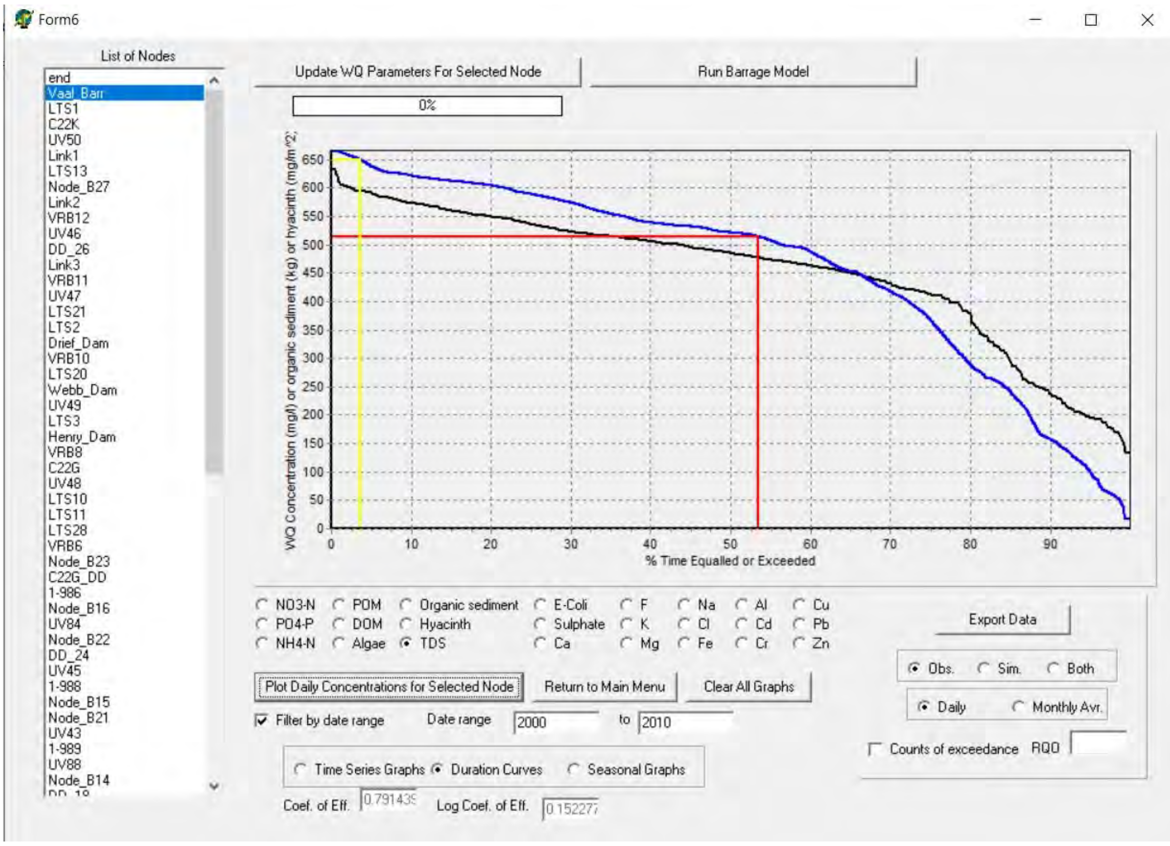


Figure 4.3: A screenshot of the representation of Vaal Barrage DSS illustrating the interpretation of the RQOs (red line) in relation to WUL for the node Vaal Barrage (Source: Odume et al., 2021).

The DSS is suitable for the present study as it addresses many of the underlying challenges that have led to the contestations of the regulatory instruments in the Vaal Barrage. Odume et al. (2021) identified shortcomings in the RQO and WUL methods, such as a lack of consideration of the differences between conservative and non-conservative variables, with the latter affected by additional processes such as chemical speciation and algal uptake (Odume et al., 2021). Secondly, the impact of upstream pollution is not included within the setting of a WUL, and upstream pollution can have a heavy impact on downstream users within the Vaal Barrage catchment (Odume et al., 2021). Lastly, the impact of non-point sources is not considered as an important factor within the WUL process, even though non-point sources contribute significantly to instream water quality, particularly for some salts and nutrients (Odume et al., 2021). The DSS, as an extension of the WQSAM, considers factors such as point and non-point sources, dilution of pollutants by natural flow, instream processes that affect non-conservative and conservative variables, settling and remobilisation of pollutants, and the residence time in reservoirs.

4.2.3 Systems representation of the Vaal Barrage within the DSS

Initially the DSS first used the same system representation of the catchment as that of the water resource planning model (WRPM). The Upper Vaal down to the Vaal Dam was modelled separately and water quality in the Vaal Barrage downstream as seen in Figure 4.5a and figure 4.5b (Odume et al., 2021). Consultation with the stakeholders determined that the resolution of this representation was insufficient. A much more detailed representation of the Vaal Barrage catchment was therefore implemented, with boundary conditions from the C22 and C21 confirming the catchment (Odume et al., 2021).

Nested hydrological unit boundaries are used in South Africa for resource planning, and for management purposes such as environmental impact and risk assessment (Maherry et al., 2013). These hydrological boundaries are divided into primary, secondary, tertiary, and quaternary catchments. These catchments were delineated from topographical maps and aerial photographs (Maherry et al., 2013). Catchments are defined as a land area of water flowing into an outlet point (Maherry et al., 2013). The quaternary catchment is regarded as the smallest hydrological unit, and these are used in decision making, with units ranging from primary to quinary catchment. Quinary catchments were recently endorsed by the Department of Water Affairs and Forestry (DWAF), are described as river networks at a finer scale. The quinary catchment represents daily rainfall, daily temperature, daily evaporation rate and baseline land cover (Maherry et al., 2013). Table 4.1 indicates the catchment units along with their catchment names of the Vaal Barrage catchment and its associated tributaries,

Table 4.1: Catchment units and catchment names of the lower section of the Upper Vaal (Source: DWS, 2015; Odume et al., 2021).

Catchment Unit (Quaternary catchment)	**Catchment name**
C21A-B	Upper Suikerbosrand
C21 C, C21 F, C21G	Lower Suikerbosrand
C21 D, C21 E	Blesbokspruit
C22 A- E	Klip River
C22 H- J	Barrage
C22K	Barrage
C22G	Barrage

Initially, the DSS first used the same system representation of the catchment as that of the WRPM. The Upper Vaal down to the Vaal Dam was modelled separately, with the water (associated water quality loads) released from the Vaal Dam represented as a boundary condition within simulation of the Vaal Barrage (Odume et al., 2021). Consultation with the stakeholders determined that the representation of the Vaal Barrage catchment by the WRPM was of insufficient resolution for representing water quality. A much more detailed representation of the Vaal Barrage catchment was therefore implemented, with boundary conditions from C22 and C21 catchments (Odume et al., 2021). The representation of the Vaal Barrage within the DSS has gone through numerous changes as a result of consultation with stakeholders, mainly related to the need to increase the spatial resolution of the model nodes within the Barrage catchment to represent the large number of users and points of interest (Odume et al., 2021). The inputs of the Klip, Suikerbosrand, Blesbokspruit and Rietspruit rivers to the Vaal Barrage catchments were represented as boundary conditions. However, since consultation with stakeholders revealed an interest in how rivers affect the water quality with the Vaal Barrage and the inclusion of these rivers within scenario modelling, the DSS was adapted to explicitly simulate these rivers (Odume et al., 2021). Figure 4.4 shows the system representation of the Vaal Barrage used by the DSS.

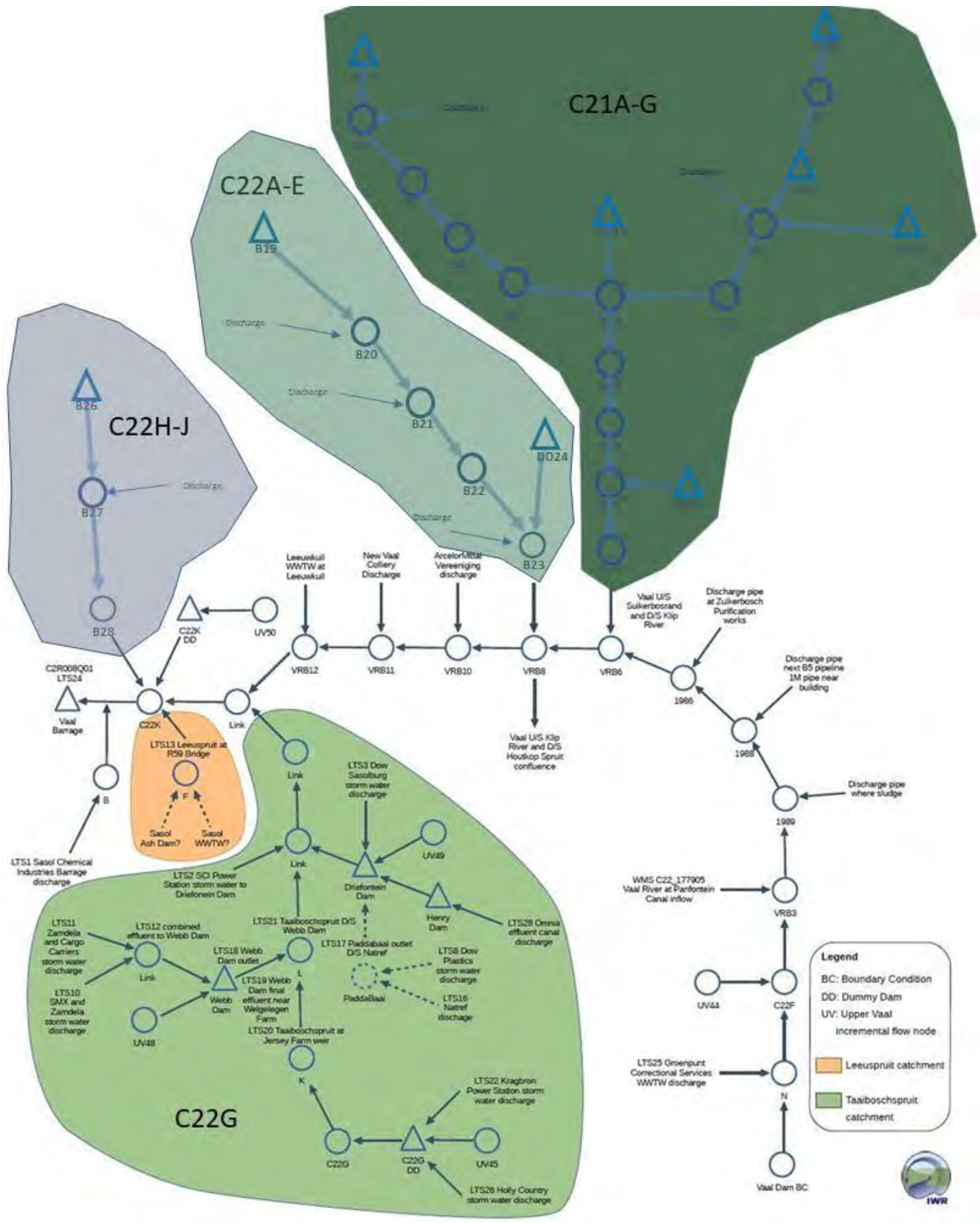


Figure 4.4: Screenshot of a system representation of the Vaal Barrage catchment within the DSS. (Source: Odume et al., 2021).

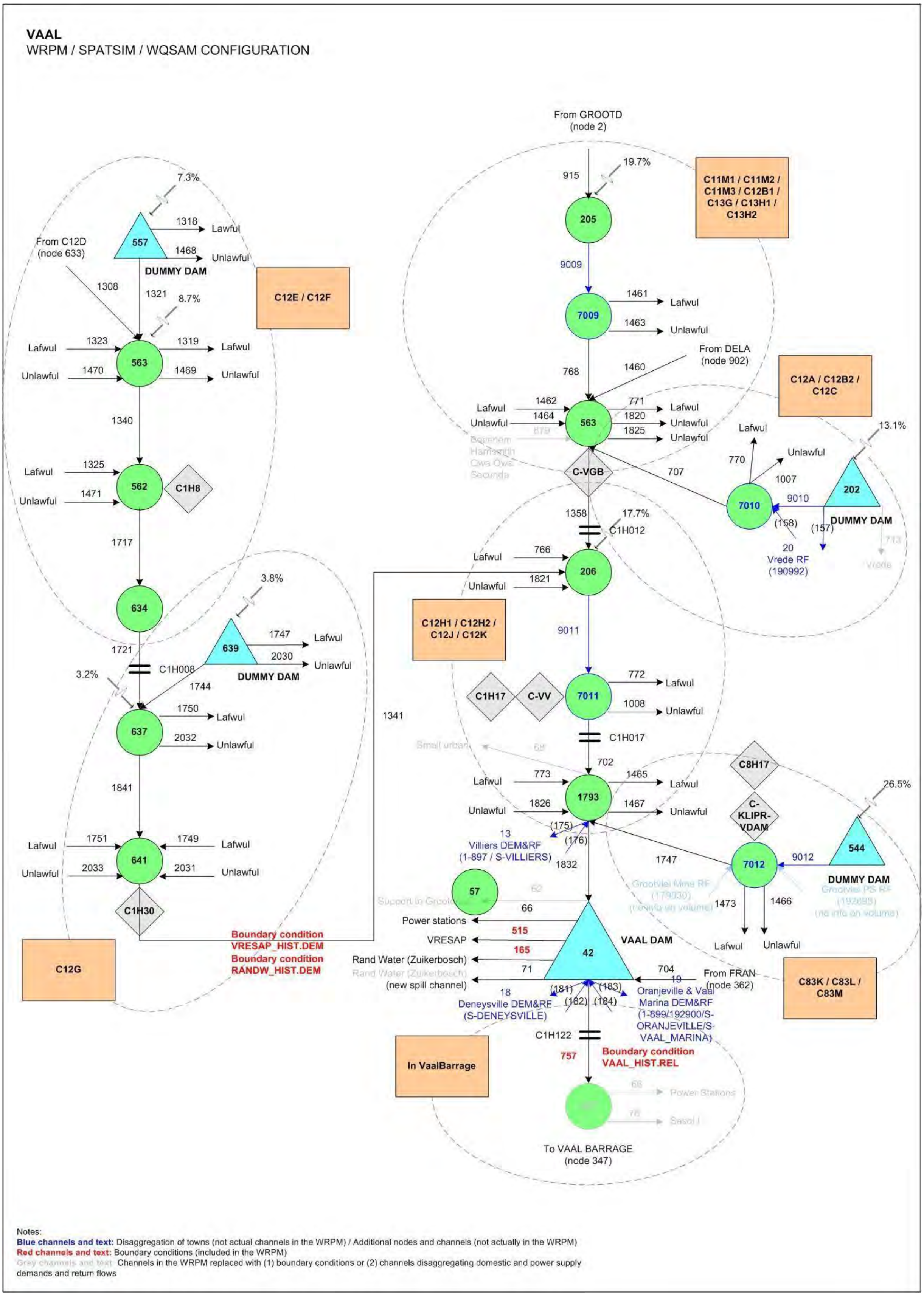


Figure 4.5a: The water resource yield model (WRYM) systems diagram of the Upper Vaal (Source: Odume et al., 2021).

