CASE STUDY FOR LINKING WATER QUALITY LICENSE CONDITIONS WITH RESOURCE QUALITY OBJECTIVES FOR THE LEEU-TAAIBOSCHSPRUIT INDUSTRIAL COMPLEX SITUATED WITHIN THE VAAL BARRAGE CATCHMENT: VOLUME 1

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Report

to the Water Research Commission

by

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EXECUTIVE SUMMARY

RATIONALE AND BACKGROUND

In South Africa, the resource-directed measures (RDM) and the source-directed controls (SDC) are the two complementary strategies designed to ensure that water resources are used and protected. The RDM are directed at water resources to ensure their protection, and include the Water Resource Classification System (WRCS), the classification of every significant water resource, the determination of the reserve and the setting of resource quality objectives (RQOs). On the other hand, the SDC are measures imposed to restrict and control the use of water resources, not only in terms of ensuring water resource protection, but also in terms of ensuring that water resources are equitably allocated and are used efficiently. Water use licencing (WUL) is an example of an SDC instrument.

To be able to use the two complementary strategies effectively, it is important that the link between them is clarified. Stakeholders within the Vaal Barrage catchment have indicated that there is a poor understanding of how the link between the water quality component of the RQOs and discharge standards in WUL is made, which can be defended scientifically. Even when the links between the RQOs and discharge standards in WUL are clear, the way in which standards in WUL are derived, considering the catchment baseline conditions, which are imperative for socio-economic development, as well as scientific credibility, need to be clarified. It has also been argued that, in subcatchments and/or river reaches where there are no RQOs, or where the RQOs are contested, the way in which site-specific conditions inform the derivation of water quality discharge standards in WUL, and the risk posed to the resource by the discharge standards in WUL needed, have to be scientifically defensible. It is also not clear to all resource users how upstream waste loads affect discharge standards for downstream users, as well as the downstream RQOs. This is particularly crucial for heavily utilised catchments such as the Vaal Barrage catchment and associated rivers such as the Klip, Suikerbosrand, Taaibosspruit and Blesbokspruit rivers, where several upstream pollution sources impact on downstream resource users and RQOs. While flow is a critical factor in instream resource water quality, it was not clear how existing methods link flow (quantity) and quality in the process of deriving discharge standards in WUL. These obscurities in the relationship between discharge standards in WUL conditions and the water quality component of RQOs necessitated this project, using the Vaal Barrage catchment, including the Klip, Suikerbosrand, Taaibosspruit and Leeuspruit rivers as case studies within the Upper Vaal river system.

This study was thus aimed at developing a decision support system (DSS) for clearly linking water quality standards in WUL conditions to gazetted RQOs, and/or site-specific conditions in the Vaal Barrage catchment, taking into account a range of complex interacting factors, such as all components of flow (flow regime, timing, pattern, frequency and magnitude), land use types, upstream waste loads, and diffuse and point effluent emitters. To realise the very essence of the project, the DSS developed in this way must be scientifically credible, defensible and transparent – based on scientific assumptions, observed and modelled data, confidence and limitations; and the process of its development must involve multiple stakeholders, including the regulator (the Department of Water and Sanitation) and resource users within the Vaal Barrage catchment.

PROJECT AIMS

The specific aims of the project are as follows:

i. Undertake a comprehensive and thorough assessment of existing practices, data, approaches, methods and tools, including a study of relevant catchment literature, regarding SDCs and RQOs in the proposed study areas. The assessment should include an analysis of all current tools, practices, methods and approaches of setting water quality condition standards in WUL and their scientific defensibility.

ii. Develop an appropriate, robust and scientifically defensible, but flexible DSS for transparently setting water quality standards in WUL conditions (point and diffuse), taking account of receiving RQOs and site-specific conditions.
iii. Demonstrate and test the implementation and applicability of the developed DSS under multiple water quality conditions, temporal/spatial, site-specific and RQO scenarios (i.e. scenario analysis) with catchment stakeholders, including the relevant units within the Department of Water and Sanitation (DWS), catchment management forums and water users As part of the scenario analysis, demonstrate how the developed DSS could be implemented so that a water user is able to determine the likely impacts on RQOs and/or site-specific conditions.
iv. Communicate widely with catchment stakeholders and build the capacity of the relevant unit or sections within the DWS and water users through training on the use and application of the developed DSS. This is to ensure that the entire process of developing the DSS is consultative and widely communicated, and that the the project outcome is acceptable to all stakeholders.

PROJECT APPROACH AND METHODOLOGY

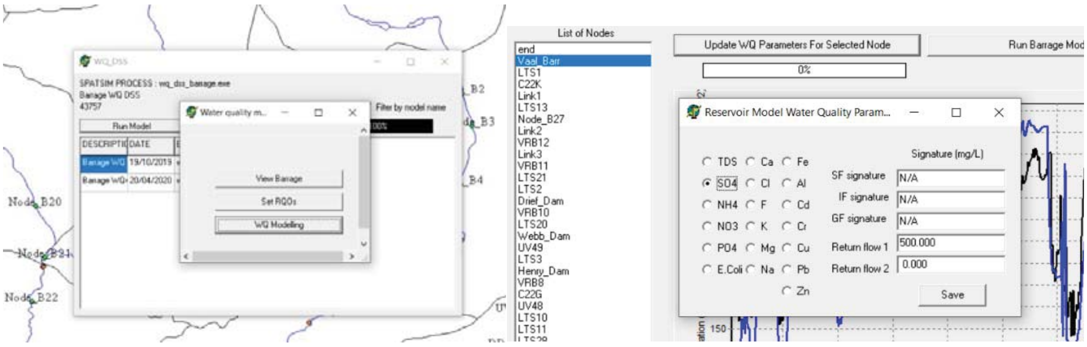
The project combines a desktop study, secondary data, and simulation of water quantity and quality within the study area to develop a DSS based on the Water Quality Simulation Assessment Model (WQSAM), as well as online training workshops to fulfil its objectives. The desktop study covers a literature review of existing practices related to WUL and RQOs in the catchment and identifies important gaps. A DSS that links water quality standards in WUL to the water quality components of the RQOs within the catchment was developed based on the WQSAM. The entire Upper Vaal water quality assessment was first modelled at a coarse spatial resolution, and this was used to determine boundary conditions for the more detailed Vaal Barrage water quality DSS. Several online training workshops were held for staff of DWS and stakeholders within the catchment, drawn from various entities such as Sasol, Eskom, Golder Associates and the Inkomati-Usuthu Catchment Management Agency (IUCMA). Workshops were aimed at training stakeholders and soliciting feedback, ensuring that the developed DSS meets stakeholders' expectations. As a result, the development of the DSS went through several iterative processes, considering inputs from the stakeholders in the catchment.

PROJECT RESULTS AND DISCUSSION

The desktop study of current practices regarding RDM and SDC revealed that DWS's current method of determining end-of-pipe discharge standards can be considered quite robust as it considers critical parameters, such as the flow mixing ratio (dilution), management class, attainable treatment in setting end-of-pipe discharge standards and receiving resource instream concentrations. However, several shortcomings in the approach are recognised:

i. There is no consideration of the differences between conservative and non-conservative variables. While the mixing ratio is of relevance to conservative water quality variables, which are predominantly affected by dilution, non-conservative variables are affected by a myriad of additional processes, such as chemical speciation and algal uptake.
ii. There is no consideration of upstream waste loads. This disadvantage is of particular relevance for heavily impacted catchments such as the Vaal Barrage and associated rivers.
iii. The potential contribution of diffuse sources to the waste loads is not considered. This is a major oversight in a catchment such as the Vaal River where diffuse sources contribute significantly to the system's waste loads.
iv. The receiving stream concentration for toxic substances is set at zero (0) for toxic substances and reference conditions for system variables. These criteria may be considered unrealistic in a heavily used catchment, where the gazetted recommended ecological category is set below Category B.

The DSS is based on a calibrated version of WQSAM and is able to simulate important water quality variables of management concern, such as the nutrients NO_3-N + NO_2-N, NH_4-N and PO_4-P; the salt SO_4, total dissolved solids (TDS), calcium, chloride, fluoride, potassium, magnesium and sodium, and metals such as iron, aluminium, cadmium, chromium, copper, lead and zinc. Observed data for metals was too sparse to allow for model calibration. The launch screen, as shown in Figure A, has a panel that shows the systems diagram "View barrage" of the model so that users can reference the position of individual nodes in the catchment and their position relative to other emitters. The "WQ modelling" button opens the water quality modelling screen. The nodes in the modelled catchment are listed on the left-hand side of the panel. From this panel, users can view the water quality of a node in the modelled catchment, either as a time series or as a frequency distribution ("Plot daily concentrations for selected node"). Water quality signatures for point and non-point sources of a node can also be set from this panel ("Update WQ parameters for selected node"). Finally, the Vaal Barrage DSS can be run from this panel ("Run barrage model").



SPATSIM PROCESS : wq_dss_barrage.exe
Barrage WQ DSS
43757

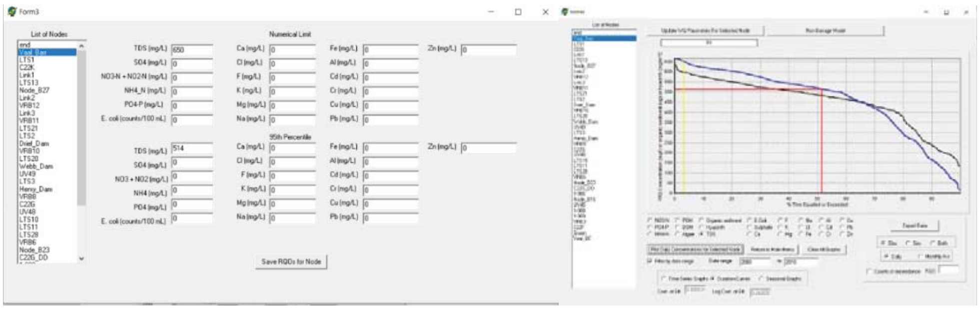
Barrage WQ 19/10/2019
Barrage WQ- 20/04/2020

0%

Signature (mg/L)
SF signature N/A
IF signature N/A
GF signature N/A
Return flow 1 500.000
Return flow 2 0.000

Figure A: The DSS's launch screen (left) and the screen for setting the water quality signature for both point and non-point sources (right)

The "Set RQOs" button on the launch screen (Figure A, left) opens a panel with which it is possible to set RQOs for each node (Figure B, left)



Numerical Limit
TDS (mg/L) 650
SO4 (mg/L) 0
NO3-N + NO2-N (mg/L) 0
NH4_N (mg/L) 0
PO4-P (mg/L) 0
E. coli (counts/100 mL) 0
Ca (mg/L) 0
Cl (mg/L) 0
F (mg/L) 0
K (mg/L) 0
Mg (mg/L) 0
Na (mg/L) 0
Fe (mg/L) 0
Al (mg/L) 0
Cd (mg/L) 0
Cr (mg/L) 0
Cu (mg/L) 0
Pb (mg/L) 0
Zn (mg/L) 0

95th Percentile
TDS (mg/L) 514
SO4 (mg/L) 0
NO3 + NO2 (mg/L) 0
NH4 (mg/L) 0
PO4 (mg/L) 0
E. coli (counts/100 mL) 0
Ca (mg/L) 0
Cl (mg/L) 0
F (mg/L) 0
K (mg/L) 0
Mg (mg/L) 0
Na (mg/L) 0
Fe (mg/L) 0
Al (mg/L) 0
Cd (mg/L) 0
Cr (mg/L) 0
Cu (mg/L) 0
Pb (mg/L) 0
Zn (mg/L) 0

Figure B: Screen within the DSS for setting resource quality objectives for particular nodes (left) and the frequency distribution curve relating the model return flow signature to the RQOs (right)

The user can then set either numerical limits and a 95% RQO for each node and for each water quality variable simulated. It was decided to allow users to set RQOs themselves to maximise the flexibility of the model. As shown in Figure B (left), as an example (these are not the official RQOs), the numerical limit and the 95% TDS RQOs (mg ℓ^{-1}) have been set to 650 mg ℓ^{-1} and 514 mg ℓ^{-1}, respectively. The interpretation of water quality simulations in relation to the RQOs is facilitated through the water quality modelling screen. Using the same RQO example, Figure B (right) shows the frequency distribution of TDS for the Vaal Barrage in relation to the numerical limit and the 95% RQO. From the frequency distribution of simulated TDS for the Vaal Barrage shown in Figure B (right panel), the yellow and red lines show where the numerical limit and the 95% RQOs cross the frequency distribution. The percentage of time that the simulated water quality exceeds either of the RQOs can be determined by the place where the vertical line crosses the x-axis of the frequency distribution graph. In this hypothetical example, the vertical line of the numerical limit RQO (yellow line) crosses the x-axis of the graph at around 3%. The vertical line of the 95% RQO (red line) crosses the x-axis of the graph at around 52%, indicating that simulated water quality exceeds the RQO around 52% of the time. For the TDS of the Vaal Barrage to fall within the 95% RQO, the red line should cross the x-axis at 5%. These results therefore show that the simulated TDS data for the Vaal Barrage exceeds the hypothetical TDS by 95% RQO.

Possible applications of the DSS include investigating the effects of upstream waste loads on downstream users and RQOs, scenario modelling of the effects of water quality standards in WUL on the RQOs, and simulating whether the receiving river system has the capacity for additional emitters, given the waste loads from the current emitters. The DSS was developed to assist catchment managers and users to create a better understanding of the situation of the catchment and management options available, i.e. it is a tool to support integrated water resource management (IWRM) and, by itself, is not the final say on an RQO or license condition. It thus needs to be used together with other relevant tools within relevant processes of IWRM.

Three training workshops were conducted, which attracted 69 stakeholders from various organisations, including within the catchments. Feedback from stakeholders informed the development of the DSS. For example, the inclusion of additional salts and metals, as well as the extension of the DSS to include the Klip and Suikerbosrand rivers, were informed by stakeholder input.

The DSS can be downloaded from https://www.ru.ac.za/iwr/research/software/spatsim/. Users would need to follow the instructions and then use the manual (Volume 2 of the project report) on how to run the DSS for various applications.

RECOMMENDATION FOR IMPLEMENTATION AND FUTURE STUDY

The DSS, as it stands, can be implemented and operationalised for daily use for the Vaal Barrage catchment and associated rivers, including the Klip, Leeuspruit, Taaibosspruit and Suikerbosrand rivers. Once the DSS is fully operational in the Vaal Barrage catchment, it is recommended that it be extended to the entire Upper Vaal catchment. One of the greatest challenges faced during the development of the DSS was access to data, particularly for metals and discharged effluent quality by emitters. Given that the catchment is highly industrialised, routine monitoring of metal concentrations in the rivers is recommended, together with a system that made effluent quality data publicly available from emitters. Such a system would facilitate access to effluent quality data that can be used as observed data for model calibration.

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Mr Rendani Ndou	Department of Water and Sanitation
Dr Jennifer Molwantwa	Inkomati-Usuthu Catchment Management Agency

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LIST OF ACRONYMS

AMD	Acid mine drainage
ACWUA	Assessment of Consideration for Water Use Applications
AEV	Acute effect value
BHNR	Basic human need reserve
CEV	Chronic effect value
COD	Chemical oxygen demand
DEA	Department of Environmental Affairs
DO	Dissolved oxygen
DSS	Decision support system
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electrical conductivity
EGS	Existing general standards
EIA	Environmental impact assessment
EIS	Ecological importance and sensitivity
ER	Ecological reserve
ERWAT	Ekurhuleni Water Care Company
ESS	Existing special standards
EWR	Ecological water requirements
GA	General Authorisation
GCM	Global Circulation Model
GIS	Geographic Information System
HNR	Human need reserve
ISO	International Organisation for Standardisation
IUA	Integrated unit of analysis
IUCMA	Inkomati-Usuthu Water Management Agency
IWRM	Integrated water resource management
MARDV	Maximum allowable resource-directed value
MC	Management Class
MLR	Multiple linear regression
MR	Mixing ratio
NATREF	National Petroleum Refiners of South Africa
NEMA	National Environmental Management Act
NWA	National Water Act
PES	Present ecological state

RDM	Resource-directed measures
RDP	Reconstruction and Development Programme
REC	Recommended ecological category
RQO	Resource quality objectives
RRDV	Recommended resource-directed value
SAWQG	South Africa Water Quality Guidelines
SDC	Source-directed controls
SDV	Source-directed value
SPATSIM	Spatial Time Series and Information Modelling
TDS	Total dissolved solids
TEC	Target ecological category
TIN	Total inorganic nitrogen
TPC	Threshold of probable concern
TUT	Tshwane University of Technology
TWQR	Target water quality range
UV	Ultraviolet
WQSAM	Water Quality Simulation Assessment Model
WRC	Water Research Commission
WRCS	Water Resource Classification System
WReMP	Water Resources Modelling Platform
WRPM	Water Resources Planning Model
WUL	Water use licensing
WWTWs	Wastewater treatment works
WRYM	Water Resources Yield Model

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CHAPTER 1: BACKGROUND TO STUDY

1.1 MOTIVATION

Water resources in South Africa are scarce, and with a growing human population and expanding socio-economic activities, particularly in the Vaal Barrage region within the lower section of the Upper Vaal river catchment, competition among users for the scarce water resources is likely to be on the rise in the foreseeable future (DWA, 2013). South Africa is, however, an acclaimed international leader with its progressive and forward-looking water legislation, the National Water Act (NWA), Act No. 36 of 1998 (RSA, 1998). Equity, sustainability and efficiency are the foundational principles of the Act, and are invoked when managing, utilising, developing, protecting and conserving water resources. The NWA, which has been hailed globally, differed radically from the 1956 Water Act by delinking land ownership from right to water. The Act concentrates ownership of all water resources in the hands of the national government. At the same time, the NWA provides for two legally binding rights to water: that for basic human needs, i.e. the human need reserve (HNR), and that for sustaining the ecological functioning of the aquatic ecosystems, i.e. the ecological reserve (ER). Once the two reserves have been determined, all remaining water resources are administratively allocated for other uses, taking account of the three foundational principles of equity, sustainability and efficiency. The implication is that, by law, water resources are to be used and protected in ways that ensure their sustainability.

Two complementary strategies have been developed to give effect to water resource use and protection. These are the resource-directed measures and the source-directed controls (RSA, 1998; DWA, 2013). The RDM are measures directed at water resources to ensure their protection. They include the national WRCS, the classification of every significant water resource, the determination of the reserve and the setting of RQOs. On the other hand, the SDC are instruments imposed to restrict and control the use of water resources, not only in terms of ensuring water resource protection, but also ensuring that water resources are equitably allocated and efficiently used (DWAF, 2003). General authorisations, special permits and water use licenses are examples of SDC (DWAF, 2006a). Used together, the two strategies (i.e. RDM and SDC) enable the balancing of water resource use and protection. However, from a water quality perspective, the link between RDM, such as the water quality component of the RQOs, and the discharge standards in WUL are often not clear to all critical stakeholders, e.g. water users and regulators. Even when the links between the RQOs and the discharge standards in WUL are clear, the way in which such standards are derived, taking into account catchment baseline conditions imperative for socio-economic development, as well as scientific credibility, can lead to contestation between stakeholders, e.g. between water resource users and regulators. It is thus critical that water quality standards in WUL conditions are credible, realistic and scientifically defensible. This criticality arises because such standards are legally binding and enforceable, and are used to give effect to water resource protection. Without a transparent, scientifically credible and defensible process for deriving water quality standards in WUL conditions, contestation may arise between stakeholders, particularly between resource users and regulators. Resource users, for example, may genuinely feel that standards are unrealistic and that complying with such standards may have serious socio-economic consequences. The regulator, on the other hand, may follow an alternative argument pathway.

The RQOs provide numerical and/or descriptive statements about the physico-chemical attributes that characterised a resource at a desired level of protection, taking into account seasonal complexity and dynamics (DWS, 2014). However, discharge standards, particularly water quality standards, are often set as single numerical limits per constituent without a clear indication of whether such limits have considered the seasonal variability inherent in instream conditions captured in RQOs (DWS, 2014). Furthermore, in subcatchments and/or river reaches where there are no RQOs, the way in which site-specific conditions inform the derivation of water quality discharge standards in WUL has become another area of interest in need of clarification.

It is also not clear to all resource users how upstream waste loads affect discharge standards for downstream users – this is particularly crucial for heavily utilised catchments such as the Vaal Barrage and associated rivers, e.g. the Klip, Suikerbosrand, Taaibosspruit and Blesbokspruit rivers, where several upstream pollution sources impact on downstream resource users. While flow is a critical factor in instream resource water quality, it is not clear how existing methods link flow (quantity) and quality in the process of deriving discharge standards in WUL. In situations where a resource user discharges effluent, of which the critical water quality variables of concern have no RQOs described for the receiving water resource, it has been argued that the way limits are set for such variables in WUL conditions remains obscured. These obscurities in ways in which water quality discharge standards in WUL conditions are derived, and the relationship between RQO and standards in WUL conditions, have necessitated the imperative to develop a decision support system for linking discharge standards in WUL to RQOs and/or other site-specific water quality guidelines in the Vaal Barrage catchment.

This study, which flows from an earlier Water Research Commission (WRC)-funded study (Odume et al., 2018), therefore presents a unique opportunity for clearly linking water quality standards in WUL conditions to gazetted RQOs and/or other site-specific guidelines, taking into account a range of complex interacting factors, such as all components of flow (flow regime, timing, pattern, frequency, etc.), land use types, upstream waste loads, and point and diffuse pollution sources. To realise the very essence of the project, the DSS so developed or refined must be scientifically credible, defensible and transparent – based on scientific assumptions, observed and modelled data, confidence and limitations; and the process of its development must involve multiple stakeholders, including the regulator (the Department of Water and Sanitation) and resource users.

The Vaal Barrage area and associated rivers were selected as a case study for the development of the DSS as regulators and resource users had indicated a willingness to collaborate on the development of such a tool. The lower section of the Upper Vaal, particularly the Vaal Barrage area and the associated rivers, is of critical importance to the South African economy as it serves as the economic heartland of the country. However, these rivers are among the most polluted, with severe water quality consequences – the relatively good water quality upstream of the Vaal Dam decreases sharply in the study area and is not able to meet management targets (DWAF, 2009a). Some consequences of these water quality issues include fish kills, diarrhoeal and other diseases, and blooms of invasive aquatic taxa and microalgae (Tempelhoff, 2009; DWAF, 2009b).

Apart from the pollution effects on water quality, the area has highly regulated and modified flow regimes. In the study area, flow along the Vaal River is modified by the Vaal Dam and the Vaal Barrage in particular (Tempelhoff, 2009; DWAF, 2009a). Several interbasin transfer schemes, including the Lesotho Highlands Water Project and the Heyshope, Zaaihoek and Tugela transfer schemes, introduce water to the catchment. Water is also transferred out of the system to support the operations of Eskom and Sasol (Turton et al., 2006; DWAF, 2009a). The river and its impoundments in the study region are also the largest source of water for the densely populated Johannesburg and Vaal Triangle regions. Flow modification is known to have a serious impact on aquatic ecosystems and water quality (Bunn and Arthington, 2000). Sasol and Eskom are two major industrial players in the proposed study area. For example, the Sasolburg complex releases effluent below the Vaal Barrage and draws water from the Vaal River downstream of the Vaal Dam. Rand Water, a leading bulk water supplier draws water from the Vaal Dam and supplies Johannesburg and other municipalities. Return flows in the form of wastewater discharges are received in the system from municipal wastewater discharges. Considering the complexity of the water quantity and quality in the catchment, this project aims to develop a DSS for linking water quality standards in WUL to the water quality components of the RQOs in ways that are scientifically defensible and credible.

1.2 PROJECT AIMS

The specific aims of the project are as follows:

i) Undertake a comprehensive and thorough assessment of existing practices, data, approaches, methods and tools, including a study of relevant catchment literature regarding SDCs and RQOs in the proposed study areas. The assessment should include an analysis of all current tools, practices, methods and approaches of setting water quality condition standards in WUL and their scientific defensibility.
ii) Develop an appropriate, robust and scientifically defensible, but flexible DSS for transparently setting water quality standards in WUL conditions (point and diffuse), taking account of receiving resource quality objectives and site-specific conditions.
iii) Demonstrate and test the implementation and applicability of the developed DSS under multiple water quality conditions, temporal/spatial, site-specific and RQO scenarios (i.e. scenario analysis) with catchment stakeholders, including the relevant units within DWS, catchment management forums and water users As part of the scenario analysis, demonstrate how the developed DSS could be implemented so that a water user is able to determine the likely impacts on RQOs and/or site-specific conditions.
iv) Communicate widely with catchment stakeholders and build the capacity of the relevant unit or sections within DWS and water users through training on the use and application of the developed DSS. This is to ensure that the entire process of developing the DSS is consultative and widely communicated, and that the project outcome is acceptable to all stakeholders.

1.3 PROJECT APPROACH AND METHODOLOGY

The project combines a desktop study, use of secondary data, and simulation of water quantity and quality within the study area to develop a DSS based on the WQSAM (Hughes and Slaughter, 2015; Hughes and Slaughter, 2016; Slaughter et al., 2015), as well as online training workshops to fulfil its objectives. The desktop study covers a literature review of existing practices related to WUL and RQOs in the catchment, and identifies important gaps, thereby fulfilling the first objective of this study. A DSS that links water quality standards to the water quality components of the RQOs within the catchment was developed based on the WQSAM, and its application and implementation were demonstrated to the catchment stakeholders, thereby fulfilling the second objective of this study. Several online training workshops were held for both the regulator and water resource users within the catchment to fulfil the third project objective, while continuously engaging with and consulting stakeholders within the catchment during the development of the DSS. As a result, the development of the DSS went through several iterative processes considering inputs from the stakeholders in the catchment.

Project scope and limitations

Although the entire Upper Vaal system was modelled during the development of the DSS in order to account for upstream activities that may influence the water quality of the Vaal Barrage and the associated rivers, the core focus of this project was the Vaal Barrage catchment, including the Klip, Blesbokspruit, Taaiboschspruit, Leeuspruit and Suikerbosrand rivers. The DSS in its current form cannot be applied to the entire Upper Vaal without some modifications. Important water quality variables of management significance have been included in the DSS. These include the nutrients NO_3-N + NO_2-N, NH_4-N and PO_4-P, as well as the salt SO_4 , and TDS, calcium, chloride, fluoride, potassium, magnesium and sodium. In addition, the DSS included metals such as iron, aluminium, cadmium, chromium, copper, lead and zinc, but the calibration of these metals in the DSS has been based largely on insufficient data. Therefore, as more metal data becomes available, such data can be used for further model calibration.

Providing guidance on whether the RQOs in the study area were realistic, as well as how to go about collecting water quality data and submitting the same to the regulator, falls beyond the scope of the project. The DSS developed in the project can, however, be used to relate the water quality standards in WUL to existing RQOs or the generic water quality guidelines, and can also be used to determine whether the river systems within the study area have the capacity to accept additional emitters, whether diffuse or point source.

CHAPTER 2: STUDY AREA AND WATER QUALITY CHALLENGES

2.1 BIOPHYSICAL CONTEXT

The Vaal River forms the boundary between the Free State and Gauteng, Mpumalanga and North West. In the study region, it flows through a part of the country that has long supported a large population and substantial mining and industrial activity in Gauteng and the northern Free State. This has led to the river in the study region being referred to as “the hardest working river in South Africa”, because of increasing regulation and pollution issues (Tempelhoff, 2009).

The Vaal Barrage was completed in 1923, following a project to secure a supply of potable water for Johannesburg and the Witwatersrand region subsequent to the growth of gold mining and financial activity in the area (Tempelhoff, 2009). Within a few years of its construction, it became largely redundant as the upstream Vaal Dam was completed to act as an irrigation water source for farming to further secure water for development in the Witwatersrand-Vaal Triangle region and, in the short term, to offer employment during a worldwide depression (Tempelhoff, 2009).

Upon completion of the Vaal Dam, the Vaal Barrage became a secondary water storage facility, and water from this region supported growing coal and gold mining, power generation and steel production (Turton et al., 2006; Tempelhoff, 2009). Later, water from the area was used to support petrochemical production and other industrialisation. Growing industrial activity in the region led to an increased population and a consequent increased wastewater load. Treated and raw wastewater from the region entered the Vaal Barrage area via several tributaries. Total dissolved solids in the river increased from 180 $mg \cdot \ell^{-1}$ in 1960 to 650 $mg \cdot \ell^{-1}$ in 1985 (Clarke, 2002).

The construction of formalised housing with water and water-borne sanitation as part of the post-1994 Reconstruction and Development Programme (RDP) led to a considerable increase in the wastewater load from the area (Tempelhoff, 2009). These services were (and still are) managed at local government level, and some areas experienced challenges in the provision of these services. In 2005, a report noted that faecal pollution in the river was largely a function of the discharge of untreated and partially treated sewage into the Vaal and its tributaries (Kolbe, 2005). More recently, attention has been given to the discharge of untreated sewage to the Vaal River (Kings, 2018).

The area has highly regulated and modified flow regimes. In the study area, flow along the Vaal River is modified by the Vaal Dam and the Vaal Barrage, in particular (Tempelhoff, 2009, DWAF, 2009a). A number of interbasin transfer schemes, including the Lesotho Highlands Water Project and the Heyshope, Zaaihoek and Tugela transfer schemes, introduce water to the catchment, and water is also transferred out of the system to support the operation of Eskom and Sasol (Turton et al., 2006, DWAF, 2009a). The river and its impoundments in the study region are also the largest water source for the densely populated Johannesburg and Vaal Triangle regions. Flow modification is known to have a serious impact on aquatic ecosystems (Bunn and Arthington, 2000).

A consequence of such development, initially without regulation, is a legacy of water quality issues. Faecal coliform counts in the area remain high (Tempelhoff, 2009; 2017 data from Rand Water and DWS). Phosphate levels, which lead to eutrophication, are consistently high (Rand Water 2017 data). Salinity levels also remain high, and these are often accompanied by high levels of sulphate, indicating an origin in acid mine drainage from gold or coal mines (Rand Water 2017 data). In general, the good water quality upstream of the Vaal Dam decreases sharply in the study area and is not able to meet management targets (DWAF, 2009b). Some consequences of these water quality issues include fish kills, diarrhoeal and other diseases, and blooms of invasive aquatic taxa and microalgae (Tempelhoff, 2009; DWAF, 2009a).

A map of the Vaal Barrage region, including the Klip, Suikerbosrand, Leeuspruit and Taaibosspruit rivers, which are the focus of this study, is presented in Figure 2.1.

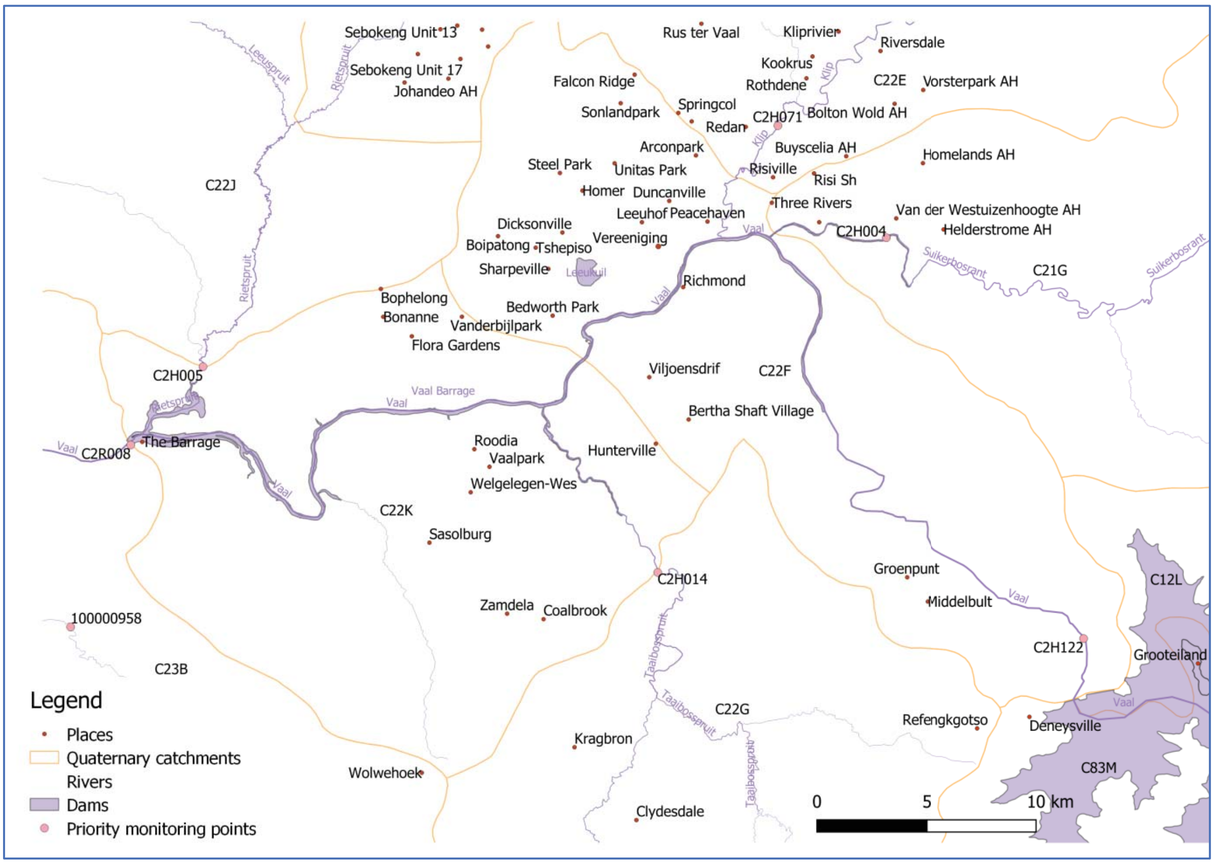


Figure 2.1: Vaal Barrage region showing place names, quaternary catchments, rivers, dams and DWS priority water quality monitoring points

2.2 SOCIO-ECONOMIC CONTEXT

The region recently supported a population of 10 million (Van Wyk, 2001; Tempelhoff, 2009). The management of the water resource in this area is complicated by the fact that the region is supported by several interbasin transfers that are necessitated by the development of a city in a semi-arid country away from a major water resource (Turton et al., 2006). As a result of these water transfers, management and planning must be undertaken in the context of the integrated Vaal river system, which includes portions of the Inkomati, Usuthu, Thukela and Senqu rivers (DWAF, 2009b).

The largest irrigation scheme in the country (the Vaalharts Irrigation Scheme) is a significant consumer of irrigation water and lies downstream of the study area. Irrigation farming in this scheme requires enough water for crops, which must also be of an adequate standard (see DWAF, 1996). The Upper Vaal region has significant irrigation water use, largely upstream of the study area (DWAF, 2009b). Water use in this sector was found to be increasing. A significant proportion of this is illegal and unregulated. Total irrigation water demand in the Upper Vaal is 304 million $m^3 \cdot yr^{-1}$. Industrial bulk water users in the region are dominated by Eskom, Sasol and ArcelorMittal (DWAF, 2009b).

Eskom operates 12 coal-fired power stations in the integrated Vaal river system, and there are plans to develop three more (DWAF, 2009b). Not all of these are active all the time, and activity depends on energy demand. Most of these power stations are outside the study area, as eight are in the Usuthu and Inkomati subsystems, but all are active within the greater integrated Vaal river system, within which the study area lies.

Sasol has two plants within the integrated Vaal river system (DWAF, 2009b). Secunda draws water from the Grootdraai Dam, far upstream of the study area, and the Sasolburg complex, which releases effluent below the Vaal Barrage, draws water from the Vaal River downstream of the Vaal Dam. Sasol's predicted water use from these sources for 2015 was 140 million $m^3 \cdot yr^{-1}$, although only 23% of this was for the Sasolburg complex.

Rand Water is responsible for the water supply to Johannesburg, the world's largest city not located on a sea, lake or major river (Turton et al., 2006). Water drawn from the system all goes to supply Johannesburg, and other municipalities are supplied by other water authorities (DWAF, 2009b). However, return flows from Johannesburg are divided by the watershed that roughly halves the city, and the Vaal River catchment only receives return flows from the south of the city. Some 27 sewage drainage areas from Johannesburg and municipalities north of the Vaal drain to the Vaal River catchment. Total water requirement predictions for Rand Water under a base level population prediction for 2015 were 1,521 million $m^3 \cdot yr^{-1}$. Of the municipalities supplied, most of the water was supplied to Johannesburg and Ekurhuleni. Predicted return flows from the southern regions to the Vaal for 2015 under base population growth was 398 million $m^3 \cdot yr^{-1}$.

Beyond Johannesburg, Sedibeng Water draws water from the Vaal River and the Allemankraal Dam (DWAF, 2009b). Water use in the region is predicted to grow from 56 million $m^3 \cdot yr^{-1}$ in 2006 to 64 million $m^3 \cdot yr^{-1}$ in 2030.

2.3 POLLUTION AND WATER QUALITY CHALLENGES

Water quality has long been an issue in the region. For example, the pollution of the Klip River led to livestock deaths in the 1890s following contamination with mine water (Turton at al., 2006). Problems with the Klip River system continue to be reported in recent times (McCarthy et al., 2007). Salinity has historically been the water quality issue in the Vaal River that has received most focus as a management issue (DWAF, 2009a). Dilution releases from the Vaal Dam were made to keep salinity below a TDS of 600 $mg \cdot \ell^{-1}$.

Flow in the Vaal River is substantially modified by upstream water transfers from the range of catchments outlined above (DWAF, 2009a). The quality of input water is currently good and acts beneficially on the water quality status of the Vaal river system. If input water quality changes negatively, this would have considerable implications for the water quality of the Vaal River. Mining and power generation in upstream catchments have been identified as potential threats to water quality in the system.

Sources impacting on water quality in the Vaal Barrage catchment include effluent wastewater treatment works operated by Johannesburg Water, the Ekurhuleni Water Care Company (ERWAT) and Metsi-a-Lekoa, as well as return flows from gold mines and several industries, most notably Sasol, Eskom and ArcelorMittal (DWAF, 2009a). Wastewater treatment works effluent input is likely to increase as service provision improves. The poor performance of wastewater treatment works, as well as sewerage systems, has been identified as having a particularly negative effect on water quality. The atmospheric deposition of sulphur salts may also contribute to salinity levels.

Salinity is an issue in the catchment, and, despite a reasonable understanding of the processes involved, remains a challenge. Salinity increases significantly downstream of the Vaal Dam and before the Vaal Barrage, and remains at this level thereafter (DWAF, 2009a). The management of salinity remains a challenge for the following reasons:

- Mine water discharge is a significant contributor to salinity and sulphate levels (McCarthy, 2011). The quantity of mine water is not well understood because future mine water management plans are not known, neither is funding availability for this purpose. Water in the various mining basins is likewise not clear, and future dewatering and decants cannot be predicted.

- Water quality in upstream impoundments is crucial to the maintenance of salinity levels in the study area. Several upstream sources are threatened by mining.
- Dilution water from the Vaal Dam is needed for salinity control downstream. This imposes an additional water demand on the system that may not be maintained in times of water shortage.