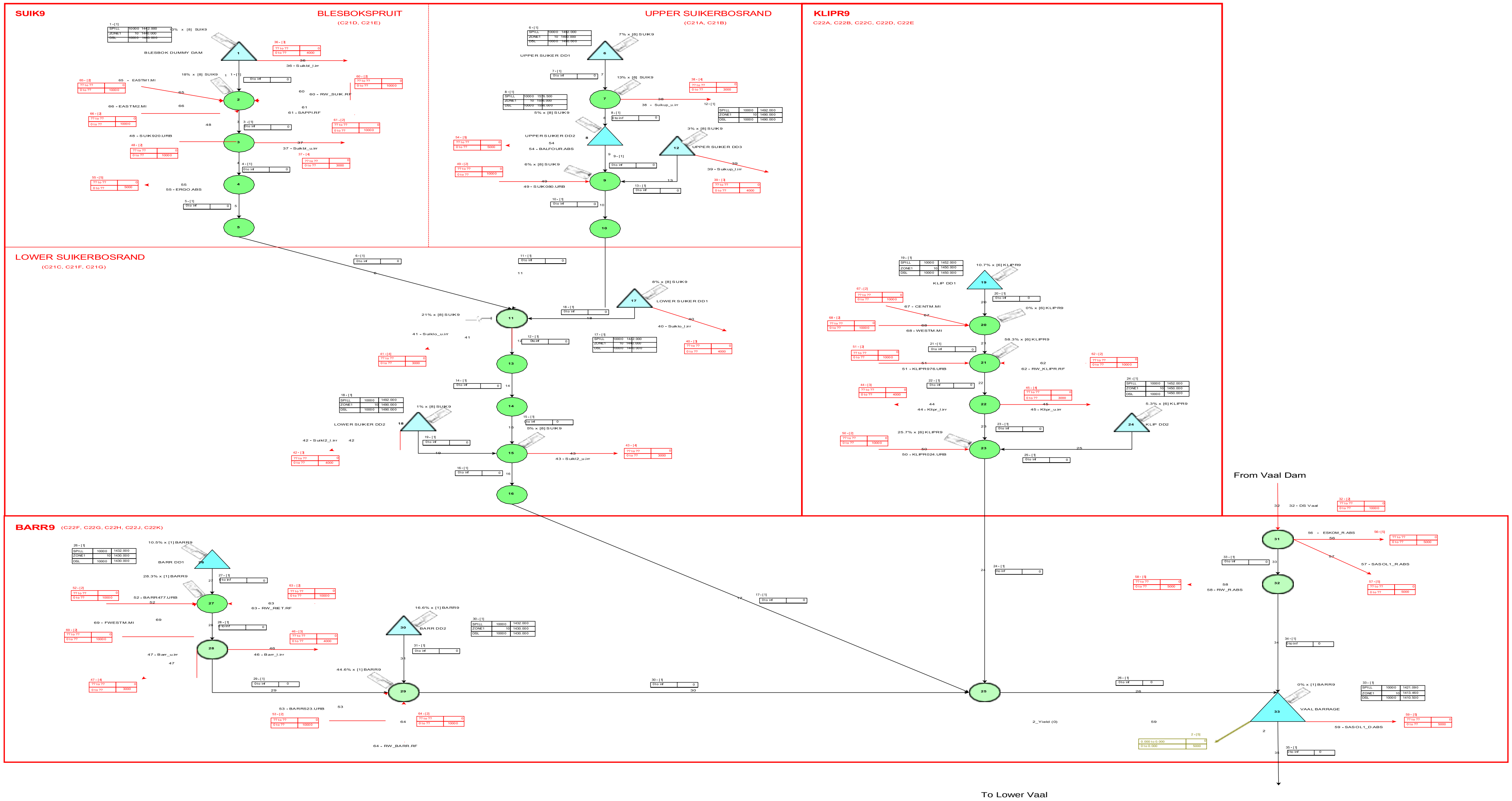


Figure 4.5b: The water resource yield model (WRYM) systems diagram of the Vaal Barrage and associated tributaries (Source: Odume et al., 2021)

4.2.4 Exploring the relationship between WUL standards and water quality components of the RQOs in the Vaal Barrage system through scenario modelling.

Scenarios are plausible predictions of future conditions for water quality (Anderson et al., 2008) and are useful because they allow the investigation of 'what-if' scenarios which benefit environmental management. This study investigated scenarios using the DSS to help establish the relationship between WUL standards and the water quality component of the RQOs. The DSS allows users to change the WUL standards of the licence holder and to set RQOs. This study investigated the relationship between the WULs and RQOs by (1) representing the spatial distribution of loads in the catchment under the present water quality situation; (2) separating the impact of water quality load inputs at a particular point in the catchment on instream water quality from impacts of loads upstream; (3) determining the capacity for a WUL standard at a particular point to be increased, or the extent to which it needed to be decreased for instream water quality to fall within the RQO; (4) determining the collaborative action needed among stakeholders within the catchment to bring water quality at a particular point to within the RQO. To achieve the demonstration of the DSS, four scenarios were developed and investigated using the available data.

Scenario 1: Establishing the current water quality conditions in the Vaal Barrage and the associated tributaries within the lower section of the Upper Vaal system.

This scenario was a baseline assessment of current water quality conditions in the Vaal Barrage catchment. Here the catchment incremental loads for various water quality variables were described using visualisations. The selected water quality variables were sulphate, TDS, phosphate, and nitrate. This scenario indicated where in the catchment water quality management action should be directed. The current water quality was simulated both in terms of instream loads and concentrations for TDS, NO3-N and +NO2-N, SO_4 and PO4-P.

In this scenario, the DSS was used to create visualisation maps for selected water quality variables as loads (kg/day). The visualisations used the simulations of the DSS for the period 1920 to 2010, with final values per quinary catchment taken as the average across the simulation period. Although the visualisation maps illustrate the breakdown of water quality loads at a quinary level, the catchment labels in the maps below show the catchments at the larger quaternary level to avoid confusingly long catchment labels. The percentage contribution of each quaternary catchment is calculated as the proportion of the incremental load of that catchment to the cumulative load in the Vaal Barrage. The visualisations shown in Figures 4.6 to 4.9 show the incremental loads of the quinary catchments.

Scenario 2: Separating the impact of water quality loads at a particular point in the catchment on instream water quality from the impact of load upstream.

This scenario separated the impact of water quality at a particular point in the catchment on instream water quality from impacts of load upstream. The Vaal Barrage was selected for this scenario and the effect of the WUL for TDS at the Vaal Barrage on the water quality in relation to the RQO was examined by making three changes to the WUL and assessing the extent to which the frequency distribution of simulated water quality exceeded the RQO. TDS was selected due to the salinity problem in the Vaal Barrage and due to the available data.

The three permutations of the WUL investigated were (1) the current WUL standard of 917mg/l; (2) halfthe current WUL standard, that is, 458 mg/l; (3) setting the WUL standard to 0 mg/l. The WULstandard at the Vaal Barrage relates directly to the water quality signature assigned to return flow at that node. The purpose of this scenario was to demonstrate the relative contribution ofupstream loads on the water quality in the Vaal Barrage in relation to the RQO, and to demonstrate how the DSS can be a platform to reduce effluent to meet the RQOs.

Resource Quality Objectives are narrative and quantitative descriptors that give acceptable levels of pollution of a water resource, and which are gazetted and supported by the law (DWAF, 2011). The RQO 95th percentile indicates that the RQO is exceeded 5% of the time, meaning that, effectively, water quality is within the RQO. The numerical limits as quantitative descriptors provide the ‘worst’ point along the continuum of change in the selected environmental indicators (DWAF, 2011). This point then indicates that having once exceeded the desired level of the environmental indicator, the RQO may no longer be achieved (DWA, 2011). As an example, Table 4.2 shows the RQOs for salt for the Vaal Barrage. This study used electric conductivity (EC) as substitutes for total dissolved solids (TDS). In this study EC was converted to TDS by multiplication of 6.5 (DWAF, 1996).

Table 4.2: RQO for salt for river water quality in the Vaal Barrage (Based on DWS, 2014; Odume et al. 2021).

Sub-component	RQO	Indicator/measure	Numerical limits	95th percentile
Salts	Salts need to be improved to levels that do not threaten the ecosystem especially fish and to provide for users.	Electrical conductivity	≤ 85 mS/m	84

Scenario 3: Determining the capacity for a WUL standard at a particular point to be increased or the extent to which it needs to be decreased for water quality to fall within the RQO.

The water quality component of the RQO is a set of objectives that need to be met to achieve the desired level of protection for the resource, thus reflecting the acceptable level of water quality conditions for management targets. One way in which the water quality component of the RQOs can serve as a future objective is to indicate a water quality threshold that should not be exceeded. The implication of the RQO not being exceeded is that the receiving resource has the capacity to receive additional emitters. In this situation, additional emitters may be licensed, if discharges from the emitters do not result in an instream water quality condition that exceeds the RQO. To model this scenario, the DSS was used to investigate the degree to which a WUL could be increased at a particular point in the Vaal Barrage catchment before instream water quality exceeded the RQO.

Scenario 4: Collaborative actions among stakeholders within the catchment to bring sulphate levels within the RQO

Collaborative action by stakeholders is one of the key ingredients to successful management of a common pool resource (Heinmiller, 2009). Collaboration is defined as the pooling of resources by the stakeholders to work towards managing problems (Wondolleck & Yafee, 2000). Collaborative measures encourage knowledge transfer and collaborative learning, as the process involves the grouping from multiple disciplines. This scenario was selected to demonstrate how using the DSS can illustrate a strategy for licence holders to work together in reducing sulphate to acceptable limits within the Vaal Barrage catchment. To achieve this scenario, the WULs along the mainstream of the Vaal River in the Vaal Barrage were established by reducing the original concentrations by 50%, 75%, and 90% to identify the collaborative action among all licence holders in bringing sulphate levels in the Vaal Barrage to within the RQO, as seen in Table 4.3.

Table 4.3: Selected nodes along the mainstream of the Vaal River into the Vaal Barrage. The WUL discharge standard of the selected nodes was reduced by 50%, 75% and 90% to test the collective effects on the RQOs at the Vaal Barrage catchment.

Nodes	**WUL discharge standard for sulphate (mg/l)**	**Reduced by 50% (mg/l)**	**Reduced by 75% (mg/l)**	**Reduced by 90% (mg/l)**
Groen	100	50	25	10
VRB3	55	27.5	13.75	5.5
1-988	18	9	4.5	1.8
1-986	20	10	5	2
VRB11	382	191	95.5	38.2
C22K	75	37.5	18.75	7.5
Vaal Barrage	262.5	131.25	65.625	26.25

Table 4. 1: descriptive information of the selected nodes along the mainstream of the Vaal River into the Vaal Barrage. The WUL discharge standard of the selected nodes was reduced by 50%, 75% and 90% to test the collective effects on the RQOs at the Vaal Barrage catchment.

	WUL discharge standard for sulphate (mg/l)	**Reduced by 50% (mg/l)**	**Reduced by 75% (mg/l)**	**Reduced by 90% (mg/l)**
Mean	130	65	33	13
Median	75	37.5	18.75	7.5
Range	362	182	60.6	36.4

4.3 Results

4.3.1 Scenario 1: Establishing the current water quality conditions in the Vaal Barrage and associated tributaries within the lower section of the Upper Vaal system.

The current water quality conditions for the Vaal Barrage catchment were simulated based on the calibrated DSS. The DSS was calibrated by adjusting water quality parameters until the simulated water quality matched the available observed water quality for various points in the catchment for which observed data were available. Once the DSS was calibrated for current water quality conditions, the model provided simulated water quality for points (nodes) distributed throughout the catchment and for a daily time step throughout the simulated period.

The model also provided simulated water quality data for the tributaries to the Vaal Barrage catchment, including the Suikerbosrand, Klip, Blesbokspruit, Leeu-Taaibospruit and Rietspruit river systems. The current water quality was simulated in terms of instream loads for TDS,NO_3-N and +NO_2 -, SO_4, and PO_4-P. Figure 4.6 shows the incremental TDS, which was calculated as the average daily load over the entire simulation period. Table 4.5. shows the contributions of the respective catchments, as percentages, to the loads in the Vaal Barrage catchment. Figures 4.6 to 4.9 show the quaternary catchment boundaries. This method was done as the quinary labels are long and confusing, and it is arguably more useful to initially geo-reference water quality in the catchment to a quaternary level. Table 4.5 shows the percentage contributions of incremental loads of the different catchments to the load in the Vaal Barrage at a quaternary catchment level. The load values shown in Table 4.5 are in kg/day and are the average taken across the entire simulation period.

Table 4. 2: Summary of the percentage contribution of the water quality load of each quaternary to that in the Vaal Barrage. The table shows the incremental (Inc.) load, cumulative (Cumul.) load and percentage average contribution of each quaternary catchments in the simulation period. This table indicates only the catchments with a high contribution to the load in the Vaal Barrage,

Total dissolved solids (TDS).

Quat	River name	Inc. (kg/d)	Cumul. (kg/d)	Percentage (%)
C21B	Upper Suikerbosrand	58,485.07	304,861.42	4.70
C22A	Klip	144,482.16	214,751.80	11.62
C22E	Klip	101,727.90	67,818.59	8.18

Sulphate

Quat	River name	Inc. (kg/d)	Cumul. (kg/d)	Percentage (%)
C21B	Upper Suikerbosrand	51,174.43	187,990.76	12.73
C22A	Klip	17,206.43	43,731.43	4.28
C22E	Klip	67,818.59	131,093.54	16.78

NO3-N and +NO2-N

Quat	River name	Inc. (kg/d)	Cumul. (kg/d)	Percentage (%)
C21D	Blesbokspruit	179.77	82.13	3.61
C22A	Klip	1,100.69	1,210.14	22.13

Phosphate

C21C	Lower Suikerbosrand	3.05	0.89	0.33
C21D	Blesbokspruit	316.32	138.03	34.00
C22A	Klip	137.59	164.90	14.79
C22J	Barrage	32.33	59.88	3.48

Figure 4.6 shows the spatial distribution of incremental TDS loads in the Vaal Barrage catchment and associated rivers within the lower section of the Upper Vaal. The TDS load across the catchment shows the incremental loads of most quaternaries falling in the range of 20 000–40 000 kg/d. The highest TDS loads are shown to be in tributary catchments of the Vaal Barrage (C21B, C22E, C22A). The order of the catchments in terms of their percentage contribution to TDS load in the Vaal Barrage was: C22A (11.60; Klip River Catchment) >C22E (8.18%; Klip River Catchment >C21B (4.10%; Upper Suikerbosrand Catchment).

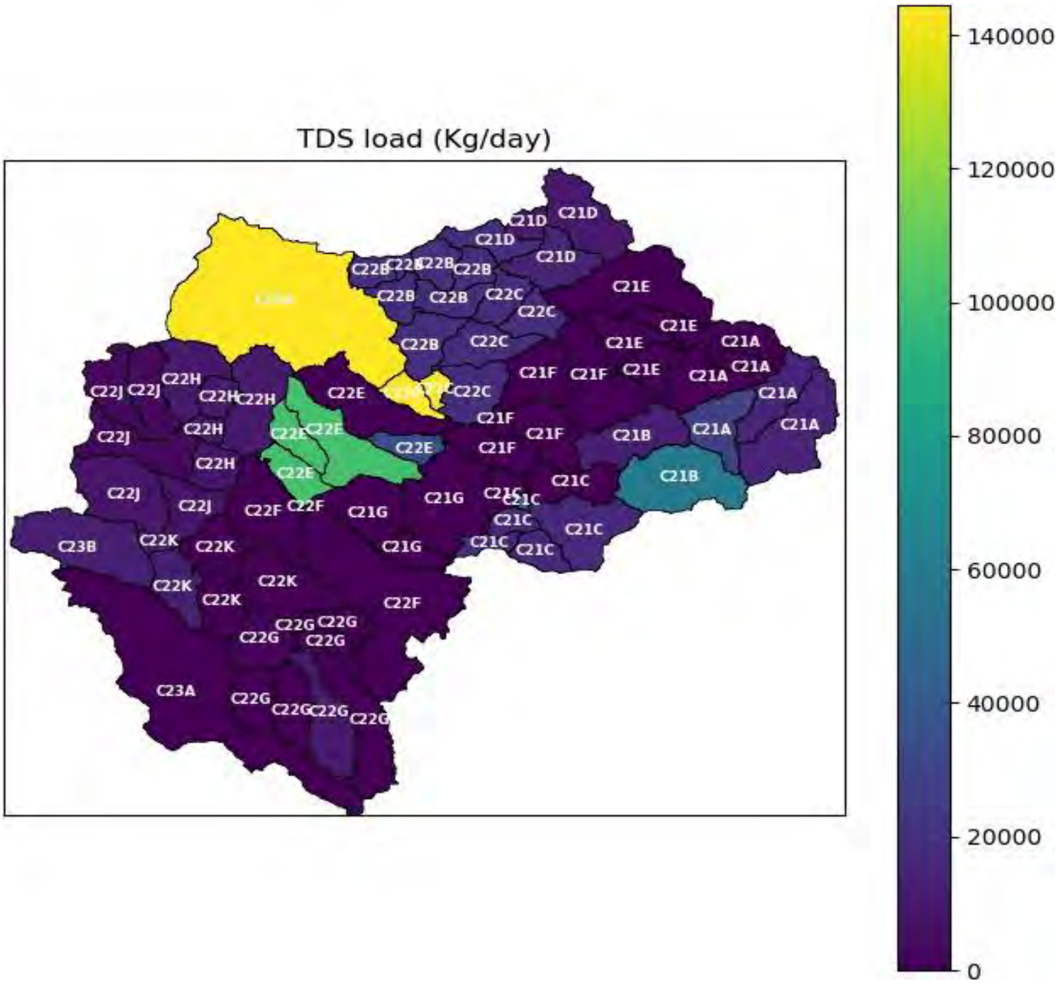


Figure 4.6: Spatial distribution of incremental loads of total dissolved solids (TDS) (kg/day) for the Vaal Barrage catchment, based on the simulated data.

Figure 4.7 shows the spatial distribution of sulphate incremental loads in the Vaal Barrage Catchment and associated rivers in the lower section of the Upper Vaal. The sulphate load varies across the catchment, with the incremental loads of most quaternaries falling in the range of 1,000 -3,000 kg/day. The highest loads of sulphate are indicated to occur in the tributary catchments of the Vaal Barrage (C22E, C21B, C22A). The order of the quaternary catchments in terms of their contribution to sulphate load in the Vaal Barrage was C22E (16.87; Klip catchment) > C21B (12.73%; Upper Suikerbosrand) >, C22A (4.28 % ; Klip River Catchment).

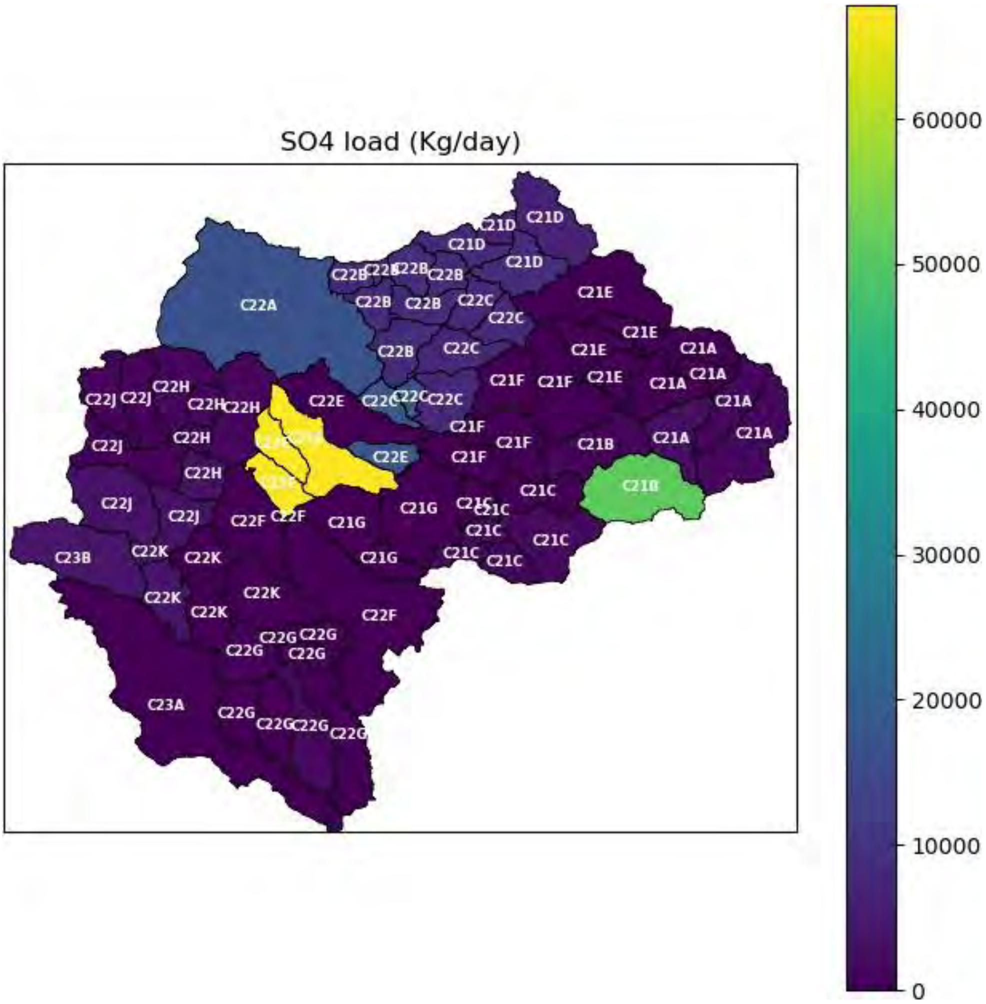


Figure 4.7: Maps showing the spatial distribution of incremental loads of Sulphate (kg/day) for the Vaal Barrage Catchment according to simulated data.

Figure 4.8 shows the spatial distribution of NO_3-N and + NO_2-N incremental loads in the Vaal Barrage catchment and associated rivers within the lower section of the Upper Vaal. The NO_3-N and + NO_2-N load varies across the catchment, with the incremental loads of most quaternaries falling in the range of 200–400 kg/d. The highest NO_3-N and + NO_2-N loads are indicated in tributary catchments of the Vaal Barrage (C22A and C21D). The order of quaternary catchments in terms of their contribution to NO_3-N and + NO_2-N load in the Vaal Barrage was C22A (22.13%; Klip catchment)> C21D (3.61 % Blesbokspruit).

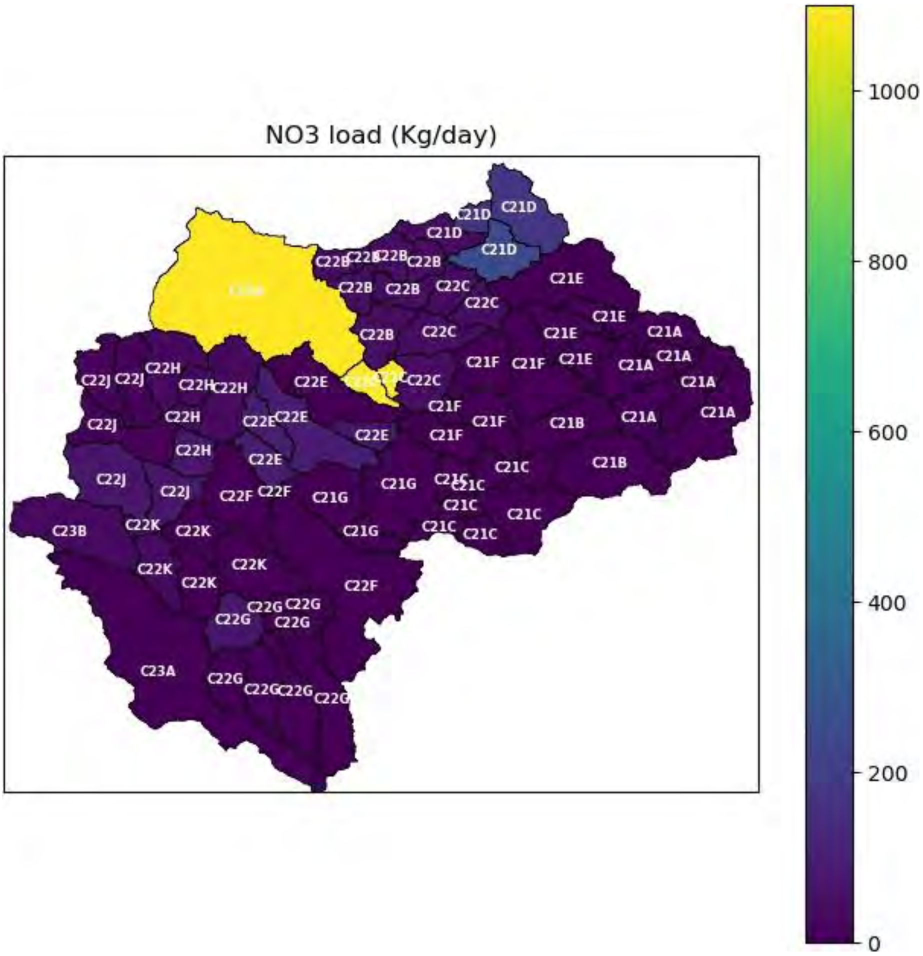


Figure 4.8: Spatial distribution of incremental loads of NO3-N and+ NO2-N (kg/day) for the VaalBarrage catchment according to simulated data.