Eutrophication in the study area is another primary challenge to water quality (DWAF, 2009a). Eutrophication leads to blooms of water hyacinth and potentially toxic microalgae, and is primarily driven by phosphate levels in the catchment. Eutrophication in the catchment has been found to have an economic impact on agriculture and the water treatment process. Eutrophication is also a challenge to manage for the following reasons:

- Several sources of nutrients in the catchment exist and are not well understood. These include irrigation return flows, urban runoff, industrial discharges and wastewater treatment works discharge.
- Many wastewater treatment works and sewerage are poorly managed. As a result, many wastewater treatment works underperform in terms of nutrient removal.
- Return flows from wastewater treatment works are anticipated to increase in future as service provision improves.
- The links between nutrient levels and land uses, discharge standards and operational management strategies are not well understood.
- Low flows in the study area contribute to the likelihood that algal blooms will form.
- The collapse of the Klip River wetlands has removed their potential contribution to nutrient removal and may, as the wetlands degrade further, contribute to nutrient loading downstream (McCarthy et al., 2007).

Microbial contamination in the river is the third of the well-known water quality management challenges in the study area (DWAF, 2009a). Problems in this regard relate to the poor operation and maintenance of wastewater works and sewerage systems. The poor maintenance of these systems has resulted in degradation in some areas that has significant cost implications for remedy. Microbial contamination instream has resulted in a significant public health threat. Monitoring data suggests that this syndrome is restricted to the area immediately below the release point. Nevertheless, very high microbial levels are found throughout the catchment (DWS and Rand Water 2017 data).

Other water quality challenges in the catchments that are not well studied are listed below.

- Non-essential metals have been found to bioaccumulate in fish in the study area (Crafford and Avenant-Oldwage, 2010). Heavy metals, present in water and sediment, were also found to cause oxidative stress in fish (Wepener et al., 2011).
- The bacterial community structure was found to be altered by changes in water quality in the study area (Jordaan and Bezuidenhout, 2013).
- Norovirus contamination of rivers in the study area was found, which could act as a cause of the norovirus infection of water users (Mans et al., 2013).
- Carcinogenic polycyclic aromatic hydrocarbons were found in rivers in the study area (Moja et al., 2013). Wepener et al. (2011) found decreased fish health linked to organic pollutants in the river.
- Changes in the diatom community structure indicate poor water quality in the study region (Taylor et al., 2007). Changes in the community structure were particularly correlated with changes in phosphate levels and salinity.

CHAPTER 3: REVIEW OF RESOURCE-DIRECTED MEASURES WITH EMPHASIS ON RESOURCE QUALITY OBJECTIVES AND SOURCE-DIRECTED CONTROL INSTRUMENTS

3.1 INTRODUCTION

The resource-directed measures comprise the classification system, the classification of significant water resources, the determination of the reserve and the setting of the RQOs. While the focus of the current project is on RQOs, particularly the water quality component of the RQOs, a brief review of practices in relation to the entire RDM process is presented here.

The entire RDM process begins with a catchment visioning exercise with the aim of bringing society together to collectively envision the desired future conditions of their catchments, considering a range of desired ecosystem services (DWAF, 2006b). The catchment visioning exercise is designed to give effect to the envisaged participatory approach to water resource management captured in the National Water Act, Act No. 36 of 1998 (RSA, 1998). Catchment visioning is critical because, in a diverse and pluralistic society such as South Africa, people tend to have diverse interests, values, aspirations and choices, and in many cases, opting for one set of choices may preclude the realisation of other sets. For this reason, catchment visioning is meant to bring together a wide range of affected and interested stakeholders within a catchment as the starting point of the RDM process, so that the catchment community can collectively work towards a shared desired future state of the catchment. It is critical to note that catchment visioning is a complex and time-consuming exercise that requires a range of skills – not only facilitation skills, but also ethics skills that would ensure that the voices of the less powerful and often marginalised groups within the catchment are considered and taken forward in the decision-making process about the desired future state of the catchment.

The approach to catchment visioning is that which is fully participatory, inclusive and context-sensitive in seeking to arrive at a consensus among competing interests within the catchment. During a catchment visioning exercise, the three foundational values of equity, sustainability and efficiency in the NWA serve as a guide, beginning with a process of sensitising all catchment communities and water resource users, including interested and affected parties who may not live within the catchment (DWAF, 2006a). Overall, the outcome of the catchment visioning exercise should reflect the collective objectives and aspirations for the catchment, which then give direction to other RDM processes that are to follow.

3.2 THE CLASSIFICATION SYSTEM AND CLASSIFICATION OF WATER RESOURCES

Section 12 of the NWA provides for the establishment of a national WRCS for the classification of every significant water resource. The WRCS (DWAF, 2008) provides a set of guidelines and procedures to follow when undertaking the classification process. The classification system allows water resources to be classified in a manner that reflects the desired protection to be afforded a water resource and use. The classification system thus aims to balance water resource protection and use in a sustainable, equitable and efficient manner. The classification process considers ecological water requirements (EWR) and water user requirements. The classification process is undertaken following a seven-step process: delineate the units of analysis and describe the status quo of the water resource; link the value and condition of the water resource; quantify the ecological water requirements and changes in non-water quality ecosystem goods, services and attributes; determine an ecologically sustainable base configuration scenario and establish the starter configuration scenarios; evaluate scenarios within the IWRM process; evaluate the scenarios with stakeholders; and gazette the class configuration (DWAF, 2007)

Depending on the desired protection and use a water resource is to be accorded, it is classified into one of three management classes: Class I (a resource with no noticeable or with minimal human impacts), Class II (a resource moderately used and impacted on by human activities with moderate deviation from natural or pre-development conditions) and Class III (a resource that is heavily used and impacted on, with significant deviation from natural or pre-development conditions) (DWAF, 2008). It is important to note that the classification accorded a water resource has social, economic and ecological implications regarding risks and development. For example, if a water resource, for whatever reason, is classified as Class I, the implication is that DWS, being the custodian of the resource, is not willing to accept the risk of impacting on that resource. This, on the other hand, can constrain further socio-economic development within the catchment. Overall, the final management class of a water resource is a combination of the ecological water requirement and the requirements of other user sectors, e.g. domestic, agricultural, industrial or recreational, within the catchment. The ecological water requirements are determined by assessing the present ecological state (PES), which is represented from category A to F, and recommended ecological category (REC), represented from category A to D. Table 3.1 shows descriptions of the categories as used during the determination of the management class of a water resource.

Table 3.1: Ecological categories and description applicable to water resources in South Africa (Kleynhans and Louw, 2008)

Ecological category name	Description	Explanation
A	Pristine, natural/unmodified	Natural
B	Largely natural	A small change in the natural functioning, processes, biota and characteristics of the ecosystem.
C	Moderately modified	Some loss of natural biota and habitats, but the basic ecosystem functioning, processes and structure remain largely unchanged.
D	Largely modified	A large loss of biota and habitats, and impact on the basic ecosystem function has occurred and is large.
E	Seriously modified	Impact on ecosystem functioning is extensive, significant loss of biota, habitats and the impact on physical, chemical and biological properties of the ecosystem is serious.
F	Critically modified	Extreme modification of the system, including loss of habitats and biota. Ecosystem functioning is extremely compromised, and changes are irreversible.

The second requirements captured in the management class are those of other users within the catchment. Unlike the ecological water requirement reflected in categories A to F, users' requirements are first reflected using the fitness-for-use categories of Ideal, Acceptable, Tolerable and Unacceptable (DWAF, 2006b) (see Table 3.2). It is important to note that fitness for use is described in terms of the specific user requirements.

Table 3.2: Water user requirement categories (adapted from DWAF, 2006b)

Fitness-for-use category	Description
Ideal	It is 100% fit for use at all time, water condition desirable for the intended use
Acceptable	Slight problems encountered on a few occasions for the intended use
Tolerable	Moderate to severe problems are encountered for the intended use for a limited period
Unacceptable	Water is unacceptable for its intended use at all times

The user requirements are mapped onto the ecological categories and are configured into the final management class as follows:

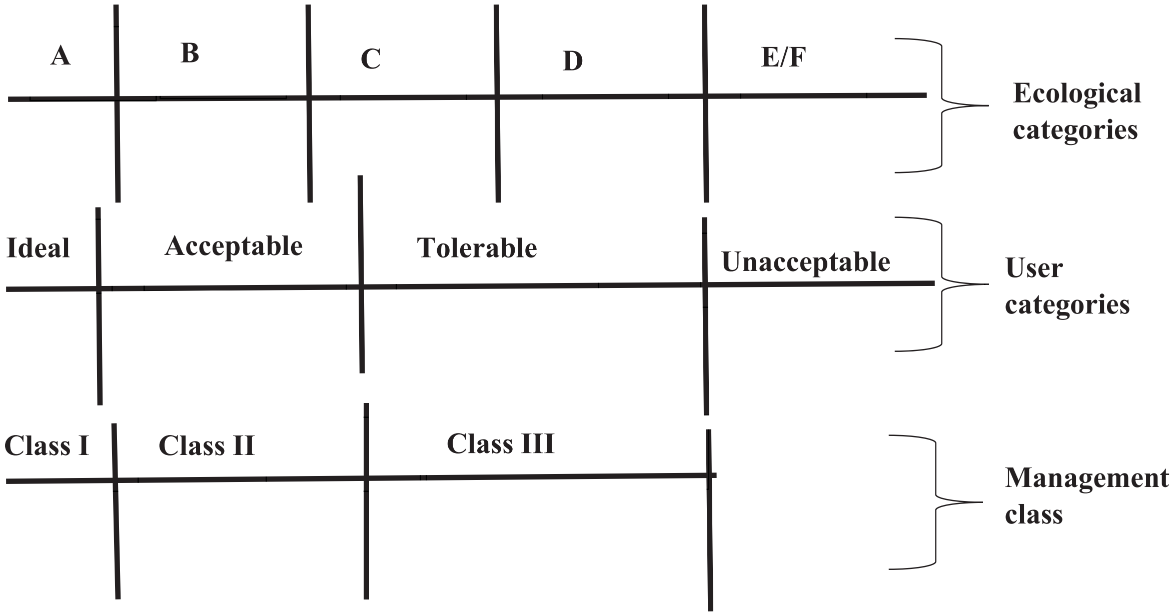


Figure 3.1: The relationship between the ecological and user categories and the management class

3.3 THE PRESENT ECOLOGICAL STATE, RECOMMENDED ECOLOGICAL CATEGORIES AND MANAGEMENT CLASS OF THE VAAL BARRAGE CATCHMENT

The present ecological state, recommended ecological categories and management class for the study area, i.e. the Vaal Barrage catchment and associated rivers (the Leeuspruit, Taaibosspruit, Klip, Blesbokspruit, Rietspruit and Suikerbosrand rivers), have been determined and gazetted (DWS, 2016). Here, we present the gazetted classes for the study area and offer some reflections on them in relation to their ecological and socio-economic implications (Table 3.3).

Table 3.3: Reflection on the management class and recommended ecological categories for the Suikerbosrand and Klip river system within the Vaal Barrage catchment

Integrated unit of analysis (IUA)	IUA class	Node name	Major river	Tributary	PES	REC	Reflections
Suikerbosrand	II	UH.1	Vaal	Suikerbosrand	B/C	B	The system has been classified as moderately used and impacted on, with the present ecological state being a transitional category from largely natural to moderately modified (UH.1). However, the desired state is to revert this trajectory to largely natural (REC B). The socio-economic implications are that the regulators, i.e. DWS, would have to work collaboratively with other catchment stakeholders on measures to restrict water use. This may involve stricter license conditions or other measures that restrict water use. Similar implications hold for EWR 9, where the current state had to be reverted to B/C. Furthermore, because the resource is classified as Category II, it is important to note that developments likely to have significant demand on water resources may not be allowed in this catchment or would have to be imposed with strict regulations to limit or control impacts.
		EWR9	Vaal	Suikerbosrand	C	B/C	
Klip River (Gauteng)	III	UI.1	Klip	Rietspruit	E	D	Water resources within these catchments are heavily used and impacted on as reflected in Management Class III. The impacts on the systems are extensive, with significant loss of biota, habitat and alteration of the physico-chemical properties of the systems, as currently indicated in PES E for UI.1, UI.2 and UI.3. Large impacts are associated with UI.4 and EWR 10 and 11. However, the regulator and society have agreed to accept significant risk in terms of protecting water resources within the catchment, as reflected in REC D for all biophysical nodes except for EWR 10, for which the REC is C/D, which is still indicative of acceptance of high risk with regard to maintaining ecological integrity. Nevertheless, despite acceptance of higher risk in relation to the ecological health of the systems, the DWS is likely to impose stricter WUL conditions to improve the system slightly and halt further deterioration. Sensitive water users are likely to be vulnerable and at risk, given that the REC for most of the system is D. However, given the strategic importance of these systems for economic development, a REC D is justifiable, especially because of the economic costs that may be incurred to improve the systems to C or C/B categories.

Integrated unit of analysis (IUA)	IUA class	Node name	Major river	Tributary	PES	REC	Reflections
		UI.2	Vaal	Klip	E	D	
		UI.3	Vaal	Klip	E	D	
		UI.4	Vaal	Rietspruit	D/E	D	
		EWR 10	Vaal	Suikerbosrand	C/D	C/D	
		EWR 11	Suikerbosrand	Blesbokspruit	D	D	

Table 3.4: Reflection on the management class and REC for the Taaibosspruit and Vaal River reach from the Vaal Dam to C23L

IUA	IUA Class	Node name	Major river	Tributary	PES	REC	Reflections
Taaibosspruit (UJ)	III	UJ.1	Vaal	Taaibosspruit	D	D	Water resources in the Taaibosspruit are currently heavily utilised and the system is largely modified with a large loss of biota, habitats and alteration of the physico-chemical conditions. However, the regulator and society have agreed to keep and maintain the status quo as recommended at REC D. The implication is that development that may significantly deviate the system from the current conditions may be prohibited or imposed with stricter WUL conditions. From a water quality perspective, effluent quality ought to, as a minimum, meet historical standards that have kept the system within a REC D. Thus, development that may significantly further impact on the system may be subject to very strict licensing conditions as the minimum acceptable REC is D, and a REC of E or F is unacceptable.
Vaal River reach from Vaal Dam to C23L (UM)	III	EWR 4	Vaal		C	B/C	The Vaal River reach from the Vaal Dam to C23L (UM) is heavily used, supporting extensive socio-economic activities as reflected in Management Class III. EWR 4 is currently moderately modified, as indicated by a PES C, and EWR 5 is in a transition state between being moderately modified and largely modified. However, for both biophysical nodes, the regulator and society have agreed to improve the system to one level higher than the current condition. The implication is that water users within the catchment may experience some sort of stricter license conditions and other measures to be able to improve the system as envisaged. For EWR 4, the regulator's appetite for risk in relation to ecological health is low, as indicated by the REC of B/C, compared to EWR 5, which has a REC of C.
		EWR 5	Vaal		C/D	C	

3.4 THE DETERMINATION OF THE RESERVE AND RESOURCE QUALITY OBJECTIVES

The reserve and the RQOs, together with the classification, are components of RDM. The outcome of the classification process is the management class, the reserve and the RQOs. The reserve has two components, the basic human need reserve (BHNR) and the ecological reserve (ER). The BHNR provides for the essential needs of individuals, such as water for drinking, preparing food and for personal hygiene, whereas the ER is the quality, quantity and assurance of supply of water needed to protect and maintain aquatic ecosystem functionality (King and Pienaar, 2011). The RQOs are descriptive and quantitative measures that characterise the desired level of protection and use of a water resource as defined by its management class and the recommended ecological categories (DWA, 2013; DWAF, 2016). The RQOs are thus the measurable goals that are assessed to determine whether or not progress is being made towards achieving the designated desired future condition as captured in the REC. Overall, the RQOs capture the management class and the ecological needs determined in the reserve into measurable objectives that give direction on how a water resource should be managed (King and Pienaar, 2011). The seven steps of ER determination and determining the RQOs are summarised in figures 3.2 and 3.3, respectively.

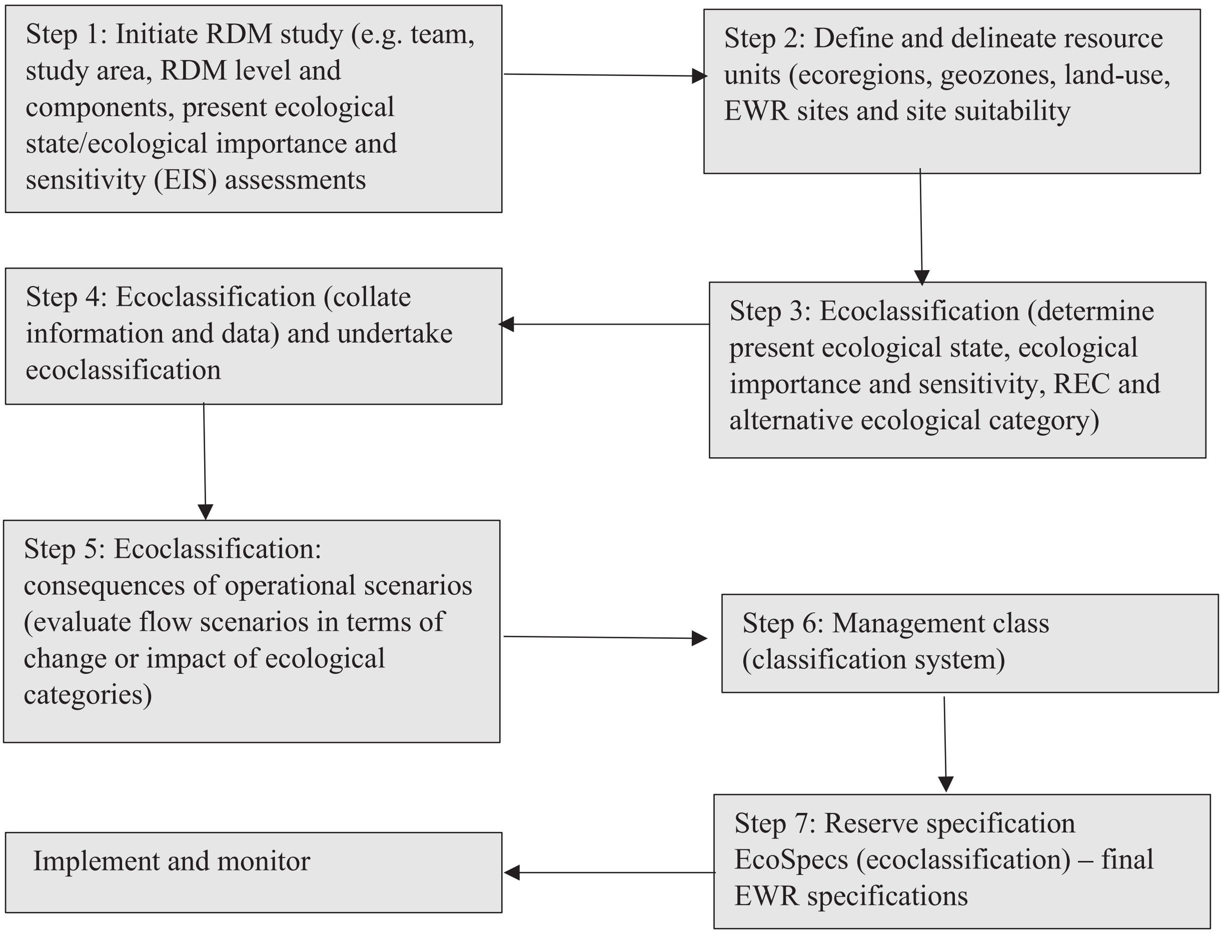


Figure 3.2: The seven steps for determining the ecological reserve (adapted from DWAF, 2008)

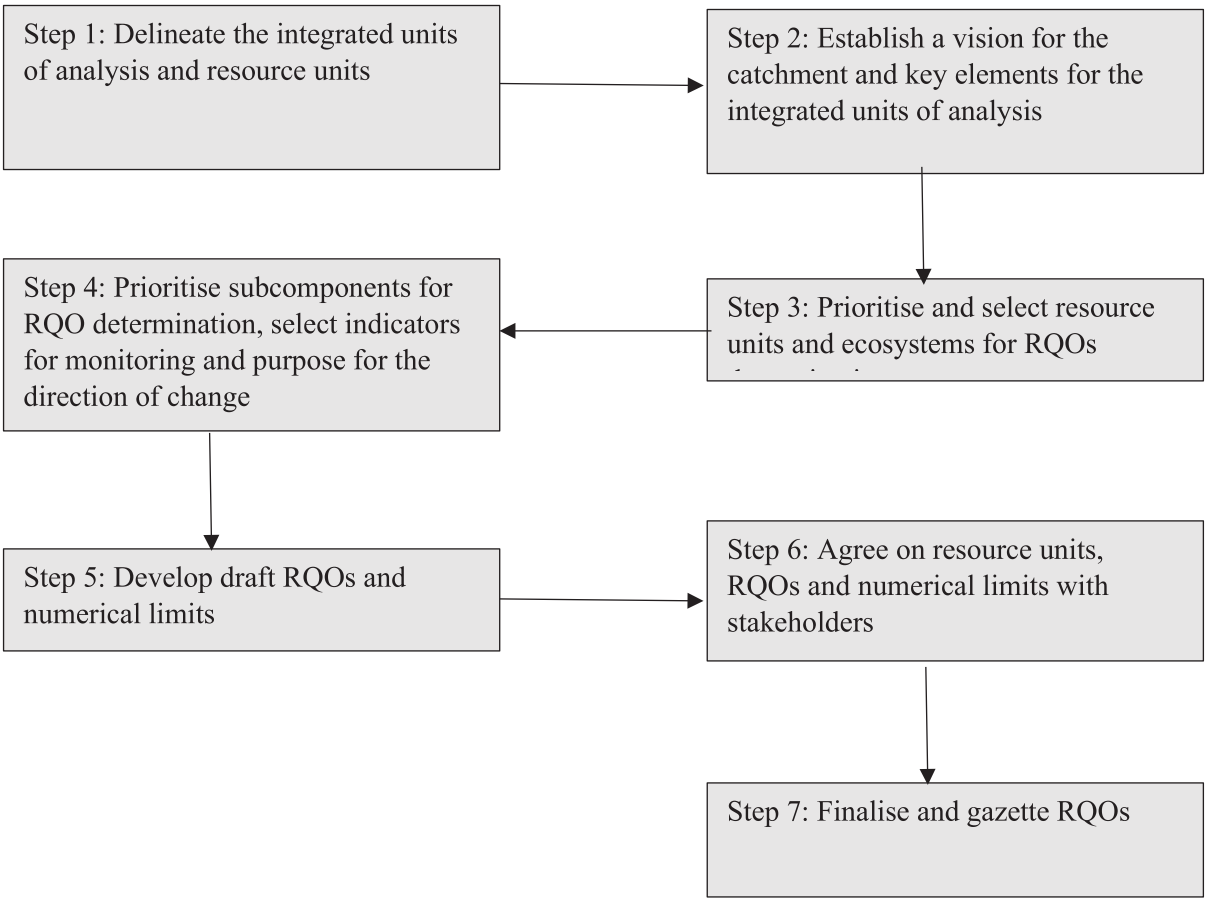


Figure 3.3: The seven steps for determining the resource quality objectives (DWA, 2011)

In December 2018, the Minister of Water and Sanitation published the proposed reserve determination of water resources for the Vaal catchment. Tables 3.5 to 3.8 provide a summary of the water quality components of the proposed reserve for the study area, as published in the government gazette (DWS, 2018). It is important to note that these are not the final reserves, but the proposed reserves, as comments were being invited from members of the public. The RQOs for the study catchments are provided in Table 3.9.

Table 3.5: Water quality component of the proposed ecological reserve for EWR 9 Suikerbosrand River, as published in Government Gazette No. 42127 (DWS, 2018)

EWR 9 Suikerbosrand River (UH): Target ecological category (TEC): B/C; ecological importance and sensitivity: high			
Water quality class	**Variable**	**Specification**	**Reflection**
Inorganic salts	$MgSO_4$	The 95th percentile of the data must be < 37 mg ℓ^{-1}	The Suikerbosrand River at EWR 9 is regarded as an ecologically important and sensitive system, and has thus been given a relatively high TEC of B/C. The system is sensitive to the input of salts, nutrients and toxins, as well as activities that are likely to alter the physical variables such as turbidity and dissolved oxygen. For these reasons, the water quality specifications for these variables are much stricter compared to EWR 10 and 11. The implication is that the DWS would impose much stricter requirements on water users within this subcatchment in order to meet the ecological reserve as set out, thus potentially limiting large-scale industrial developments and other activities that are likely to impact significantly on the ecological health of the system.
	Na_2SO_4	The 95th percentile of the data must be < 51 mg ℓ^{-1}	
	$MgCl_2$	The 95th percentile of the data must be < 30 mg ℓ^{-1}	
	$CaCl_2$	The 95th percentile of the data must be < 57 mg ℓ^{-1}	
	NaCl	The 95th percentile of the data must be < 45 mg ℓ^{-1}	
	$CaSO_4$	The 95th percentile of the data must be < 351 mg ℓ^{-1}	
Physical variables	Electrical conductivity (EC)	The 95th percentile of the data must be < 55 m^S/m	
	pH	The 5th percentile of the data must be 6.5 to 8.0 and the 95th percentile must be 8.0 to 8.8	
	Temperature	Small deviation from the natural temperature range	
	Dissolved oxygen (DO)	The 5th percentile of the data must be ≥ 8 mg ℓ^{-1}	
	Turbidity	Varies by a small amount from the natural turbidity range, minor silting of instream habitats acceptable	
Nutrients	Total inorganic nitrogen (TIN)	The 50th percentile of the data must be < 0.7 mg ℓ^{-1}	
	PO_4-P	The 50th percentile of the date must be < 0.020 mg ℓ^{-1}	
Response variables	Chl-a phytoplankton	The 50th percentile of the data must be < 20 mg ℓ^{-1}	
	Chl-a periphyton	The 50th percentile of the data must be < 21 mg/m^2	
Toxins	Ammonia	The 95th percentile of the data must be ≤ 0.073 mg ℓ^{-1}	
	Fluoride	The 95th percentile of the data must be ≤ 1.5 mg ℓ^{-1}	

Table 3.6: Water quality component of the proposed ecological reserve for EWR 10 Suikerbosrand River, as published in Government Gazette No. 42127 (DWS, 2018)

EWR 10: Suikerbosrand downstream: Target ecological category: C/D; ecological importance and sensitivity: moderate			
Water quality class	**Variable**	**Specification**	**Reflection**
Inorganic salts	$MgSO_4$	The 95th percentile of the data must be < 37 mg ℓ^{-1}	The Suikerbosrand River downstream at EWR 10 is regarded as being moderate in terms of ecological importance and sensitivity, and has thus been given a moderate TEC of C/D. The system is sensitive to the input of salts, nutrients and toxins, although less so compared with EWR 9. Its present ecological state of C/D implies that DWS and potentially water users within the catchment would minimise development likely to change the status quo if the water quality component of the reserve is to be met. Nevertheless, the specifications at this EWR site are less strict compared with those of EWR 9.
	Na_2SO_4	The 95th percentile of the data must be < 51 mg ℓ^{-1}	
	$MgCl_2$	The 95th percentile of the data must be < 51 mg ℓ^{-1}	
	$CaCl_2$	The 95th percentile of the data must be < 105 mg ℓ^{-1}	
	NaCl	The 95th percentile of the data must be < 191 mg ℓ^{-1}	
	$CaSO_4$	The 95th percentile of the data must be < 351 mg ℓ^{-1}	
Physical variables	EC	The 95th percentile of the data must be < 85 mS/m	
	pH	The 5th percentile of the data must be 6.5 to 8.0 and the 95th percentile must be 8.0 to 8.8	
	Temperature	Small deviation from the natural temperature range	
	DO	The 5th percentile of the data must be ≥ 7 mg ℓ^{-1}	
Nutrients	TIN	The 50th percentile of the data must be < 0.7 mg ℓ^{-1}	
	PO_4-P	The 50th percentile of the data must be < 0.125 mg ℓ^{-1}	
Response variables	Chl-a phytoplankton	The 50th percentile of the data must be < 30 µg ℓ^{-1}	
	Chl-a periphyton	The 50th percentile of the data must be < 21 mg/m^2	
Toxins	Ammonia	The 95th percentile of the data must be ≤ 0.100 mg ℓ^{-1}	
	Fluoride	The 95th percentile of the data must be ≤ 1.5 mg ℓ^{-1}	

Table 3.7: Water quality component of the proposed ecological reserve for Vaal River at De Neys, as published in Government Gazette No. 42127 (DWS, 2018)

EWR 4: Vaal River at De Neys: Target ecological category: B/C; ecological importance and sensitivity: high			
Water quality class	**Variable**	**Specification**	**Reflection**
Inorganic salts	$MgSO_4$	The 95th percentile of the data must be $\leq$ 37 mg ℓ^{-1}	The Vaal river system at De Neys is regarded as being highly ecological important and sensitive with a TEC of B/C. Compared with a PES of C, a slight improvement is expected to achieve the TEC of B/C. Given the sensitivity of the system, relatively stricter specifications are foreseen in order to achieve the determined water quality components of the reserve. The implication is that, while existing water users may not experience a very strict imposition of water quality specifications in their WUL, measures are likely to be taken by the regulators in collaboration with catchment stakeholders to improve the water quality conditions of the system in order to achieve the proposed TEC, and to achieve the determined reserve.
	Na_2SO_4	The 95th percentile of the data must be $\leq$ 33 mg ℓ^{-1}	
	$MgCl_2$	The 95th percentile of the data must be $\leq$ 30 mg ℓ^{-1}	
	$CaCl_2$	The 95th percentile of the data must be $\leq$ 57 mg ℓ^{-1}	
	NaCl	The 95th percentile of the data must be $\leq$ 191 mg ℓ^{-1}	
	$CaSO_4$	The 95th percentile of the data must be $\leq$ 351 mg ℓ^{-1}	
Physical variables	EC	The 95th percentile of the data must be $\leq$ 30 mS/m	
	pH	The 5th percentile of the data must be 6.5 to 8.0 and the 95th percentile must be 8.0 to 8.8	
	DO	The 5th percentile of the data must be $\geq$ 7 mg ℓ^{-1}	
Nutrients	TIN	The 50th percentile of the data must be < 0.70 mg ℓ^{-1}	
	PO_4-P	The 50th percentile of the data must be < 0.125 mg ℓ^{-1}	
Response variables	Chl-a phytoplankton	The 50th percentile of the data must be < 10 µg ℓ^{-1}	
	Chl-a periphyton	The 50th percentile of the data must be $\leq$ 1.7 mg/m^2	
Toxins	Ammonia	The 95th percentile of the data must be $\leq$ 0.1 mg ℓ^{-1}	
	Fluoride	The 95th percentile of the data must be $\leq$ 1.5 mg ℓ^{-1}	

Table 3.8: Water quality component of the proposed ecological reserve for the Vaal River at Skandinavia, as published in Government Gazette No. 42127 (DWS, 2018)

EWR 5: Vaal River at Skandinavia: Target ecological category: C; ecological importance and sensitivity: high			
Water quality class	**Variable**	**Specification**	**Reflection**
Inorganic salts	$MgSO_4$	The 95th percentile of the data must be ≤ 37 mg ℓ^{-1}	The Vaal river system at EWR 5 is regarded as being highly ecologically important and sensitive, and has thus been accorded a high EIS designation with a TEC of C. The system is sensitive to further inputs of inorganic salts, nutrients, toxic substances and activities that would impact on system variables such as dissolved oxygen and electrical conductivity. However, given its PES of C/D, the reserve has been determined at an REC of C, implying that very serious measures that restrict current water use are not envisaged, but water users are likely to be imposed with reasonable license requirements to be able to afford the slight improvement from a C/D to a C. These conditions are envisaged to be less strict if, for example, the system is to be improved from a C/D to a B/C. Nevertheless, license conditions and/or other SDC instruments would still need to be imposed to achieve the reserve as determined.
	Na_2SO_4	The 95th percentile of the data must be ≤ 51 mg ℓ^{-1}	
	$MgCl_2$	The 95th percentile of the data must be ≤ 36 mg ℓ^{-1}	
	$CaCl_2$	The 95th percentile of the data must be ≤ 105 mg ℓ^{-1}	
	NaCl	The 95th percentile of the data must be ≤ 191 mg ℓ^{-1}	
	$CaSO_4$	The 95th percentile of the data must be < 351 mg ℓ^{-1}	
Physical variables	EC	The 95th percentile of the data must be < 85 mS/m	
	pH	The 5th percentile of the data must be 6.5 to 8.0 and the 95th percentile must be 8.8 to 9.2	
	Temperature	Temperatures should be close to natural range	
	DO	The 5th percentile of the data must be ≥ 6.0 mg ℓ^{-1}	
Nutrients	TIN	The 50th percentile of the data must be ≤ 1 mg ℓ^{-1}	
	PO_4-P	The 50th percentile of the data must be ≤ 0.025 mg ℓ^{-1}	
Response variables	Chl-a phytoplankton	The 50th percentile of the data must be ≤ 20 µg ℓ^{-1}	
	Chl-a periphyton	The 50th percentile of the data must be ≤ 21 mg/m^2	
Toxins	Ammonia	The 95th percentile of the data must be ≤ 0.1 mg ℓ^{-1}	
	Fluoride	The 95th percentile of the data must be ≤ 1.5 mg ℓ^{-1}	
	Atrazine	The 95th percentile of the data must be ≤ 100 µg ℓ^{-1}	
Inorganic ions	Sulphate	The 95th percentile of the data must be ≤ 200 mg ℓ^{-1}	

Table 3.9: RQOs for river water quality in priority resource units in the Upper Vaal Barrage (UJ = Taaibosspruit, UI = Klip River (Gauteng), UM = Vaal River from Vaal Dam to C23L) (based on DWS, 2014 and DWS, 2015)

IUA	Class	River	RU	Node	REC	Component	Sub-component	RQO	Indicator/ measure	Numerical limits	95th percentile
UI	III	Suikerbosrand	RU62	EWR11	D	Quality	Nutrients	The nutrient concentrations must be improved to an acceptable mesotrophic state.	Phosphate (PO_4)	≤ 0.125 mg ℓ^{-1} P	0.5
			RU 65	UI.3					Nitrate (NO_3); Nitrite (NO_2)	≤ 4.00 mg ℓ^{-1} N	1.7
			RU 66	UI.4					Phosphate (PO_4)	≤ 0.125 mg ℓ^{-1} P	0.5
									Nitrate (NO_3); Nitrite(NO_2)	≤ 4.00 mg ℓ^{-1} N	1.7
UM	III	Vaal	RU75	EWR5	C	Quality	Nutrients	The nutrients should be improved to an acceptable state	Phosphate (PO_4)	≤ 0.025 m mg ℓ^{-} P	0.2
									Nitrate (NO_3); Nitrite (NO_2)	≤ 1.00 mg ℓ^{-1} N	0.25
									Total ammonia	≤ 73 µg/L N	1.5
UH	II	Vaal	RU 60	EWR 9	B/C	Quality	Nutrients	The nutrient condition must be improved to an acceptable level for the ecosystem	Phosphate (PO_4)	≤ 0.020 mg ℓ^{-1} P	0.6
									Nitrate (NO_3); Nitrite (NO_2)	≤ 0.85 mg ℓ^{-1} N	1.62
UI	III	Suikerbosrand	RU62	EWR11	D	Quality	Salts	Salts need to be improved to levels that do not threaten the ecosystem and to provide for users.	Electrical conductivity	≤ 111 m^S/m	135
			RU65	UI.3							90.6
		Vaal	RU66	UI.4							98.1

IUA	Class	River	RU	Node	REC	Component	Sub-component	RQO	Indicator/ measure	Numerical limits	95th percentile
UJ	III	Vaal	RU67	UJ.1	D	Quality	Salts	Salts need to be improved to levels that do not threaten the ecosystem and to provide for users	Electrical conductivity	≤ 111 m^{S}/m	79.1
UM	III	Vaal	RU75	EWR5	C	Quality	Salts	Salts need to be improved to levels that do not threaten the ecosystem, especially fish, and to provide for users.	Electrical conductivity	≤ 85 m^{S}/m	84
									Sulphates	≤ 200 mg ℓ$^{-1}$	173
UI	III	Vaal	RU66	UI.4	D	Quality	System variables	Dissolved organic carbon concentrations should not cause the ecosystem to become unsustainable.	DOC	30-day median ±20% of median background mg ℓ$^{-1}$ C	No data
UI	III	Suikerbosrand and Vaal	RU62 RU65 RU66	EWR11 UI.3 UI.4	D	Quality	Toxins	The river water should not be toxic to aquatic organisms or be a threat to human health.	F	≤ 3.0 mg ℓ$^{-1}$	0.465
									Al	≤ 150 µg ℓ$^{-1}$	No data
									As	≤ 130 µg ℓ$^{-1}$	No data
									Cd hard	≤ 5.0 µg ℓ$^{-1}$	No data
									Cr(VI)	≤ 200 µg ℓ$^{-1}$	No data
									Cu hard	≤ 8.0 µg ℓ$^{-}$	No data
									Hg	≤ 1.70 µg ℓ$^{-1}$	No data
									Mn	≤ 1300 µg ℓ$^{-1}$	No data

IUA	Class	River	RU	Node	REC	Component	Sub-component	RQO	Indicator/ measure	Numerical limits	95^{th} percentile
									Pb hard	≤ 13.00 µg ℓ^{-1}	No data
									Se	≤ 30 µg ℓ^{-1}	No data
									Zn	≤ 36 µg ℓ^{-1}	No data
									Chlorine	≤ 5.0 µg ℓ^{-1} free Cl	No data
									Endosulfan	≤ 0.200 µg ℓ^{-1}	No data
									Atrazine	≤ 100 µg ℓ^{-1}	No data
UJ	III	Vaal	RU67	UJ.1	D	Quality	Toxins	The river water should not be toxic to aquatic organisms or be a threat to human health.	F	≤ 3.0 mg ℓ^{-1}	4.95
									Al	≤ 150 µg ℓ^{-1}	No data
									As	≤ 130 µg ℓ^{-1}	No data
									Cd hard	≤ 5.0 µg ℓ^{-1}	No data
									Cr(VI)	≤ 200 µg ℓ^{-1}	No data
									Cu hard	≤ 8.0 µg ℓ^{-1}	No data
									Hg	≤ 1.70 µg ℓ^{-1}	No data
									Mn	≤ 1300 µg ℓ^{-1}	No data
									Pb hard	≤ 13.00 µg ℓ^{-1}	No data
									Se	≤ 30 µg ℓ^{-1}	No data
									Zn	≤ 36 µg ℓ^{-1}	No data
									Chlorine	≤ 5.0 µg ℓ^{-1} free Cl	No data
									Endosulfan	≤ 0.200 µg ℓ^{-1}	No data
UI	III	Suikerbosrand	RU62	EWR11	D	Quality	Pathogens	Pathogens should be maintained at levels safe for human use (excluding for direct consumption).	*E. coli*	≤ 130 counts/ 100 ml	No data
		Vaal	RU65	UI.3						≤ 130 counts/ 100 ml	No data
			RU66	UI.4						≤ 130 counts/ 100 ml	No data

IUA	**Class**	**River**	**RU**	**Node**	**REC**	**Component**	**Sub-component**	**RQO**	**Indicator/ measure**	**Numerical limits**	**95th percentile**
UM	III	Vaal	RU75	EWR5	C	Quality	Pathogens	Pathogens should be maintained at levels safe for human use (excluding for direct consumption).	*E .coli*	≤ 130 counts/ 100 ml	No data

3.5 CATCHMENT STAKEHOLDER-DERIVED INSTREAM GUIDELINES

Stakeholders within the lower section of the Upper Vaal catchment have historically taken an interest in managing the water quality of the Vaal Barrage catchment and associated rivers (CEC, 2001). To this effect, prior to the determination of the reserve and the RQOs, catchment stakeholders, led by Rand Water, published instream water quality guidelines for the Vaal Barrage, which were available on the Reservoir's website, http://www.reservoir.co.za/, during the project implementation period. The process for the derivation of the stakeholder-led guidelines is documented in the proceedings of a workshop held at Rand Water on 13 October 2001 (CEC, 2001). The primary principle informing the development of the guidelines is to facilitate water quality management, and to identify and track water quality hotspots and seasons, i.e. the guidelines are to be viewed as management tools. Given this management imperative and taking a range of considerations into account, including water users within the catchment, the analytical detection limit and activities within the catchment, a four-tiered system approach that facilitates management consideration was adopted.