Figure 4.9 shows the spatial distribution of incremental phosphate loads in the Vaal Barrage catchment and associated rivers in the lower section of the Upper Vaal. The phosphate load varies across the catchment, with the incremental loads of most quaternaries falling within the range of 50–150 kg/day. The order of the quaternary catchments in terms of their contribution to phosphate load in the Vaal Barrage is C21D (24.56%; Blesbokspruit) >C22A (14.79%; Klip River) >C22H (3.48%) >C22J (3.48%; Vaal Barrage) >C22C (0.33%; Klip River).

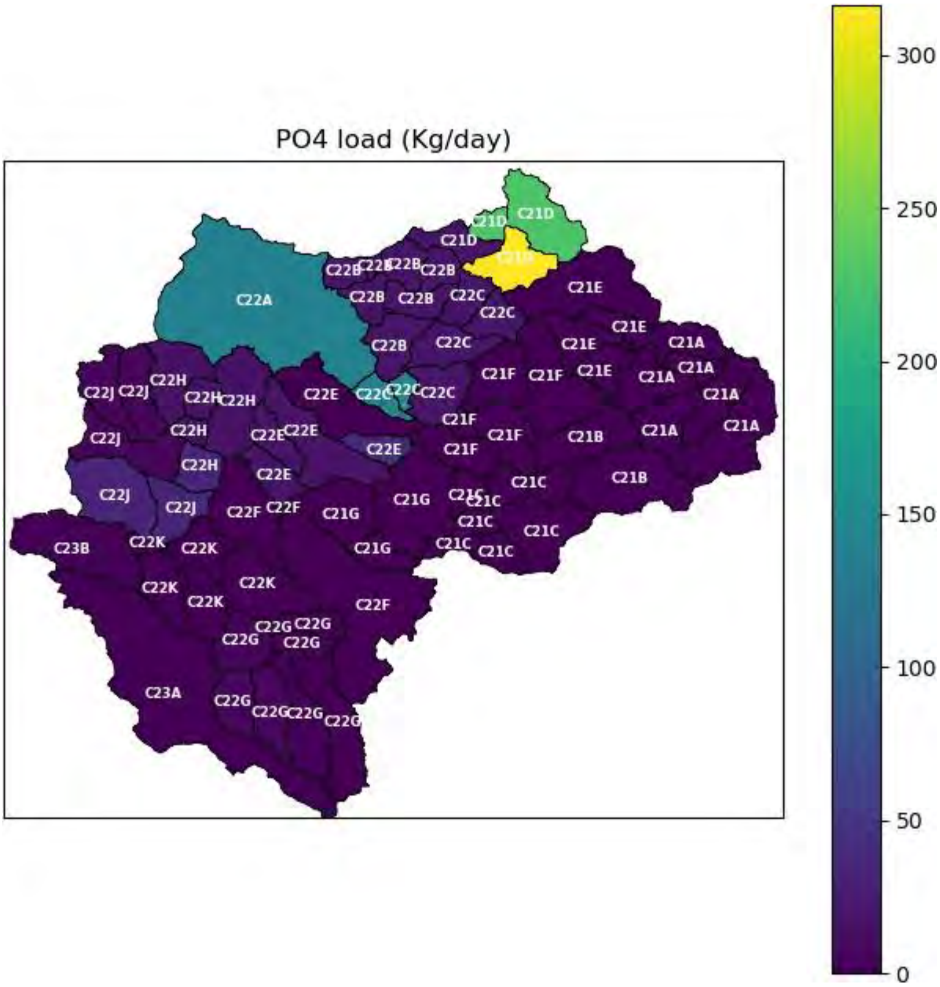


Figure 4.9: Spatial distribution of incremental phosphate loads (kg/day) for the Vaal Barrage catchment according to simulated data.

4.3.2 Scenario 2: Separating the impact of water quality loads at a particular point in the catchment on instream water quality from the impact of load upstream.

The scenario focuses on the WUL standard for TDS at the Vaal Barrage. Three permutations (sub-scenarios) of the TDS WUL standard at the Vaal Barrage were investigated. Sub-scenario 1 WUL standard of 917 mg/l as the TDS effluent return flow concentration. Sub-scenario 2 assumes that the WUL standard is decreased by 50% to a TDS effluent concentration of 458.5

mg/l, and sub-scenario 3 assumes the WUL standard is reduced to a TDS concentration of 0 mg/l. An examination of how frequently the TDS concentration exceeds the RQOs among the different WUL standard permutations can indicate whether the contribution of the WUL at the Vaal Barrage exceeds the RQO relative to upstream loads.

The results for sub-scenario 1 are shown in Table 4.5 and Figure 4. 10 at the current WUL standard of 917 mg/l, the 95th percentile is exceeded 31% of the time, but no exceedance was observed for the numerical limit of the RQO for TDS. The numerical limit refers of an RQO is the quantitative descriptor that must not be exceeded for a given component of the resource in order to meet the goal of balancing resource protection and use (DWAF, 2011).At a reduced WUL standard of 458 mg/l,the 95th percentile of the RQO for TDS is exceeded 27% of the time but no exceedance was observed for the numerical limit of the RQO for TDS. At the reduced TDS concentration 0 mg/l, the 95th percentile is exceeded 24% of the time, no exceedance was observed for the numerical limit of the RQO for TDS

Table 4. 3: The results of TDS simulation for the three sub-scenarios indicating the % time the 95th percentile and numerical limit for the RQO for TDS is exceeded for the three sub-scenarios of TDS discharge standard.

WUL standard for TDS (mg/l)	**95th RQO for TDS (mg/l)**	**RQO numerical limit for TDS (mg/l)**	**95th percentile (% exceedance for TDS)**	**Numerical Limit (% exceedance for TDS)**
917	514	721	31%	0 %
458.5	514	721	27%	0 %
0	514	721	24%	0 %

Table 4. 4: Descriptions based on table 4.6 (DWS, 2018; Odume et al., 2021).

Terms	Brief Description
Water use licence (WUL) standards	Water quality conditions in the water use licence are enforceable and legally binding.
95^{th} RQO	95th percentile of RQO set for a designated sub-catchment.
RQO numerical limit	The numerical value of RQO is set for a designated sub-catchment.

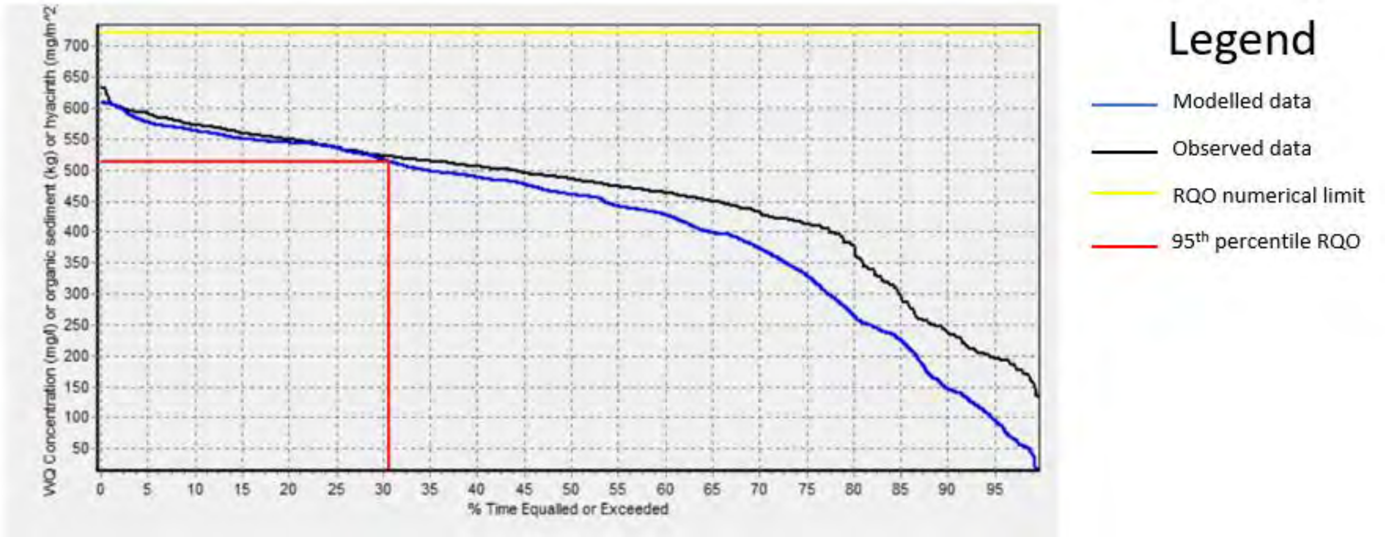


Figure 4.10. Frequency distribution of simulated total dissolved solids (TDS) at the Vaal Barrage for 2000–2010 in relation to the RQOs. The modelled data are indicated by the blue line, observed data by the black line; the yellow line indicates the RQO numerical limits, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of TDS, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence discharge standard for TDS is set at 917 mg/l.

Sub-scenario 2: Discharge standard set at 458mg/l

Figure 4.10 shows that, under a WUL standard of d of 917 mg/l, the numerical limit of the RQO (yellow line) is not exceeded, whereas the 95th RQO is exceeded 31% of the time (Table 4.5). As shown in Figure 4.11 when the WUL TDS discharge limit is decreased to 458.5 mg/l, the 95th percentile RQO is exceeded by 27% of the time and the numerical limit RQO is not exceeded. This suggests that halving the TDS discharge standard only slightly decreases the percentage of time at which the TDS concentration exceeds the 95th percentile RQO.

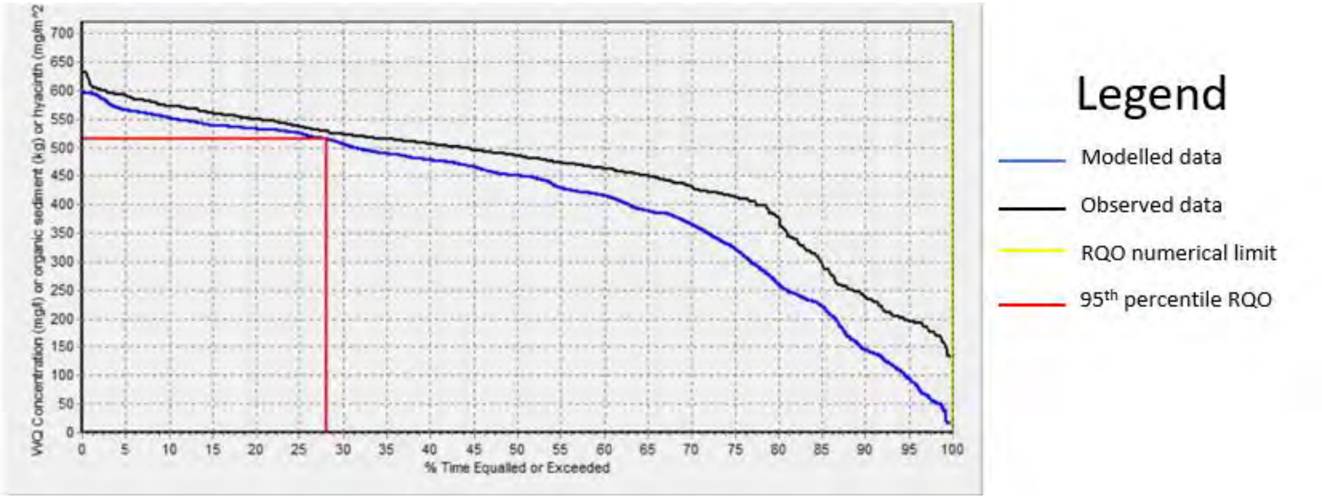


Figure 4.11: Frequency distribution curve showing the simulation of total dissolved solids (TDS) for the Vaal Barrage as compared to available observed data for 2000–2010. The modelled data are indicated by a blue line, the observed data indicated by black; the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. They-axis shows the concentration of the TDS and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence discharge standard for TDS is set at 458.5 mg/l.

Sub-scenario 3: Discharge standard flow set 0mg/l

As shown in Figure 4.12, setting the TDS discharge standard to 0 mg/l results in the 95th percentile RQO being exceeded 24% of the time. These results suggest that the WUL for TDS at the Vaal Barrage has very little effect on instream water quality relative to the loads entering the river from upstream. The results reflect the influence of non-point sources such as groundwater, surface water and interflow have on salinity on the Vaal Barrage catchment, as the only changes were made to the WULs for TDS which are sourced from point sources.

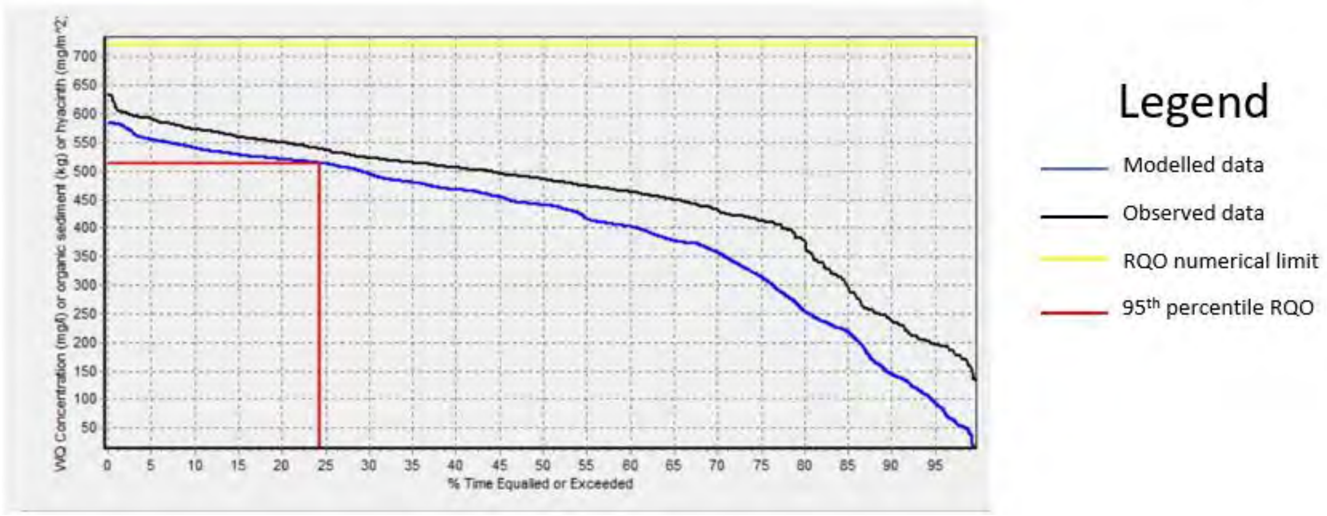


Figure 4.12: Frequency distribution curve showing the simulation of total dissolved solids (TDS) for the Vaal Barrage as compared to available observed data for 2000–2010. The modelled data are indicated as blue line, the observed data indicated as black line; the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of the TDS, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence discharge standard for TDS is set at 0 mg/l.

4.3.3 Scenario 3: Determining the capacity for a WUL at a particular point to be increased or the extent to which it needs to be decreased for water quality to fall within the RQO. A case study of the WUL standard for Nitrate at C22K.

Sub-scenarios were used to investigate the capacity of the WUL for nitrate at C22K to be increased or the extent to which it needs to be decreased to fall within the relevant RQO. At node C22K, the WUL discharge standard for nitrate was 0.500 mg/l. Thus, in the first sub-scenario, the current WUL discharge standard of 0.500 mg/l was used, and thereafter, the discharge standard was reduced to 0 mg/l. Figure 4.13 shows the modelled relationship between the effluent discharge standard of 0.500 mg/l and the RQOs for nitrate at C22K. The nitrate at C22K RQO 95^{th} percentile is 0,25 mg/l and RQO numerical limit is 1 mg/l. The results show that after re-setting the WUL discharge standards, there were no observed changes to the 95^{th} percentile RQO, indicating that any decreases/changes in the current WUL discharge standards would result in no changes on the nitrate RQO for C22K.

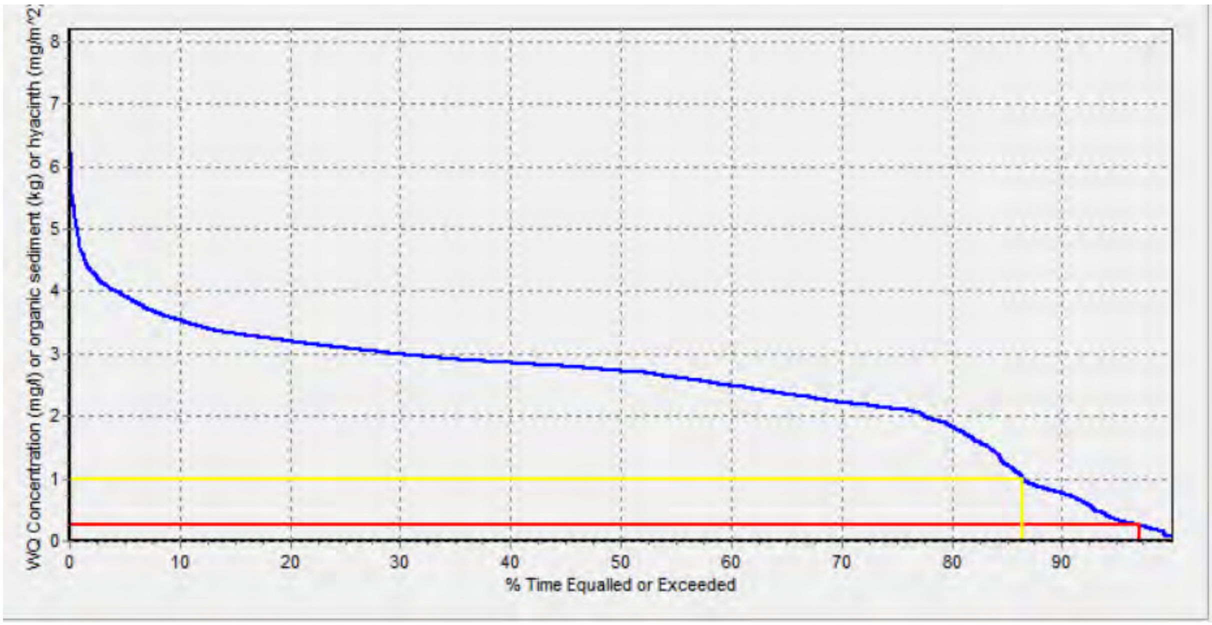


Figure 4.13: Frequency distribution curve of simulated nitrate at the Vaal Barrage for 2000–2010 in relation to the RQOs. The modelled data are indicated as the blue line, the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of nitrate, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence discharge standard for TDS is set at 0.500mg/l.

Sub-scenario 2: Effluent set at 0 mg/l

For the second sub-scenario, the discharge standard for nitrate was reduced to 0 mg/l. Figure 4.14 shows the modelled relationship between the effluent discharge standard of 0 mgl/ and the RQOs for nitrate at C22K. The result indicates that even after re-setting the effluent discharge to 0 mg/l, no changes occurred to the 95th percentile and numeral limit. This result indicates that, regardless of the changes made to the effluent discharges, nitrate at C22K will always exceed the RQO.

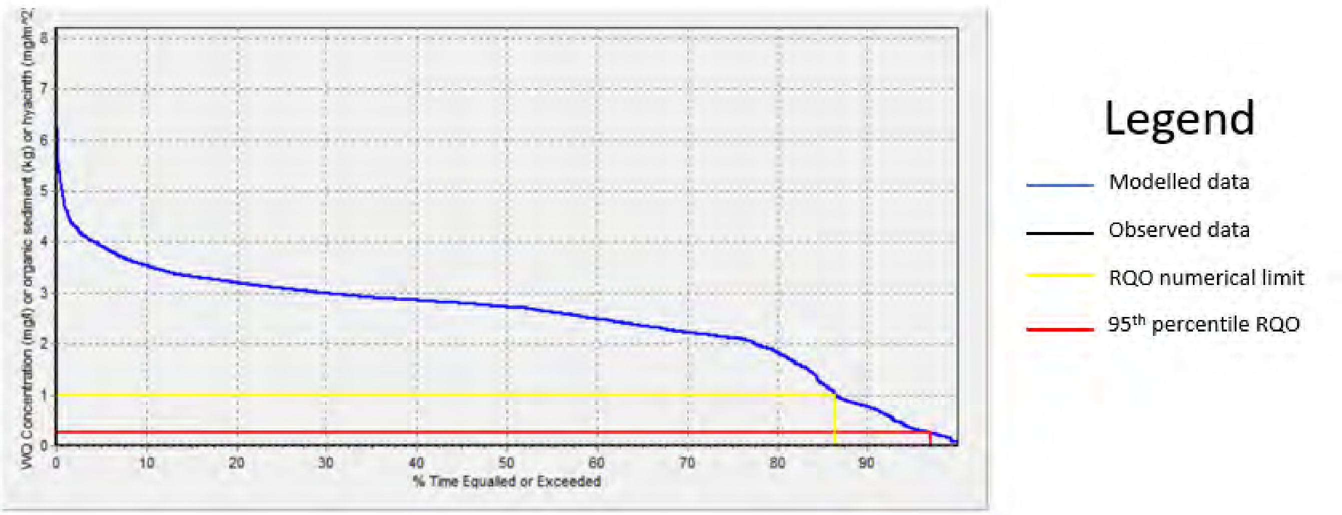


Figure 4.14: Frequency distribution curve showing the simulation of nitrate for the Vaal Barrage as compared to available observed data for 2000–2010. The modelled data are indicated as a blue line, the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of the nitrate, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence discharge standard for nitrate is set at 0 mg/l.

4.3.4 Scenario 4: Collaborative action among stakeholders within the catchment to bring sulphate levels within the RQO.

Sulphate is recognised as one of the problematic water quality variables occurring in the lower section of the Upper Vaal. Collaborative actions among stakeholders are regarded as a useful process in water quality management. This scenario investigated collaborative actions among stakeholders with WUL discharge standards along the Vaal River running through the Vaal Barrage catchment from below the Vaal Dam to the Vaal Barrage. The discharge standards of all stakeholders were decreased by the same proportion in a series of sub-scenarios to determine whether collaborative action could successfully improve the concentrations of sulphate in the Vaal Barrage. Here, the discharge limits for sulphate for all stakeholders were decreased by 0%, 50%, 75% and 90%. Table 4.6 shows the results of the percentage reduction of the WUL discharge standards in the WUL. The percentage decrease influences the numerical limit and 95^{th} percentile of the RQOs in the Vaal Barrage.

Table 4. 5: Percentage decrease of WUL discharge standards for sulphate by 50%, 75% and 90% at the Vaal Barrage catchment.

Sulphate discharge standards (mg/l)	RQO for sulphate (numerical limit) (mg/l)	RQO for sulphate (95th percentile) (mg/l)	Percentage reduction in the discharge standard for sulphate	Percentage time the numerical limit RQO is exceeded	Percentage time the 95th percentile RQO is exceeded
262.5	173	200	0%	22%	36%
131.25	173	200	50%	20%	35%
65.625	173	200	75%	18%	34%
26.25	173	200	90%	17%	33%

Sub-scenario 1: Percentage reduction in sulphate discharge standard by 0%.

The results in Figure 4.15 shows reduction of the WUL sulphate discharge at 0%, implying no change occurred to the discharge standard. The RQO 95th percentile (200 mg/l) is exceeded by 36% of the time and the numerical limit (173 mg/l) by 22% of the time. The results indicate that, at the current WUL discharge with no changes, sulphate RQO is exceeded.

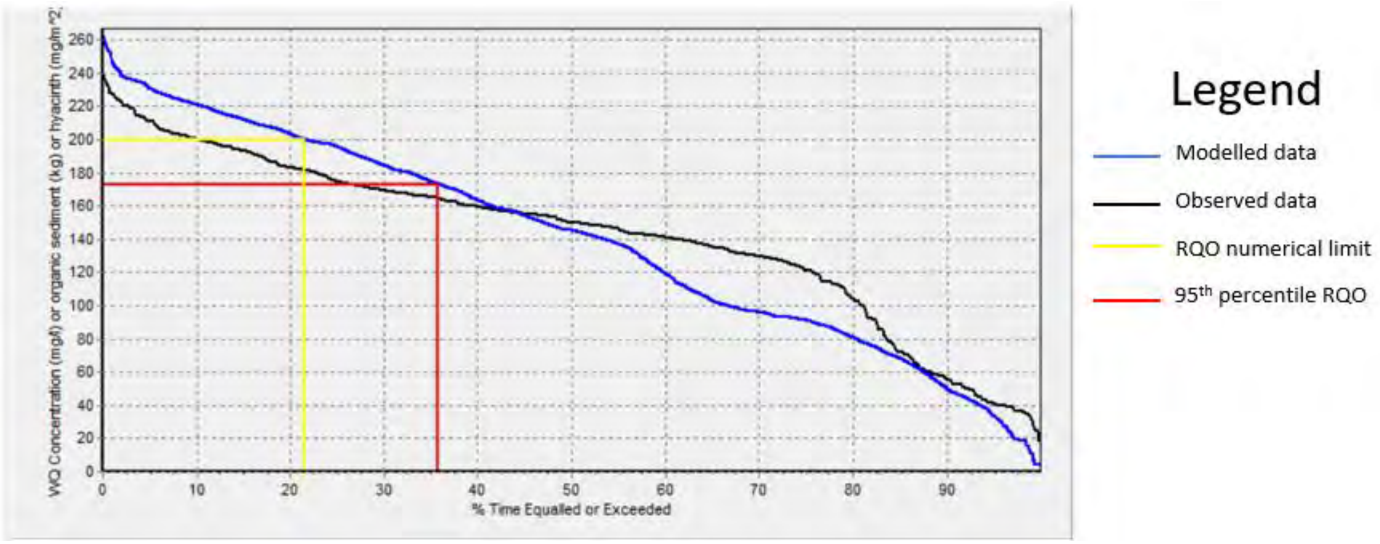


Figure 4.15: Frequency distribution of simulated sulphate at the Vaal Barrage for 2000–2010 in relation to the RQOs. The modelled data are indicated by the blue line, the observed data indicated by the black line; the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of sulphate, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water

use licence (WUL) discharge standards for sulphate TDS for stakeholders along the Vaal River from below the Vaal Dam to the Vaal Barrage were decreased by 0%.