The four-tiered approach that was followed is as follows:

- **Tier 1:** Catchment background – this translates roughly into the ideal category, and, in the case of the upper catchment, the baseline water quality status prior to heavy modifications arising from inter-basin transfer schemes and industrialisation (CEC, 2001).
- **Tier 2:** Management target – this translates roughly into the generic acceptable water quality limit for the intended users. This was the situation to strive for from a management perspective. In the case of the barrage, for example, setting the limit for the management target was guided by water quality conditions at the exit point of the Vaal Barrage reservoir (CEC, 2001).
- **Tier 3:** Interim management target: This level was set primarily to identify the direction of water quality deterioration away from or towards either Tier 2 or Tier 4. If the direction is away from Tier 2 and towards Tier 4, management action is to be triggered to halt and/or reverse the trajectory of change. Thus, the interim target can be seen as the tolerable level, and a short-term management tool.
- **Tier 4:** Maximum allowable level: The maximum allowable level depicts water quality concentrations that are deemed unacceptable. This was guided by the upper limit Class 1 water as defined in SABS 241 (SABS, 2001): Guidelines for drinking water.

It seems that the interim target was the minimum acceptable target agreed upon by the stakeholders prior to the determination of the water quality components of the RQOs in the catchment. However, within the legal framework, once the RQOs have been gazetted, they take precedence over the stakeholder-derived instream guidelines. Tables 3.10 to 3.15 provide a summary of the guidelines as published on the Reservoir's website (http://www.reservoir.co.za/).

Table 3.10: Stakeholder-derived instream water quality guideline for the Vaal Barrage Reservoir catchment, published on the Reservoir's website (http://www.reservoir.co.za/)

Instream Water Quality Guidelines for the Barrage Reservoir Catchment, effective June 2003					
Physical variables	**Measured as**	**Ideal catchment background**	**Acceptable management target**	**Tolerable interim target**	**Unacceptable**
Conductivity	m^{S}/m	< 18	18 to 30	30 to 70	> 70
Dissolved oxygen (O_2)	mg ℓ^{-1} O_2		> 6.0	5 to 6.0	< 5.0
pH	pH units	7.0 to 8.4	6.5 to 8.5	6 to 9.0	< 6.0; > 9.0
Suspended solids	mg ℓ^{-1}	< 20	20 to 30	30 to 55	> 55
Organic					
Atrazine	µg ℓ^{-1}	< 5	5 to 10	10 to 20	> 20
Chemical oxygen demand (COD)	mg ℓ^{-1}	< 10	10 to 20	20 to 30	> 30
Phenols	mg ℓ^{-1}		< 0.01	0.01 to 0.1	> 0.1
Macro elements					
Aluminium (Al)	mg ℓ^{-1}		< 0.3	0.3 to 0.5	> 0.5
Ammonia (NH_4)	mg ℓ^{-1}		< 0.5	0.5 to 1.0	> 1.0
Chloride (Cl)	mg ℓ^{-1}	< 5	5 to 50	50 to 75	> 75
Fluoride (F)	mg ℓ^{-1}	< 0.19	0.19 to 0.70	0.7 to 1.00	> 1.00
Iron (Fe)	mg ℓ^{-1}		< 0.5	0.5 to 1.0	> 1.0
Magnesium (Mg)	mg ℓ^{-1}	< 8	8 to 30	30 to 70	> 70
Manganese (Mn)	mg ℓ^{-1}		< 0.15	0.15 to 0.20	> 0.20
Nitrate (NO_3)	mg ℓ^{-1}	< 0.5	0.5 to 3.0	3 to 6.0	> 6.0
Phosphate (PO_4)	mg ℓ^{-1}		< 0.03	0.03 to 0.05	> 0.05
Sodium (Na)	mg ℓ^{-1}	< 15	15 to 50	50 to 100	> 100
Sulphate (SO_4)	mg ℓ^{-1}	< 20	20 to 100	100 to 200	> 200
Bacteriological					
E. coli	counts/ 100 ml	< 130	130 to 200	200 to 400	> 400
Faecal coliforms	counts/ 100 ml		< 126	126 to 1,000	> 1,000
Biological					
Daphnia	Percentage survival	100	90 to 100	80 to 90	< 80

Table 3.11: Stakeholder-derived instream water quality guideline for the Blesbokspruit catchment, published on the Reservoir's website (http://www.reservoir.co.za/)

Instream Water Quality Guidelines for the Blesbokspruit Catchment, effective June 2003					
Physical variables	**Measured as**	**Ideal catchment background**	**Acceptable management target**	**Tolerable interim target**	**Unacceptable**
Conductivity	m^S/m	< 45	45 to 70	70 to 120	> 120
Dissolved oxygen (O_2)	$mg\ \ell^{-1}\ O_2$		> 6.0	5 to 6.0	< 5.0
pH	pH units	6.5-8.5			< 6.5; > 8.5
Suspended solids	$mg\ \ell^{-1}$	< 20	20 to 30	30 to 55	> 55
Organic					
COD	$mg\ \ell^{-1}$	< 20	20 to 35	35 to 55	> 55
Macro elements					
Aluminium (Al)	$mg\ \ell^{-1}$		< 0.3	0.3 to 0.5	> 0.5
Ammonia (NH_4)	$mg\ \ell^{-1}$	< 0.1	0.1 to 1.5	1.5 to 5.0	> 5.0
Chloride (Cl)	$mg\ \ell^{-1}$	< 80	80 to 150	150 to 200	> 200
Fluoride (F)	$mg\ \ell^{-1}$	< 0.19	0.19 to 0.70	0.7 to 1.00	> 1.00
Iron (Fe)	$mg\ \ell^{-1}$	< 0.1	0.1 to 0.5	0.5 to 1.0	> 1.0
Magnesium (Mg)	$mg\ \ell^{-1}$	< 8	8 to 30	30 to 70	> 70
Manganese (Mn)	$mg\ \ell^{-1}$	< 0.2	0.2 to 0.5	0.5 to 1.0	> 1.0
Nitrate (NO_3)	$mg\ \ell^{-1}$	< 0.5	0.5 to 3.0	3 to 6.0	> 6.0
Phosphate (PO_4)	$mg\ \ell^{-1}$	< 0.2	0.2 to 0.4	0.4 to 0.6	> 0.6
Sodium (Na)	$mg\ \ell^{-1}$	< 70	70 to 100	100 to 150	> 150
Sulphate (SO_4)	$mg\ \ell^{-1}$	< 150	150 to 300	300 to 500	> 500
Bacteriological					
E. coli	counts/100 ml	< 130	130 to 200	200 to 400	> 400
Faecal coliforms	counts/100 ml		< 126	126 to 1,000	> 1,000
Biological					
Daphnia	Percentage survival	100	90 to 100	80 to 90	< 80

Table 3.12: Stakeholder-derived instream water quality guideline for the Klip catchment, published on the Reservoir's website (http://www.reservoir.co.za/)

Instream Water Quality Guidelines for the Klip Catchment, effective June 2003					
Physical variables	**Measured as**	**Ideal catchment background**	**Acceptable management target**	**Tolerable interim target**	**Unacceptable**
Conductivity	m^S/m	< 80	80 to 100	100 to 150	> 150
Dissolved oxygen (O_2)	mg ℓ^{-1} O_2		> 6.0	5 to 6.0	< 5.0
pH	pH units	6 to 9.0			< 6.0; > 9.0
Suspended solids	mg ℓ^{-1}	< 20	20 to 30	30 to 55	> 55
Organic					
COD	mg ℓ^{-1}	< 15	15 to 30	30 to 40	> 40
Macro elements					
Aluminium (Al)	mg ℓ^{-1}		< 0.3	0.3 to 0.5	> 0.5
Ammonia (NH_4)	mg ℓ^{-1}	< 0.5	0.5 to 1.5	1.5 to 4.0	> 4.0
Chloride (Cl)	mg ℓ^{-1}	< 50	50 to 75	75 to 100	> 100
Fluoride (F)	mg ℓ^{-1}	< 0.19	0.19 to 0.70	0.7 to 1.00	> 1.00
Iron (Fe)	mg ℓ^{-1}	< 0.5	0.5 to 1.0	1 to 1.5	> 1.5
Magnesium (Mg)	mg ℓ^{-1}	< 8	8 to 30	30 to 70	> 70
Manganese (Mn)	mg ℓ^{-1}	< 1	1 to 2	2 to 4	> 4
Nitrate (NO_3)	mg ℓ^{-1}	< 2	2 to 4	4 to 7	> 7
Phosphate (PO_4)	mg ℓ^{-1}	< 0.2	0.2 to 0.5	0.5 to 1.0	> 1.0
Sodium (Na)	mg ℓ^{-1}	< 50	50 to 80	80 to 100	> 100
Sulphate (SO_4)	mg ℓ^{-1}	< 200	200 to 350	350 to 500	> 500
Bacteriological					
E.coli	counts/100 ml	< 130	130 - 200	200 - 400	> 400
Faecal coliforms	counts/100 ml	< 1,000	1,000 to 5,000	5,000 to 10,000	> 10,000
Biological					
Daphnia	Percentage survival	> 95	95 to 90	90 to 80	< 80

Table 3.13: Stakeholder-derived instream water quality guideline for the Leeuspruit catchment, published on the Reservoir's website (http://www.reservoir.co.za/)

Instream Water Quality Guidelines for the Leeuspruit Catchment, effective June 2003					
Physical variables	**Measured as**	**Ideal catchment background**	**Acceptable management target**	**Tolerable interim target**	**Unacceptable**
Conductivity	m^S/m	< 45	45 to 70	70 to 120	> 120
Dissolved oxygen (O_2)	mg ℓ^{-1} O_2		> 6.0	5 to 6.0	< 5.0
pH	pH units	6.5 to 8.5			< 6.5; > 8.5
Suspended solids	mg ℓ^{-1}	< 20	20 to 30	30 to 55	> 55
Organic					
COD	mg ℓ^{-1}	< 20	20 to 35	35 to 55	> 55
Macro elements					
Aluminium (Al)	mg ℓ^{-1}		< 0.3	0.3 to 0.5	> 0.5
Ammonia (NH4)	mg ℓ^{-1}	< 0.1	0.1 to 1.5	1.5 to 5.0	> 5.0
Chloride (Cl)	mg ℓ^{-1}	< 80	80 to 150	150 to 200	> 200
Fluoride (F)	mg ℓ^{-1}	< 0.19	0.19 to 0.70	0.7 to 1.00	> 1.00
Iron (Fe)	mg ℓ^{-1}	< 0.1	0.1 to 0.5	0.5 to 1.0	> 1.0
Magnesium (Mg)	mg ℓ^{-1}	< 8	8 to 30	30 to 70	> 70
Manganese (Mn)	mg ℓ^{-1}	< 0.2	0.2 to 0.5	0.5 to 1.0	> 1.0
Nitrate (NO_3)	mg ℓ^{-1}	< 0.5	0.5 to 3.0	3 to 6.0	> 6.0
Phosphate (PO_4)	mg ℓ^{-1}	< 0.2	0.2 to 0.4	0.4 to 0.6	> 0.6
Sodium (Na)	mg ℓ^{-1}	< 70	70 to 100	100 to 150	> 150
Sulphate (SO_4)	mg ℓ^{-1}	< 150	150 to 300	300 to 500	> 500
Bacteriological					
E. coli	counts/100 ml	< 130	130 to 200	200 to 400	> 400
Faecal coliforms	counts/100 ml		< 126	126 to 1,000	> 1,000
Biological					
Daphnia	Percentage survival	100	90 to 100	80 to 90	< 80

Table 3.14: Stakeholder-derived instream water quality guideline for the Taaibosspruit catchment, published on the Reservoir's website (http://www.reservoir.co.za/)

Instream Water Quality Guidelines for the Taaibosspruit Catchment, effective June 2003					
Physical variables	**Measured as**	**Ideal catchment background**	**Acceptable management target**	**Tolerable interim target**	**Unacceptable**
Conductivity	mS/m	< 42	42 to 60	60 to 70	> 70
Dissolved oxygen (O_2)	mg ℓ^{-1} O_2		> 6.0	5 to .0	< 5.0
pH	pH units	6.5-8.5			< 6.5; > 8.5
Suspended solids	mg ℓ^{-1}	< 27	27 to 50	50 to 90	> 90
Organic					
COD	mg ℓ^{-1}	< 10	10 to 15	15 to 20	> 20
Macro elements					
Aluminium (Al)	mg ℓ^{-1}	< 0.15	0.15 to 0.50	0.5 to 1.00	> 1.00
Ammonia (NH_4)	mg ℓ^{-1}	< 0.25	0.25 to 0.50	0.5 to 1.00	> 1.00
Chloride (Cl)	mg ℓ^{-1}	< 50	50 to 60	60 to 75	> 75
Fluoride (F)	mg ℓ^{-1}	< 0.4	0.4 to 0.7	0.7 to 1.0	> 1.0
Iron (Fe)	mg ℓ^{-1}	< 0.4	0.4 to 0.5	0.5 to 0.8	> 0.8
Magnesium (Mg)	mg ℓ^{-1}	< 8	8 to 30	30 to 70	> 70
Manganese (Mn)	mg ℓ^{-1}	< 0.2	0.2 to 0.5	0.5 to 1.0	> 1.0
Nitrate (NO_3)	mg ℓ^{-1}	< 0.5	0.5 to 3.0	3to 6.0	> 6.0
Phosphate (PO_4)	mg ℓ^{-1}	< 0.2	0.2 to 0.4	0.4 to 0.6	> 0.6
Sodium (Na)	mg ℓ^{-1}	< 70	70 to 100	100 to 150	> 150
Sulphate (SO_4)	mg ℓ^{-1}	< 150	150 to 300	300 to 500	> 500
Bacteriological					
E.coli	counts/100 ml	< 130	130 to 200	200 to 400	> 400
Faecal coliforms	counts/100 ml		< 126	126 to 1,000	> 1,000
Biological					
Daphnia	Percentage survival		90 to 100	80 to 90	< 80

Table 3.15: Stakeholder-derived instream water quality guideline for the Reitspruit catchment, published on the Reservoir's website (http://www.reservoir.co.za/)

Instream Water Quality Guidelines for the Rietspruit Catchment, effective June 2003					
Physical variables	**Measured as**	**Ideal catchment background**	**Acceptable management target**	**Tolerable interim target**	**Unacceptable**
Conductivity	m^{S}/m	< 45	45 to 70	70 to 120	> 120
Dissolved oxygen (O_2)	mg ℓ^{-1} O_2		> 6.0	5 to 6.0	< 5.0
pH	pH units	6.5 to 8.5			< 6.5; > 8.5
Suspended solids	mg ℓ^{-1}	< 20	20 to 30	30 to 55	> 55
Organic					
COD	mg ℓ^{-1}	< 20	20 to 35	35 to 55	> 55
Macro elements					
Aluminium (Al)	mg ℓ^{-1}	< 0.3	0.3 to 0.4	0.4 to 0.5	> 0.5
Ammonia (NH_4)	mg ℓ^{-1}	< 0.1	0.1 to 1.5	1.5 to 5.0	> 5.0
Chloride (Cl)	mg ℓ^{-1}	< 80	80 to 150	150 to 200	> 200
Fluoride (F)	mg ℓ^{-1}	< 0.19	0.19 to 0.70	0.7 to 1.00	> 1.00
Iron (Fe)	mg ℓ^{-1}	< 0.1	0.1 to 0.5	0.5 to 1.0	> 1.0
Magnesium (Mg)	mg ℓ^{-1}	< 8	8 to 30	30 to 70	> 70
Manganese (Mn)	mg ℓ^{-1}	< 0.2	0.2 to 0.5	0.5 to 1.0	> 1.0
Nitrate (NO_3)	mg ℓ^{-1}	< 0.5	0.5 to 3.0	3 to 6.0	> 6.0
Phosphate (PO_4)	mg ℓ^{-1}	< 0.2	0.2 to 0.4	0.4 to 0.6	> 0.6
Sodium (Na)	mg ℓ^{-1}	< 70	70 to 100	100 to 150	> 150
Sulphate (SO_4)	mg ℓ^{-1}	< 150	150 to 300	300 to 500	> 500
Bacteriological					
E. coli	counts/100 ml	< 130	130 to 200	200 to 400	> 400
Faecal coliforms	counts/100 ml	< 126	126 to 1,000	1,000 to 10,000	> 10,000
Biological					
Daphnia	Percentage survival	100	90 to 100	80 to 90	< 80

3.6 SOURCE-DIRECTED CONTROLS

In order to control and minimise the impact on water resources, Chapter 4 of the NWA provides for source-directed controls (DWAF, 2003). The SDC are measures that ensure that activities likely to impact on water resources are controlled and minimised. Thus, the SDC are the instruments used to achieve the objective of resource-based protection captured in RDM. A variety of instruments fall under SDC, including general authorisations (GAs), waste discharge charge systems, compulsory licencing, special permits, economic incentives, self-regulation, environmental impact assessments (EIAs), local municipal by-laws and the precautionary principle (Scherman and Palmer, 2013). The NWA, under section 21, defines water use broadly, including taking water from a resource, storing water, impeding or diverting water flow, stream flow reduction activities, discharging waste or effluent directly into a water resource, recreation, altering a water course, etc. Nevertheless, the NWA also provides for permissible water use for which no licencing is required. Such uses are captured in section 22, regarded as Schedule 1 uses.

Other permissible uses are those that are a continuation of existing lawful use or use that is authorised under a GA, provided that the use complies with the specification in the GA. It is important to note that, apart from Schedule 1 use, the DWS is moving towards compulsory licensing, and moving away from GAs. Table 3.16 provides a summary of SDC-based tools currently being used to regulate and control impacts on water resources. Some of these tools are outside the function of DWS and rest with other departments or tiers of government, such as the Department of Environmental Affairs (DEA) and local municipalities.

Table 3.16: SDC-based tools currently being used to regulate, control and minimise impact on water resources in South Africa

Tools	**Brief description**
General Authorisation	A GA is an instrument recognised in the Act that facilitates the use of water by a section of society or a large group of people for identified uses without the need for specific individual licenses. Users of water under a GA must register their use and adhere strictly with the provision of the GA, which is revised from time to time and published in the Government Gazette.
Existing lawful use	This refers to water being lawfully used under the previous Act prior to the enactment of the NWA.
Water use license	Licenses are instruments used to control the use of water that falls outside the GA and Schedule 1 uses, as well as those within the confines of lawful use. The Act makes provision for a range of conditions that can be written into and specified in a license, depending on the type, nature and extent of water use and potential impact, risk and severity. Users who have been issued a license are required to adhere strictly to the conditions of the license and may use water only for the specified intended use(s). Compulsory licenses are important in catchments considered stressed and/or with competing users, e.g. in the Vaal Barrage catchment.
Water quality standards or limits	These are water quality limits written into WUL that form part of the WUL conditions. These standards are legally binding and enforceable by the regulators.
Water use charges	Waste discharge charge systems and water resource management charges are the two instruments in this category. The objective is to enforce the polluter pays principle, as well as the user pays principle in the case of water resource management charges.
Self-regulatory instruments, e.g. International Organisation for Standardisation (ISO) standards	Water users are encouraged to invoke the principle of self-regulation by meeting identified criteria. The ISO 14001 certification is a widely used instrument in this category.
Green Drop programme	This is an incentive-driven system that mainly targets the wastewater treatment sector. The programme encourages excellence by providing incentives that promote good standards and behaviour in the sector, while improving effluent quality.
Environmental impact assessment	The EIA is provided for under the National Environmental Management Act, Act No 107 of 1998 (NEMA). Certain developments trigger an EIA, with the objective of seeking ways to minimise the impact of such developments on the environment, including water resources. The DEA has the responsibility to implement an EIA.

3.7 CONSIDERATIONS THAT INFLUENCE THE ISSUANCE OF WATER USE LICENSES AND LICENSE CONDITIONS

A range of factors are considered when issuing a license and specifying license conditions. These include ecological, social, economic and legal considerations. In the past, the DWS developed a decision support system – the Assessment of Consideration for Water Use Applications (ACWUA) (DWAF, 2006c) – that allowed a multi-criteria decision analysis, drawing from a range of ecological, economic and social indicators to inform decisions on license allocations. Evidence based on the indicators is characterised based on impact (the extent to which criteria are met) and uncertainty (the level of confidence in the available evidence). The decision support system uses Bayesian mathematics to quantify the likelihood of issuing a license on the strength of the evidence evaluated. Indicators and evaluation of evidence are based on both narratives provided by users of ACWUA and quantitative information. It is widely believed that ACWUA has not been taken up by DWS regional offices (Scherman and Palmer, 2013). Figure 3.4 summarises the important considerations that are taken into account when issuing a WUL, showing that both RDM and SDC are linked.

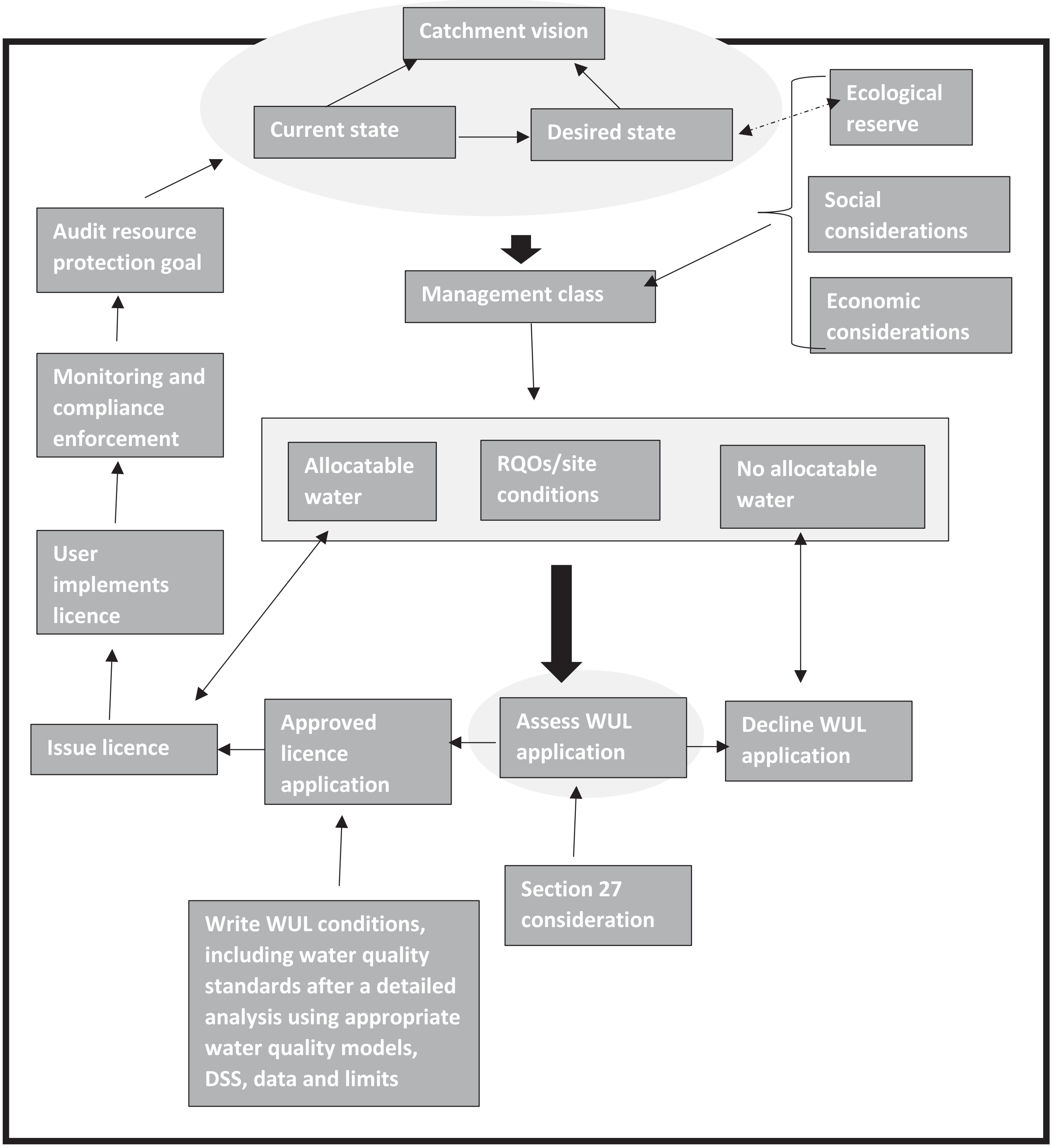


Figure 3.4: Factors influencing the issuance of a water use licenses and specifications of conditions showing the link between the RDM and SDC (adapted from DWAF, 2006a).

3.8 SETTING END-OF-PIPE DISCHARGE STANDARDS

A critical objective of the current project is to review the existing methodology of setting end-of-pipe discharge standards for effluent treatment facilities. Based on the 2006 documentation of the DWS – then known as the Department of Water Affairs and Forestry (DWAF) – an approach to setting end-of-pipe discharge standards that takes into account the receiving instream concentration, the RQO, the mixing ratio, the management class, and realistic and achievable treatment that is attainable using recognised treatment processes was developed (DWAF, 2006b).

The end-of-pipe discharge standard could be set as the recommended resource-directed value (RRDV), being the standard protecting the receiving water resource for a specific mixing ratio and management class, or the maximum allowable resource-directed value (MARDV), being the discharge standard protecting the resource at the specific mixing ratio and a class lower than the class for the RRDV. In such instances, however, the recommendation is that such a discharge standard be considered short term and the goal would be to strive for the RRDV (DWAF, 2006b). A third possible end-of-pipe discharge standard is the source-directed value (SDV), being the discharge value that is achievable by using recognised treatment processes on a predominantly domestic effluent (DWAF, 2006b). The SDV is set as the discharge standard where the RRDV is less than the SDV, but the SDV is less than or equal to the MARDV. As with the second scenario, this should also be a short-term discharge standard. The SDV is calculated as the 25th percentile value of the effluent quality of the 25th percentile wastewater treatment works (WWTW), drawn from a large number of treatments works for domestic effluent; i.e. to determine the SDV, a water quality concentration for the variable of interest is investigated for a large pool of WWTWs, and the 25th percentile value for the 25th percentile treatment works is taken as the SDV.

The basic formula for calculating the end-of-pipe discharge standard as given in DWAF (2006b), as shown below:

$$C_w = \frac{C_R(MR + 1)C_s}{MR}$$

Where C_w is the end-of-pipe discharge standard (RRDV or MARDV)

$C_R = \text{Desired maximum instream concentration (RQO)}$

$C_s = \text{Receiving stream concentration}$; MR = mixing ratio

The mixing ratio (MR) refers to the rate of discharge, Q_w, divided by the rate of stream flow, Q_s, i.e. MR = Q_w/Q_s

According the DWAF guidelines (DWAF, 2006b), the mixing ratio, the receiving stream concentration, C_s, and the desired maximum instream concentration, C_R(in catchments or subcatchments where the RQOs have not been determined), have to be calculated separately for toxic substances and system variables.

Toxic substances

For toxic substances, e.g. metals, the mixing ratio is determined by using the 5th percentile flow for the driest month of the year, Q_s, and the design capacity of the facility, Q_w. The receiving instream concentration, C_s, is determined using the recommended standards in Table 3.17 or zero (0). For catchments or subcatchments without gazetted RQOs, the desired maximum instream concentration, C_R, is to be calculated using South Africa Water Quality Guidelines (SAWQG), as shown in Table 3.18.

Table 3.17: End-of-pipe discharge standards for water quality constituents (DWAF, 2006b)

							Recommended standard	
Constituents	**Units**	**EGS**	**ESS**	**SDV**	**RRDV**	**MARDV**	**Short term**	**Long term**
Aluminium	mg ℓ^{-1}	-	-	0.045	0.281	0.315	0.28	0.28
Arsenic	mg ℓ^{-1}	0.5	0.1	0.05	0.244	0.273	0.24	0.24
Cadmium	mg ℓ^{-1}	0.05	0.05	0.01	0.011	0.013	0.01	0.01
Chlorine	mg ℓ^{-1}	0.1	0		0.056	0.063	0.063	0.056
Chrome iii	mg ℓ^{-1}	0.05	0.5	0.005	1.913	2.142	0.5	0.5
Chrome vi	mg ℓ^{-1}			0.005	0.375	0.420	0.05	0.05
Copper	mg ℓ^{-1}	1.0	0.02	0.01	0.009	0.010	0.01	0.01
Cyanide	mg ℓ^{-1}	0.5	0.5	0.03	0.206	0.231	0.21	0.2
Fluoride	mg ℓ^{-1}	1.0	1.0	0.1	1.350*	1.500*	1.0	1.0
Lead	mg ℓ^{-1}	0.1	0.1	0.05	0.013	0.015	0.015	0.013
Manganese	mg ℓ^{-1}	0.4	0.1	0.261	0.580*	4000*	0.4	0.4
Mercury	mg ℓ^{-1}	0.02	0.02	0.01	0.003	0.004	0.004	0.003
Phenol	mg ℓ^{-1}	0.1	0.01	-	0.938	1.050	0.1	0.1
Selenium	mg ℓ^{-1}	0.05	0.05	0.1	0.169	0..189	0.05	0.05
Zinc	mg ℓ^{-1}	5	0.3	0.098	0.68	0.076	0.076	0.068
Iron	mg ℓ^{-1}	-	0.3	1.87	-	-	0.3	0.3
Boron	mg ℓ^{-1}	1.0	0.5	0.288	-	-	1.0	1.0
Sulphides	mg ℓ^{-1}	1.0	0.05	-	-	-	1.0	1.0
COD	mg ℓ^{-1}	75	30	50	94	122	75	75
Suspended solids	mg ℓ^{-1}	25	10	15	33	37	25	25
pH		5.5 to 9.5	5.5 to 7.5	7.5 to 8.0	6.0 to 9.0	6.0 to 9.0	6.0 to 9.0	6.0 to 9.0
Temperature	^{o}C		25	-	35	39	35	35
Orthophosphate	mg ℓ^{-1}	-	1.0	0.8	0.60	0.90	0.8	0.6
TDS	m^{S}/m above intake	75	15%		90	190	75	75
Nitrate/nitrate	mg ℓ^{-1}	-	1.5	7.0	15*	20*	15	20
Ammonia	mg ℓ^{-1}	10.0	1.0	2.0	11.6	27	10	10

*Domestic use determines value.

EGS = Existing general standards; ESS = Existing special standards; MARDV = Maximum allowable resource-directed value; RRDV = Recommended resource-directed value; SDV = Source-directed value

Table 3.18: Determination of generic RQO for freshwater ecosystems based on the SAWQG

Category A (Ideal)	1.25 TWQR (target water quality range)
Category B (Acceptable)	1.0 CEV (chronic effect value)
Category C (Tolerable)	1.25 AEV (acute effect value)
Category D (Unacceptable)	1.40 AEV

System variables

For system variables, the mixing ratio is determined by using the average daily flow for the 5th percentile year, Q_s (i.e. the total flow for the driest year on record ÷ 365), and the design capacity of the treatment facility, Q_w (DWAF, 2006b). The receiving instream concentration, C_s, is determined using the long-term record of reference condition for the receiving water resource. The median value of the low flow periods is used as the C_s.

Some reflections on the approach of DWAF (2006b) to setting end-of-pipe discharge standards

The approach of DWAF (2006b) in determining end-of-pipe discharge standards can be considered as being sufficiently robust as it considers critical parameters such as flows, mixing ratio, receiving resource instream concentrations, the resource management class, as well as the RQO. However, several aspects regarding the approach deserve further consideration and interrogation. These are outlined below:

- The approach does not take into account the differences between conservative and non-conservative variables, even though the former are non-easily degradable and are less affected by biological processes so that their concentrations are only reduced by dilution compared to the latter that are affected by biological processes.
- The approach does not seem to consider upstream waste loads, which is particularly important in heavily used catchments such as the Vaal Barrage catchment and associated rivers.
- The approach does not account for the potential contribution of diffuse sources to the waste loads. In catchments such as the Vaal, where diffuse sources contribute significantly to the system's waste loads, it may become difficult to improve instream resource quality, even though point source dischargers are meeting their effluent discharge standards.
- The receiving stream concentration for toxic substances is set at zero (0) for toxic substances and reference conditions for system variables. These criteria may be considered unrealistic in heavily used catchment, where the gazetted REC is set below Category B.

3.9 CONCLUSION

The review presented here briefly outlines the practices currently being undertaken in relation to RDM and SDC in South Africa. The review shows that commendable progress has been made with regard to methods development and approaches. The area that needs urgent attention is the control of diffuse pollution sources and further refinement of the methods for setting end-of-pipe discharge standards.

CHAPTER 4: DECISION SUPPORT SYSTEMS, WATER QUALITY MODELLING AND THE WATER QUALITY SIMULATION ASSESSMENT MODEL

4.1 INTRODUCTION

Integrated water resource management, as a paradigm, explicitly demands the integration of multiple ecological, social and economic perspectives. Therefore, any tool derived for facilitating IWRM should be through the participation of a wide range of stakeholders. In the case of a decision support system for the negotiation of water quality license conditions, as in the case of the present study, a tool should be developed to facilitate stakeholder participation. The common attributes of a DSS include facilities for providing system integration, deriving operational guidelines, and implementing sensitivity analysis and risk assessment (Andreu at al., 1996). Another important attribute is the ability to support the stakeholder participation and negotiation process (Pedro-Monzonís et al., 2016). Key features of a DSS to allow effective participatory modelling, outlined by Basco-Carrera at al. (2017), include a focus on the goals of the decision makers and stakeholders, a user-friendly interface and visualisation capacities, and the ability to allow effective stakeholder model interactions. Importantly, a DSS should improve the understanding of a water resource system and provide a way of conceptualising the uncertainties within the decision-making process (Haasnoot et al., 2014; Jakeman and Letcher, 2003; Loucks et al., 2005; Refsgaard et al., 2005). Ultimately, a DSS should communicate modelling outputs in a manner that is transparent and understandable to all stakeholders, including those without a background in science or engineering, to facilitate a common understanding of a water resource system. Finally, ideally, the software used to construct the DSS should be free and open-source to allow the wide distribution and use of the DSS among stakeholders, and the continual and transparent community development of the DSS. In summary, the main attributes of a water-quality-licensing DSS for facilitating participatory modelling can be summarised as follows:

- It should be developed through wide-ranging consultation with multiple stakeholders, experts and decision makers.
- There should be a transparent process of DSS development, with scientific rigour and credibility.
- There should be an integration of flow and water quality.
- It should provide an indication of the sensitivity of the system to pollutant inputs.
- It should provide a measure of risk of pollutant inputs that exceeds the threshold of probable concern (TPCs), typically RQOs, along with the uncertainties in this measure.
- It should support stakeholder negotiation.
- It should allow the exploration of pollutant loading and dilution (flow) scenarios.
- It should focus on the goals of decision makers and stakeholders.
- It should have a user-friendly interface and visualisation capabilities.
- It should facilitate a common understanding of the system among all stakeholders, including those without a scientific or engineering background.
- It should be open source and free, developed in a language that is well supported under current computing technologies and placed on an online platform to allow community development, such as GitHub.

The Water Quality System Assessment System has been developed in response to identified gaps in water quality modelling to support decision making in South Africa, and was implemented in this study as a DSS to facilitate water quality licensing in the Vaal Barrage region.

4.2 CONCEPTUAL MODEL OF WQSAM

The WQSAM can be conceptually described as consisting of various tiers or layers (Figure 4.1). Each tier requires a certain degree of user interaction to set up a WQSAM model application. The WQSAM takes the same node link structure as the established yield models, where a node represents a catchment element, such as a reservoir, a river junction or some sort of demand node, such as irrigation or a major water demand, whereas the links between nodes represent channels through which there is directed flow between the nodes, and can represent a natural channel or water diversion channel. With regard to the bottom-most tier (A in Figure 4.1), WQSAM forms part of the Spatial Time Series and Information Modelling (SPATSIM) platform. SPATSIM allows a geographic information systems (GIS)-type representation of a modelled catchment, and the first step in establishing a WQSAM setup would be to recreate yield model nodes in SPATSIM. One would use a yield model systems diagram to determine the nodes and their links. Once the nodes are established in SPATSIM, WQSAM allows the user to link nodes in the yield model with the corresponding nodes in SPATSIM. The yield model flow outputs and model parameters are then uploaded to relevant attributes in SPATSIM.

The WQSAM simulates water quality at a daily time step, as processes affecting water quality, such as rainfall runoff, typically operate at a small temporal resolution (think of a rainstorm event, for example). However, the yield models typically operate at a monthly time step. To overcome this challenge, the developers of WQSAM incorporated a monthly-to-daily flow disaggregation routine. This is represented by Tier B in Figure 4.1.

The WQSAM represents the input of loads from non-point sources such as irrigation. To achieve this, WQSAM recognises that rainfall runoff is the primary transport mechanism of non-point loads into a river system, and that this flow medium consists of both surface and subsurface components, which may have very different water quality signatures. The daily-to-monthly flow disaggregation routine described above disaggregated monthly incremental flows (effective estimates of natural flow) into daily incremental flows. Tier C in Figure 4.1 provides a routine for separating daily incremental flow into the individual flow components using a baseflow separation technique (Hughes et al., 2003). These flow fractions are assigned water quality signatures (concentrations) within WQSAM to represent non-point source load inputs.

The WQSAM generates daily cumulative flows by adding up daily incremental flows from upstream to downstream flows, taking into account daily abstractions, return flows, reservoir storage and evaporation. However, some user input is required for this component of WQSAM, for example, stipulating the approach taken for disaggregating monthly evaporation and monthly reservoir releases to daily flows and implementing some sort of routing of flow downstream. This is represented by Tier D in Figure 4.1.

The actual water quality simulations occur in Tier E in Figure 4.1, and include routines for simulating water temperature, salinity, nutrients, microbial water quality, and sediment transport and metals, which have been included in the course of this project. The WQSAM provided the capacity to simulate water quality both in river reaches and in reservoirs, and this tier includes processes such as point and non-point source pollutant loading and instream water quality processes such as algal growth and nitrification.

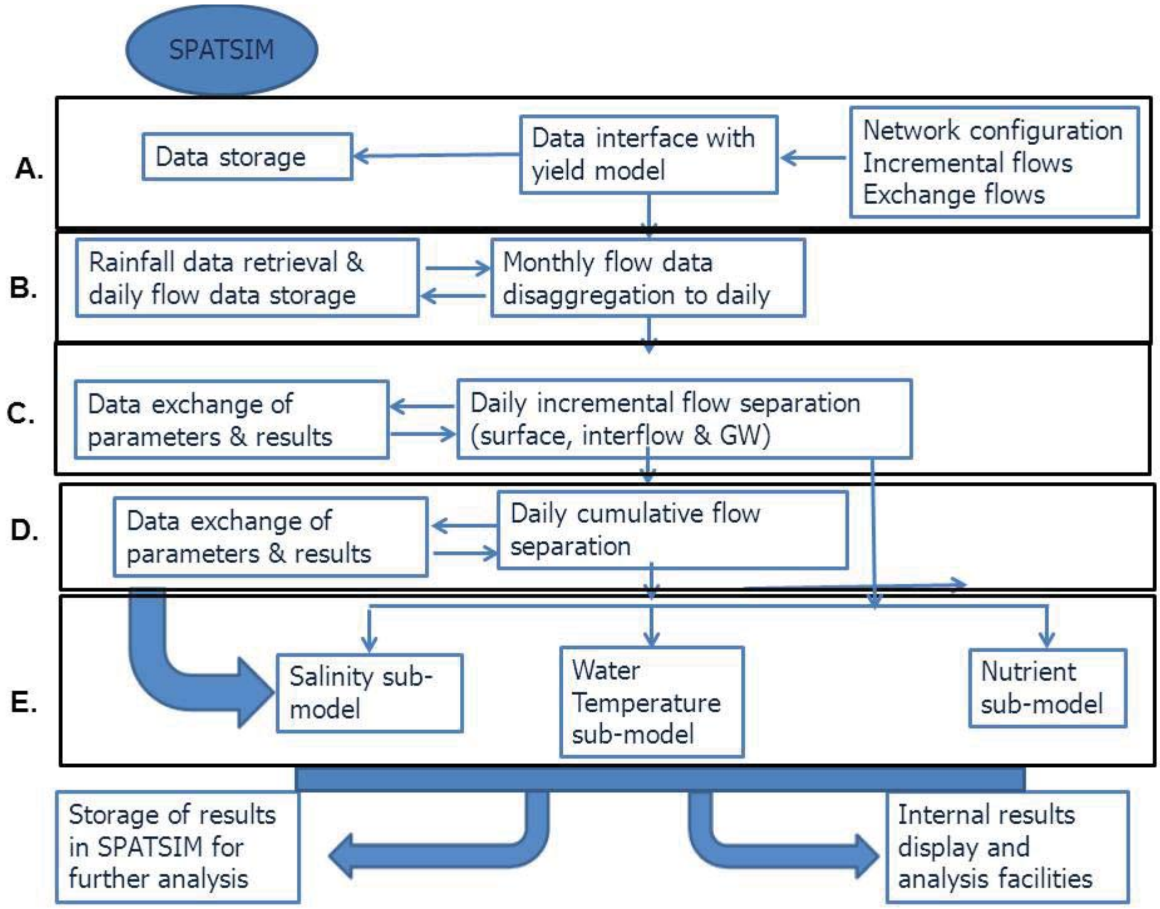
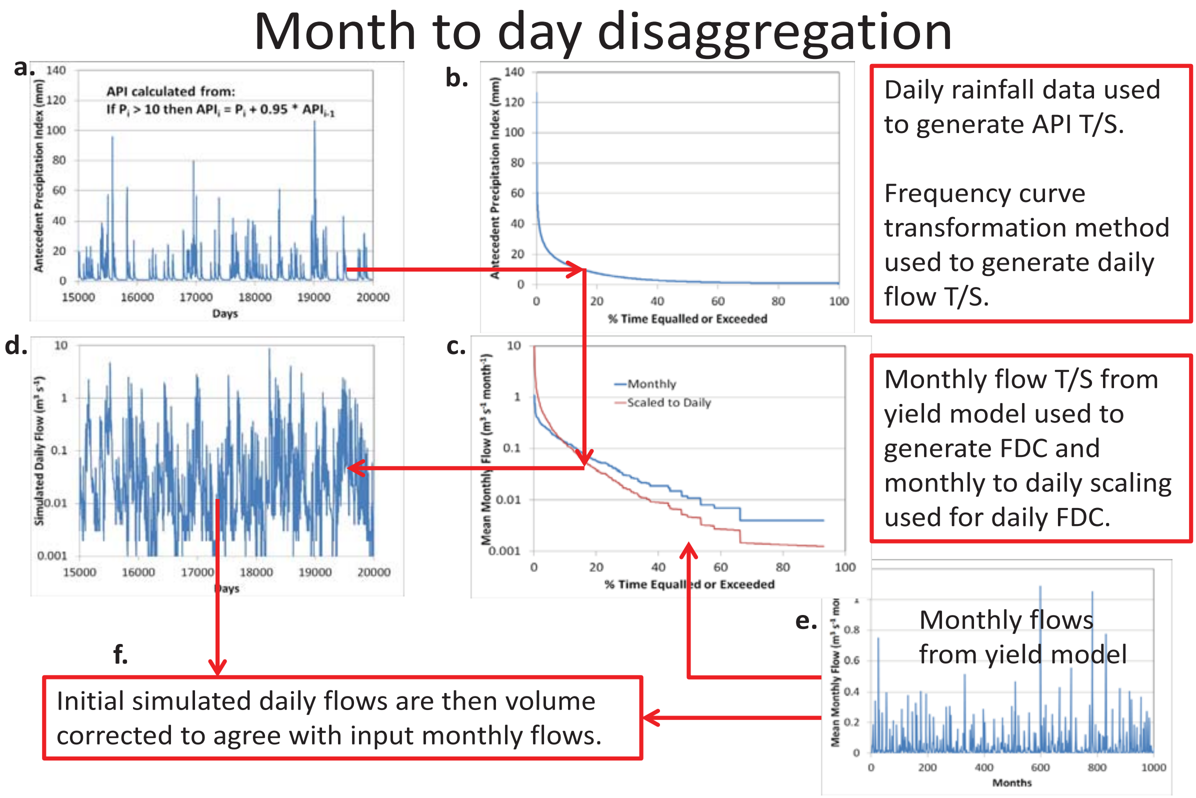


Figure 4.1: Conceptual representation of the model components in the WQSAM: Tier A: Input of the Water Resources Modelling Platform (WReMP) output data and storage to the modelling framework SPATSIM system, and replication of the nodal structure from the WReMP to WQSAM and SPATSIM. Tier B: Disaggregation of simulated monthly incremental flow to daily flow and storage to SPATSIM. Tier C: Base flow separation of simulated daily incremental flow to the flow components' surface water flow, interflow and ground water flow. Tier D: Disaggregation of monthly cumulative flows to daily flows. Tier E: Water quality modelling components for salinity, water temperature and nutrients.

4.3 A DESCRIPTION OF THE WQSAM FUNCTIONALITY AS A DECISION SUPPORT SYSTEM

4.3.1 Hydrological (flow) functionality

Although WQSAM is a water quality decision support system, the functions provided in this model also provide an aspect of decision support for flow. The yield model provides estimates of flows at a monthly time step. Included are estimates of incremental flow (natural flow), which are typically derived from the Pitman Model (Pitman, 1973; Hughes, 2004; Hughes et al., 2010). The WQSAM allows a routine to disaggregate monthly incremental flows to daily flows. A conceptual representation of the routine is shown in Figure 4.2.



Month to day disaggregation

Daily rainfall data used to generate API T/S.

Frequency curve transformation method used to generate daily flow T/S.

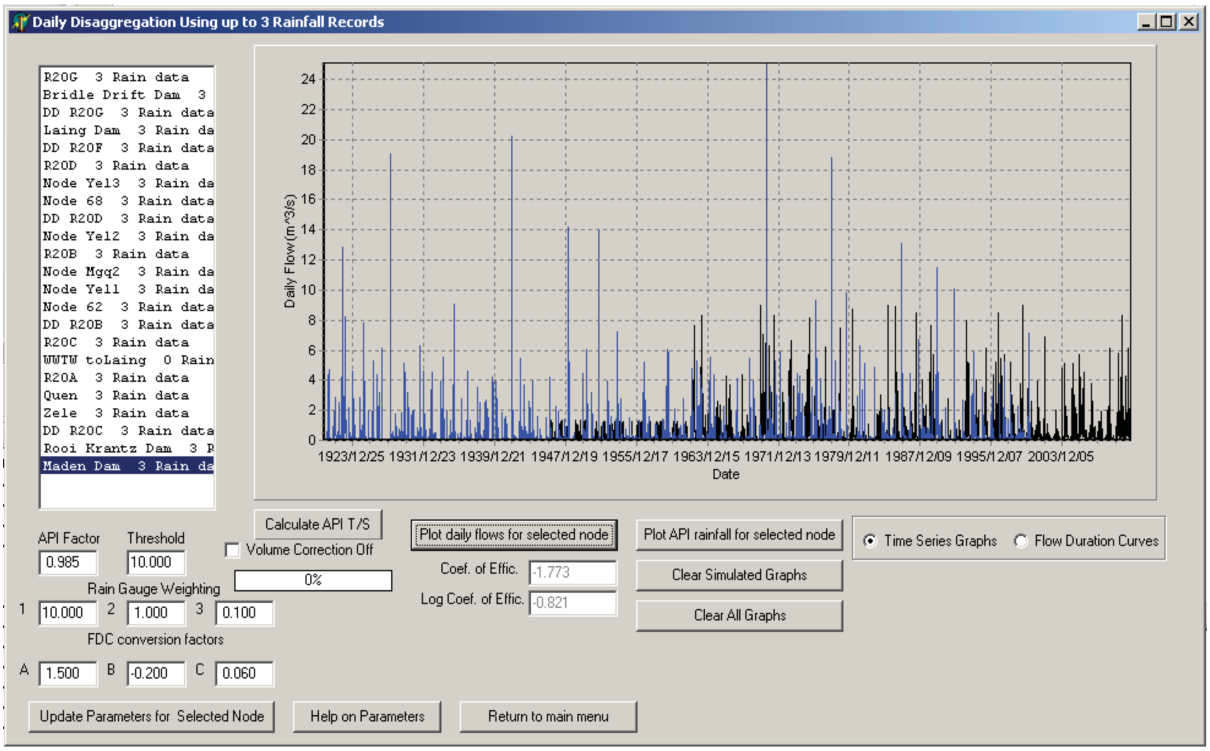
Monthly flow T/S from yield model used to generate FDC and monthly to daily scaling used for daily FDC.

Monthly flows from yield model

Initial simulated daily flows are then volume corrected to agree with input monthly flows.

Figure 4.2: A conceptual representation of the monthly-daily flow disaggregation process implemented in WQSAM

The WQSAM uses the time series and frequency distribution of antecedent daily rainfall to disaggregate monthly flow to daily flow. Antecedent daily rainfall refers to daily observed rainfall that has been adjusted to account for preceding rainfall events, with the underlying knowledge that increased rainfall runoff occurs if the soil already contains moisture from previous rainfall events. The procedure has already been published in multiple scientific journals (Hughes and Slaughter, 2015; Hughes and Slaughter, 2016; Slaughter et al., 2015). WQSAM provides an easy-to-use interface for the input of parameters for the disaggregation routine, and users can plot the daily flows as a time series or frequency distribution (see Figure 4.3).



```
R20G   3 Rain data
Bridle Drift Dam   3
DD R20G   3 Rain data
Laing Dam   3 Rain da
DD R20F   3 Rain data
R20D   3 Rain data
Node Yel3   3 Rain da
Node 68   3 Rain data
DD R20D   3 Rain data
Node Yel2   3 Rain da
R20B   3 Rain data
Node Mgq2   3 Rain da
Node Yel1   3 Rain da
Node 62   3 Rain data
DD R20B   3 Rain data
R20C   3 Rain data
WWTW toLaing   0 Rain
R20A   3 Rain data
Quen   3 Rain data
Zele   3 Rain data
DD R20C   3 Rain data
Rooi Krantz Dam   3 R
Maden Dam   3 Rain da
```

API Factor 0.985

Threshold 10.000

☐ Volume Correction Off

0%

Rain Gauge Weighting

1 10.000 2 1.000 3 0.100

FDC conversion factors

A 1.500 B -0.200 C 0.060

Coef. of Effic. -1.773

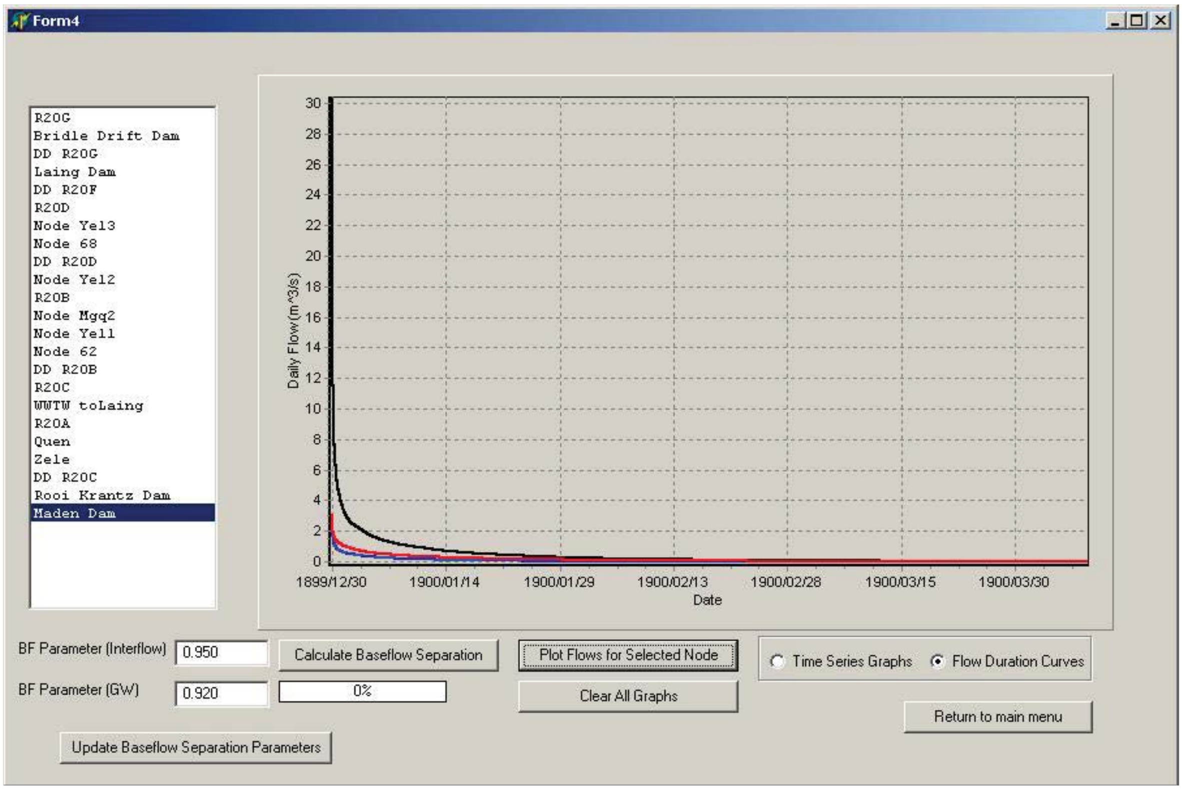
Log Coef. of Effic. -0.821

● Time Series Graphs ○ Flow Duration Curves

Figure 4.3: A screenshot of the user interface to implement monthly-daily flow disaggregation in the WQSAM

Estimates of daily incremental flows may be of use outside the water quality modelling function provided by WQSAM, e.g. estimating extremes in rainfall runoff at a low temporal resolution that would not be represented in the monthly incremental flows. This could have application in various forms of water research, such as simulating additional water quality variables not represented in WQSAM, e.g. pesticides.

The WQSAM also disaggregates daily incremental flows into surface flow, interflow and groundwater flow via a simple statistical baseflow separation technique (Hughes et al*.,* 2003). An easy-to-use user interface within WQSAM, in which the relevant parameters can be input and in which the time series or frequency distribution of flow fractions can be viewed, is shown in Figure 4.4.



BF Parameter (Interflow) 0.950

BF Parameter (GW) 0.920

○ Time Series Graphs ● Flow Duration Curves

Figure 4.4: A screenshot of the user interface to implement disaggregation of daily incremental flow into flow fractions in the WQSAM

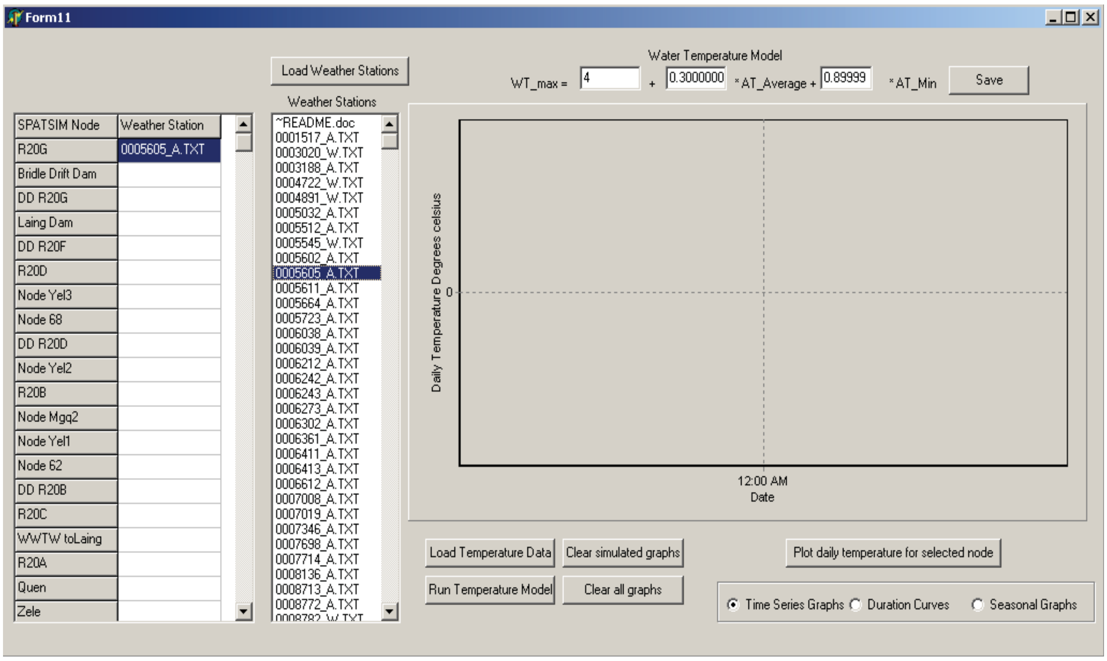
Finally, WQSAM effectively provides a daily time-step version of the monthly yield model by disaggregating monthly incremental flows to daily flows and disaggregating monthly abstractions, return flows and reservoir evaporation, and releases to daily flows, thereby effectively providing an estimate of daily cumulative flow in the modelled catchment.

The usefulness of this facility cannot be understated. Yield modelling in South Africa has been constrained by the fact that, traditionally, hydrological modelling and water management for flow has generally been implemented at a monthly time scale, as this was regarded as sufficient for water resource management in South Africa. An additional constraint is the computing resources required to run a daily time-step yield model. However, emerging challenges, such as a changing climate that may see an increase in flow extremes, may provide justification for water resource planning on a finer temporal scale. The flow disaggregation technique provided by WQSAM provides a less resource-intensive method of converting monthly flows to daily flows, while still allowing established monthly time-step yield models to remain in use.

4.3.2 Simulation of water temperature

Besides water temperature being a stressor to the aquatic environment (Dallas and Ross-Gillespie, 2015), water temperature is an important rate moderator of various important water quality processes (Chapra, 1997). Therefore, it was considered important to model water temperature in WQSAM. In accordance with the overall strategy of simple water quality modelling using the available limited observed water quality data, a relatively simple approach of water temperature modelling was identified. WQSAM essentially uses the approach of Rivers-Moore et al. (2008), which uses multiple linear regression (MLR) models, where the predictor variables are mean and minimum air temperatures. Although other factors, such as flow and relative humidity, have been found to have significant effects on water temperature in other regions of the world, the relatively extreme hydrological conditions of South African rivers result in these factors having less of an effect.

Since daily air temperature data is relatively accessible for South Africa, such as the consolidated database of Schulze and Maharaj (2004), WQSAM adopted this simple approach of simulating water temperature. WQSAM allows the user to link to the weather station data in the database of Schulze and Maharaj (2004) and to link stations to nodes in the modelled system. The user is able to input parameters into the multiple linear regression and then plot the resulting water temperature simulation against available observed water temperature on a time series, frequency distribution and seasonal distribution basins, thereby allowing the user to “calibrate” the MLR model (Figure 4.5).



WT_max = 4 + 0.3000000 *AT_Average + 0.89999 *AT_Min

● Time Series Graphs ○ Duration Curves ○ Seasonal Graphs

SPATSIM Node	Weather Station
R20G	0005605_A.TXT
Bridle Drift Dam	
DD R20G	
Laing Dam	
DD R20F	
R20D	
Node Yel3	
Node 68	
DD R20D	
Node Yel2	
R20B	
Node Mgq2	
Node Yel1	
Node 62	
DD R20B	
R20C	
WWTW toLaing	
R20A	
Quen	
Zele	

~README.doc
0001517_A.TXT
0003020_W.TXT
0003188_A.TXT
0004722_W.TXT
0004891_W.TXT
0005032_A.TXT
0005512_A.TXT
0005545_W.TXT
0005602_A.TXT
0005605_A.TXT
0005611_A.TXT
0005664_A.TXT
0005723_A.TXT
0006038_A.TXT
0006039_A.TXT
0006212_A.TXT
0006242_A.TXT
0006243_A.TXT
0006273_A.TXT
0006302_A.TXT
0006361_A.TXT
0006411_A.TXT
0006413_A.TXT
0006612_A.TXT
0007008_A.TXT
0007019_A.TXT
0007346_A.TXT
0007698_A.TXT
0007714_A.TXT
0008136_A.TXT
0008713_A.TXT
0008772_A.TXT
0008782_W.TXT

Figure 4.5: A screenshot of the user interface to implement water temperature modelling in the WQSAM

The database of daily air temperature by Schulze and Maharaj (2004) runs from 1950 to 2000, which limits the applicability of the model to more recent historical simulations, unless actual observed and unbroken air temperature data exists for the modelled catchment. However, the WQSAM allows the user to input average monthly water temperatures as a way of circumventing this problem. These can be estimated through expert knowledge or observed data for the modelled catchment or a representative catchment close. The outputs of the Global Circulation Model (GCM) usually include estimates of daily air temperature, which allow this approach to estimate water temperature under future scenarios.

4.3.3 Impact of point sources on water quality

Point sources are very simplistically modelled in WQSAM. Essentially, the WRYM (Water Resources Yield Model) or WReMP provides estimates of monthly return flows from industry or WWTWs, which are regarded as point sources in WQSAM. The WQSAM allows the user to disaggregate the monthly return flows to daily flows by uniformly dividing the total monthly return flow by the days in the month, or alternatively randomly distributing the total monthly return flow among the days in the month. A study by Slaughter and Hughes (2013) found that both the flow rates and effluent concentrations from WWTWs tended to be highly random, possibly because of inconsistently managed and overloaded WWTWs.

The daily effluent return flows are then assigned a water quality “signature” for each modelled water quality variable, which is effectively a concentration (mg ℓ^{-1}). These signatures can be informed by any observed data available for wastewater effluent quality, and the user can calibrate the signatures against instream water quality as part of the general water quality modelling process.

In this way, WQSAM can identify the progressive effects of effluent release from upstream to downstream, and attribute the contribution of individual effluent producers to overall instream water quality. Modelling “what-if” scenarios can also be investigated by changing the effluent flow rate or water quality signatures. So, for example, the model can investigate the water quality consequences of additional polluters, the implementation of improved water treatment technology or the increase in capacity of WWTWs.

4.3.4 The impact of non-point sources on water quality

Non-point source inputs of pollutant loads are much more difficult to model compared to point-source inputs. Essentially, as mentioned in Section 4.3.1, WQSAM disaggregates daily incremental flow into surface flow, interflow and groundwater flow fractions. Incremental flow represents runoff from the catchment, which would be the primary medium of transport of non-point pollutant loads into a river. To simulate the water quality impacts of non-point loads, the user essentially assigns water quality signatures for each water quality variable modelled, which is essentially a concentration (mg ℓ^{-1}), to each flow fraction. One could rely on model calibration against available observed instream water quality data to set these water quality signatures, but there are several factors that make this approach highly uncertain: most positions in a modelled catchment would not have observed data available against which to calibrate model simulations, and it is difficult to separate non-point impacts on instream water quality from the myriad of other processes that affect instream water quality.

To reduce the aforementioned uncertainty, a link between land cover and the water quality signatures of non-point sources was made. Land cover and land use are the primary influencers of non-point source inputs into a river. The link between these water quality signatures and land cover was done through statistical models, and is summarised in Slaughter and Mantel (2013).

Briefly, regionalised MLR models between land cover classes and water quality signatures for surface water flow were established. It was assumed that regional characteristics of catchments would affect these relationships, so regions were divided according to the biome classification of Low and Rebelo (1996), which divides South Africa into forest, fynbos, grassland, Nama Karoo, savanna, succulent Karoo and thicket biomes. Land cover is as according to the South African Land Cover Dataset (Van den Berg et al., 2008). Statistical relationships between the proportions of different land cover categories (according to total surface area covered within a modelled catchment) and the surface water flow water quality signatures for nutrients were determined using MLR for both a 100 m buffer zone and the entire catchment area.

The land cover categories represented in the model are as follows:

A: Bare rock and soil

B: Cultivated dryland

C: Cultivated irrigated

D: Sugar cane

E: Natural areas

F: Mining areas

G: Water bodies

H: Urban areas

I: Degraded natural areas

J: Forest

To determine the surface water flow water quality signature, the following equation is used:

$$SF = (\alpha \times A) + (\beta \times B) + (\gamma \times C) + (\delta \times D) + (\varepsilon \times E) + (\zeta \times F) + (\eta \times G) + (\theta \times H) + (\iota \times I) + (\kappa \times J), \qquad \text{Equation 4.1}$$

where *SF* represents the surface flow concentration ($\text{mg } \ell^{-1}$), A to J represent the land cover category fractions, and α to κ represent the regression parameters (Table 4.1).

Table 4.1: The parameters associated with Equation 4.1 and representative land cover categories

Parameter	Land cover category
α	Bare rock and soil
β	Cultivated dryland
γ	Cultivated irrigated
δ	Sugar cane
ε	Natural
ζ	Mining
η	Water bodies
θ	Urban
ι	Degraded natural

Table 4.2: Parameters derived for multiple regression in Excel using the equation format given in Equation 3.1. Parameters were estimated using Solver.

	NO_2-N + NO_3-N		NH_4-N		PO_4-P	
Parameter	**Full**	**Buffer**	**Full**	**Buffer**	**Full**	**Buffer**
Fynbos biome						
α	0.000	0.000	0.000	0.000	0.000	0.000
β	4.738	1.717	0.284	0.155	0.000	0.000
γ	0.000	0.000	2.295	0.384	0.449	0.000
δ	0.000	0.000	0.000	0.000	0.000	0.000
ε	0.016	0.015	0.064	0.063	0.033	0.033
ζ	0.000	0.000	0.000	0.000	0.000	0.000
η	0.000	0.000	1.204	0.901	0.613	0.626
θ	17.245	30.793	0.961	1.452	13.918	4.239
ι	0.000	0.000	0.000	0.000	0.000	0.000
κ	1.622	1.600	0.101	0.100	0.071	0.070
Grassland biome						
α	0.000	0.000	0.000	0.000	0.000	0.283
β	0.000	0.000	0.000	9.687	0.000	0.000
γ	2060.067	0.000	107.856	0.000	733.146	0.000
δ	0.000	0.000	0.000	0.000	0.000	0.000
ε	0.000	0.000	0.000	0.000	0.000	0.031
ζ	0.000	0.000	0.000	0.000	0.000	0.000
η	0.000	0.000	0.000	1.107	0.000	0.000
θ	89.985	498.141	37.021	102.480	41.886	266.912
ι	0.000	69.364	0.000	0.000	0.000	0.000
κ	0.000	2901.192	0.000	0.000	0.000	16.489

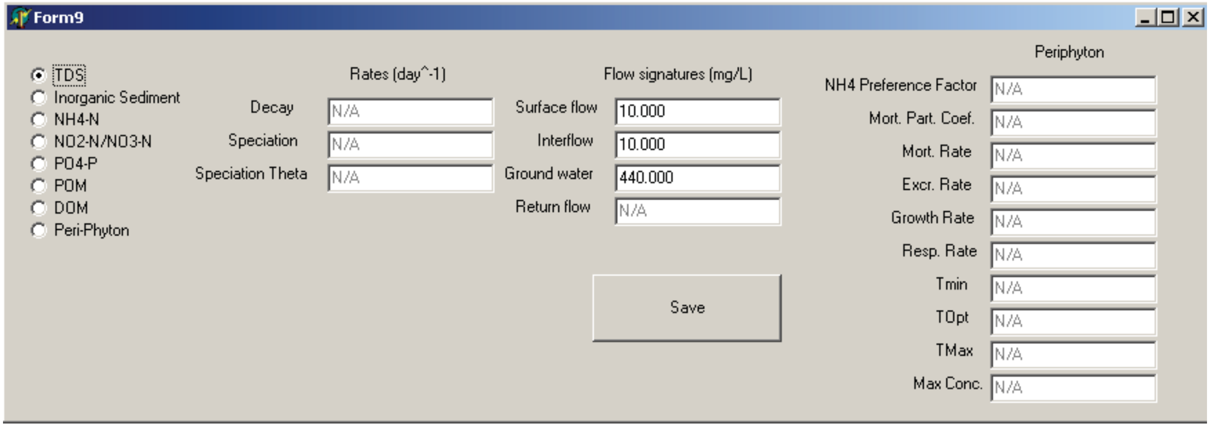
Table 4.3: Continued parameters derived for multiple regression in Excel using the equation format given in Equation 3.1. Parameters were estimated using Solver.

	NO_2-N + NO_3-N		NH4-N		PO4-P	
Parameter	**Full**	**Buffer**	**Full**	**Buffer**	**Full**	**Buffer**
Savanna biome						
α	0.000	0.000	0.000	0.000	0.000	0.000
β	0.000	0.000	0.000	0.000	0.000	0.000
γ	0.000	48.088	0.000	1.551	0.000	1.130
δ	0.000	0.000	0.000	0.000	0.000	0.000
ε	1.416	0.074	0.085	0.232	0.214	0.197
ζ	0.509	0.000	69.623	0.000	9.732	0.000
η	0.000	2.380	0.000	0.000	0.000	0.000
θ	0.000	3.463	0.000	6.216	0.000	0.940
ι	71.213	74.864	0.000	0.000	0.000	0.000
κ	0.000	0.000	0.747	0.041	0.131	0.000
Thicket biome						
α	0.000	0.000	0.000	0.000	0.000	0.371
β	0.000	0.000	0.000	0.000	0.069	0.199
γ	0.000	0.000	0.000	1.288	28.682	7.871
δ	0.000	0.000	0.000	0.000	0.353	0.111
ε	2.881	0.288	0.288	0.035	0.000	0.091
ζ	0.000	0.000	0.000	0.000	0.000	0.000
η	710.856	1.339	1.339	9.382	0.000	0.000
θ	0.000	1.453	1.453	6.612	0.697	19.555
ι	0.000	0.000	0.000	0.000	0.062	0.000
κ	0.395	0.004	0.004	0.563	0.000	0.120

Essentially, the WQSAM user needs to determine in which biome the modelled catchment occurs and the proportion of different land cover categories in the modelled catchment in terms of area covered, and then apply Equation 4.1 using the values for the parameters listed in Table 4.2.

Simulation of conservative water quality variables

By definition, conservative water quality variables do not change their chemical form throughout their life cycles. In WQSAM, conservative water quality variables are modelled considering only the processes of point and non-point inputs, evaporation, extraction and dilution. The explicit conservative water quality variables modelled are TDS as a generic measure of salinity and sulphates. However, for this project, WQSAM has been updated to include the simulation of additional salts, which can be included explicitly by name or as generic variables that the user assigns to conservative water quality variables of interest. The process described here for point and non-point inputs of conservative water quality variables also apply to non-conservative water quality variables, and so will not be repeated in the subsequent section. As mentioned in the previous section, incremental flows in WQSAM are divided into surface water, interflow and groundwater flows. WQSAM then allows the user to set water quality signatures for each flow fraction and each water quality variable in mg ℓ^{-1} (Figure 4.6).



● TDS
○ Inorganic Sediment
○ NH4-N
○ NO2-N/NO3-N
○ PO4-P
○ POM
○ DOM
○ Peri-Phyton

Rates (day^-1)
Decay: N/A
Speciation: N/A
Speciation Theta: N/A

Flow signatures (mg/L)
Surface flow: 10.000
Interflow: 10.000
Ground water: 440.000
Return flow: N/A

Periphyton
NH4 Preference Factor: N/A
Mort. Part. Coef.: N/A
Mort. Rate: N/A
Excr. Rate: N/A
Growth Rate: N/A
Resp. Rate: N/A
Tmin: N/A
TOpt: N/A
TMax: N/A
Max Conc.: N/A

Figure 4.6: A screenshot of the user interface to input water quality signatures for flow fractions in WQSAM

In Figure 4.6, the fields for the flow fraction signatures for TDS are clearly visible. For conservative variables such as salts, groundwater usually has distinctively different signatures to surface water. The appropriate signature may be guided by any available borehole water quality data for the study area. Also visible in Figure 3.6 is the field for setting a return flow (point source) water quality signature if the node modelled, in fact, receives return flows. Any available water quality data for effluent water quality can be used to guide the setting of this signature. These signatures (for both point and non-point inputs) can also be used as part of the decision support process and to explore “what-if” scenarios, such as an improvement in the water quality of effluent, for example.

Simulation of non-conservative water quality variables

The processes for inputs of conservative water quality variables, i.e. point and non-point inputs, also apply to non-conservative water quality variables, and so will not be repeated here. Although WQSAM has attempted to represent the processes affecting non-conservative water quality variables as simplistically as possible, the processes remain complex. These processes include nitrification, the decomposition of organic matter and algal growth. The WQSAM contains a fairly large number of parameters to represent these processes. It is recommended that, for a modelled catchment, only modellers familiar with the software should set these parameters through model calibration, following which the parameters related to water quality load inputs, i.e. point and non-point inputs, can be changed during the decision support and scenario investigation process. However, the conceptual description of the processes that affect the non-conservative water quality variables represented in WQSAM is provided below, along with Figure 4.7 and Figure 4.8.

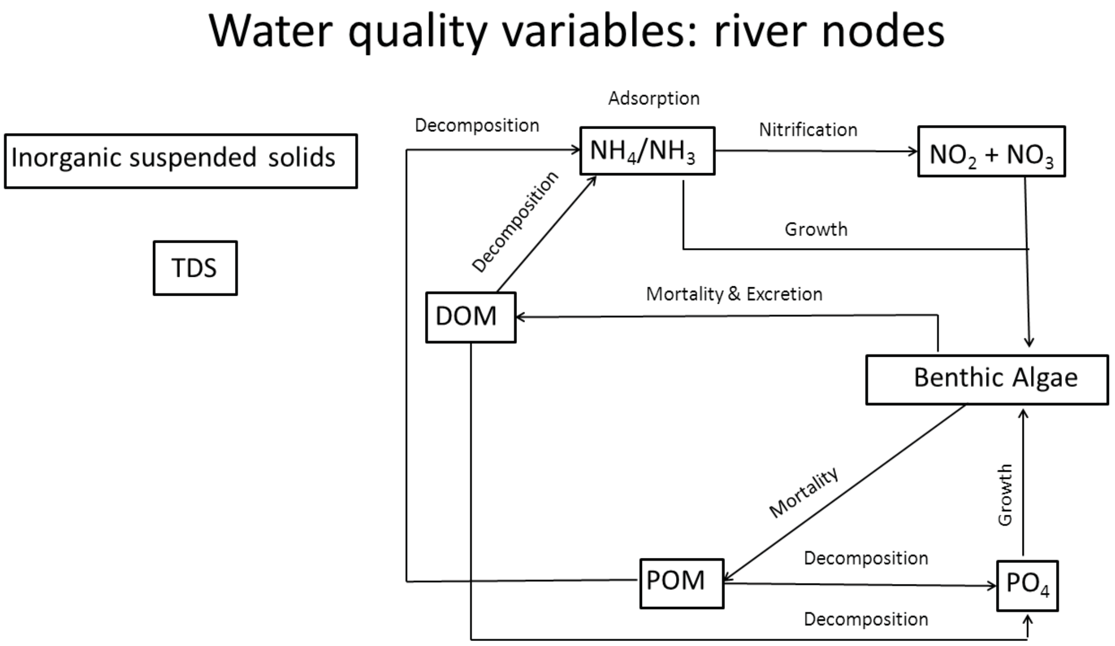


Figure 4.7: Conceptual representation of the in-river water quality processes represented in WQSAM

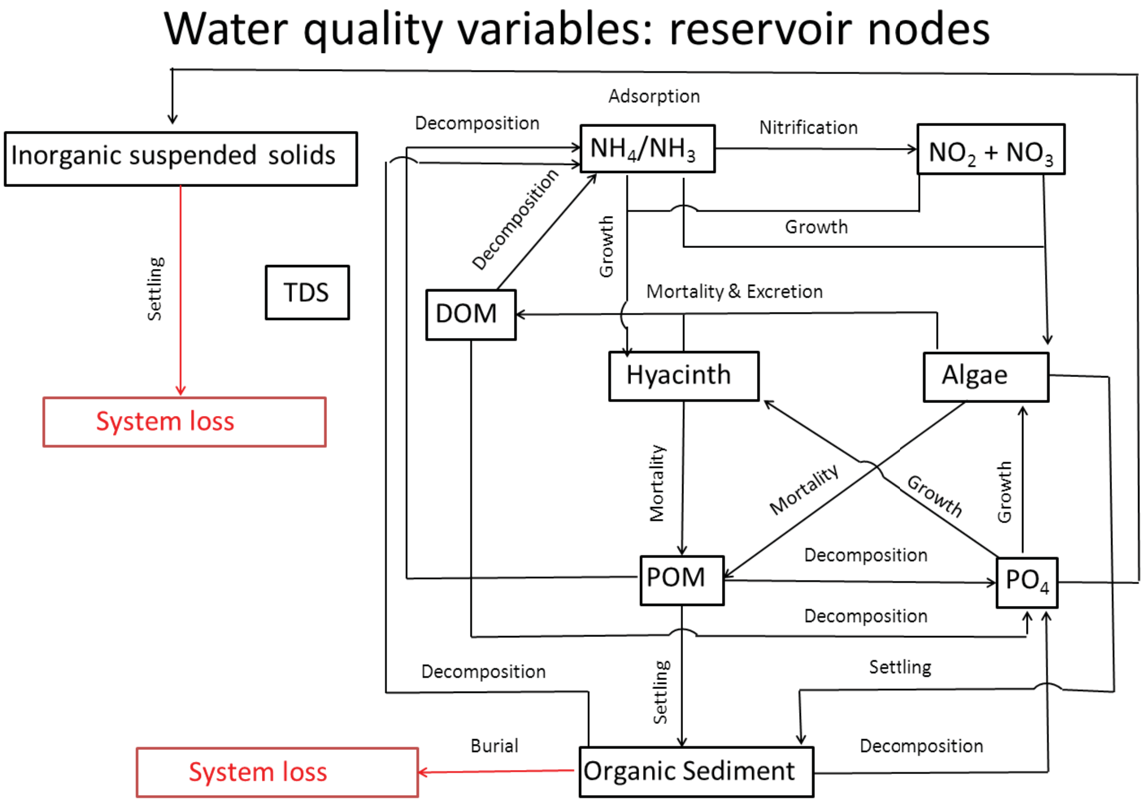


Figure 4.8: Conceptual representation of the reservoir water quality processes represented in WQSAM

Figure 4.7 represents the water quality processes that affect non-conservative variables in river nodes represented in WQSAM, and includes nitrification, the uptake of nutrients by algae and the decomposition of organic matter. Importantly, the figure shows how these processes are interlinked. As is evident in Figure 4.8, the water quality processes that affect non-conservative variables in reservoirs are more complex, and, in addition to the processes represented in the river nodes, include interaction with macrophytes such as hyacinth and organic sediment.