Sub-scenario 2: Percentage reduction in sulphate discharge standard by 75%.

The WUL discharge for sulphate at the Vaal Barrage was decreased by 50%; the results show the RQO 95th percentile was exceeded 35% of the time and the numerical limit exceeded 20% of the time. The results indicate that if waste emitters along the Vaal River from below the Vaal Dam decrease their WUL discharge by 50%, it will result in a slight improvement in moving towards achieving the sulphate RQO at the Vaal Barrage.

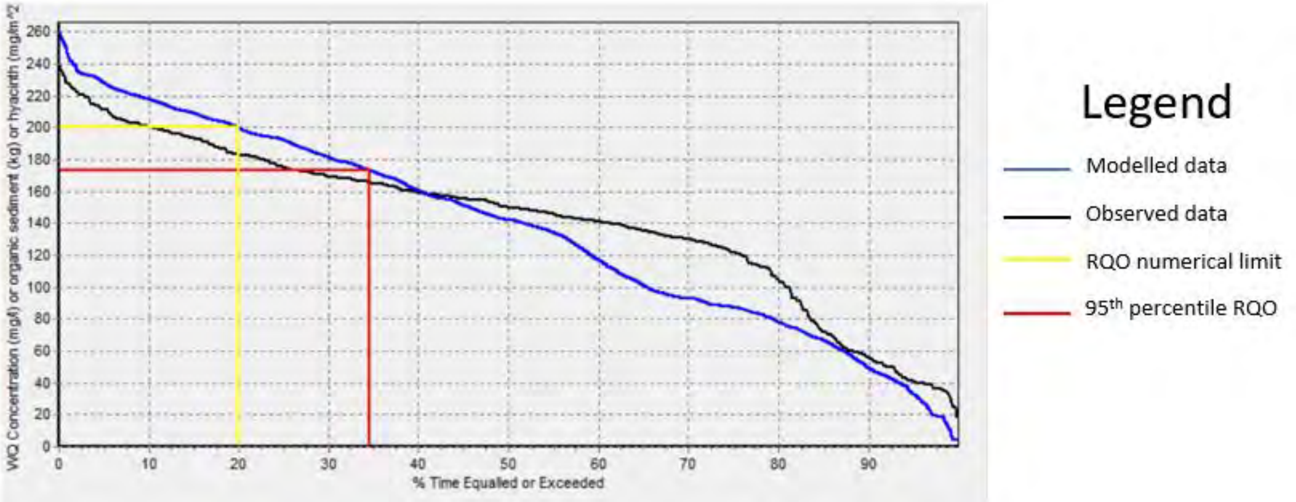


Figure 4.16**:** Frequency distribution of simulated sulphate at the Vaal Barrage for 2000–2010 in relation to the RQOs. The modelled data are indicated by the blue line, the observed data indicated by the black line; the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of sulphate, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence (WUL) discharge standards for sulphate TDS for stakeholders along the Vaal River from below the Vaal Dam to the Vaal Barrage were decreased by 50%.

Sub-scenario 3: Percentage reduction in sulphate discharge standard by 75%

The results show that a re-setting of WUL discharge concentration reduced by 75%, the RQO 95th percentile is exceeded 34% of the time and the numerical limit 18% of the time. This indicates that if stakeholders from the selected nodes further decrease their emissions to reduce sulphate contribution to the Vaal Barrage will result in a slight decrease in RQO and numerical limit. However, the RQO is still exceeded in the Vaal Barrage catchment.

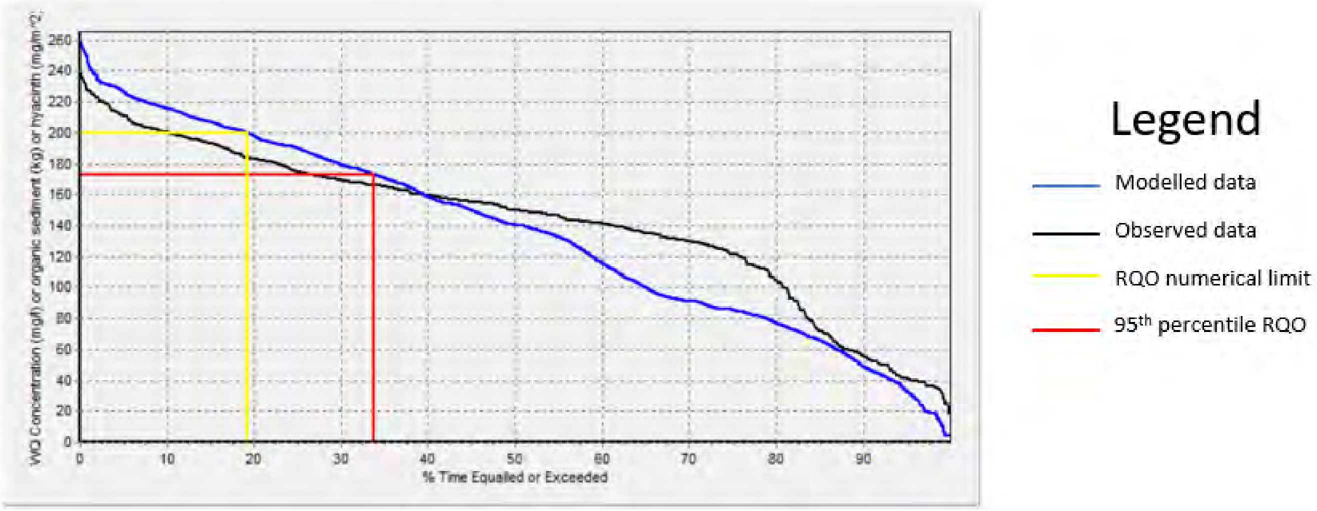


Figure 4.17: Frequency distribution of simulated sulphate at the Vaal Barrage for 2000–2010 in relation to the RQOs. The modelled data are indicated by the blue line, the observed data are indicated by the black line; the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of sulphate, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence (WUL) discharge standards for sulphate TDS for stakeholders along the Vaal River from below the Vaal Dam to the Vaal Barrage were decreased by 75%.

Sub-scenario 4: Percentage reduction in sulphate discharge standard by 90%

Figure 4.18 shows that reducing the WUL discharge of sulphate by 90% resulted in RQO 95th percentile being exceeded by 33% of the time with the numerical limit being exceeded by 17% of the time. The results imply that even after reducing WUL discharge for sulphate, the RQOs for sulphate are still not met all the time.

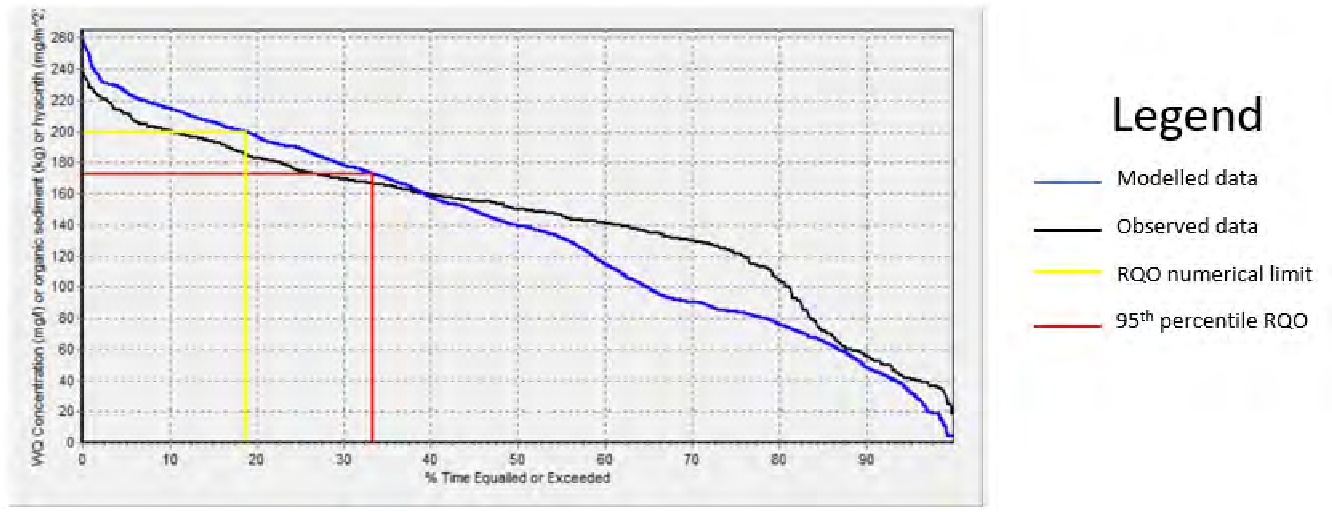


Figure 4.18: Frequency distribution of simulated sulphate for the Vaal Barrage for 2000–2010 in relation to the RQOs. The modelled data are indicated by the blue line, the observed data indicated by the black line; the yellow line indicates the RQO numerical limit, and the red line indicates the 95th percentile RQO. The y-axis shows the concentration of sulphate, and the x-axis shows the percentage time a value on the y-axis is equalled or exceeded. Here, the water use licence (WUL) discharge standard for sulphate TDS for stakeholders along the Vaal River from below the Vaal Dam to the Vaal Barrage were decreased by 90%.

4.4 Discussion

The Vaal Barrage catchment is highly influenced by the tributaries such as the Klip River, and the Suikerbosrand, Leeu-taaiboschpruit and Rietspruit. The water quality results observed in the Vaal Barrage catchment show that tributaries such as the Klip River and Upper Suikerbosrand contribute the highest TDS and sulphate levels into the catchment. These results imply that the Klip River and Upper Suikerbosrand catchments have higher elevated TDS and sulphate levels than other tributaries within the Vaal Barrage catchment. The increased levels of sulphate and TDS in the Klip and Upper Suikerbosrand catchments may be attributed to the extensive economic activities in these two catchments. For example, the Klip River catchment is heavily polluted by industrial, mining, and agricultural activities (Chihomvu et al., 2014) which can result in high nutrient and suspended solids in the river system. Historically, the Klip

River catchment has been reported to have elevated sulphate and EC levels due to mining residues in the Witwatersrand (Makumbe, 2008). Agricultural runoff has also been recognised as one of the main causes of elevated levels of sulphate in the Vaal Barrage River system that is sourced from the Klip tributary (Wepener et al., 2015). A study by Kotze (2008) further indicated water quality in the Klip River catchment to be severely impacted by EC, sulphate, and TDS. Further degradation in water quality in the Klip River was attributed to the agricultural activities and the wastewater treatment works along the Rietspruit (Seretlo, 2012). The visualisation results demonstrate the influence of pollution caused by anthropogenic activities in the catchment and call for stringent regulatory conditions.

The visualisation results revealed that high nutrient loads such as nitrate and phosphate in the Vaal Barrage catchment were mainly from the Klip River and Blesbokspruit tributaries. Similar results have been reported in the Vaal Barrage catchment where high nutrient levels emanated from the Blesbokspruit and the Klip River system (McCarthy et al., 2007; Seretlo, 2012). Elevated phosphorus levels are evident in the Klip River from domestic waste, fertiliser, and leaching (Makumbe, 2018). The Klip River is regarded as a severely polluted catchment which contributes to the deteriorating water quality in the Vaal Barrage catchment (Seretlo, 2012). Nutrient enrichment is a persistent problem for water resources in the Vaal Barrage catchment. The ecological effects of nutrient enrichment in the Vaal Barrage catchment are reduced species diversity, and the abnormal growth of plants and algal blooms. The increased algal blooms result in oxygen depletion threatening aquatic life and fish species (Seretlo, 2012).

The current study applied the newly developed WQSAM DSS to link WUL to RQOS in the Vaal Barrage catchment. Scenario 2 explored the impact of water quality loads in the Vaal Barrage catchment on instream water quality by applying the different WUL TDS concentration permutations. The results revealed a decrease in the percentage exceedance of TDS RQO. However, with 0 mg/l WUL standards TDS RQO for the Vaal Barrage is still being exceeded. Similar results were demonstrated in Scenario 3, where the instream capacity of WUL was investigated using nitrate at C22K. The overall results indicated that re-setting nitrate WUL effluent standard to 0mg/l made no changes to exceeding the 95th percentile andthe numerical limit of the RQOs. These results highlight the impact of upstream loads on the downstream catchment and the degree to which water quality downstream adheres to the RQOs and the capacity to assimilate additional licences.

River catchments are hydrologically connected, and downstream pollution originating from activities upstream of river catchments affects the ability of downstream users to meet their WUL standards. The hydrological connectivity effect of pollution is evident in the first three scenarios explored in this study, specifically demonstrated in Scenarios 2 and 3. Scenario 3 also aimed to determine the instream capacity of the Vaal Barrage catchment to accept additional WULs. However, in Scenario 3 nitrate at C22K exceeded the instream capacity, indicating no capacity for additional WULs for this variable.