Microbial water quality

The modelling of microbial water quality can indicate important individual sources of contamination, thereby allowing the prioritisation of mitigation measures. The levels of a representative indicator organism are usually used as a measure of microbial water quality. In WQSAM, *Escherichia coli* was used as the indicator organism as it is a common measure internationally (Hipsey et al., 2008) and there is some limited observed data available for *E. coli* in South African surface waters. The WQSAM models *E. coli* in a relatively simplistic, but generally established way and considers the effects of temperature and salinity on the mortality of *E. coli*. Since WQSAM already simulates water temperature and salinity, the only parameter input required is a degradation rate, which can be set by calibrating simulated instream microbial water quality against observed data. It is recommended that a modeller who is familiar with water quality processes sets the degradation rate, after which users of the water license DSS only adjust the microbial treatment efficiencies of effluent to explore scenarios.

4.4 IMPORTANT UPDATE TO WQSAM IN RESPONSE TO THE PROJECT REQUIREMENTS

The application of WQSAM in the Vaal Barrage region raises awareness about the need to update the model to be able to simulate metals and important salts as stakeholders considered metals an important water quality variable to be managed in the catchment. In the Vaal Barrage region, heavy non-essential metals have been found to bioaccumulate in fish (Crafford and Avenant-Oldwage, 2010; Wepener et al., 2011). Stakeholders may also be interested in certain salts, as some salts are known to be more toxic than others, and simulating salts as a group, such as TDS, may not capture this toxicity. There is therefore value in adding simulation capacity to WQSAM for specific salts and toxic metals.

Simulation of salts

The capacity to simulate sulphates has already been implemented in WQSAM. Generally, the only water quality process considered by WQSAM for non-conservative water quality variables is dilution. While this has been found to be adequate in perennial systems, there are additional processes of salt precipitation and re-suspension that must be considered in ephemeral systems. The process of modelling additional specific salts in WQSAM can either be implemented by including variables for specific salts, or by including several generic “salt” variables, which the user will assign to salts of interest.

Simulation of metals

The simulation of metals is more complex, and in addition involves more parameters, which unfortunately increases the uncertainty of simulations. The equations were primarily taken from the seminal text of Chapra (1997) on water quality modelling. The modelling of metals will be according to two compartments (water and sediment) and two forms of metals (dissolved and particulate), and modelled with the assumption of complete stirring, i.e. a completely stirred tank reactor (Figure 4.9).

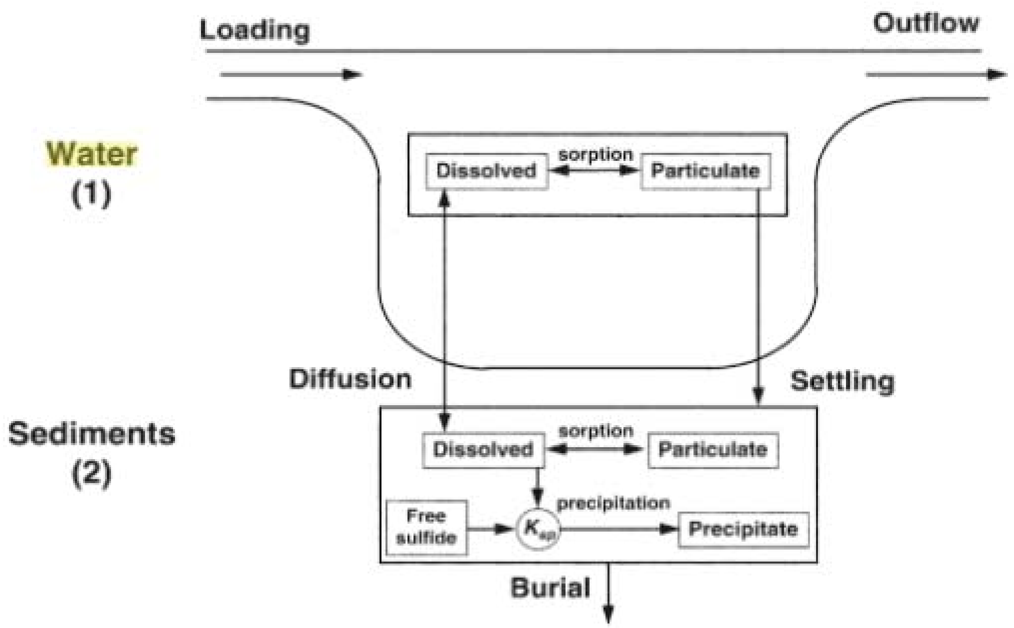


Figure 4.9: Water quality processes considered for modelling metals (taken from Chapra, 1997)

The equations used, as per Chapra (2007), are as follows:

$$V_1\ \frac{dc_1}{dt} = Q_{Cin} - Q_{C1} - v_s AFp_1 c_1 + v_r Ac_2 + v_d A(F_{d2c2} - F_{d1c1}) \qquad \text{(Equation 4.2)}$$

$$V_2\ \frac{dc_2}{dt} = v_s AFp_1 c_1 - v_r Ac_2 - v_b Ac_2 + v_d A(F_{d1c1} - F_{d2c2}), \qquad \text{(Equation 4.3)}$$

Where *t* is time (day), c_1 is the concentration in the water compartment ($\mu g\ \ell^{-1}$), c_2 is the concentration in the sediment compartment ($\mu g\ \ell^{-1}$), V_1 is the volume of water (m^3), V_2 is the volume of sediment, C_{in} is the inflow concentration ($\mu g\ \ell^{-1}$), *A* is the sediment surface area (m^2), v_s is the settling velocity ($m\ d^{-1}$), v_d is the sediment-water diffusion mass transfer coefficient ($m\ d^{-1}$), v_r is the re-suspension velocity ($m\ d^{-1}$), v_b is the burial velocity ($m\ d^{-1}$), F_{d1} is the dissolved fraction in the water compartment, F_{d2} is the dissolved fraction in the sediment compartment, F_{p1} is the particulate fraction in the water compartment and F_{p2} is the particulate fraction in the sediment compartment.

The particulate and dissolved fractions can be calculated as follows:

$$F_{d1} = 1 - F_{p1} = \frac{1}{1 + K_{d1} m}, \qquad \text{(Equation 4.4)}$$

$$F_{d2} = 1/(\emptyset + K_{d2}(1 - \emptyset)\rho), \qquad \text{(Equation 4.5)}$$

Where K_d is a partition coefficient ($m^3\ g^{-1}$), *m* is the suspended solids concentration ($g\ m^{-3}$), ρ is the sediment density ($g\ m^{-3}$) and $\emptyset$ is the sediment porosity. The large number of parameters requiring calibration are unfortunately a major source of uncertainty. It is proposed that, after implementation in WQSAM, common ranges for these parameters identified in the literature will be applied, and it will be assessed whether some of the parameters can be made constants or regionalised to reduce the parameter burden for the model user. Setting *m* might require the simulation of sediment transport, which has been implemented in WQSAM, but would impose additional modelling effort.

Although the method of DWAF (2006) is recognised in considering the instream concentration, the RQO, the flow mixing ratio (dilution), management class and attainable treatment in setting end-of-pipe discharge standards, several shortcomings in the approach are recognised:

i. There is no consideration of the differences between conservative and non-conservative variables. While the mixing ratio is of relevance to conservative water quality variables, which are predominantly affected by dilution, non-conservative variables are affected by a myriad of additional processes, such as chemical speciation and algal uptake.

ii. There is no consideration of upstream waste loads. This disadvantage is of particular relevance for heavily impacted catchments such as the Vaal Barrage and associated rivers.

iii. The potential contribution of diffuse sources to the waste loads is not considered. This is a major oversight in a catchment such as the Vaal, where diffuse sources contribute significantly to the system waste loads.

4.5 WQSAM as the DSS to challenges in linking the water quality component of the RQOs and water quality licensing

As argued earlier, an important attribute of a water quality DSS is to support stakeholder participation and negotiation. For this to happen, there should be a shared understanding of the water resources system and a way to conceptualise the uncertainties within the decision-making process. The WQSAM provides a very good conceptualisation of catchment connectivity, particularly in relation to pollution loads and how pollution discharge upstream may affect water quality and allocable water quality downstream. The WQSAM, in particular, considers the following processes that affect the downstream impact of upstream pollutant loading:

- Point and non-point loading
- Dilution by good quality flow
- Instream processes affecting non-conservative water quality variables, including the following:
    - Travel time calculated through simple routing
    - Water temperature, which affects chemical speciation, degradation and algal growth
    - The settling and re-mobilisation of pollutants
    - Residence time in reservoirs
    - Uptake by algae and macrophytes

The WQSAM allows the output of simulated water quality variables as frequency distributions. In this format, an estimation of the risk of exceedance of certain water quality thresholds, which could be the RQOs, is possible. Since many of the RQOs are given as percentile values, these RQOs can be directly related to thresholds in the frequency distributions produced by the WQSAM. This is further illustrated in Chapter 5 on the implementation of the DSS.

CHAPTER 5: SIMULATING WATER QUALITY BOUNDARY CONDITIONS FOR THE UPPER VAAL CATCHMENT

5.1 INTRODUCTION

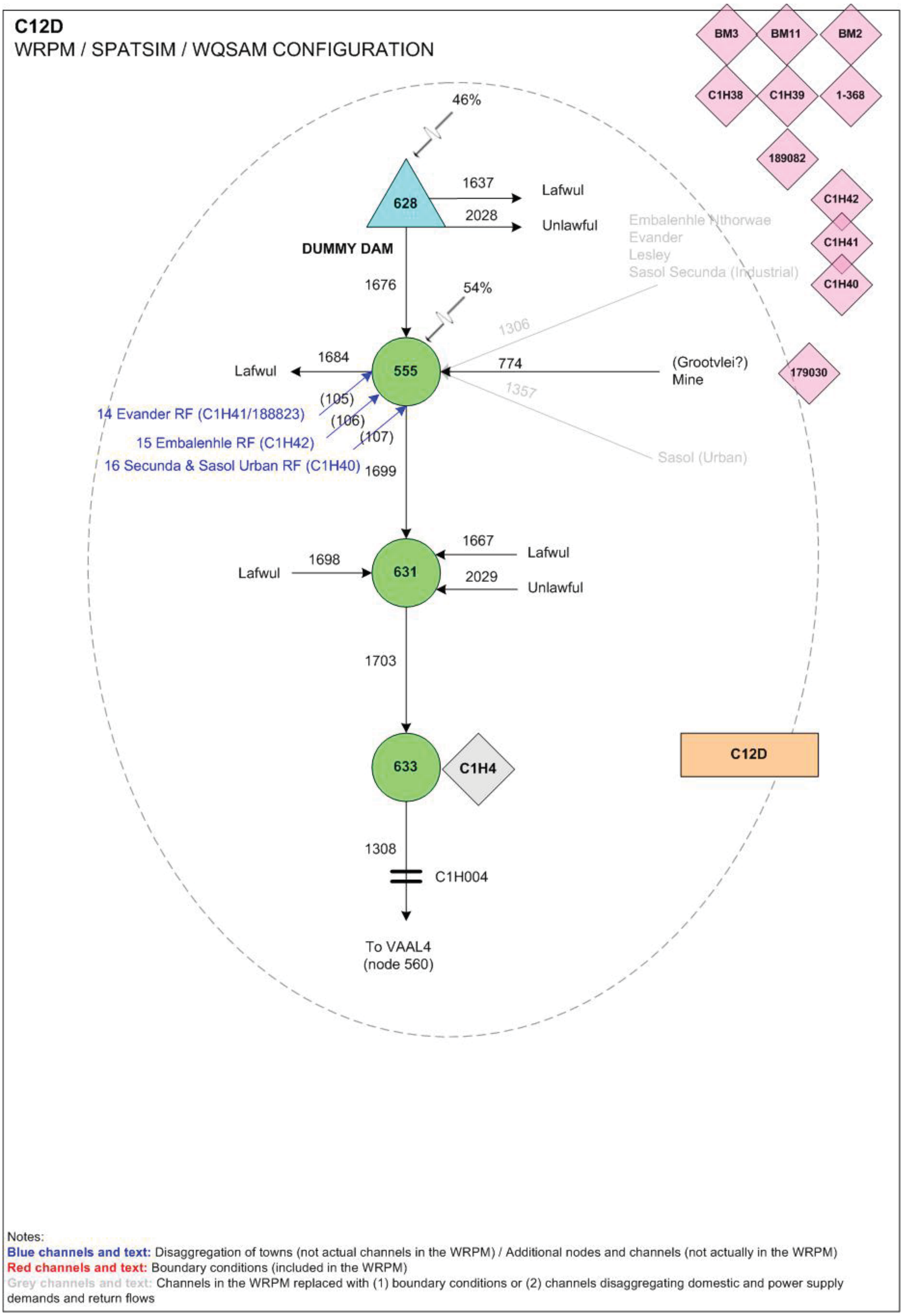
The water quality of the Vaal Barrage and associated river systems cannot be modelled in isolation, as these systems are affected by the water quality of the entire Upper Vaal catchment above the Vaal Dam. Therefore, an approach of applying water quality boundary conditions to the barrage from these regions is needed. Unfortunately, it would not be realistic to apply the averages of observed data to set these boundary conditions, firstly because not all the boundary points into the barrage are gauged for water quality, or the temporal resolution or extent of the measured period is inadequate. It is also important to consider that the Vaal catchment shows definite trends in water quality that might not be captured by summarising observed data. Therefore, it was decided to model water quality for the entire Upper Vaal down to and including the Vaal Dam, and for the Klip, Suikerbosrand and Blesbokspruit rivers, which were later included in the detailed DSS, as described later in this chapter. Establishing water quality models for these regions can also allow future water conditions of the barrage to be investigated by using flow or demand scenarios, although this is not part of the current project.

The project team collaborated with Aurecon to model flow for the entire Upper Vaal using the Water Resources Planning Model (WRPM). Aurecon provides flows for the catchment as simulated by the WRPM, and since Aurecon was interested in modelling the water quality of the Upper Vaal, the project team assisted Aurecon in simulating water quality for the Upper Vaal using the WQSAM.

5.2 UPPER VAAL BOUNDARY CONDITIONS

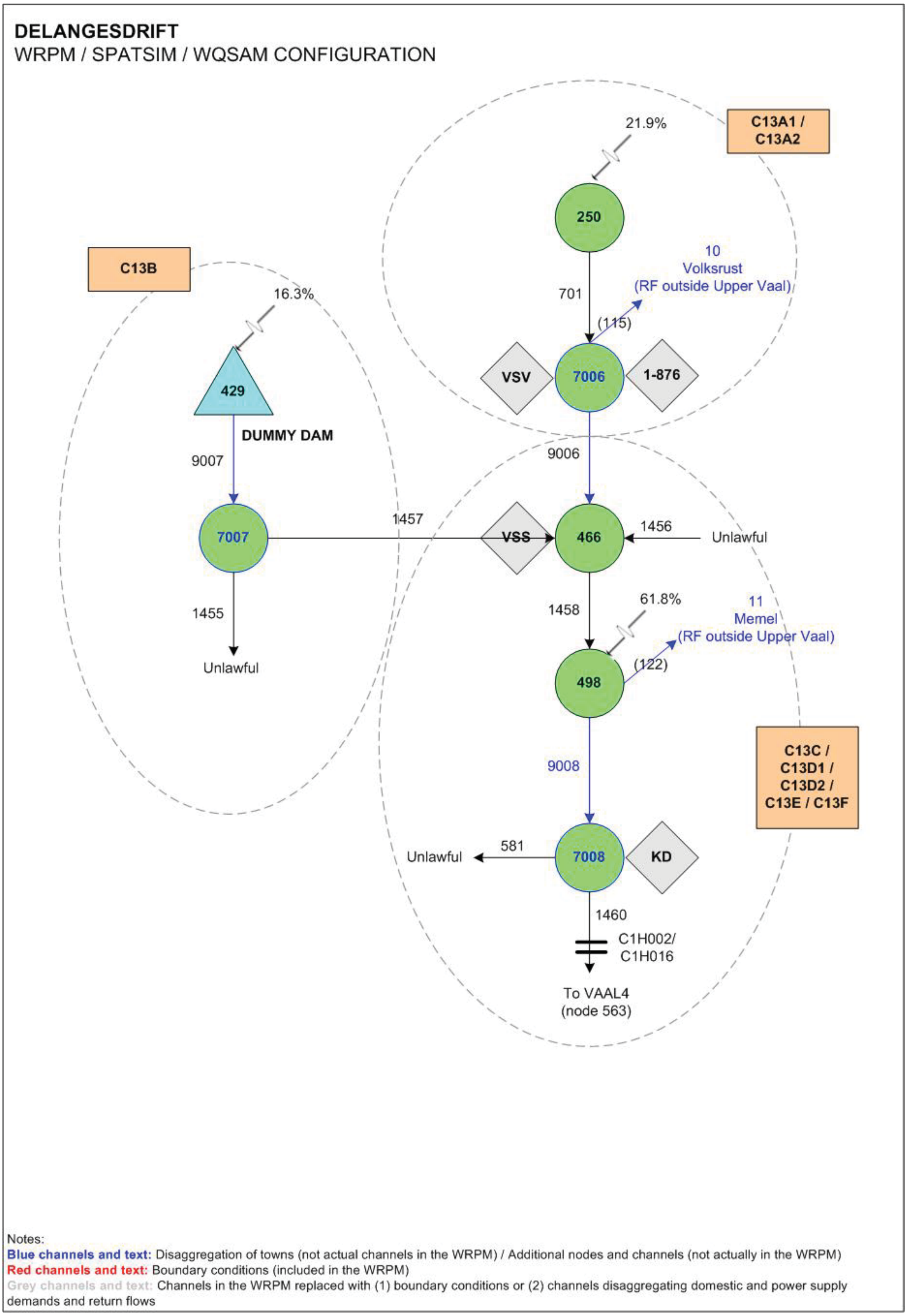
5.2.1 Systems diagram

The model application of the WRPM extended from 1920 to 2010. This is because the incremental flow (natural flow) available only extends to 2010. The Upper Vaal catchment is extremely complex and includes various transfers into and out of the catchment. The model structure of the WRPM is represented by Figure 5.1 to Figure 5.5. Ultraviolet (UV) nodes not shown in the systems diagram were added to the WQSAM implementation, representing points of incremental flows. Generally, one UV node per quaternary catchment was included. The incremental flows shown in Figure 5.1 to Figure 5.5 were combined for multiple quaternary catchments and assigned to individual nodes. Therefore, with guidance from Aurecon, the incremental flows were disaggregated to quaternary catchment level and applied to appropriate places in the model.



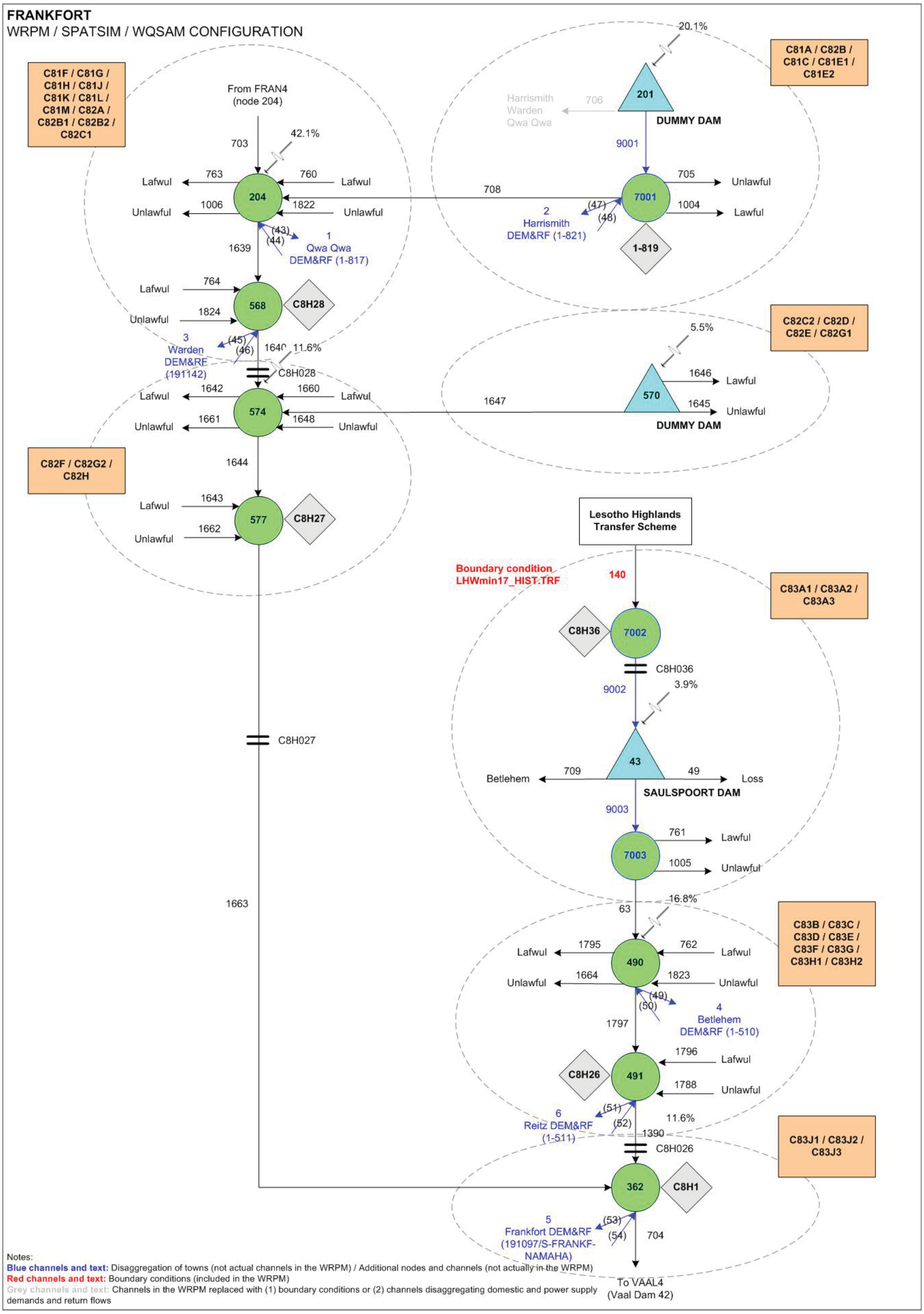
Notes:
Blue channels and text: Disaggregation of towns (not actual channels in the WRPM) / Additional nodes and channels (not actually in the WRPM)
Red channels and text: Boundary conditions (included in the WRPM)
Grey channels and text: Channels in the WRPM replaced with (1) boundary conditions or (2) channels disaggregating domestic and power supply demands and return flows

Figure 5.1: Systems diagram for the Upper Vaal representing C12D



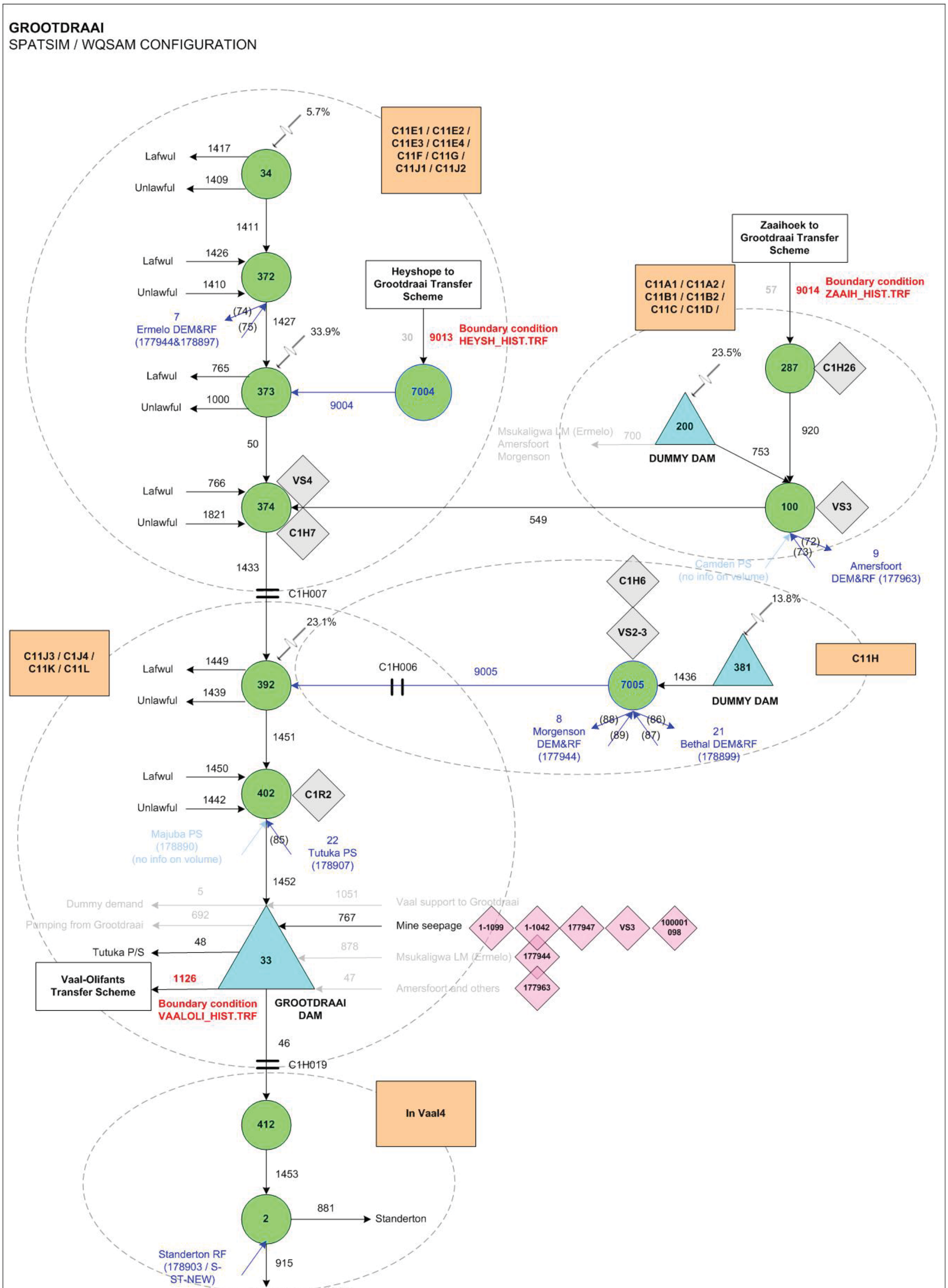
Notes:
Blue channels and text: Disaggregation of towns (not actual channels in the WRPM) / Additional nodes and channels (not actually in the WRPM)
Red channels and text: Boundary conditions (included in the WRPM)
Grey channels and text: Channels in the WRPM replaced with (1) boundary conditions or (2) channels disaggregating domestic and power supply demands and return flows

Figure 5.2 Systems diagram for the Upper Vaal representing Delangesdrift



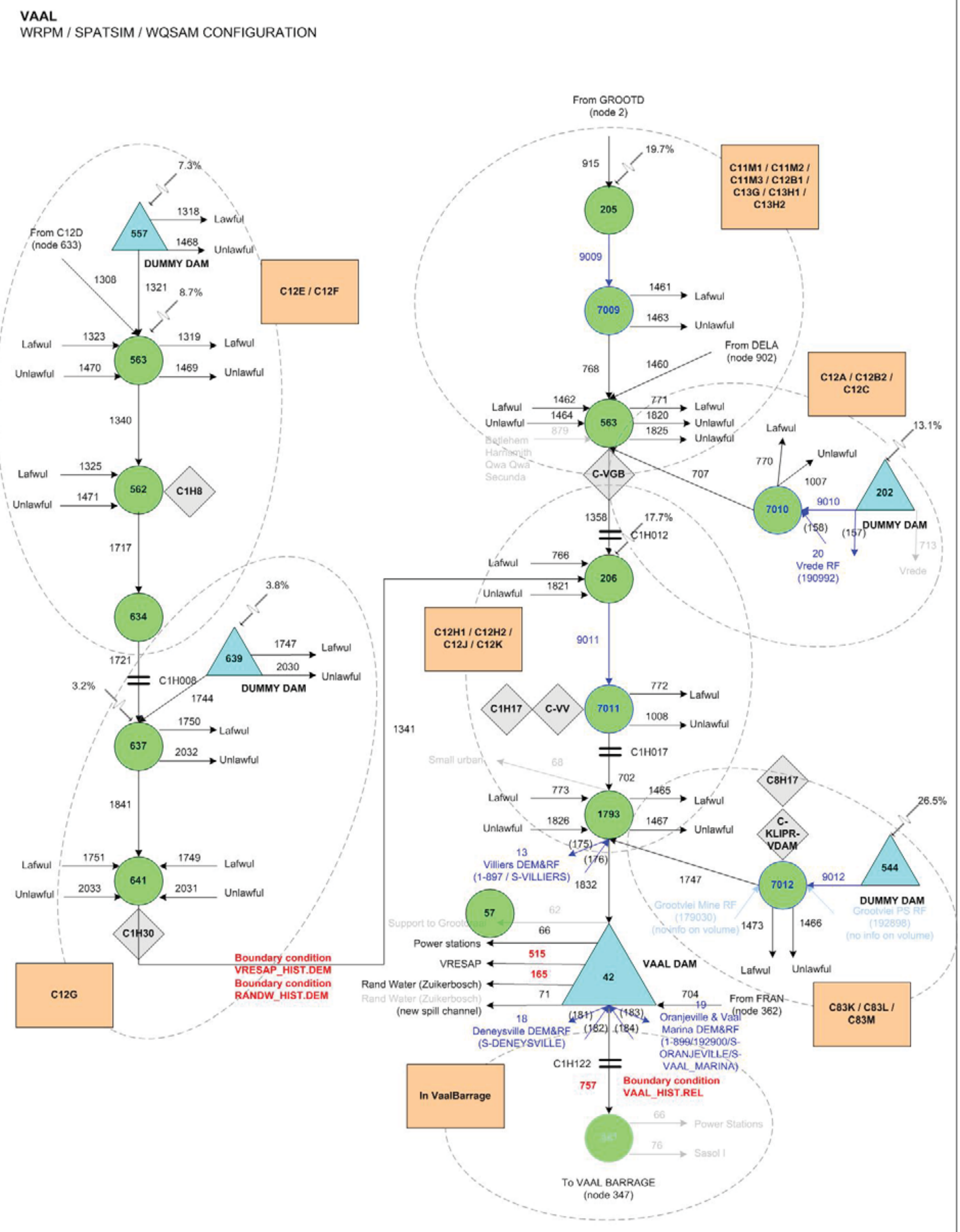
Notes:
Blue channels and text: Disaggregation of towns (not actual channels in the WRPM) / Additional nodes and channels (not actually in the WRPM)
Red channels and text: Boundary conditions (included in the WRPM)
Grey channels and text: Channels in the WRPM replaced with (1) boundary conditions or (2) channels disaggregating domestic and power supply demands and return flows

Figure 5.3: Systems diagram for the Upper Vaal representing Frankfort



Notes:
Blue channels and text: Disaggregation of towns (not actual channels in the WRPM) / Additional nodes and channels (not actually in the WRPM)
Red channels and text: Boundary conditions (included in the WRPM)
Grey channels and text: Channels in the WRPM replaced with (1) boundary conditions or (2) channels disaggregating domestic and power supply demands and return flows

Figure 5.4: Systems diagram for the Upper Vaal representing the Grootdraai Dam catchment



Notes:
Blue channels and text: Disaggregation of towns (not actual channels in the WRPM) / Additional nodes and channels (not actually in the WRPM)
Red channels and text: Boundary conditions (included in the WRPM)
Grey channels and text: Channels in the WRPM replaced with (1) boundary conditions or (2) channels disaggregating domestic and power supply demands and return flows

Figure 5.5: Systems diagram for the Upper Vaal representing the Vaal region

5.2.2 Observed water quality gauges

All available water quality data was used for the calibration, but it is important to consider that much of the data was too sparse to assess the calibration performance of the model. These gauges with little data were used to obtain a general range of water quality parameters and will not be reported on in the calibration report. Table 5.1 shows the gauges identified for the model calibration.

The Upper Vaal has various incoming transfers, which will have an impact on water quality. Where possible, gauges were identified to represent the water quality of these transfers as boundary conditions. The seasonal averages of these gauges were calculated as there was too little data available to represent the boundary conditions as a time series. Table 5.2 shows the gauges used to set the boundary conditions for water quality. Table 5.3 shows the gauges identified measuring the water quality of particular return flows. The flow signatures of these return flows were set to the 50th percentile values of the records in the gauge as a starting point, after which they may have been slightly altered to achieve model calibration. Table 5.4 shows the gauges for regions in which there were ungauged return flows. The 25th to 75th percentile ranges of these gauges were calculated as the range in which the return flow signatures will be changed for calibration.

Figure 5.6 to Figure 5.10 visualise the water quality of the Upper Vaal according to available observed data. The average value of the records over the entire measurement period was used to construct the maps. Therefore, one must be aware that there may be extreme values in short records that may skew the results of the visualisation. However, the visualisations offer a quick and easy way of evaluating the water quality in the catchment.

Table 5.1: Observed water quality gauges used for the Upper Vaal water quality model, as well as the node to which the gauge was assigned and the quaternary catchment in which the node is placed

Quaternary catchment	Node	Gauge
C11L	Grootdraai Dam	C1R002
C83J	Node 362	C8H001
C83F	Node 490	C8H020
C82C	Node 568	C8H028
C82H	Node 577	C8H027
C12D	Node 631	C1H004
C12F	Node 634	C1H008
C11H	Node 904	C1H006
C83C	Node 907	C8H007
C12L	Node 913	C1H017
C83A	Saulspoort Dam	C8R004
C11K	UV10	C1H005
C12J	UV21	C1H010
C12K	UV22	C1H009
C81B	UV50	C8H002
C81C	UV51	C8H010
C81F	UV54	C8H005
C81G	UV55	C8H006
C81H	UV56	C8H011
C81J	UV57	C8H012
C81M	UV60	C8H023

Quaternary catchment	Node	Gauge
C82B	UV62	C8H003
C82E	UV65	C8H018
C83D	UV72	C8H009
C83H	Node 491	C8H026
C83K	UV78	C8H016
C83L	Node 915	C8H017
C83M/C12L	Vaal Dam	C1R001
C11J	Node 374	C1H007
C11M	Node 412	C1H019
C12C	Node 563	C1H012
C13B	Node 900	1-876
C13B	Node 466	C-VSS
C81E	Node 905	1-819
C12B	Node 563	C-VGB
C12G	Node 641	C1H030
C13F	Node 902	C-KD

Table 5.2 Observed water quality gauges used for setting incoming transfer boundary conditions

Quaternary catchment	Node	Gauge
C83A	Node 916	C8H036
C11A	Node 287	C1H026

Table 5.3 Observed water quality gauges identified for particular return flow gauges along with the 50th percentiles of the water quality records

Node	Return flow number	Gauge	TDS	NH_4	NO_3	PO_4	SO_4
555	2	C1H41	508.05	18.29	2.28	4.78	4.78
555	3	C1H42	508.05	18.29	2.28	4.78	4.78
555	4	C1H40	571.93	35.33	4.45	6.41	6.41
568	3	191142	500.07	12.61	5.60	5.61	5.61
7001	1	1-821	483.18	20.28	1.24	4.39	4.39
204	3	1-817	2359.83	0.43	31.38	8.85	
490	3	1-510	697.70	7.08	10.29	5.41	5.41
491	3	1-511	401.11	15.99	2.91	5.22	5.22
362	1	191097	544.17	21.42	1.11	5.92	5.92
372	3	177944	326.08	2.52	11.61	2.05	2.05
100	1	177963	319.05	4.63	5.00	1.37	1.37
7005	1	177944	816.65	11.64	7.49	7.41	7.41
7005	1	178899	251.89	4.02	16.04	3.23	3.23
402	3	178907	519.17	28.74	1.18	4.37	4.37
2	1	178903	406.53	5.50	4.95	1.67	0.64
7010	1	190992	382.08	10.63	2.82	4.19	4.31
Vaal Dam	1	192900	545.20	26.79	2.05	8.22	8.24

Table 5.4 Observed water quality gauges identified for regions with ungauged return flows along with the 25th to 75th percentile range of the water quality records (mg ℓ^{-1})

Node	Return flow number	Gauge	TDS 25th	TDS 75th	SO_4 25th	SO_4 75th	NH_4 25th	NH_4 75th	NO_3 25th	NO_3 75th	PO_4 25th	PO_4 75th
372	3	177944	442.00	559.00	65.00	133.00	1.95	30.60	0.10	3.23	2.23	5.70
904	2	177944	442.00	559.00	53.00	79.25	1.95	30.60	0.10	3.23	2.23	5.70
100	1	177963	524.55	642.20	49.00	79.00	23.00	48.25	0.05	5.80	4.27	8.60
904	1	178899	435.50	567.45	46.00	64.00	1.35	21.08	0.50	7.90	1.30	8.10
2	1	178903	445.25	516.75	43.00	59.00	9.40	29.80	0.05	1.20	2.50	5.78
402	3	178907	383.50	463.45			8.70	17.80	0.10	5.23	2.30	4.70
910	1	190992	517.56	685.75	43.00	64.50	1.15	8.30	4.50	14.73	3.43	6.83
362	1	191097	337.51	448.50	38.00	49.00	8.55	22.55	0.38	4.28	3.96	6.55
568	3	191142	472.88	663.00	44.50	57.25	12.28	34.65	0.05	1.88	3.28	8.58
Vaal Dam	1	192900	295.10	355.88	37.00	49.00	0.05	1.15	4.45	18.75	1.13	3.00
490	3	1-510	293.15	343.20	30.00	42.00	0.30	6.90	2.35	6.60	0.20	2.00
491	3	1-511	253.50	425.75	16.00	26.25	0.30	12.90	2.30	11.50	2.90	9.80
204	3	1-817	234.00	273.00	21.00	31.00	1.40	6.50	13.65	19.78	2.50	4.00
905	1	1-821	453.54	578.50	27.25	53.50	24.13	35.80	0.05	0.43	1.38	6.10
555	4	C1H40	343.20	390.00	59.65	77.84	2.00	3.00	2.00	6.01	0.25	2.40
555	2	C1H41	326.63	422.50	40.00	50.00	0.70	16.50	0.10	4.35	1.55	5.28
555	3	C1H42	507.00	578.34	61.00	85.00	18.00	32.93	0.10	2.95	5.60	10.90