The results highlight the need for water quality tools in South Africa to consider the influence of upstream releases in river systems as rivers are hydrologically connected. In this regard, the results of this study demonstrated that DSS has the potential to monitor the effects of upstream waste on the downstream catchment. The consideration of upstream releases on water quality promotes the fair application of water quality standards in the WULs. The elevated levels of pollutants downstream originate from activities such as human population, industrial and agricultural activities in the upstream areas. The impact of pollution on the capacity of rivers to assimilate waste, especially in the downstream sites, has been demonstrated in the previous studies (Darmian et al., 2020; Hobbs et al., 2008). Overall, the results of this study illustrate the interconnectedness of river systems, supporting the need for collaborative efforts between the resource users upstream and downstream for water quality to fall within the RQOs in many regions.

Collaborative action among a limited number of stakeholders resulted in a distinct improvement in water quality conditions downstream. Thus, the scenarios reflect the possibility of collective action to improve water quality in the Vaal Barrage catchment. The results of the study show the potential of collaborative action amongst stakeholders at a largerspatial scale to improve water quality conditions in the Vaal Barrage catchment, illustrating how collaborative efforts could enhance the efficacy of regulation and compliance. The collaboration of stakeholders from different backgrounds mirrors the complexity of socio-ecological systems. The DSS can be used as a tool by regulators to negotiate collaborative action among multiple stakeholders to improve water quality through their WUL conditions. The results indicate the DSS can be used as a platform for joint efforts by stakeholders to deal with water quality allocation and licence complexities.

4.5 Conclusion

The findings of this study showed that WQSAM DSS can be used to explicitly link the WUL standards to RQOs. The WQSAM DSS that was used in this current study proved to be useful in revealing that upstream catchments indeed have an impact on water quality in the Vaal Barrage catchment. The impact of an upstream catchment influences the instream capacity of the Vaal Barrage catchment to accept additional licences. The WQSAM DSS also proved useful in demonstrating that collaborative efforts from resource users in the Vaal Barrage catchment can lead to improved water quality conditions and ultimately increasing the possibility of meeting the RQOs. The promising results in this study should serve as input for the RQO and WUL determination process, contributing to the South Africa water quality regulatory instruments. Further research should be applied to catchments across South Africa, and, since the WQSAM DSS is newly developed, to gain trust from water resource users in dealing with water quality problems.

Chapter 5: General Discussion, Conclusion, and Recommendations

5.1 General Discussion

South Africa's water legislation is regarded as some of the most progressive in the world, emphasising, as it does, the balance between water use and its protection (Schreiner, 2013; Hope, 2014). The National Water Act (NWA) No. 36 of 1998, provides a framework on how water resources should be managed at catchment level (Schreiner, 2013). Nevertheless, water quality has been recognised as a concern for freshwater systems in South Africa and there are challenges in the implementation of water quality instruments, especially for resource users. Stakeholders in the Vaal Barrage catchment currently contest the water quality standards in their water use licence (WUL). The purpose of this study was to integrate the stakeholder perceptions of the water quality instruments and demonstrate the usefulness of the WQSAM DSS to the Vaal Barrage catchment. This study employed a qualitative approach with a semi-structured questionnaire to explore the perceptions and motivations influencing stakeholder contestations of water quality use and management instruments within the Vaal Barrage catchment (Chapter 3). The newly developed WQSAM DSS that explicitly linked the WUL and RQOs was applied through scenario modelling (Chapter 4). The intention of this thesis was to fill some of the knowledge gaps identified through the study and demonstrate the inherent complexity of water quality management in socio-ecological systems, together with the need for a holistic approach to addressing challenges associated with water quality. This study revealed that such an approach would include technical and non-technical solutions to identifying stakeholders' perceptions of water quality regulatory instruments and understanding their motivations for contesting such instruments. Chapter 3 of this study explored stakeholders' perceptions and motivations for contesting applicable water quality regulatory instruments.

The results described in Chapter 3 indicate that stakeholders within the catchment perceive the resource quality objectives RQOs as largely unrealistic and not reflective of historical water quality trajectories within the catchment. The Vaal Barrage catchment is one of the most impacted river systems, and therefore, the view that the RQOs were unrealistic has severe implications for the implementation of regulatory instruments and sustainability of water resources in the catchment. The effectiveness of RQOs and WULs relies on understanding the scientific processes of freshwater systems such as the Reserve and water resource classification, which lead to formulating realistic objectives (Holly et al., 2017). The processesof RQO and WUL formulation rely on an understanding of the Reserve and water resource classification which determines the ecological protection level of water resources (DWAF, 2011), and a better understanding of these processes will enable the formulation of realistic goals. Unrealistic water quality goals will negatively affect the water resource in the Vaal Barrage catchment. Therefore, there is a need for goals of RQOs in water quality policies to berealistic to achieve the balance between water resources protection and use.

The perceived lack of scientific credibility and the legitimacy of WULs standards were revealed as critical sources of contestations in the Vaal Barrage catchment in Chapter 3. The lack of scientific credibility of the water quality standards in WULs have implications for the effectiveness of water quality policies and for the ecological integrity of water resources. Scientific credibility and legitimacy are vital ingredients in the interface between science and environmental policy (Heink et al., 2015). An essential element of scientific credibility is building trust among the resource users and regulators by ensuring transparency of the methods used to derive the water quality standards in the WULs. A high level of trust increases the chances of stakeholders engaging in environmental policies (Dincer & Fredriksson, 2013). For example, a study by Von Stackelberg and Nielson (2012) demonstrated how stakeholder collaboration in the water quality model of QUAL2Kw promoted transparency and a scientifically defensible tool, reflecting the need for open and transparent methods in deriving the water quality standards for the WULs. Transparency in the water quality standards is essential for establishing credibility and for reducing potential conflict between resource users and regulators (Brouwer et al., 2020). The results of this study suggest transparency in the water quality derivation process and other tools, such as awareness, education, and punitive measures (as demonstrated in Chapter 4 of this thesis), can promote compliance among resource users. Awareness, education, and punitive measures were identified as having the potential to influence stakeholder motivation and action towards compliance with water quality regulatory instruments (Chapter 3 of this study).

Compliance is necessary to balance resource use and protection, and measures such as awareness, education, and penalties are ingredients for balancing resource use and protection. A study by Rodriguez et al. (2014) indicated that stakeholders perceived awareness and educational programmes as practical tools to encourage water conservation strategies in the Lincoln Lakes watershed, confirming the usefulness of education and awareness for promoting compliance with water quality regulatory instruments.Okumah et al. (2018) also indicated that awareness by farmers influenced their compliance towater quality instruments.

Chapter 4 of this study showed how the WQSAM DSS provides a technical solution to addressing the contestations of the water quality regulatory instruments in the Vaal Barrage catchment. The study demonstrated the WQSAM DSS in modelling water quality scenarios linked to water quality standards in WULs and RQOs in the Vaal Barrage catchment. The applied WQSAM DSS enabled stakeholder participation and engagement through scenario modelling. The study used WQSAM DSS that was helpful in demonstrating that the Vaal Barrage catchment cannot accept additional WULs for the selected water quality variables. As previously mentioned, nutrient enrichment for example is one of the key water quality challenges (Sertlo, 2012), and the results indicated the severity of the nutrient enrichment in the Vaal Barrage. The WQSAM was useful as a platform to interrogate the key water quality challenges.

The results in the current study indicated that collaborative efforts from stakeholders within the Vaal Barrage catchment reduced sulphate levels close to the RQOs. However, the attempt for the sulphate levels to fall within the RQO was not attainable, further proving perceptions that RQOs may be unrealistic and difficult to achieve are true. These results imply that collective action can reduce pollution in the Vaal Barrage catchment. A study by Hornbeek etal. (2013) highlighted the positive role of collaborative action of stakeholders within a catchment in Ohio and West Virginia in reducing total maximum daily loads of multiple pollutants. The total maximum daily loads approach focused on reducing individual pollutantsin the catchment (Hoornbeek & Hansen, 2013). Hornbeek and Hansen's study advocated collaborative action as it played a role in successfully implementing water quality restoration (Hoornbeek & Hansen, 2013). A sustainable collaboration will require proactive management from multiple stakeholders with shared values on freshwater resources (Mohamad et al., 2015).

5.2 Conclusion

This study helped to achieve the aim, namely, demonstrating how stakeholder perspectives and technical solutions can provide a holistic approach to water quality management in the Vaal Barrage catchment. The study highlighted the scientific credibility of the water quality standards as motivations for contesting the water quality instruments in the Vaal Barrage catchment and emphasised the need for water quality methods that are transparent and scientifically credible, such as the WQSAM DSS, in contributing to effective water quality management. For example, the results of the WQSAM DSS in Chapter 4 helped achieve the second objective of this study, demonstrating the linkage between RQO and WUL. The WQSAM DSS illustrated how water quality conditions in WUL give effect to RQOs. Overall, the WQSAM DSS contributed to understanding the relationship between RQO and WULs, ultimately achieving the balance between water resource protection and use. The WQSAM DSS was also helpful in demonstrating the positive outcome of collaborative efforts in the Vaal Barrage catchment, indicating the contribution of joint efforts in achieving successful water quality management.

5.2.1 Recommendations for future study and water quality management

Further work on the model is needed to ensure water quality data are correct, and advanced water quality variables, and other effluent discharged by emitters, are added.

• Metal pollution is a critical water quality challenge in the lower section of the Upper Vaal, and therefore key to the overall study.

• The need to revise and revisit the gazetted RQOs.

• To improve scientific credibility of the water standards in the RQO is implementing the participatory process.

• Stakeholders could implement the developed WQSAM DSS and apply it to the different catchments within the lower section of the Upper Vaal such as the Klip River, Rietspruit, Suikerbosrand, and the Blesbokspruit. This scenario may provide more insight into the water quality challenges faced within the upstream catchments.

• It is suggested that the regulator, particularly the DWS, should embark on active education and awareness-raising of all water resource users to increase compliance within the catchment.

• Lastly, water quality managers should explore different scenarios in the model; for example, comparing the impact of diffuse and point sources within the Vaal Barrage could be useful for water quality management.

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Appendices

Appendix A: Semi-Structured Questionnaire

Questions

1) In your opinion, how important are water resources of the lower section of the Upper Vaal River catchment, including the Vaal Barrage, to the South African economy?

   a) Very important
   b) Important
   c) Not important
   d) Not sure

2) With respect to your response to Question 1 above, use the space below to provide further explanation.

3) On a scale of 1–5, where 1 indicates most serious and 5 least serious, rank the following in terms of the seriousness of threat they pose to the water resources of the lower section of the Upper Vaal River, including the Vaal Barrage

Option	**Scale 1- 5**
a) Bulk water abstractions	
b) Large-scale irrigation schemes	
c) Mining	
d) Growing human population	
e) Industrial water use	
f) Dams	
g) Urbanisation	

h) Others, please specify:

4) Deteriorating quality of water resources in the lower section of the Upper Vaal has been identified as a threat to the sustainability of the system; in your view, how serious is the situation?
   a) Very serious
   b) Serious
   c) Mild
   d) Not serious

5) Use the space provided to kindly elaborate on your response to Question 4 above.

6) On a scale of 1–5, where 1 indicates the most serious and 5 the least serious, rank the following in terms of the seriousness of threat they pose to the quality of the water resources of the lower section of the Upper Vaal River.

Option	**Scale 1- 5**
a) Discharges of treated and inadequately treated effluents from municipal wastewater treatment works	
b) Effluent discharges from industrial facilities	
c) Runoff and discharges from mining operations	
d) Runoff from agricultural farmlands	
e) Runoff from informal settlements	
f) Upstream waste loads from activities in the upper section of the catchment	
g) Recreational, spiritual and cultural activities	

h) Others, please specify:

7) In South Africa, resource water quality objectives (RWQOs) are numeric and narrative descriptors of water quality conditions that need to be met in order to achieve the desired management goal for a water resource. RWQOs have been gazetted for water resources of the Upper Vaal. What is the likelihood that these RWQOs would be met given the current management trajectory?
   a) Highly likely
   b) Likely
   c) Unlikely
   d) Highly unlikely
   e) I'm not aware of the RWQOs
   f) Not sure

8) Using the space provided, kindly elaborate on your response to Question 7 above.

9) In your view, how realistic are the RWQOs gazetted for water resources of the Upper Vaal catchment?
   a) Very realistic
   b) Realistic
   c) Unrealistic
   d) Very unrealistic
   e) I'm not aware of the RWQOs
   f) Not sure

10) Using the space provided, kindly elaborate on your response to Question 9 above.

11) Which of the following is likely to be the most serious consequence of not meeting the RWQOs? Mark only one option.
   a) Degraded ecosystems and impaired ecosystem functionality
   b) Job losses due to increased operational costs related to treating raw water

c) Risk of human infections and diseases due to impaired water quality
d) Business profitability due to increased operational costs
e) Impact on water quality sensitive crops and general agricultural productivity
f) Aesthetic value of the water resources within the catchment
g) Others, please specify…

12) To meet the RWQOs, a number of required actions can be taken to control water use activities within the Upper Vaal. On a scale of 1–5, where 1 is the most important and 5 the least important, rank the following actions in order of their importance.