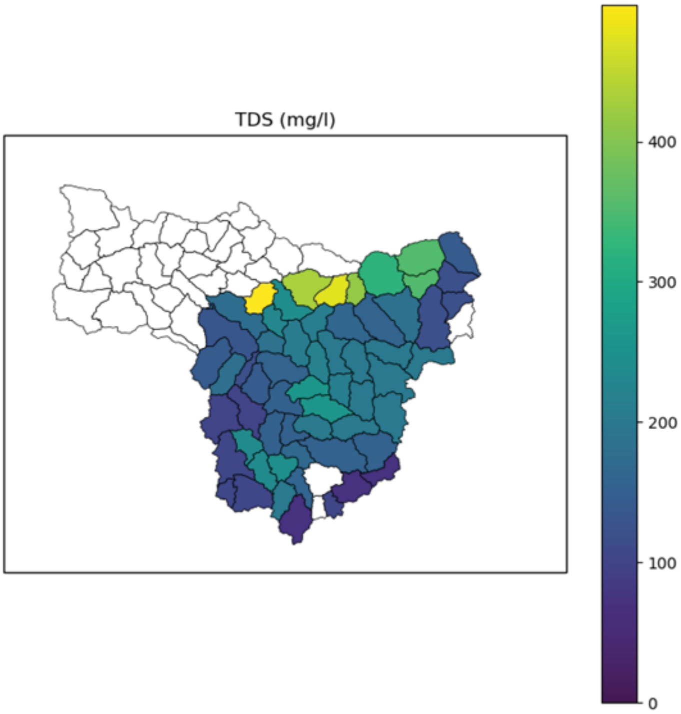


Figure 5.6: Visualisation of TDS (mg $ℓ^{-1}$) for the catchment according to observed data

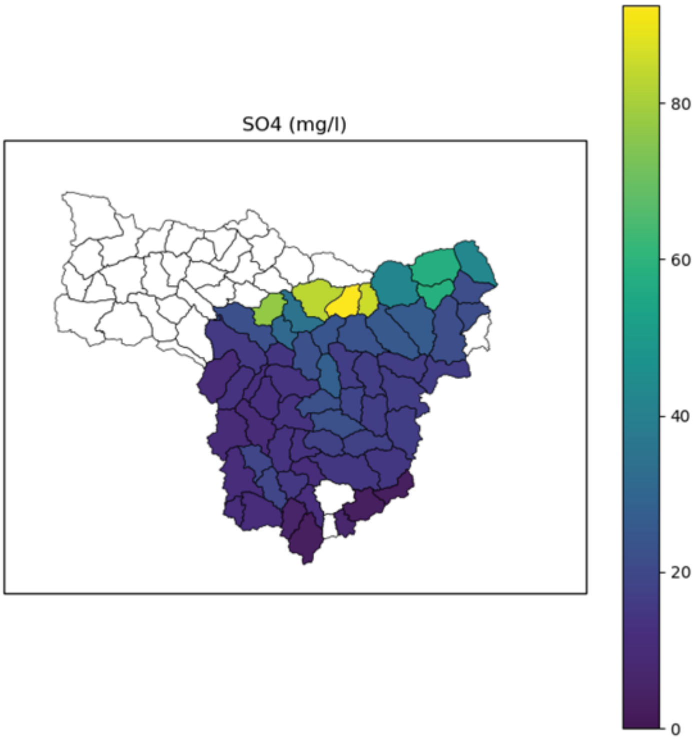


Figure 5.7: Visualisation of SO_4 (mg $ℓ^{-1}$) for the catchment according to observed data

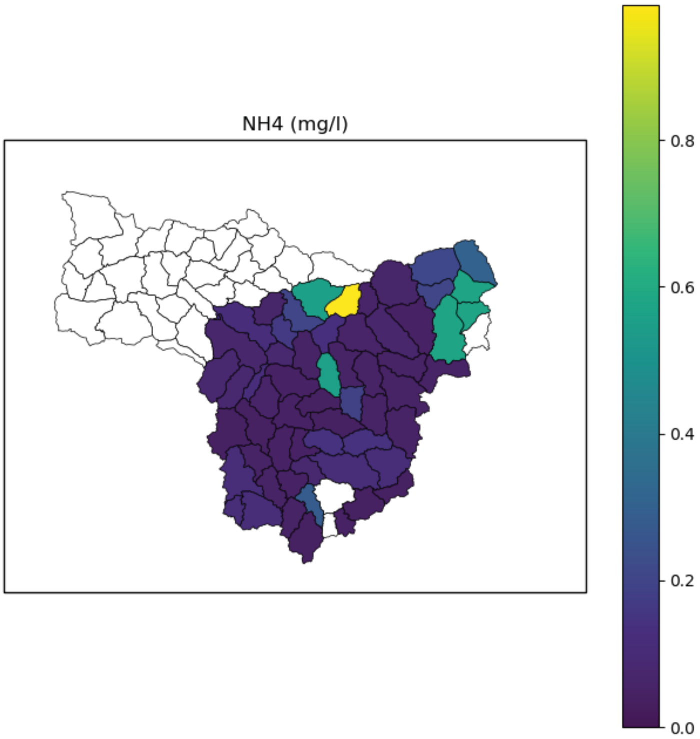


Figure 5.8 Visualisation of NH_4 (mg ℓ^{-1}) for the catchment according to observed data

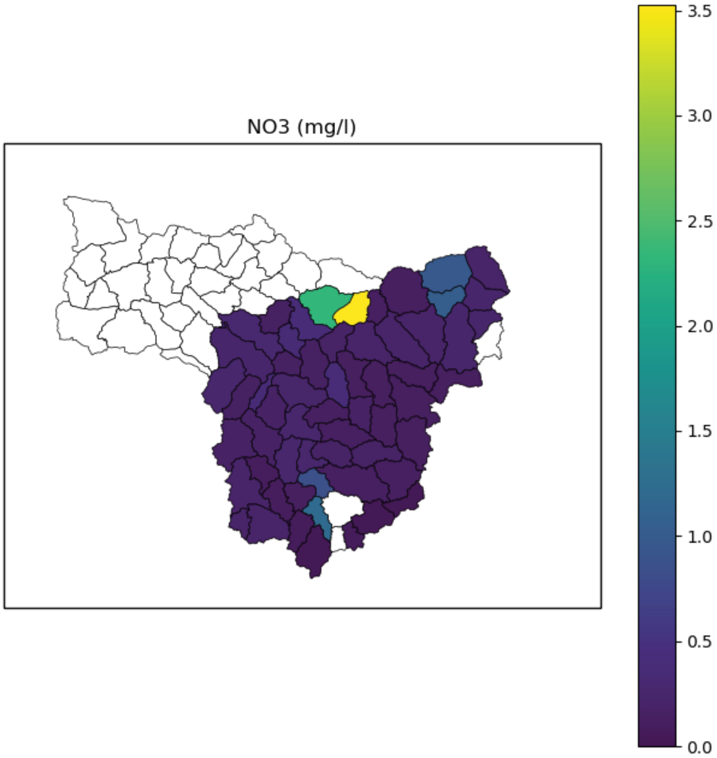


Figure 5.9 Visualisation of NO_3 (mg N/ℓ) for the catchment according to observed data

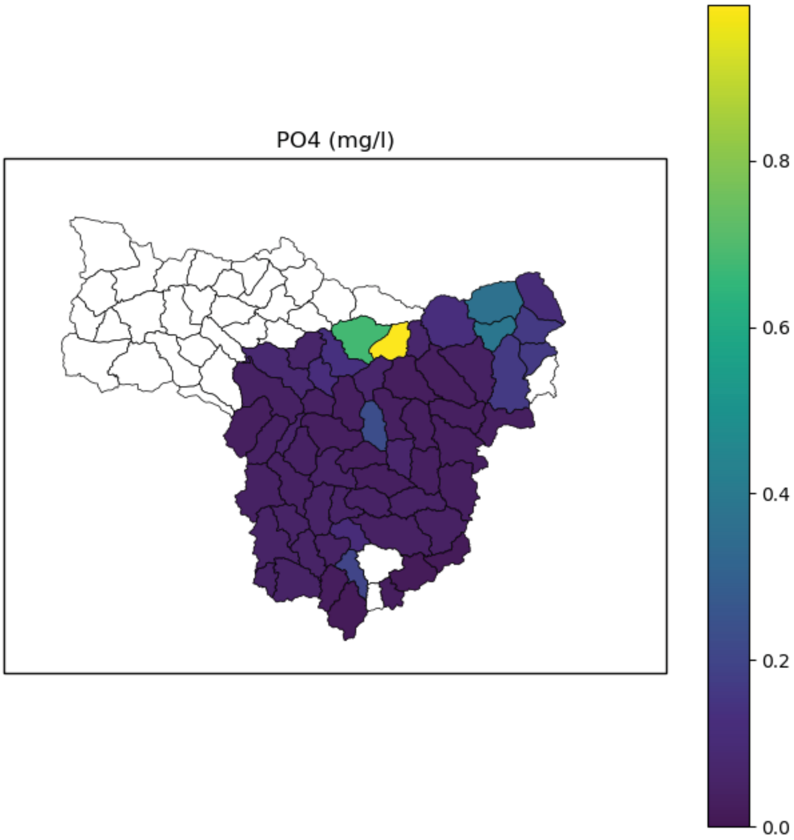


Figure 5.10 Visualisation of PO_4 (mg P/ℓ) for the catchment according to observed data

5.2.3 Model calibrations

The model calibration results for the Upper Vaal are shown in Figure 5.11 to Figure 5.15.

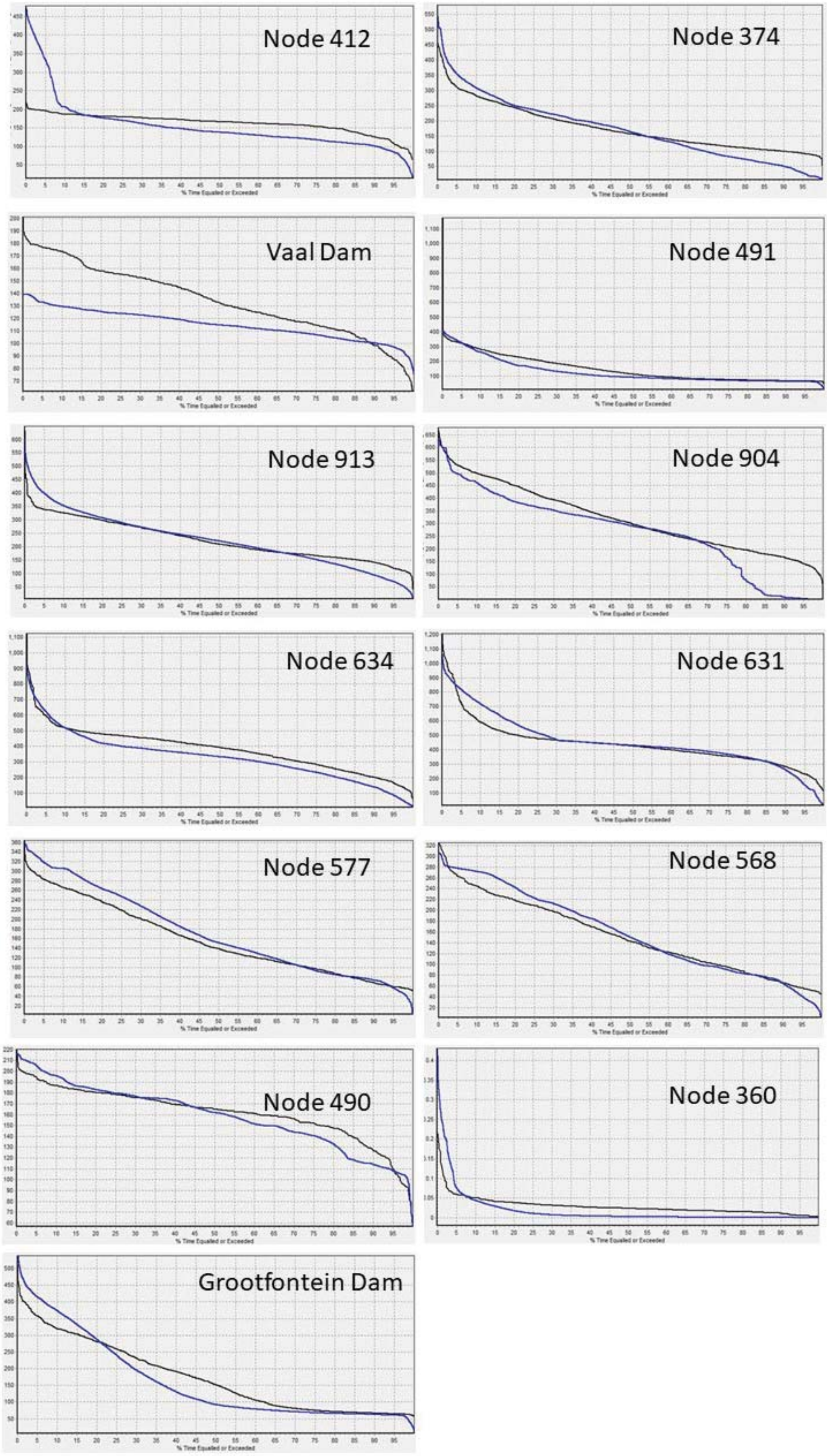


Figure 5.11 Calibrations for TDS for the Upper Vaal as frequency distributions. Black is observed data and blue is simulated data.

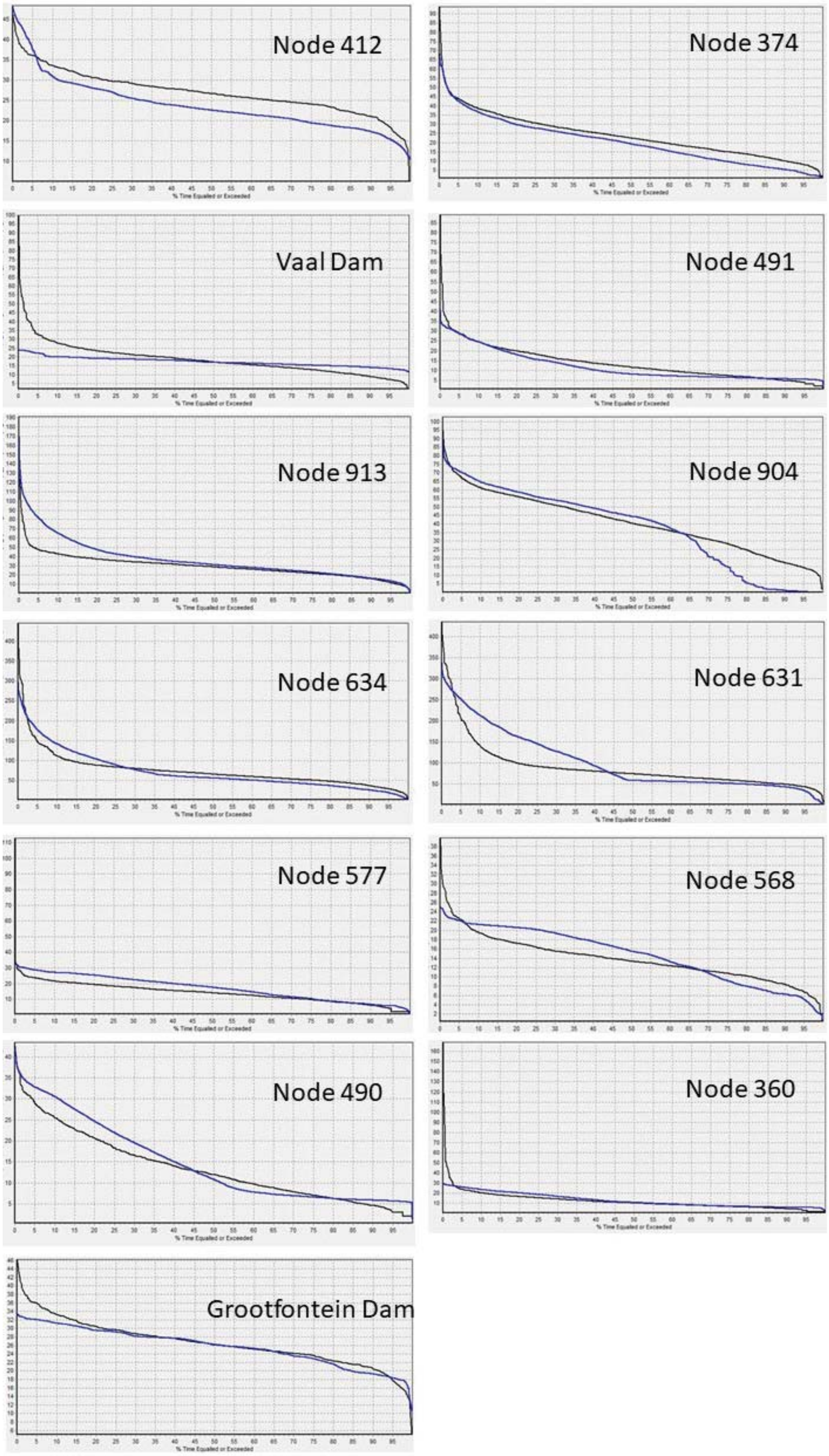


Figure 5.12 Calibrations for SO_4 for the Upper Vaal as frequency distributions. Black is observed data and blue is simulated data.

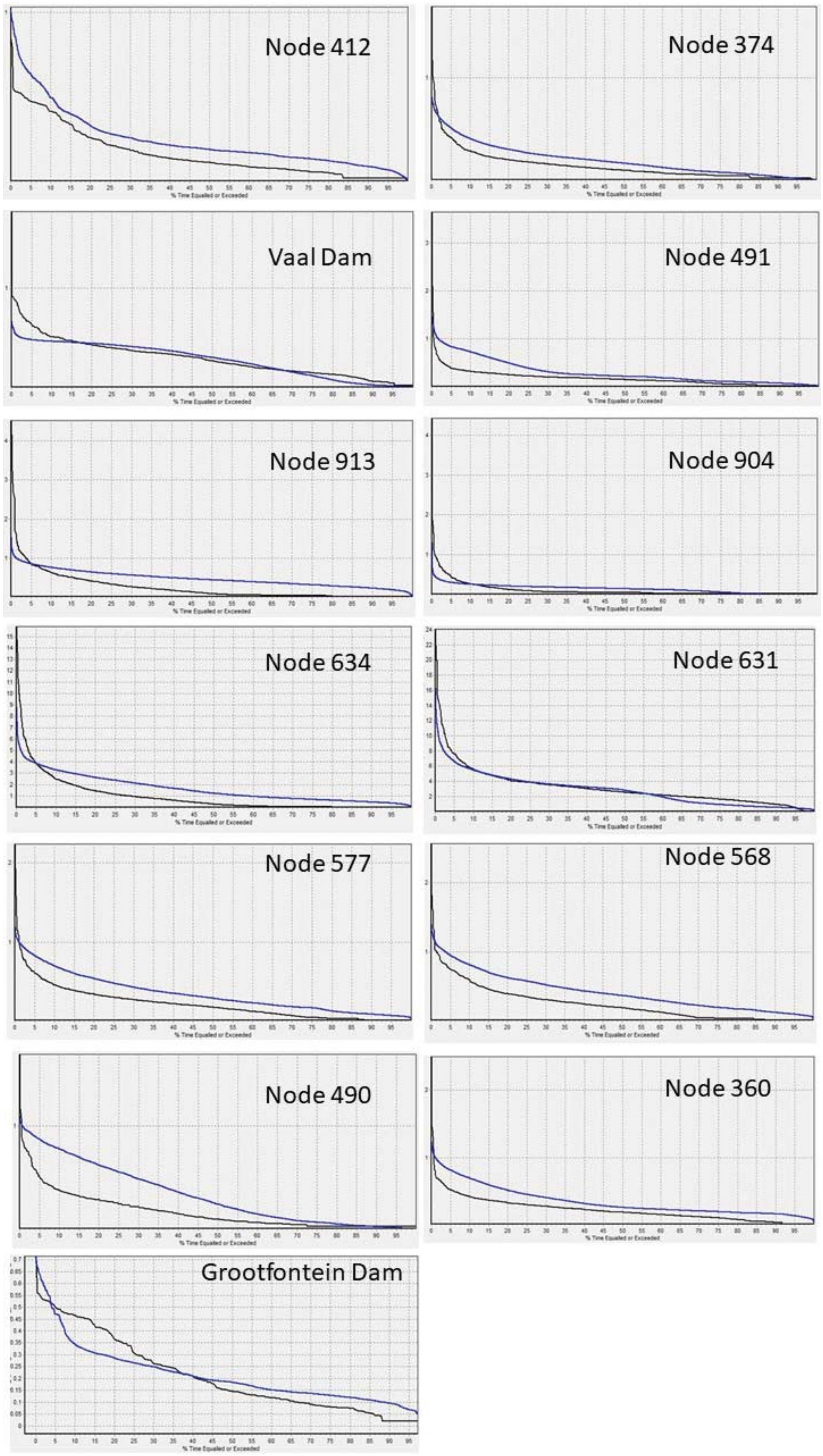


Figure 5.13 Calibrations for NO_3 for the Upper Vaal as frequency distributions. Black is observed data and blue is simulated data.

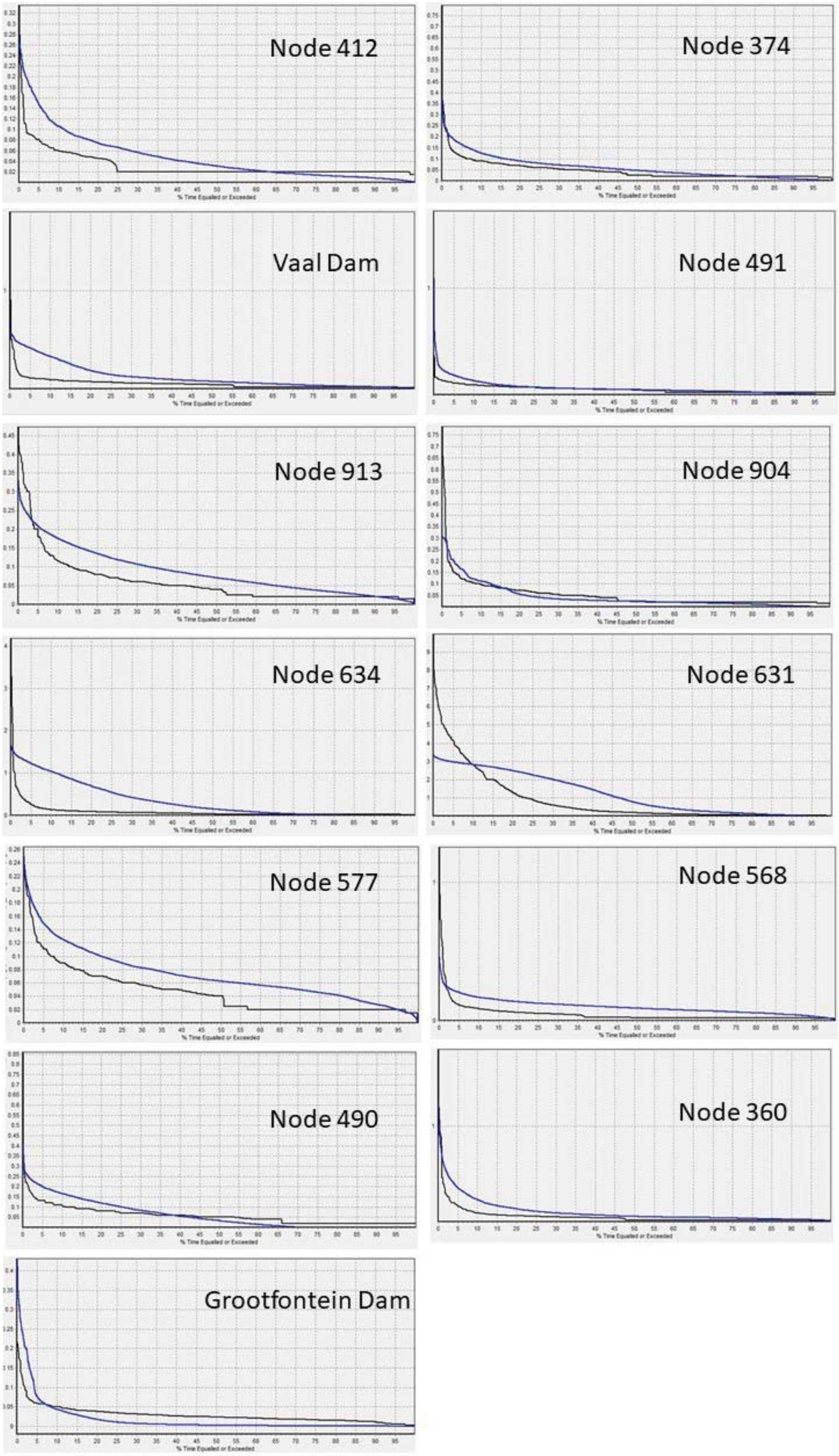


Figure 5.14 Calibrations for NH_4 for the Upper Vaal as frequency distributions. Black is observed data and blue is simulated data.

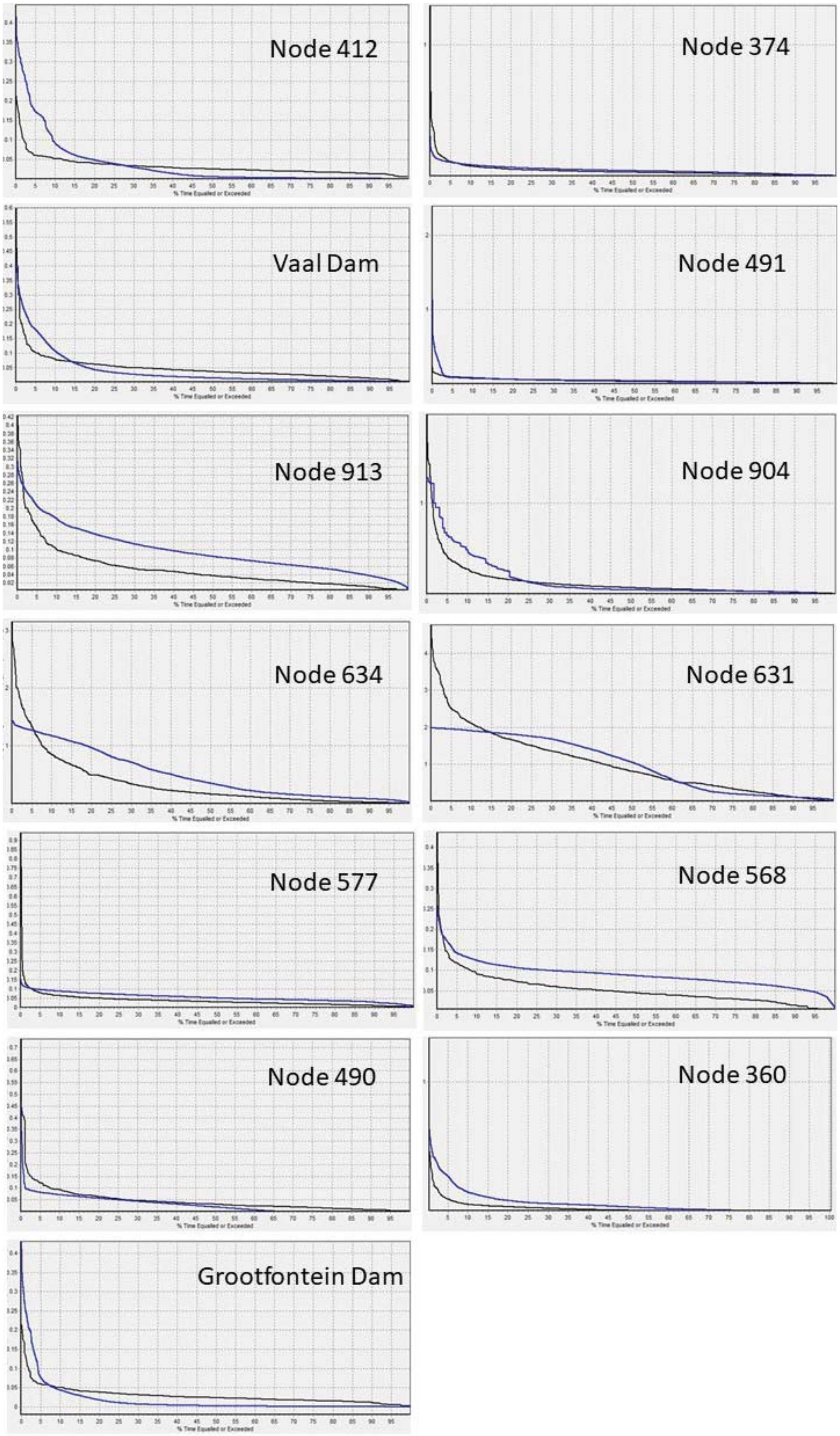


Figure 5.15 Calibrations for PO_4 for the Upper Vaal as frequency distributions. Black is observed data and blue is simulated data.

CHAPTER 6: DEVELOPMENT AND IMPLEMENTATION OF THE DECISION SUPPORT SYSTEM FOR LINKING WATER QUALITY LICENSE STANDARDS TO THE WATER QUALITY COMPONENT OF THE RESOURCE QUALITY OBJECTIVES FOR THE VAAL BARRAGE AND ASSOCIATED RIVER SYSTEMS

6.1 THE VAAL BARRAGE DECISION SUPPORT SYSTEM

6.1.1 System representation

The development of the DSS for the Vaal Barrage has gone through various iterations and changes through consultation with stakeholders. Originally, the DSS was based on the WRMP system representation indicated in Figure 6.1. However, it was soon realised that this representation was not of a sufficiently fine spatial resolution to represent stakeholder contributions to water quality within the Vaal Barrage catchment itself (quaternaries C22K, C22F and C22G). It was therefore decided to use the more spatially coarse systems representation indicated in Figure 6.1 to generate boundary conditions of water quality, particularly for the Klip and Suikerbosrand rivers, to feed into a more detailed representation of the Vaal Barrage itself, as shown in Figure 6.2. However, stakeholders in the catchment subsequently indicated that they would like to be able to represent and investigate loads coming into the Vaal Barrage from the Klip, Blesbokspruit and Suikerbosrand rivers within the DSS. Therefore, the approach of using boundary conditions for these tributaries into the Vaal Barrage becomes insufficient, and a decision was taken to integrate these additional catchments within the DSS. Figure 6.3 represents the most recent systems diagram of the Vaal Barrage catchment, which integrates the Klip, Blesbokspruit and Suikerbosrand rivers. The team attempted to identify all individual effluent emitters in the catchment using the DWS Google map of gauges (http://www.dwa.gov.za/iwqs/wms/data/WMS_pri_txt.asp, last accessed on 27 October 2019), as well as Figure 6.4. The main limitation of the current implementation is a lack of effluent flow data for individual emitters. The project team has, to date, only received water quality and effluent flow data from one main water user. The approach was taken of assigning the effluent flows provided by this main water user, and then dividing the remaining effluent flows (as represented in a combined manner in the coarser model) equally among the other emitters. While this situation is not ideal, it is hoped that the flows can be updated as individual emitters provide further data.

6.1.2 Observed water quality gauges

Table 6.1 gives the water quality gauges that were used to calibrate the WQSAM. Within the Vaal Barrage itself, instream water quality data was found for the points VRB12, VRB10, VRB8 and VRB6, corresponding to the DWS monitoring points. In addition, observed water quality data was available for the Vaal Barrage (CR2008), as well as immediately downstream of the Vaal Dam (C2H003). Water quality data was also available for the points LTS20 (00000953) and LTS21 (100001005). Observed water quality gauges used to set the return flow signatures of individual return flows are shown in Table 6.2. The 25th to 75th percentile ranges were calculated to guide the calibration process.

Table 6.1: Observed water quality gauges identified for the barrage catchment against which the model was calibrated

Node	Gauge
Node 5	C2H177
Node 11	C2H133
Node 15	C2H234
Node 16	C2H004
Node 20	C2H039
Node 21	C2H141
Node 23	C2H015
Node 28	C2H005
Node 29	C2H014
Node 31	C2H122
Vaal Barrage	C2H140/CR2008/C2H003
VRB12	VRB12
VRB10	VRB10
VRB8	VRB8
VRB6	VRB6
LTS20	00000953
LTS21	100001005

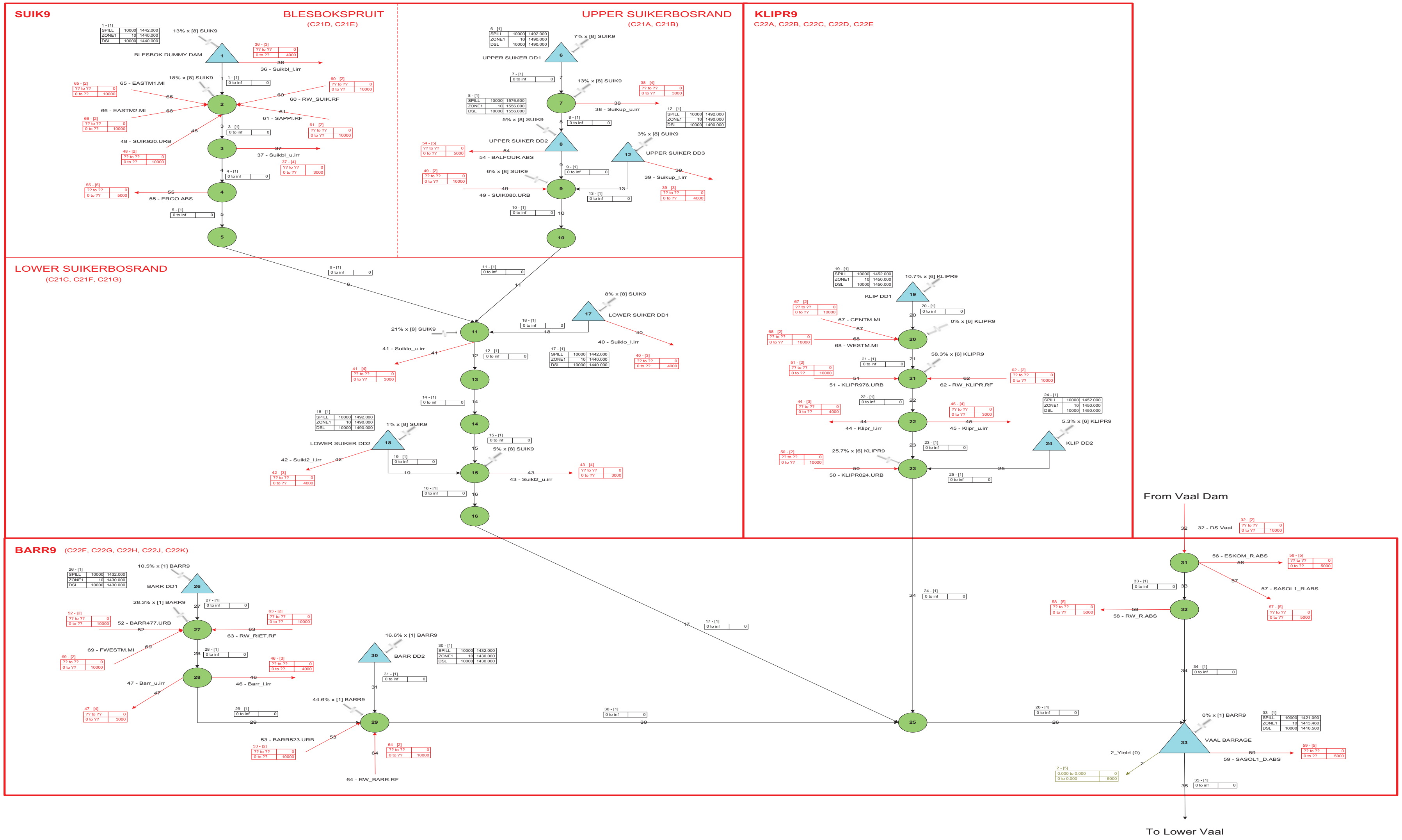


Figure 6.1: Water Resources Planning Model systems diagram of the barrage catchment, including the Suikerbosrand, Blesbokspruit and Klip rivers

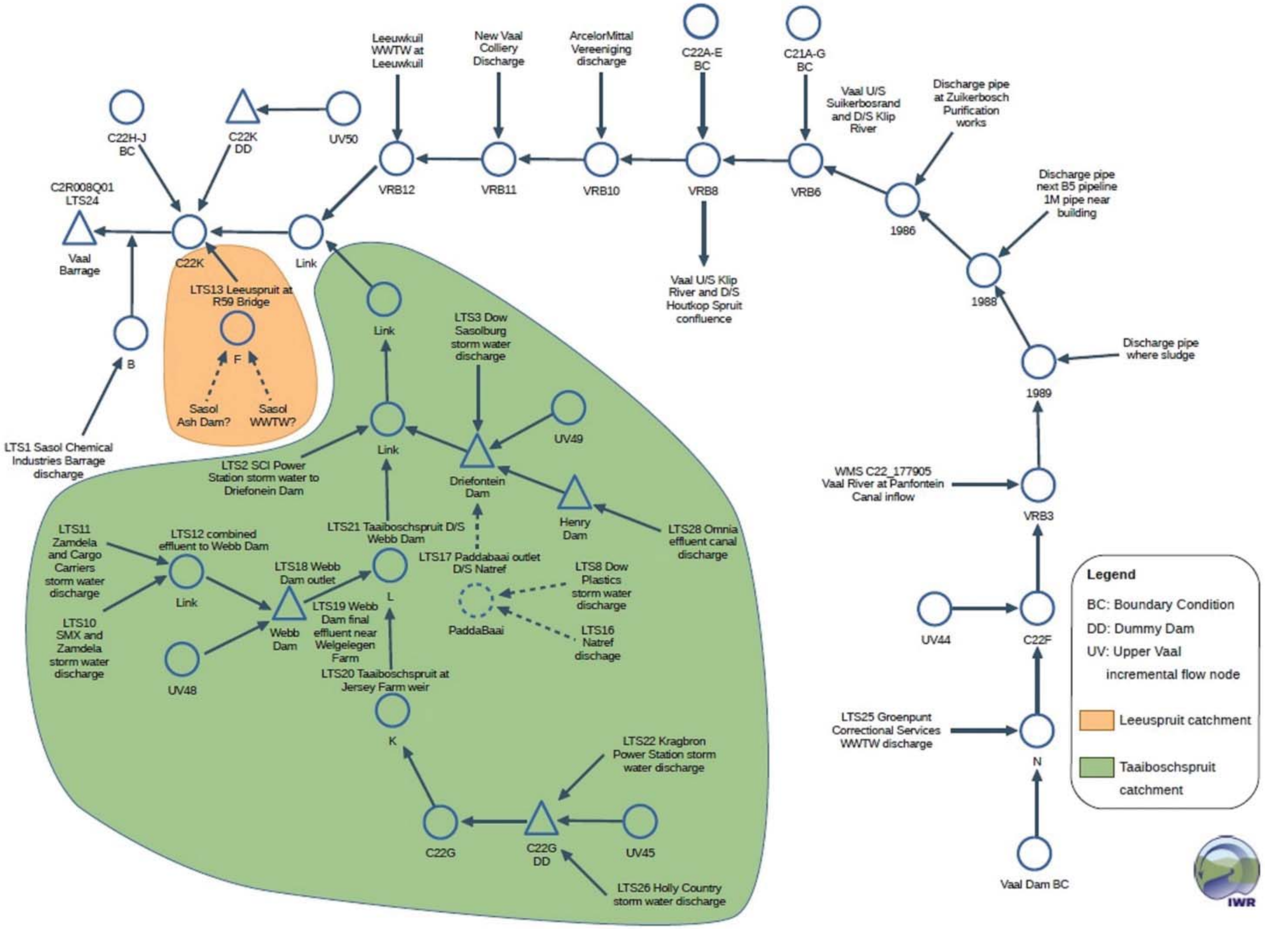


Figure 6.2: Initial finer-scale systems diagram for the barrage study, excluding the Klip, Blesbokspruit and Suikerbosrand rivers area used to construct the barrage water quality DSS

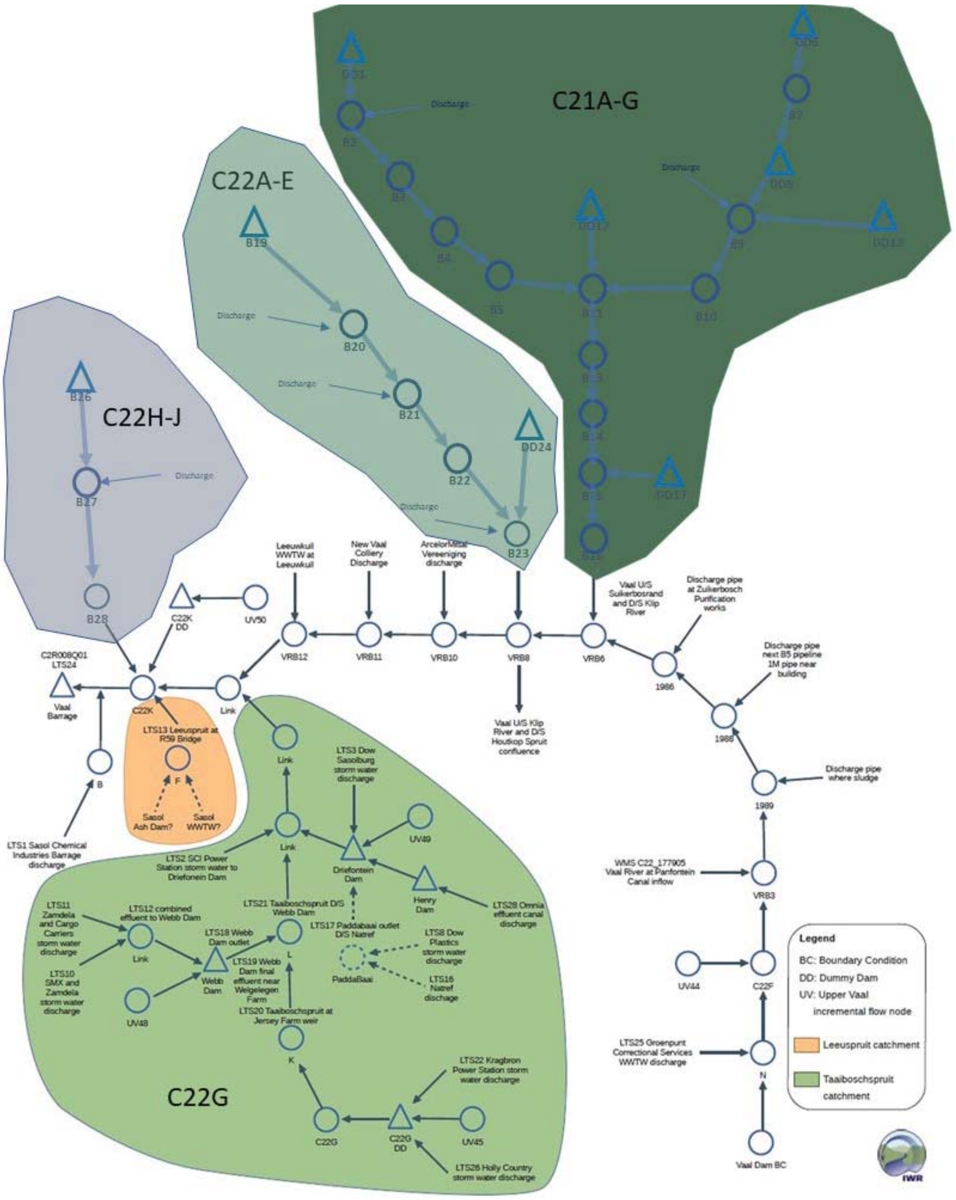
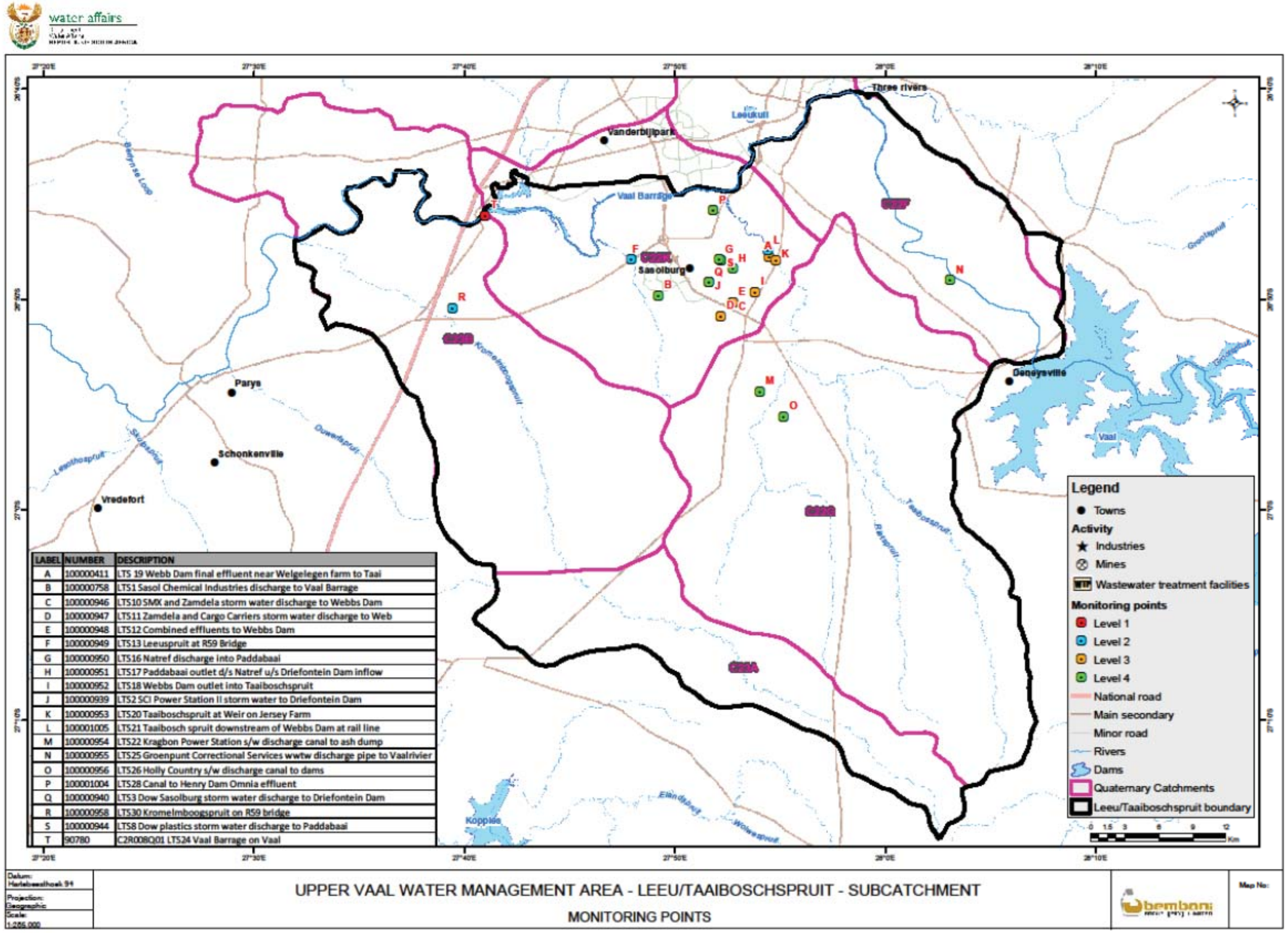


Figure 6.3: Final systems diagram for the Vaal Barrage DSS, which integrates the Klip, Blesbokspruit and Suikerbosrand rivers

Table 6.2: Observed water gauges used to set the return flow signatures in the barrage catchment

Node	TDS			SO_4			NH_4			NO_3			PO_4		
	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th
LTS1	793.00	897.00	1040.00	230.00	284.00	368.00	0.05	0.05	1.56	1.10	2.30	4.30	0.05	0.10	0.20
LTS10	570.38	1027.00	1745.25	137.75	302.50	447.50	0.33	2.00	17.60	4.00	22.00	89.50	0.72	2.10	4.10
LTS11	208.00	266.50	355.88	17.25	27.00	46.00	0.24	0.45	1.48	0.10	0.30	0.87	0.20	0.45	0.89
LTS12	464.75	539.50	630.50	73.75	97.00	128.50	0.05	0.40	1.25	2.08	4.15	8.45	0.05	0.30	0.70
LTS13	310.38	494.33	658.13	32.75	75.50	129.75	0.05	0.30	0.60	0.10	0.50	1.35	0.10	0.23	0.40
LTS16	263.25	442.00	646.75	50.00	67.00	97.00	0.16	1.10	3.00	7.68	19.50	35.93	0.34	0.68	1.20
LTS17	291.85	422.50	604.50	55.00	78.00	104.00	0.05	0.25	0.70	7.33	15.85	31.25	0.40	0.60	1.10
LTS18	526.50	565.50	624.00	74.00	90.00	107.50	0.05	0.05	0.30	0.20	0.75	1.60	1.20	1.70	2.65
LTS19	520.00	565.50	630.50	83.25	96.00	111.75	0.05	0.05	0.30	0.29	0.61	2.00	0.93	1.60	2.40
LTS2	411.13	534.63	767.00	86.00	106.00	215.00	0.65	2.80	18.50	2.90	6.55	10.00	0.10	0.10	0.78
LTS20	249.93	377.00	539.50	47.75	66.50	91.25	0.05	0.30	0.55	0.05	0.30	1.33	0.10	0.50	1.03
LTS21	331.50	474.50	552.50	69.25	87.50	101.25	0.20	0.30	0.55	0.25	0.90	2.60	0.50	0.90	1.40
LTS22	310.38	351.00	397.80	39.50	50.50	68.25	13.50	13.50	13.50	1.35	7.40	15.10	1.55	3.20	4.80
LTS25	253.50	292.50	341.25	27.87	30.00	38.00	2.30	5.40	8.50	9.35	14.00	21.40	2.70	3.80	5.90
LTS26	276.41	338.00	414.70	26.00	34.00	41.00	5.05	13.05	19.00	0.10	0.50	6.15	1.40	2.55	3.80
LTS28	2861.63	5528.25	8992.75	157.25	298.50	567.75	440.00	499.00	674.00	213.00	716.00	1295.00	8.45	36.00	160.75
LTS3	525.85	851.50	1118.00	140.00	232.00	377.00	0.09	0.14	0.18	4.05	23.95	69.00	0.55	1.45	3.65
LTS30	188.50	305.50	474.50	51.00	68.00	83.00	0.05	0.05	0.30	0.05	0.05	0.40	0.05	0.20	0.50
LTS8	321.43	448.50	555.10	60.00	88.50	124.00									
1-986	156.00	162.50	182.00	16.00	20.00	30.00	0.05	0.05	0.40	0.30	0.60	1.10	0.05	0.05	0.05
1-988	123.50	143.00	162.50	11.00	18.00	23.00	0.05	0.05	0.20	0.30	0.50	0.60	0.05	0.05	0.05
1-989	152.75	169.00	185.25	16.50	23.00	42.50	0.05	0.05	0.13	0.60	0.90	0.95	0.05	0.05	0.05
VRB11	731.25	830.38	940.88	275.00	382.30	481.34	0.05	0.05	0.10	0.07	0.30	1.00	0.05	0.05	0.09
VRB3	159.95	207.03	286.00	38.72	55.00	87.00	0.04	0.05	0.20	0.10	0.30	0.48	0.05	0.05	0.10



LABEL	NUMBER	DESCRIPTION
A	100000411	LTS 19 Webb Dam final effluent near Welgelegen farm to Taai
B	100000758	LTS1 Sasol Chemical Industries discharge to Vaal Barrage
C	100000946	LTS10 SMX and Zamdela storm water discharge to Webbs Dam
D	100000947	LTS11 Zamdela and Cargo Carriers storm water discharge to Web
E	100000948	LTS12 Combined effluents to Webbs Dam
F	100000949	LTS13 Leeuspruit at R59 Bridge
G	100000950	LTS16 Natref discharge into Paddabaai
H	100000951	LTS17 Paddabaai outlet d/s Natref u/s Driefontein Dam inflow
I	100000952	LTS18 Webbs Dam outlet into Taaiboschspruit
J	100000939	LTS2 SCI Power Station II storm water to Driefontein Dam
K	100000953	LTS20 Taaiboschspruit at Weir on Jersey Farm
L	100001005	LTS21 Taaibosch spruit downstream of Webbs Dam at rail line
M	100000954	LTS22 Kragbon Power Station s/w discharge canal to ash dump
N	100000955	LTS25 Groenpunt Correctional Services wwtw discharge pipe to Vaalrivier
O	100000956	LTS26 Holly Country s/w discharge canal to dams
P	100001004	LTS28 Canal to Henry Dam Omnia effluent
Q	100000940	LTS3 Dow Sasolburg storm water discharge to Driefontein Dam
R	100000958	LTS30 Kromelmboogspruit on R59 bridge
S	100000944	LTS8 Dow plastics storm water discharge to Paddabaai
T	90780	C2R008Q01 LTS24 Vaal Barrage on Vaal

Figure 6.4: Upper Vaal water management area showing the Leeuspruit/Taaibosspruit monitoring points

6.1.3 Additional water quality variables

The WQSAM was originally designed to simulate water quality variables of management concern and for which there is sufficient observed data. These are the nutrients NO_3-N + NO_2-N, NH_4-N and PO_4-P, as well as the salt SO_4 and TDS. However, consultation with stakeholders revealed that there is interest in additional water quality variables within the Vaal Barrage, particularly in some of the other salts and certain metals. It was therefore decided to add additional simulation capacity to the Vaal Barrage DSS to represent at least some of these variables. The additional salts chosen were calcium, chloride, fluoride, potassium, magnesium and sodium, since these salts are relatively well represented within the observed data. In addition, the model was updated to simulate the metals iron, aluminium, cadmium, chromium, copper, lead and zinc. Unfortunately, there was insufficient observed water quality data to allow calibration of the Vaal Barrage DSS for metals. However, one of the main water users in the catchment provided return flow data for their licenced inputs, which included data for these metals. Therefore, the model reflects the input of these metals from this water resource user.

6.1.4 Model calibration

Model simulations were calibrated against the available observed data. The calibration strategy adopted was to calibrate the most upstream points in the catchment for which there was observed data first, and then to progressively move downstream. Non-point inputs into the catchment were represented by setting water quality signatures of incremental surface flow, interflow and groundwater flow. Water quality signatures of return flows were set to be within the 25th to 75th percentile of observed effluent water quality data where these are available (Table 6.2). Model calibration was according to a best visual fit between the frequency distributions of observed and simulated data, guided by the Nash-Sutcliffe (Nash and Sutcliffe, 1970) value of the fit. Figure 6.5 to Figure 6.8 show visualisation maps of both observed (left-hand side) and simulated (right-hand side) water quality data at a quaternary spatial scale. The water quality of quaternaries is indicated by the colour of the quaternary, which can be cross-referenced with the colour grading bar to the right of each map. These visualisations are helpful to obtain a quick idea of water quality within the Vaal Barrage catchments and contributing tributaries, to rapidly assess problematic areas of the catchment in terms of loads of particular pollutants, and to assess whether simulated water quality data is generally spatially representative of observed data.

The results for TDS (Figure 6.5) show that the Upper Suikerbosrand quaternary catchments C21A and C21B appear to be particularly problematic in terms of inputs of salts. This pattern is also evident for the individual salts calcium (Figure 6.6), chlorine (Figure 6.6), potassium (Figure 6.7), magnesium (Figure 6.7) and sodium (Figure 6.7). SO_4 inputs appear to be highest in the C21E, C21G and C22E catchments (see Figure 6.5).

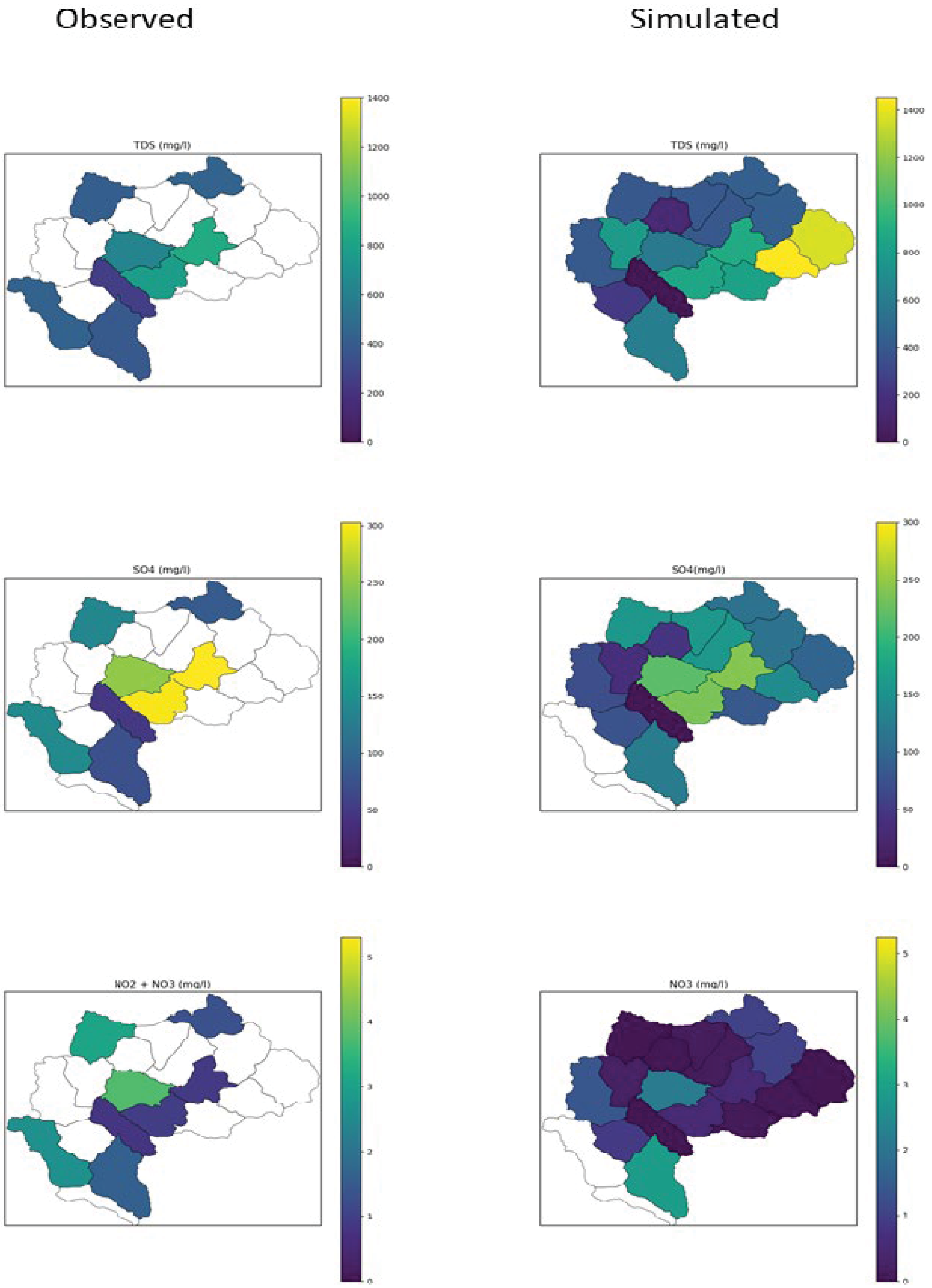


Figure 6.5: Visualisations of observed (left-hand side) and model-simulated (right-hand side) water quality data for the Vaal Barrage catchment for TDS, SO_4 and NO_3-N + NO_2-N

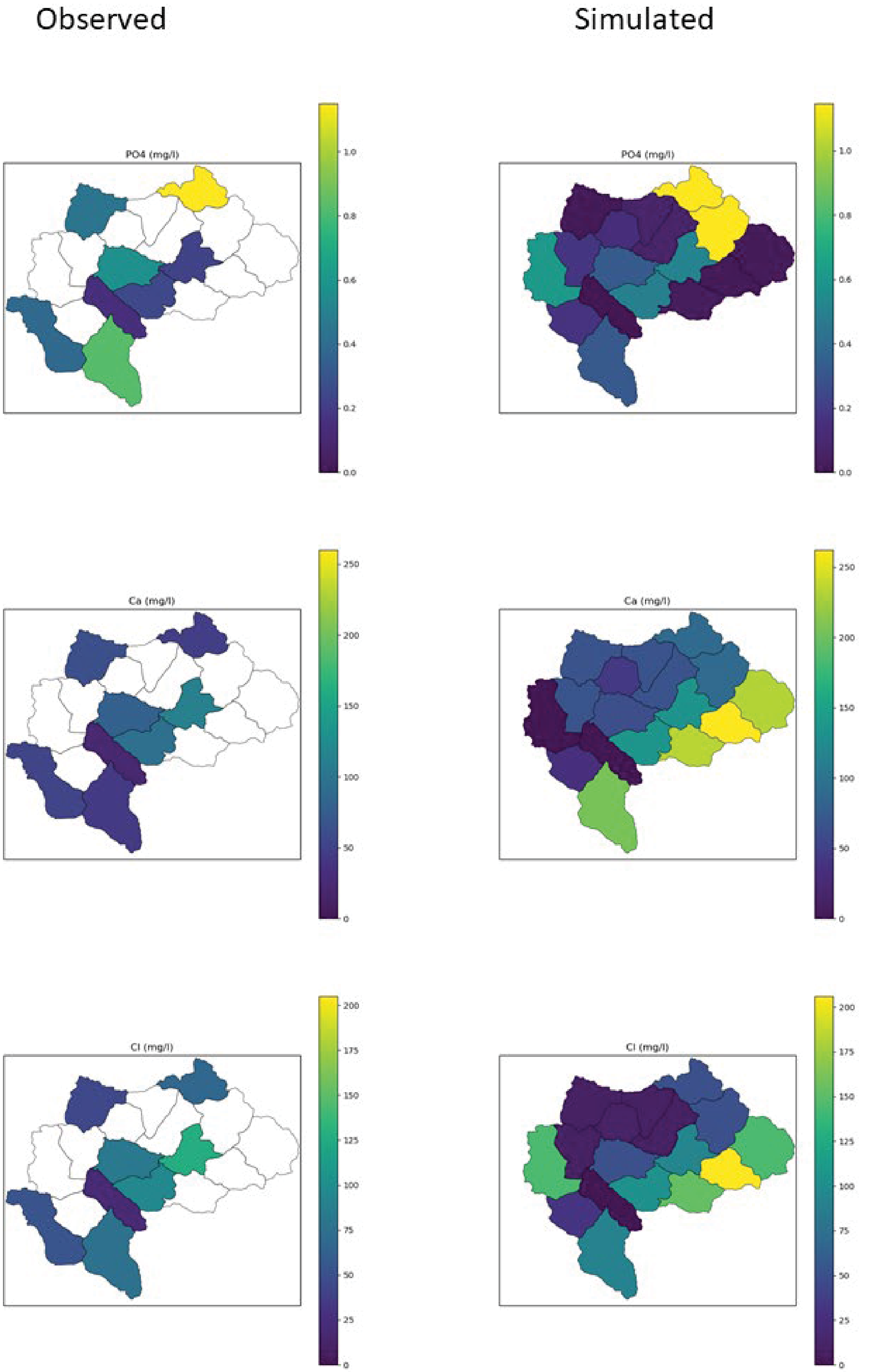


Figure 6.6: Visualisations of observed (left-hand side) and model-simulated (right-hand side) water quality data for the Vaal Barrage catchment for PO_4-P, Ca and Cl

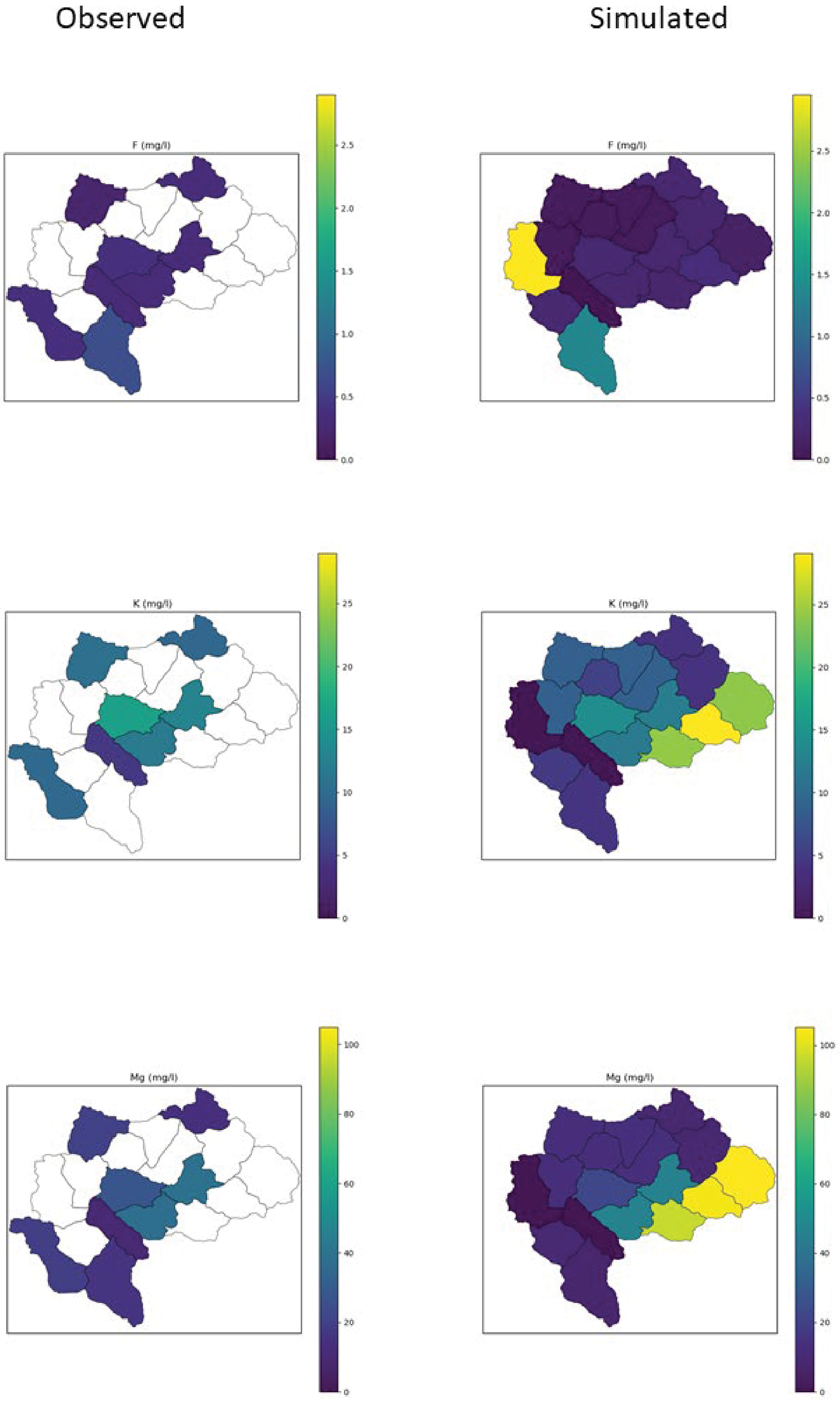


Figure 6.7: Visualisations of observed (left-hand side) and model-simulated (right-hand side) water quality data for the Vaal Barrage catchment for fluorine, potassium and magnesium

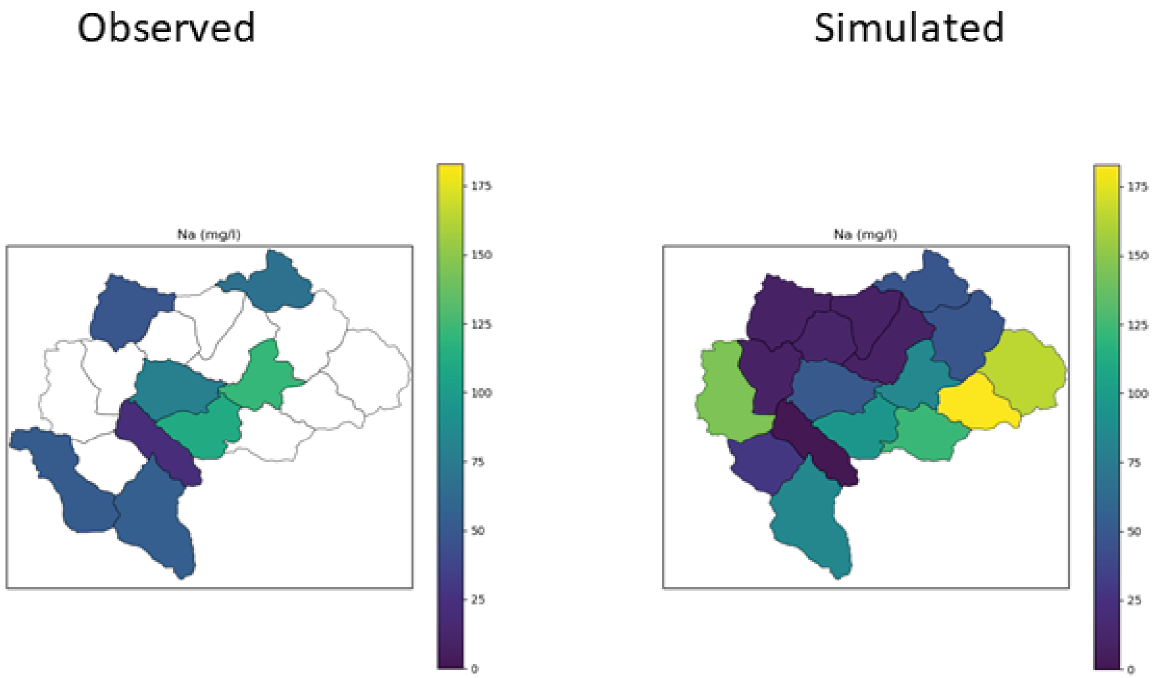


Figure 6.8: Visualisations of observed (left-hand side) and model-simulated (right-hand side) water quality data for the Vaal Barrage catchment for sodium

Inputs of the nutrients NO_3-N + NO_2-N appear to be highest in C22E (Figure 6.5), whereas inputs of PO_4-P appear to be highest in C21D and C21E. These results appear to show that the tributaries into the Vaal Barrage catchment (the Suikerbosrand, Klip and Blesbokspruit rivers) contribute a large proportion of the total load of pollutants in the Vaal Barrage. Figure 6.9 to Figure 6.12 show more detailed results of the calibration process as comparisons between model simulated and observed water quality data as frequency distributions for various points in the catchment. Figure 6.9 shows the calibration results for Node 5 on the Blesbokspruit River. The results show that the model simulations generally matched observed data well in terms of frequency distributions. The calibrations were not as good for the individual salts calcium, fluorine, potassium, magnesium and sodium, but this can be attributed to the relatively limited observed data available for these variables. Figure 6.10 shows the calibrations for Node 11 on the lower Suikerbosrand River. Once again, model-simulated water quality data generally matched observed data, with the model fits for chlorine, fluorine, magnesium and sodium not being as good. Figure 6.11 shows the calibrations for Node 15 on the Lower Suikerbosrand River. Here, the frequency distributions of model-simulated data were generally similar to those of the observed data, even for the individual salts.

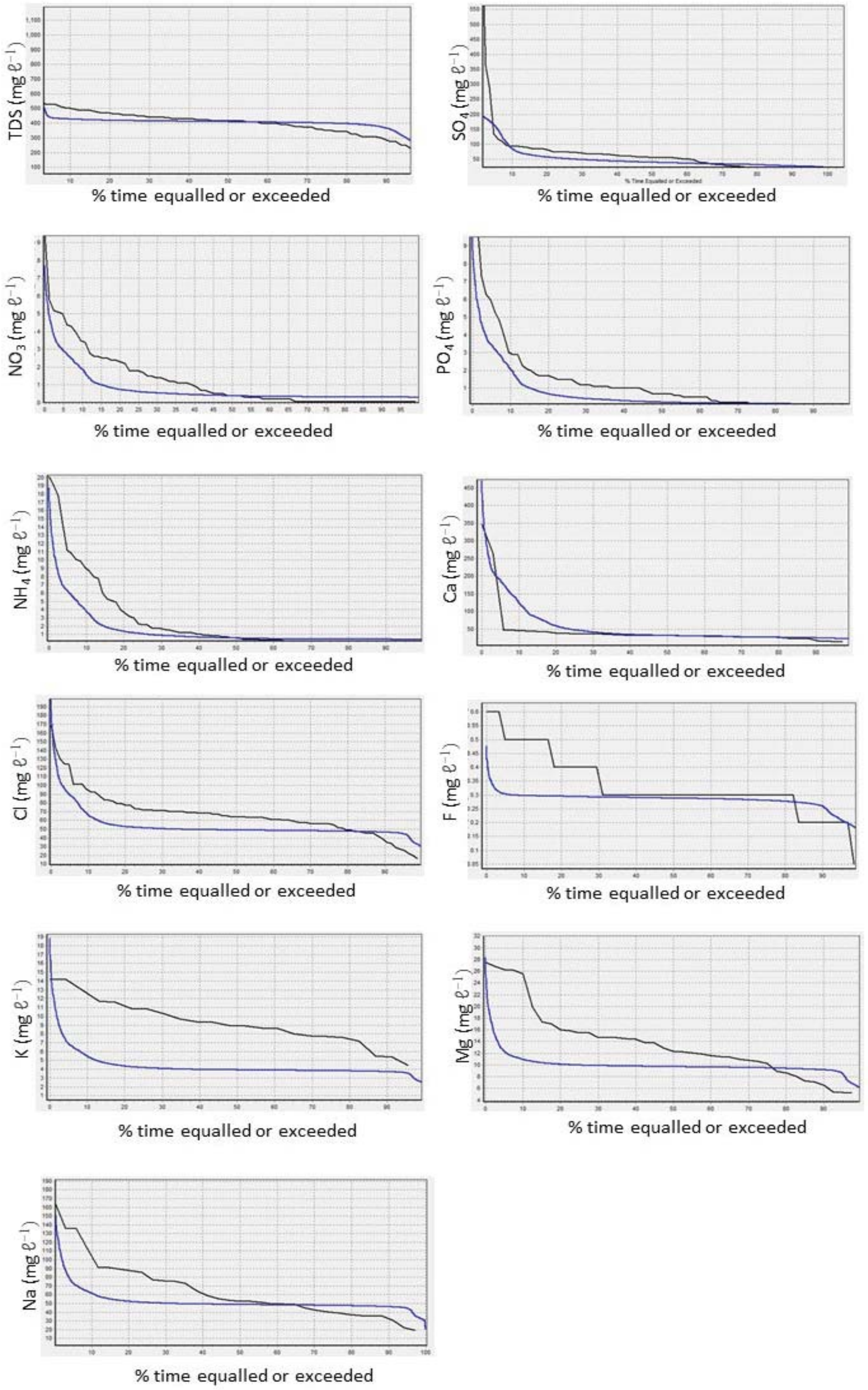


Figure 6.9: Calibrations for Node 5 in the Vaal Barrage catchment as frequency distributions. Black is observed data and blue is simulated data.

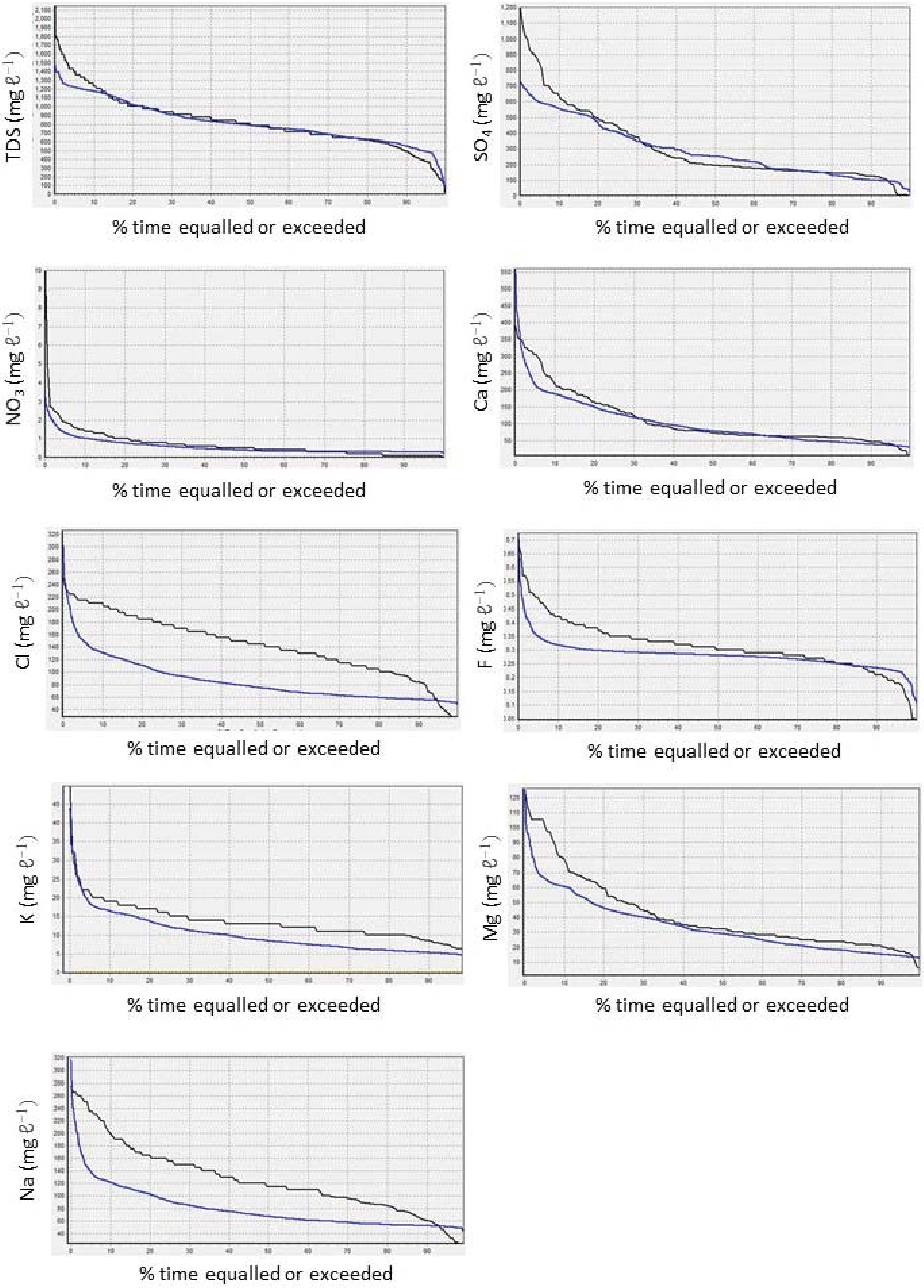


Figure 6.10: Calibrations for Node 11 in the Vaal Barrage catchment as frequency distributions. Black is observed data and blue is simulated data.