Scale 1- 5

Possible actions

a) Compulsory licencing as per the National Water Act

b) Voluntary self-regulation e.g., through ISO

c) Statutory enforcement and compliance monitoring of water use activities

d) Awareness-raising, education and continuous stakeholder engagement

e) Environmental impact assessment

f) Incentive/reward to water users for perceived good behaviour

g) Polluter pay

h) Others, please specify:

13) With regard to your response to Question 12, use the space provided to elaborate further

14) If for any reason, licence conditions are disputed, which of the following action(s) would you take to address the dispute? On a scale of 1–5, rank the action according to how you would prioritise them, where 1 indicates highest priority and 5 lowest priority.

Possible actions **Scale 1- 5**

a) Appeal

b) Negotiation between parties

c) Mediation and arbitration

d) Reconsideration and reformulation of licence conditions

e) Legal challenge in the court of law

f) Others, please specify:

15) In your experience, what are the primary reasons for disputing water quality licence conditions?

16) In your opinion/experience, which of the following are the top challenges associated with water quality licencing? You may circle more than one option.

   a) Scientific credibility and defensibility of methods for deriving water quality standards in licence conditions.
   b) Institutional efficiency and effectiveness in issuing water quality licences.
   c) Perceived fairness in enforcement, compliance monitoring and sanctions.
   d) Institutional capacity, including expert knowledge, to deal with water quality licencing.
   e) Clarity regarding the relationship between RWQOs and water quality licencing.
   f) Over-stretched regulators who are unable to cope with new applications.
   g) Backlog of licence applications.
   h) Lack of transparency in the way licence conditions are derived.
   i) Others, please specify ………………………………………

17) Kindly use the space provided to elaborate further on your response to Question 16.

18) Compulsory water quality licencing is one of the instruments for controlling water use in South Africa. On a scale of 1–5, where 1 is the most important and 5 least important, rank the following according to their importance with regard to the objectives of issuing water quality licences.

Possible actions **Scale 1–5**

a) To prevent job losses due to increased operational costs that may arise from impaired source water quality

b) To prevent/minimise risk of infections/diseases due to polluted water sources

c) To ensure equitable share of water resources between all users

d) To ensure that water resources are protected for future generation

e) To maintain ecosystem health/ecological integrity

f) To maintain the aesthetic appeal of water resources

g) To ensure business (including agriculture) sustainability by ensuring that source water quality is maintained

i) Others, please specify:

19) In your experience why is it important for quality standards in water use licence conditions to be perceived as realistic?
    a) To protect ecosystem and maintain ecological integrity
    b) To avoid high costs that may be associated with implementing unrealistic standards
    c) To protect other users of the water resource
    d) To ensure that all water users have their fair and equitable share of the water resource
    e) Others, please specify ……………………………….

20) Self-regulation, voluntary monitoring and compliance are necessary ingredients for achieving the RWQOs and water quality licence conditions. In your experience, which of the following is likely to stimulate the spirit of self-regulation, voluntary monitoring and compliance among water resource users in the catchment?
    a) Incentives for sustained good behaviour by water users e.g., investment in technology that minimises pollution
    b) Severe punishment for sustained bad behaviour by water users e.g., sustained pollution
    c) Trust and credibility of the regulatory environment

d) Scientific credibility and defensibility of methods for deriving water quality licence conditions
e) Perceived institutional efficiency and effectiveness in dealing with issues relating to water quality licencing
f) Perceived fairness in dealing with issues relating to water quality licencing
g) Others, please specify………………………….

21) If the necessary conditions where to be provided, how likely would water users engage in self-regulation, voluntary monitoring, and compliance?
a) Highly likely
b) Likely
c) Unlikely
d) Highly unlikely
e) Not sure

How strongly do you agree/disagree with the following statements?

22) Pollution of water resources of the lower section of the Upper Vaal has significantly impacted on drinking water security
a) Strongly agree
b) Agree
c) Disagree
d) Strongly disagree

23) Pollution of water resources of the lower section of the Upper Vaal has significantly impacted on raw water-dependent business profitability within the area
a) Strongly agree
b) Agree
c) Disagree
d) Strongly disagree

24) The process of deriving the RWQOs is very consultative and stakeholder involved
a) Agree
b) Disagree
c) Strongly agree
d) Strongly disagree

25) The process of deriving water quality standards in water use licence conditions is very consultative and stakeholder involved

a) Agree
b) Disagree
c) Strongly agree
d) Strongly disagree

In order for us to classify our research participants, we would like to ask you the followingquestions:

26) Which organisation do you work for? E.g., private, public, civil society, NGO, NPO etc.

27) What is your role in your organisation?

28) What is your area of specialisation? E.g., hydrologist, chemist, ecologist, zoologist, etc.

29) What is your highest qualification? E.g., Secondary school leaving certificate, BSc, MSc, Diploma, PhD etc.

30) What is your primary interest in the water sector?

Appendix B: Minutes from the Leeu-Taaiboschspruit Forum Meeting and List of Documents Analysed

MINUTES OF THE LEEU-TAAIBOSCHSPRUIT FORUM	
Venue:	Sasol Kliplapa
Date and Time:	13 February 2020 10:00 – 13:00
Chairperson:	Zain Mohamed
Scribe:	S Doyle

No.	Item	Responsible Person
1.	**Opening and Welcome**	
	• Zain Mohamed welcomed everyone to the meeting and asked everyone to introduce themselves again. • Special welcome to the Rhodes University study group • Thanks to Mogale Matseba for chairing the previous meeting	Zain Mohamed
2.	**Apologies**	
	• Apologies to be noted on the attendance register	All
3.	**Venues**	
	• The Sasol Kliplapa can be used again for the LTF meetings in 2020.	
4.	**Confirmation of the Previous Minutes (February 2019)**	
	• Sandra Doyle volunteered to take the minutes of the meeting again. • Corrections: Two surname corrections were made (de Fontaine and Nqelensa) • Point 9.5 was corrected – it should read two departments falling under oneMinister.	Sandra Doyle

5.	**Matters Arising from Previous meeting/Action Register**	
	All action items to be consolidated onto the Action register* Please refer to the Action Register for the detailed discussions	
6.	**Additions to the Agenda**	
	A proposal for a standardised water forum agenda was sent out prior to the meeting and accepted as the new standard. ***7.1 Rhodes University Study Presentation*** ***7.2 Groundwater Monitoring Results Template Upper Vaal Catchment SACNAS Accreditation***	
7.	**Items for Presentation**	

7.1 **7.2**	***Rhodes University Study Presentation*** Presentation to be sent in full to the Forum via the Google groups Functionality. Asanda is requesting the role players present to please complete the questionnaire. The electronic link to complete the questionnaire is: https://docs.google.com/forms/d/e/1FAIpQLScI7GhMZN04EjLqNQpbPrc1MGjbO7doe_S-2pCMSybO8I_gCA/viewform?usp=sf_link ***Groundwater Monitoring Results Template Upper Vaal Catchment*** Basic Excel template developed to facilitate soft copy information sharing and not just hard copies, including variables per borehole, WUL limits and comments on each borehole (e.g., vandalism limits access). Latitude and Longitude of boreholes included. Graphs are then compiled to track groundwater quality over time. Longer term plan is to report back to the Water Forums. All information is welcome to be submitted, and not just WUL based groundwater monitoring. Request was made to submit formal written request for information to WUL holders through the official DWS channels, for this information, as currently the WUL requirement is for the submission of hard copies. Interaction with the Department is ideally two-way and should improve the outcome and the method of presenting and capturing the data. *Contact:* Gebhardtz@dws.gov.za	Asanda Chili asahchili@gmail.com Zoë Norton
8.	**Committee Updates**	
8.1.	**Technical Committee Update** No further updates.	
8.2	***Finance/Admin*** Current bank balance at R6500. Zain will send out a communication for funding for the Forum for the year. Two lunches have to be paid from the funds, and on average it costs about R2500 per meeting lunch. A request was made that the LTF needs to submit a letter for sponsorship to the various industries to allow for budgeting of this sponsorships.	Zain Mohamed
9.	**Water Quality Monitoring**	
9.1	**Department of Water and Sanitation** Please update the description of *LTS 2: SCI power station II stormwater discharge to Driefontein Dam* to *LTS 2: Stormwater sample point upstream to Driefontein Dam.* E.coli levels are high especially at LTS13. Water Quality report was sent out electronically	Nosibusiso Mfuyna

9.2	**Rand Water** • Site LS1 showed Unacceptable levels of E.coli for the last quarter exceeding 2,500,000 counts indicating discharge of wastewater into the stream. • Site T1 situated in the upper reaches of the catchment showed Unacceptable levels of Suspended Solids and COD. This would indicate that organic discharge into the stream has caused a deterioration in oxygen availability. • Site TW2 should a slight improvement of Chloride and a deterioration of Phosphate for the past quarter. This site drains the south-eastern most part of Sasolburg and surrounding townships. • Site T3 showed significant deterioration in water quality for the past quarter. Analyses from Rand Water indicates that on both 1 Oct and 29 Oct 2019 there high levels recorded for Ammonia, COD, Conductivity, Fluoride, Nitrate and Phosphate. Driefontein Dam continues to be a source of poor water quality.	Marc de Fontaine

9.3	**Fezile Dabi District Municipality** No representative present	
9.4	**Metsimaholo Local Municipality** No representative present	
9.5	**New Vaal Colliery** Request to be removed from the list as there are no applicable water quality reporting requirements from the WUL.	Kim McCann
9.6	**Sasol Industry** Reporting is done with reference to the WUL, and quarterly reporting is now aligned with the LTF quarters. No issues in pH, COD; EC was slightly more elevated, although still within compliance limits. This was related to poor quality coal received and used, but this is not apparent upfront and could only be managed after the fact. This is being addressed at the moment. Ammonia is tapering down, interventions have been successful. Midlands Site – slight excursion of pH above licence requirement due to shutdown activity, has been communicated to regulator. EC & COD are within compliance and stable. TSS is variable, but capital outlay to address previous issues have been successful.	Anne Naidoo
9.7	**Omnia** No official report presented.	
9.8	**Sasol Sigma Mooikraal** There is a discharge into the Kromellenboogspruit, downstream from the Barrage. Since July there were no exceedances on the on the WUL.	Lisa Grobler
9.9	**Safripol** Voluntary reporting on Stormwater discharge – initial values show higher chlorides but this was prior to the rainy season. All parameters measured in stormwater were stable during the quarter. Reporting should be improved to	Sandra Doyle

	only report Stormwater Quality when there has been rainfall during the previous 24 hours.	
10.	**Government Department Feedback**	
10.1	**Department of Water and Sanitation**	
10.1.1	**CMA Process** With the changes in the Department, with a new Minister, the advisory committee will need some updating.	Mogale Matseba – DWS
10.1.2	**Compliance Monitoring and Enforcement (CME)** No issues	DWS
10.1.3	**Water Use Licence Application (WULA) Status** Report was sent to the Forum. Two applications are still in progress – Sasol Mooikraal (Mining) and Dreamland Piggery. A meeting will be schedule with the civils side to ensure that the conveyor belt relocation is progressed (Sasol Mooikraal application).	DWS

10.1.4	**Water Services Regulation** Nceba Ketelo was requested to attend the meeting, but he did not attend today. Will be invited again to present or send a report.	Luvuyo Nqelensa
11.	**Local Authorities feedback**	
11.1	**Fezile Dabi District Municipality** No local authority attendants.	
11.2	**Metsimaholo Local Municipality** No local authority attendants.	
12.	**Organisations Report Back**	
12.1	**Clariant** No representation	None
12.2	**Eskom** Nothing to report	Carl Woodehouse
12.3	**Natref** No representation	Aletia Chapman/ Patrick Cebekhulu
12.4	**New Vaal Colliery** The Life extension EIA is being planned, and this requires a Water Use Licence. The EIA process will kick off within the next few months.	Kim McCann
12.5	**Omnia** Nothing to report	Andrisha Govender
12.6	**Safripol** Nothing to report	Sandra Doyle
12.7	**Sasol** Nothing to report	Anne Naidoo

12.8	**Sasol Sigma** Sasol Mining had applied for a mine closure permit, which called for assessments of the risk of subsidence on water (surface and underground). Subsidence beneath the Leeuspruit was identified as posing a high risk to surface water. To mitigate the possible impact, mine-filling using ash was selected. The required authorisations were obtained (including WUL) and work began late 2019 with drilling of investigation boreholes. High water pressure in the shallow aquifer and subsequent release of water into the Leeuspruit prompted the ash-backfilling to be deferred temporarily to allow time for an in-depth investigation into the cause of the high pressure. The incident was reported to DWS.	Kobus Coetser
12.9	**Senmin** Nothing to report	Sylvanna Wilson
12.10	**Transnet** No representation	
13.	**NGO's/Other Report Back**	
13.1	**SAVE**	No

13.2	No attendance **VEJA** No attendance	representation
14	**Pollution Incidents Noted/Reported**	
	No incidents reported or noted	
15	**Discussion of Additions to the Agenda**	
15.1	**SACNASP accreditation for forum meetings** Rand Water has been approved as an organisation who can upload meeting minutes for the Water Forums to obtain credits. Approval was obtained that meeting minutes can be uploaded dating back for 2016 which can be used to claim points, up to the end of 2020. Going forward, points need to be claimed within 6 months after upload. Marc de Fontaine will communicate to the LTF, electronically, on the details and process.	Marc de Fontaine
16	**Next Meeting** *Next meeting to be held on 14 May 2020, at the Sasol Kliplapa.*	
16.	**Closure** *Meeting was closed at 13:00*	
	END OF MINUTES	

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