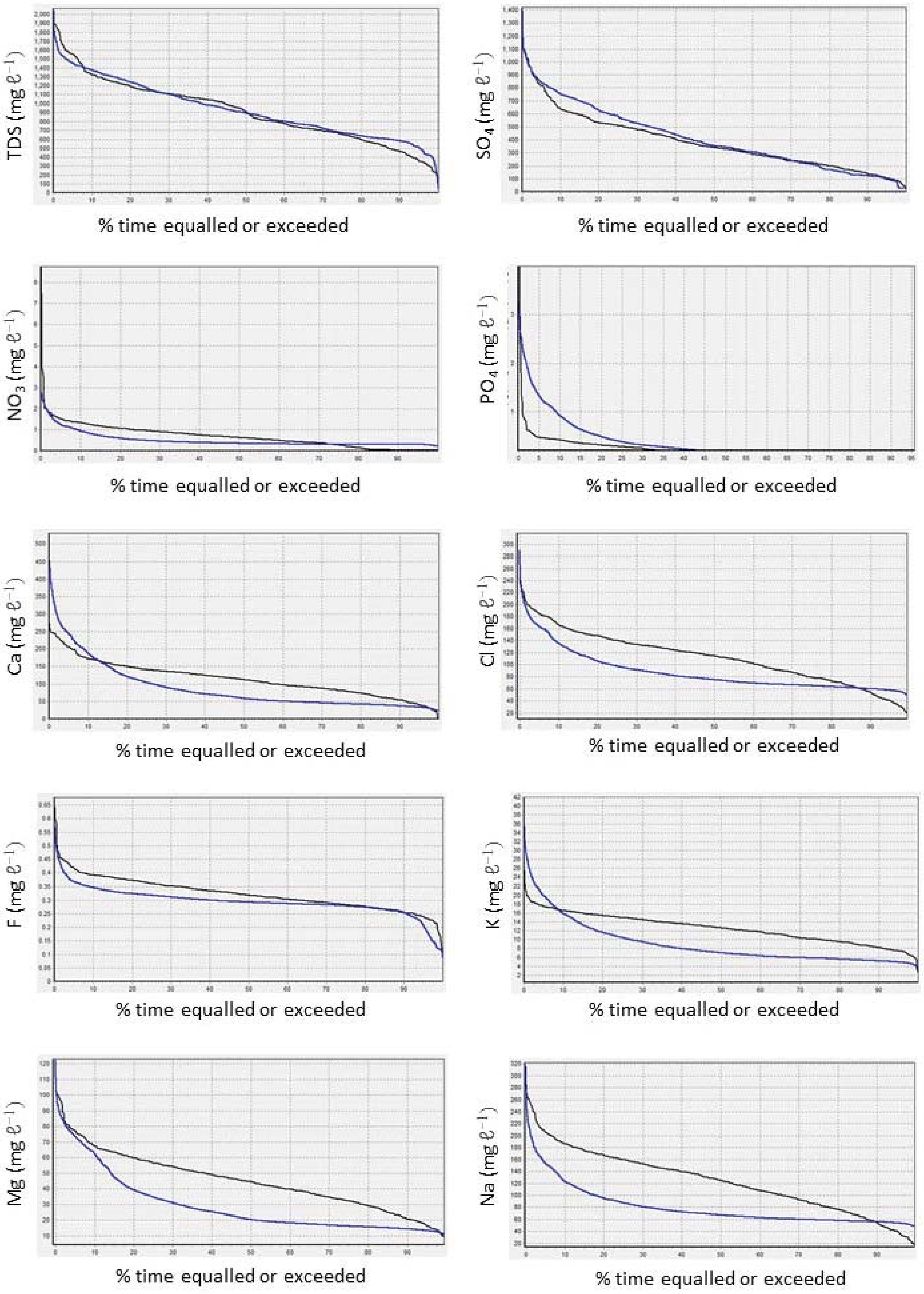


Figure 6.11: Calibrations for Node 15 in the Vaal Barrage catchment as frequency distributions. Black is observed data and blue is simulated data.

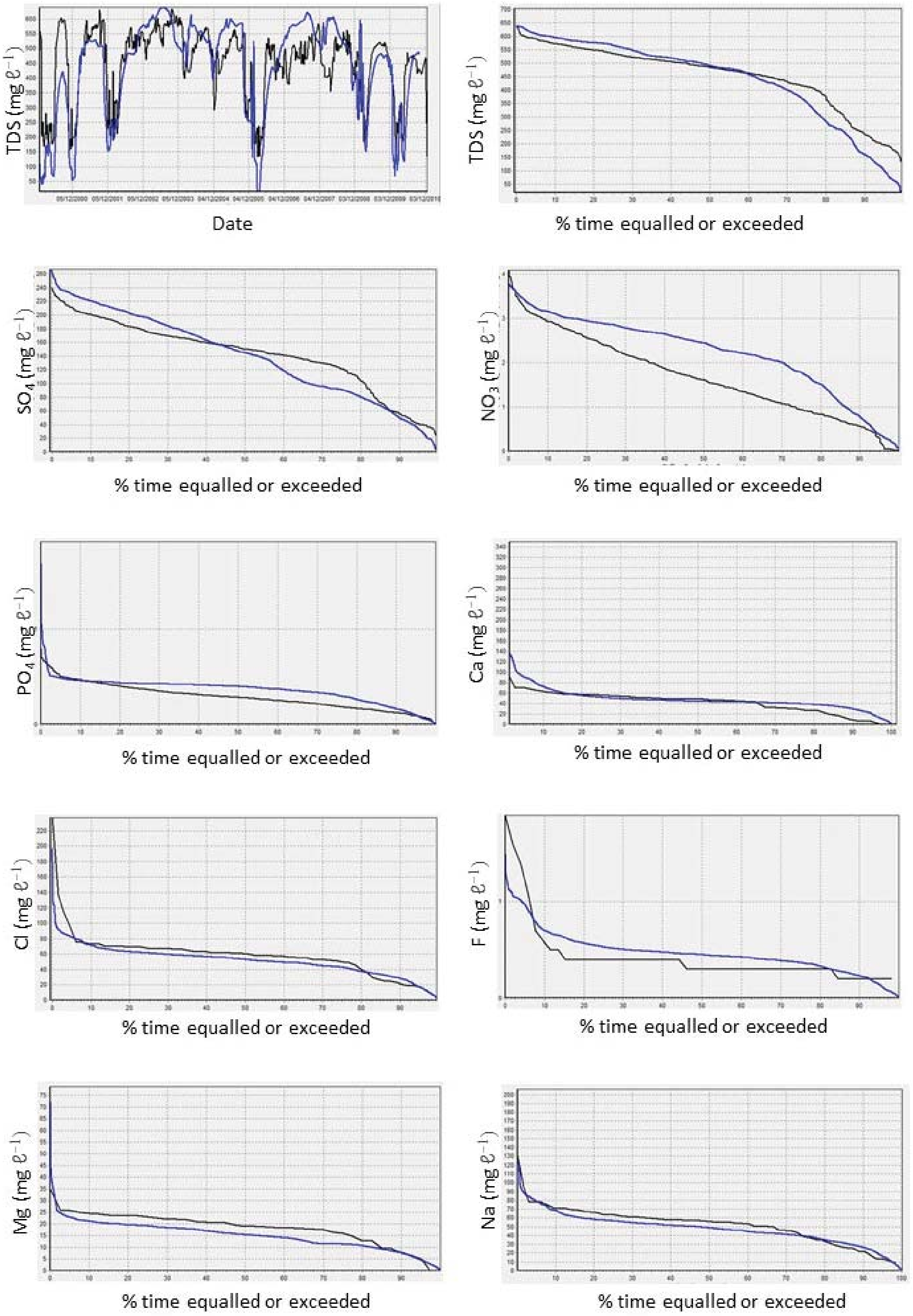


Figure 6.12: Calibrations for the Vaal Barrage in the Vaal Barrage catchment as frequency distributions. Black is observed data and blue is simulated data.

As shown in Figure 6.12, the model calibrations for the Vaal Barrage itself were relatively good. In particular, the model appeared to capture the variability of salts over time.

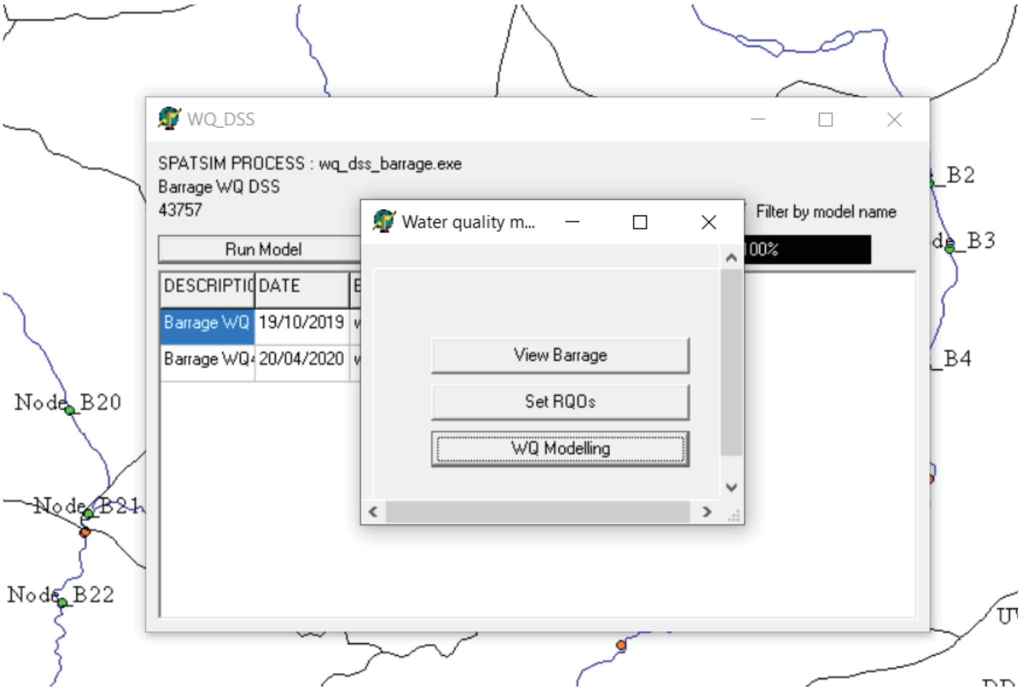
6.2 BARRAGE WATER QUALITY DSS

The DSS that was developed provides a means of linking calibrated models of water quality with an interface that allows users to assess the changes to the system that would result from changes to effluent quality and diffuse pollution inflows. Changes to effluent quality can be specified with respect to several parameters at once or separately. Changes to effluent quality can be specified for several users at different points in the river. However, new emitters cannot be added to the DSS at new nodes without modifying the underlying WQSAM systems design and repeating the model generation process.

6.2.1. Design overview of the DSS

The approach was taken of providing a calibrated version of WQSAM as the barrage water quality DSS. However, all additional functionality not required by stakeholders in the barrage has been removed from this version of the model. The model therefore does not allow water temperature to be simulated as this is already set in the model. In addition, the only parameters users can change are those associated with point and non-point sources, as all other parameters have already been set for the model.

The launch screen of the DSS is as shown in Figure 6.13. The DSS has a panel showing the systems diagram “view barrage” of the model so that users can reference the position of individual nodes in the catchment and their position relative to other emitters. The “WQ modelling” button in the launch screen opens the water quality modelling screen (Figure 6.14). The nodes in the modelled catchment are listed on the left-hand side of the panel. From this panel, users can view the water quality of a particular node in the modelled catchment, either as a time series or frequency distribution (“plot daily concentrations for selected node”). Water quality signatures for point and non-point sources of a particular node can also be set from this panel (“update WQ parameters for selected node”). Finally, the Vaal Barrage DSS can be run from this panel (“run barrage model”).



SPATSIM PROCESS : wq_dss_barrage.exe
Barrage WQ DSS
43757

DESCRIPTI	DATE
Barrage WQ	19/10/2019
Barrage WQ	20/04/2020

Figure 6.13: Launch screen of the barrage water quality DSS

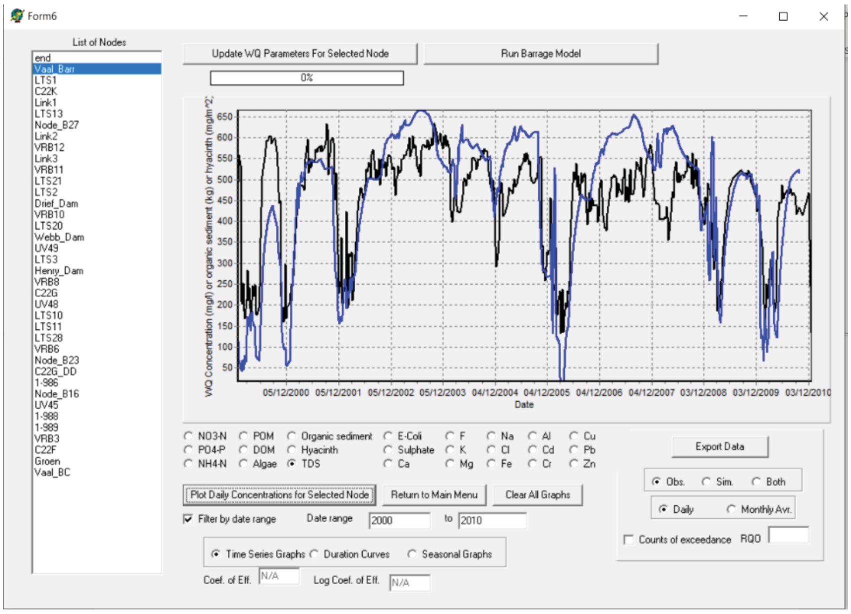


Figure 6.14: Water quality modelling screen of the Vaal Barrage water quality DSS

The screen for updating water quality signatures for point and non-point sources for a particular node is shown in Figure 6.15.

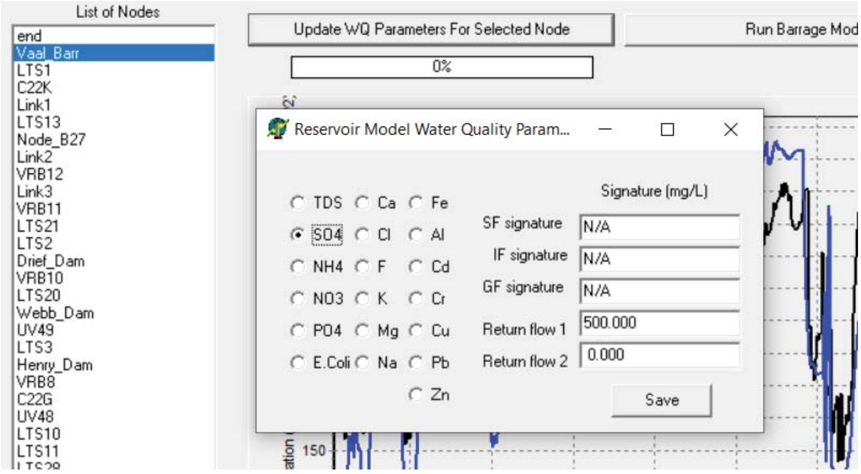
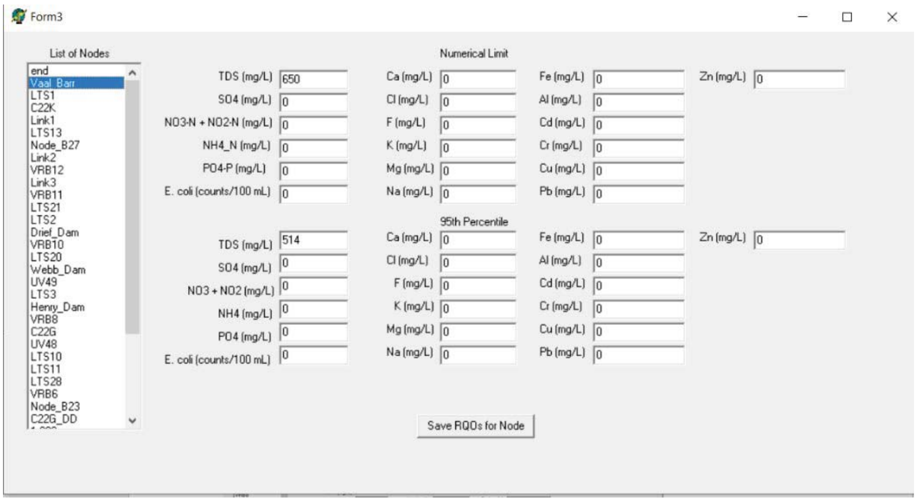


Figure 6.15: Screen within the Vaal Barrage water quality DSS for setting water quality signatures of point and non-point sources

Not all nodes will have incremental (natural) flow, and it is only possible to change non-point source water quality signatures for those that do. There is currently capacity to set the return flow signatures for two point sources per node. The DSS can be adapted to accommodate a larger number of point sources per node if needed.

The “set RQOs” button on the launch screen opens a panel that allows the user to set the RQOs for each node (see Figure 6.13 and Figure 6.15). Where RQOs do not exist for a node, DWAF (2006b) provides guidelines on how to use the SAQWG as interim RQOs.



Numerical Limit

TDS (mg/L) 650
SO4 (mg/L) 0
NO3-N + NO2-N (mg/L) 0
NH4_N (mg/L) 0
PO4-P (mg/L) 0
E. coli (counts/100 mL) 0
Ca (mg/L) 0
Cl (mg/L) 0
F (mg/L) 0
K (mg/L) 0
Mg (mg/L) 0
Na (mg/L) 0
Fe (mg/L) 0
Al (mg/L) 0
Cd (mg/L) 0
Cr (mg/L) 0
Cu (mg/L) 0
Pb (mg/L) 0
Zn (mg/L) 0

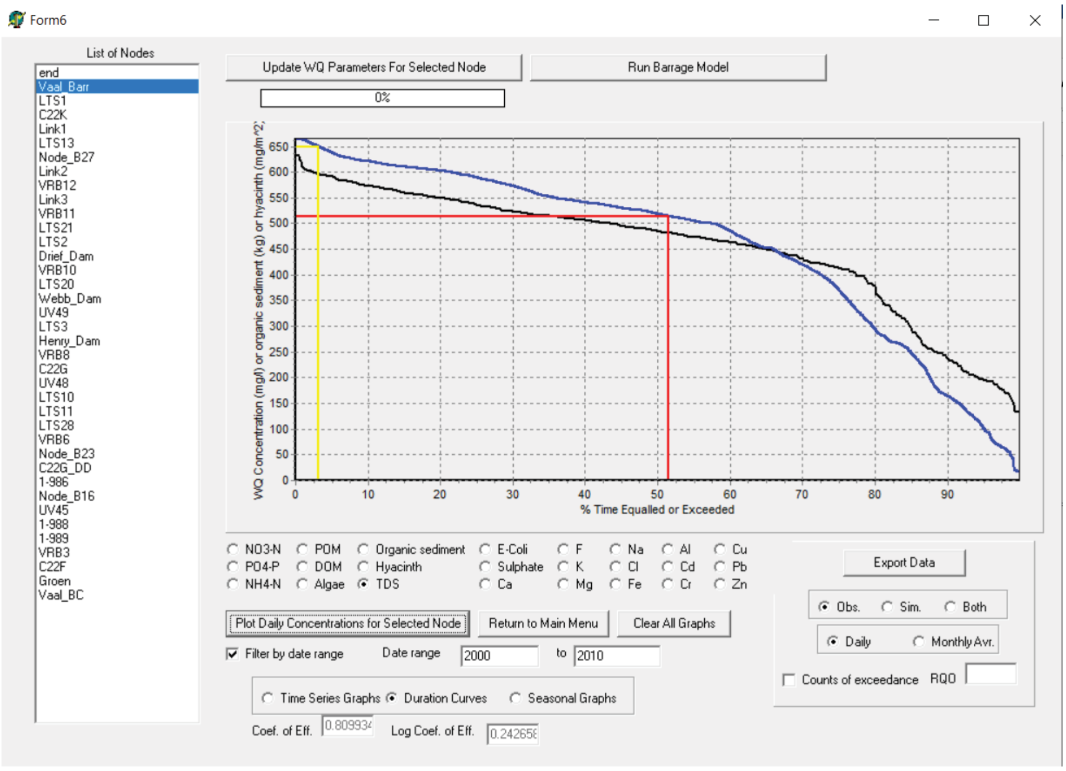
95th Percentile

TDS (mg/L) 514
SO4 (mg/L) 0
NO3 + NO2 (mg/L) 0
NH4 (mg/L) 0
PO4 (mg/L) 0
E. coli (counts/100 mL) 0
Ca (mg/L) 0
Cl (mg/L) 0
F (mg/L) 0
K (mg/L) 0
Mg (mg/L) 0
Na (mg/L) 0
Fe (mg/L) 0
Al (mg/L) 0
Cd (mg/L) 0
Cr (mg/L) 0
Cu (mg/L) 0
Pb (mg/L) 0
Zn (mg/L) 0

Figure 6.16: Screen within the Vaal Barrage water quality DSS for setting the water quality component of the RQOs for particular nodes

It is possible to set both a numerical limit and a 95% RQO for each node and for each water quality variable that is simulated. It was decided to allow users to set RQOs themselves to maximise the flexibility of the model. As shown in Figure 6.15, as an example (these are not the official RQOs), the numerical limit and 95% TDS RQOs (mg ℓ $^{-1}$) have been set to 650 mg ℓ $^{-1}$ and 514 mg ℓ $^{-1}$, respectively.

The interpretation of water quality simulations in relation to the RQOs is facilitated through the water quality modelling screen. Using the same RQO example, Figure 6.16 shows the frequency distribution of TDS for the Vaal Barrage in relation to the numerical limit and 95% RQO example mentioned in the previous paragraph.



○ NO3-N ○ PO4-P ○ NH4-N ○ POM ○ DOM ○ Algae ○ Organic sediment ○ Hyacinth ● TDS ○ E-Coli ○ Sulphate ○ Ca ○ F ○ K ○ Mg ○ Na ○ Cl ○ Fe ○ Al ○ Cd ○ Cr ○ Cu ○ Pb ○ Zn

☑ Filter by date range Date range 2000 to 2010

○ Time Series Graphs ● Duration Curves ○ Seasonal Graphs

Coef. of Eff. 0.809934 Log Coef. of Eff. 0.24265

● Obs. ○ Sim. ○ Both

● Daily ○ Monthly Avr.

☐ Counts of exceedance RQO

Figure 6.17: Water quality modelling screen within the Vaal Barrage water quality DSS, illustrating the interpretation of RQOs in relation to the model simulations

From the frequency distribution of simulated TDS for the Vaal Barrage shown in Figure 6.16, the yellow and red lines show where the numerical limit and 95% RQOs cross the frequency distribution. The percentage of time that the simulated water quality exceeds either of the RQOs can be determined by where the vertical line crosses the x-axis of the frequency distribution graph. In this hypothetical example, the vertical line of the numerical limit RQO (yellow line) crosses the x-axis of the graph at around 3%. Ideally, the frequency distribution of the simulated data should fall below the numerical limit, which is not the case in this hypothetical example. The interpretation is that the effluent discharge causes the instream water quality to exceed the RQOs 3% of the time, implying that 97% of the time the discharges would not cause instream water quality to exceed the RQOs. The vertical line of the 95% RQO (red line) crosses the x-axis of the graph at around 52%, indicating that simulated water quality exceeds the RQO around 52% of the time. For the TDS of the Vaal Barrage to fall within the 95% RQO, the red line should cross the x-axis at 5%. This results therefore show that the simulated TDS data for the Vaal Barrage exceeds the hypothetical TDS at a 95% RQO.

The DSS is downloadable from https://www.ru.ac.za/iwr/research/software/spatsim. Users would need to follow the instructions and then use the manual (Volume 2) to run the model.

Simulations of metals

As mentioned previously, there was insufficient observed data for metals in the Vaal Barrage catchment to adequately calibrate the model. However, the ability to simulate various metals has been included in the DSS. One of the main water users in the catchment has provided data for metals within its effluents. The return flow signatures for metals in the DSS for nodes at which it releases effluents have been updated accordingly. Figure 6.17 and Figure 6.18 show model simulations of iron and lead in the Vaal Barrage, respectively.

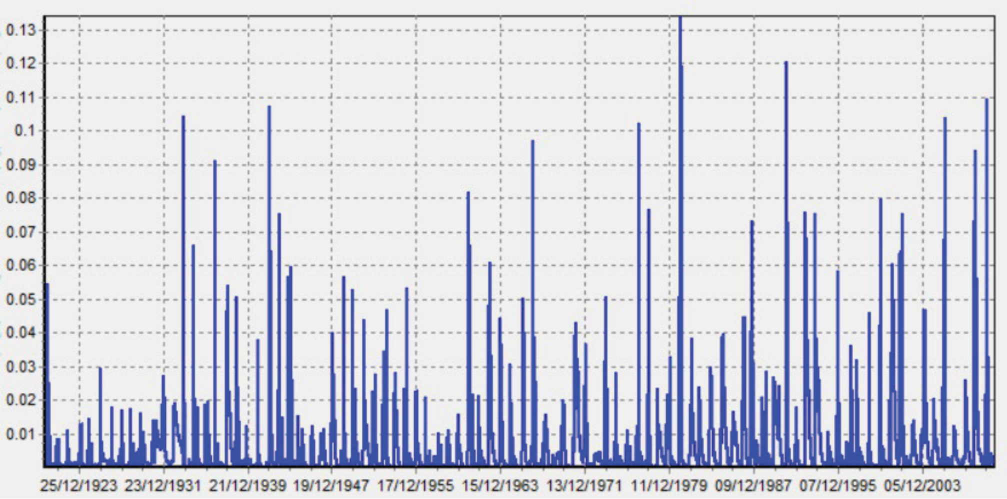


Figure 6.18: Time series model simulations of iron within the Vaal Barrage

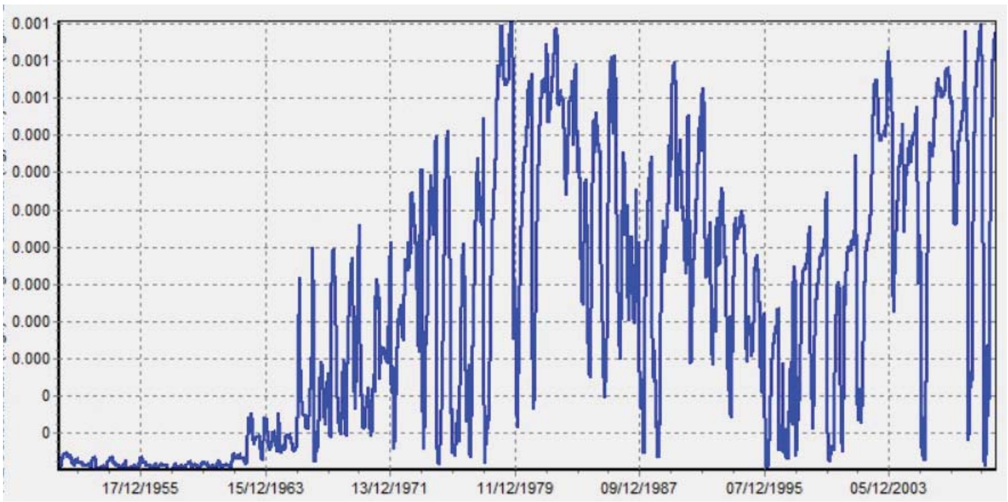


Figure 6.19: Time series model simulations of lead within the Vaal Barrage

6.3 APPLICATIONS OF THE DSS

The developed DSS can find application in a variety of ways in water quality management and the issuance of water use licenses. These are briefly discussed below. A user manual for the DSS is presented as Volume 2.

1. **Effects of upstream waste load on downstream users:** As the WQSAM set-up follows a catchment connectivity, it is possible to use the DSS to investigate the effects of upstream waste loads on downstream users. Users of the DSS can do this by inputting the water quality signatures (in mg ℓ^{-1}) of effluent emitters in upstream nodes, and then relating this effect to instream water quality in downstream nodes, where downstream water users are likely to emit effluents. Another application of upstream-downstream effects is to investigate how upstream waste loads may impact on the realisation of downstream RQOs by assigning the appropriate water quality signatures to upstream emitters at the appropriate nodes.
2. **Investigation of scenarios of water quality standards in WUL in relation to the RQOs:** A key objective of this study was to develop a DSS that allows both the regulator and water resource users to transparently relate water quality standards in WUL to the water quality component of the RQOs. The developed DSS allows users to investigate "what if" conditions. The users can investigate the effects of various WUL scenarios on the RQOs. For example, the regulator can decide to set TDS for a given effluent emitter as a return flow signature at a node and then investigate the effect of that return flow signature on the RQOs. Based on this principle, several other scenarios can be investigated, making the DSS an important negotiation tool between the regulator and water resource users. There are stakeholder-derived water quality guidelines in the Vaal Barrage catchment (see Chapter 3.) These can be used in nodes without RQOs. Alternatively, users can use methods in DWAF (2006b) to derive fitness-for-use categories based on the SAWQGS for Aquatic Ecosystems
3. **Investigate whether the river system has capacity for additional effluent emitters:** In terms of water quality, once the TPC has been determined, the DSS can be used to simulate whether the system has additional capacity to accept new emitters based on the waste load by current emitters. This can be done by the user inputting the TPC (in mg ℓ^{-1}) for the variable of interest and then simulating the effect of the return flow signature (in mg ℓ^{-1}) on the TPC. The DSS would return a risk estimation (percentage time exceedance) of whether the TPC is exceeded based on current emitters. The risk estimation in the form of percentage time exceedance can be used as a basis to decide whether the system has the capacity to accept new emitters, or whether current emitters have exceeded the TPC.

CHAPTER 7: CAPACITY DEVELOPMENT AND STAKEHOLDER ENGAGEMENT

7.1 INTRODUCTION

One of the primary objectives of this study was to engage with stakeholders in the catchment and build capacity in the application of the DSS. As already indicated in Chapter 5, the development of the DSS follows an interactive process, with stakeholder feedback informing the final product. Three training workshops were held online at various times with a diverse set of stakeholders in the catchment. Physical training, which had been envisaged, was not possible due to the COVID-19 pandemic. The project team thus made use of the Zoom and Skype online platforms. The three training workshops followed the same pattern and are thus reported below.

7.2 DECISION SUPPORT TRAINING WORKSHOPS

The following online training workshops took place:

- **Sasol stakeholders:** This workshop was held on 2 April 2020 using the Skype Business platform. It attracted 15 participants from Sasol and three members of the project team.

- **Water users and other stakeholders:** This workshop was held on 21 April 2020 using the Zoom platform. The workshop attracted 33 participants, including four project team members. This workshop was meant to build capacity across a diverse set of stakeholders. Participants were drawn from different organisations, including WRC, Sasol, Safripol, Eskom, the Inkomati-Usuthu Catchment Management Agency (IUCMA), the Tshwane University of Technology (TUT), Ekurhuleni Water Care Company, Jones and Wagener, Golder Associates, National Petroleum Refiners of South Africa (NATREF) and Rhodes University. Representatives from the DWS could not attend this workshop due to unforeseen circumstances. The project team thus took a decision to organise a third training workshop for DWS staff.

- **DSS workshop:** A third and final workshop was organised for staff of the DWS on 26 August 2020. The training attracted 21 delegates from the DWS's regional and national offices.

Apart from the DWS training workshop that took place towards the end of the project, the aim of the training workshops was twofold: to develop capacity by demonstrating its implementation and application, and to solicit stakeholder feedback, which can then be used during the interactive process of developing the DSS.

7.3 FORMAT OF THE WORKSHOPS

Stakeholders were presented with a rationale to produce a DSS to facilitate water quality management and to provide an explicit link between instream water quality targets, in particular RQO, WUL and other SDC instruments. The importance in this regard of realistic, scientifically defensible instream and emission standards was highlighted, as was the importance of a credible DSS in assessing the importance of seasonal change, in accounting for all waste streams simultaneously, and elucidating the links between water quality and water quantity in the catchment. The potential for using the WQSAM to address these issues was reviewed, and experience in modelling and model testing was outlined.

An overview of the Vaal Barrage catchment was presented to stakeholders, highlighting the industrialised nature of the catchment, the altered and non-natural flows, the number of water users and effluent emitters, and the problems with water quality experienced in the catchment.

This was followed by a conceptual presentation of the WQSAM. The structure of the WQSAM was presented to stakeholders, with an explanation of how the modelling process used a monthly time-step yield model as input, how this was disaggregated to different daily flow components, and an outline of how various conservative and non-conservative water quality parameters were modelled. Data sources of yield models and water quality data for the Vaal Barrage catchment were elucidated, and the modelling steps for the Vaal Barrage catchment with this data were presented. The same steps were undertaken for the lower resolution models for the broader Vaal Barrage catchment and the Upper Vaal catchment. System diagrams for the three water quality models were presented and explored in the workshops. Model calibration results at nodes in all catchments for various water quality parameters were also presented. After the conceptual presentation, the project team demonstrated the DSS by taking the workshop participants on a step-by-step process of how to use the DSS.

A major objective of the project was to allow exploration of the effect of changing WUL conditions on achieving instream water quality targets. This would allow stakeholders and the regulator to assess what the impact of changes to WUL conditions might be. This facility was included in the DSS as follows: Users were offered a facility to input instream targets so as to assess the proportion of the time that these might be exceeded under the conditions selected, as already demonstrated in Chapter 5 (see Figure 6.1). Instream targets would, in many cases, be RQOs, but where other guidelines are used (for example, catchment management forum guidelines), these can be entered into the DSS. The use of a load duration curve, as in Figure 6.1, allows users to determine exceedance rates for a particular target, which provides an estimate of the ecological risk attached to particular changes in emission rates.

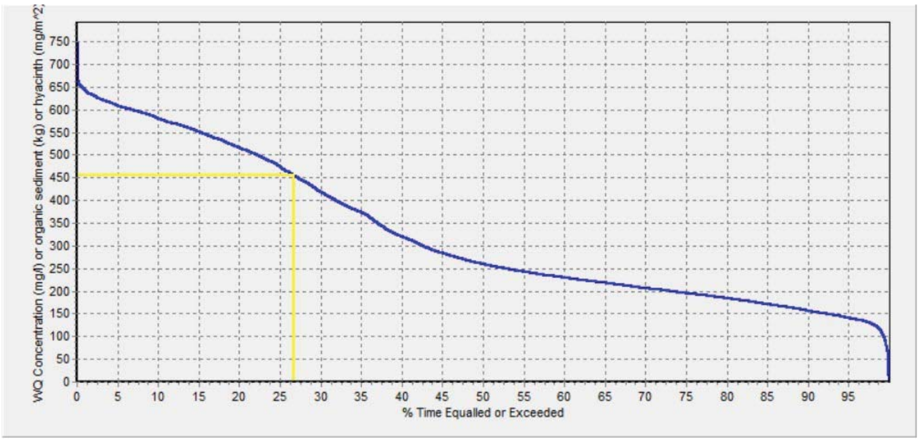


Figure 7.1: Example of a load duration curve (blue), showing the selected instream target in yellow. The y-axis shows the concentration of the water quality parameter assessed, and the x-axis shows the proportion of the time the target is exceeded.

7.4 CRITICAL FEEDBACK FROM STAKEHOLDERS

Feedback from the workshops included the following:

- Stakeholders generally expressed an interest in the DSS and its application for managing water quality in the Vaal Barrage catchment.
- The DSS does not initially include the Klip and Suikerbosrand river systems at a fine scale, but stakeholders expressed an interest in having these system model the river systems at a fine spatial resolution. These were thus included in the final DSS, as indicated in Chapter 5. In the same vein, stakeholders indicated the need to improve the modelling resolution for the Leeuspruit and Taaibosspruit rivers to capture any potential impacts associated with Sasol Midlands. This was also addressed in the final DSS described in Chapter 5.

- Stakeholders indicated that metals and individual salt ions were very important for the catchment, given its industrialised nature, as well as the challenge of legacy acid mine drainage (AMD). As already indicated in Chapter 5, the metals have been included in the DSS, although calibration has been done largely with sparse data. Several individual salts have been added in response to stakeholders' feedback (see Chapter 5).
- The potential of the DSS for application in its current form to explore the relationship of RQOs and other instream guidelines with WUL and other water quality management instruments in the Vaal Barrage catchment was recognised. Likewise, the potential for expanding the DSS to other catchments, where WQSAM water quality models exist, was also noted. The IUCMA has used WQSAM in water quality management and expressed an interest in adapting the DSS for catchment management planning using regionally appropriate water quality data.

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

8.1 INTRODUCTION

This study arises from the realisation that the understanding of the link between the resource quality objectives and the discharge standards in water use licenses was not clear to water resource users within the Vaal Barrage catchment. Clarifying this link between the RQOs and WUL was important because these are legal instruments used by the DWS to ensure water resource use and protection. In Chapter 3 of the study, current practices related to WUL and RQOs were reviewed, and it was concluded that current methods used for setting end-of-pipe discharge standards were robust, but with several shortcomings. These shortcomings included the non-consideration of the differences between conservative and non-conservative water quality variables, the non-consideration of upstream waste loads on downstream resource users and RQOs, the non-consideration of the contribution of diffuse pollution sources to instream waste loads, which is critical for a highly developed catchment such as the Vaal Barrage catchment, and the setting of receiving stream concentrations for toxic substances at zero (0) and reference conditions for system variables, which could be unrealistic given the developed nature of the Vaal Barrage catchment.

To address the identified challenges, a Vaal Barrage water quality decision support system was developed. The developed DSS is based on a calibrated version of the WQSAM and is able to simulate important water quality variables of management concern such as the nutrients NO_3-N + NO_2-N, NH_4-N and PO_4-P, the salt SO_4, TDS, calcium, chloride, fluoride, potassium, magnesium and sodium, and metals such as iron, aluminium, cadmium, chromium, copper, lead and zinc. Possible applications of the DSS include investigating the effects of upstream waste loads on downstream users and RQOs, the scenario modelling of the effects of water quality standards in WUL on the RQOs, and simulating whether the receiving river system has the capacity for additional emitters, given waste loads from current emitters. It is believed that the DSS addresses stakeholders' concern about scientific credibility and defensibility around the way discharge standards in WUL are being set. The development of the DSS went through several iterations, with stakeholders' input informing several considerations, such as modelled catchments and water quality variables.

The DSS has been developed so that users can input the RQOs and the discharge standards as water quality signatures of return flow at nodes of interest. Users are therefore able to simulate the relationship between WUL and RQOs or other instream guidelines. The major limitation of the DSS is that, in some instances, it has been calibrated using insufficient data, such as those of metals and return flow signatures. This limitation can be addressed as more data becomes available.

As part of capacity development during the project, three training workshops were conducted, which attracted 69 stakeholders from various organisations, including within the catchments. The training workshops served two primary purposes: capacity development and feedback from stakeholders. For example, the inclusion of additional salts and metals, as well as the extension of the DSS to include the Klip and Suikerbosrand rivers, was informed by stakeholders' input.

8.2 RECOMMENDATIONS FOR IMPLEMENTATION AND FUTURE STUDY

The DSS, as it stands, can be implemented and operationalised for daily use for the Vaal Barrage catchment and associated rivers, including the Klip, Leeuspruit, Taaibosspruit and Suikerbosrand rivers. Once the DSS is fully operational in the Vaal Barrage catchment, it is recommended that it be extended to the entire Upper Vaal catchment.

One of the greatest challenges faced during the development of the DSS was access to data, particularly for metals and discharged effluent quality by emitters. Given that the catchment is highly industrialised, routine monitoring of metal concentrations in the rivers is recommended, together with a system that made effluent quality data from the various emitters publicly available. Such a system would facilitate access to effluent quality data that can be used as observed data for model calibration. The WQSAM is an important model that has been developed to address the identified gaps in water quality management in South Africa, and it is possible for the model to be implemented in other catchments. It is recommended that investment is needed for the wide implementation of the WQSAM, supporting similar DSSs as developed for the Vaal Barrage catchment. Finally, it needs to be noted that the DSS was developed to assist catchment managers and users to create a better understanding of the situation on the catchment and the management options available, i.e. as a tool to support IWRM, and, by itself, is not the final say on an RQO or license condition. It thus needs to be used together with other relevant tools within relevant IWRM processes.

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