Developing Long- and Short-Term Technical Solutions, Mitigation Measures and Decision Support Strategies that will Improve Water Quality in the Grootdraai Dam Catchment

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

The upper Vaal River catchment, and Grootdraai Dam catchment within it, has significance within the country as a result of the industry, energy generation, and agriculture within the catchment. Historically the catchment has had good water quality, such that water from the Grootdraai Dam, which lies near Standerton at the base of the catchment, was suitable for a number of users. However, more recently, a trend to varying water quality has been observed. The drivers of water quality change are many: agricultural land use, mining, or semi or untreated sewage release. This is compounded by factors such as climate change, differences between regulators, different legal frameworks, etc. Progress has been stalled by the lack of a means of predicting the changes needed, and exploring scenarios for amelioration.

AIMS

The following were the aims of the project:

➢ The overall objective is to predict current and future water quality changes in the Grootdraai catchment because of various activities both (present and planned) as well as varying scenarios that are likely to occur. The following are the sub-objectives:
  - Identify potential solutions and determine actions that should be prioritised in order to reduce potential impacts as a result of quality deterioration.
  - Identify all man-made and naturally occurring current and potential future sources of pollution in the catchment.
  - Establish the short- and long-term drivers of water quality deterioration in the catchment.
  - Develop a predictive tool which can inform what the status of water quality will be in the future.
  - Identify potential solutions to address quality in the short and long term.

METHODOLOGY

In order to model the catchment, it was necessary to locate data sets to underlie the modelling process. The Department of Water and Sanitation (DWS) were approached for water flow and quality data from their monitoring points in the catchment. Rand Water also contributed data from their datasets. Data from a prior project provided the climate change yield data that underlay the climate change results presented here (Aurecon, 2020). Finally, spatial data on the catchment was accessed from a range of sources and used to set up the models and for any spatial analyses that are presented.

Workshops were held to introduce potential stakeholders to the project. The project team undertook a search process to identify stakeholders from the regulator, from local government, from business, from academia, from consultants, and elsewhere to assemble a list of names for invitation to stakeholder's workshops. The first workshop was largely introductory, and aimed to present the project, and also to highlight, by means of an example of a prior project and its outcomes (most notably a Decision Support System (DSS) that allow users to examine Water Use License (WUL) conditions in terms of river Resource Quality Objectives (RQOs) or other targets) how user-led catchment might proceed, and the sorts of tools that might support that. Likely developments for the catchment were presented, as were reports on known water issues in the catchment and their drivers.

A second workshop was held later to workshop likely water quality-related changes in the catchment. In this workshop, known drivers of water quality were discussed, as was what might cause any changes in these. Given the identified decrease in water quality in the catchment, these discussions linked changes that may be due to population growth or changes in economic climate with the likely changes in water quality in the catchment. Explicitly, this was located against a background of climate change, and the likely changes to the climate in the catchment and the socio-environmental consequences of these.

A water yield model of the upper Vaal catchment together with a water quality aspect already exists. In it, water yield was modelled using the Water Resources Planning Model (WRPM) and water quality was modelling using the Water Quality Systems Assessment Model (WQSAM) from daily flow data. The resolution of this model was insufficient to model the Grootdraai Dam catchment adequately, and the decision was taken to remodel the yield model using Pywr, a water resource network modelling library in Python. This would enable the addition of extra nodes within the model for adequate spatial representativity.

To do this, the run-offs from the WRPM model were redistributed to a quaternary level. The WRPM model structure was replicated in Pywr. Using the redistributed runoff, additional inflow nodes were added to the model, along with appropriate link nodes. The return flows were related with actual effluent inflows where possible by consulting DWS and Rand Water data. Data, parameters, and recorders were then added to the Pywr model. The model read in driving data, and the model simulations were compared to those of the WRPM to ensure the models simulated the same flow.

Monthly incremental flows were disaggregated to daily flow, and redistributed to a quaternary level. Data such as land use, soils, elevation, and rainfall distribution were used to redistribute the WRPM flow to a more distributed level in Pywr.

RESULTS AND DISCUSSION

When the distributed daily flow data for the catchment were available and agreed with the WRPM model, the water quality model, or Pywr-WQ model, was calibrated such that simulated data, generated from Pywr daily flow data, were a good simulation of observed data. Initially, we had planned to use WQSAM for this process. However, we encountered difficulty in using WQSAM in this context, and so a decision was made to recode WQSAM's modelling functions in Python to produce a functionally identical model to WQSAM that ran using the Pywr framework.

Scenarios that were prioritized in the scenario workshop were assessed using a multiple regression model. Land cover data from 2013 and 2020 were downloaded and reclassified to a simpler set of land uses per quaternary catchment. Land use areas were correlated with nutrient and selected salt concentrations using multiple regression. This provided a statistical model that linked land area use with water quality parameters. Changes in area covered by three land uses were assessed: mining, urban areas, and cultivated land. These land uses had been identified in the scenario workshop as land uses that had implications for water quality and were liable to change in the studied region for various reasons. The rates of change of these land use areas were determined from change from 2013 to 2020 in each quaternary catchment. Knowing the rate of change enabled modelling water quality at 2050 and 2099. Increases in any of the three land uses leads to decreased water quality in the future. All lead to increased nutrients, with mining resulting in higher marginally phosphate levels in the future, and urban and cultivated land more associated with nitrogen nutrients. Increases in nutrients were outweighed by salinity increases, with mining having the major impact. This approach is explicitly a model of non-point contamination. The result from the modelling exercise highlights the threat to water quality posed by insufficiently managed coal mining in this region.

The climate change impact on water resources in this region was assessed by taking yield models predicted for this catchment under catchment and using the flow data to predict water quality after disaggregation and redistributing of flows. Then the calibrated Pywr-WQ model can be used to predict water quality from the flow data. This assumes that conditions in the catchment do not change significantly. Climate change should result in decreased flows, with minor changes in water quality. Small decreases in nutrients and some ions, and small increases in salinity and some other ions are anticipated. As has been predicted, climate change also has effects on extreme weather conditions, with increased frequency and intensity of extreme weather events. Floods may result in a short-term increase in nutrient levels. In contrast, the concentrations of salts initially decreased, but this increase occurred more slowly. Salts show an increase in concentration from the onset of the drought event. This culminates in peak values, after which a gradual decline ensues, ultimately leading to the conclusion of the drought event. On the other hand, nutrients decrease during a drought.

Finally, a number of mixed-use models were run, which attempt to simulate the effect of a plausible future for the catchment. All the models ran under conditions of climate change, as that is occurring. All included a reduction in coal mining, on the principle that Eskom will reduce coal-fired electricity generation under South Africa's Just Energy Transition programme. Finally, an increase in abstraction by the Sasol-Secunda plant or other users has been identified as likely in the future, and the mixed-use model assessed the impact of a small to very large increase in abstraction of water from Grootdraai Dam. All model outcomes showed the same results: regardless of the rate of abstraction, large drops in salinity were found in all scenarios. The different abstraction rates could not be statistically distinguished, indicating that varying within the range of dilution capacity assessed here had to impact on salinity. Regardless of the increase in salinity consequent on climate change, reduction in mining as simulated here led to an improved overall salinity for the catchment. The reduction relies on the model assumptions of a cessation of mine water entering the ground water being met.

CONCLUSIONS

The project established a new modelling platform for use in South Africa. Pywr was found to be suitable for yield modelling and was used in this project to expand on an existing yield model so as to improve the model's resolution. Pywr-WQ is a system written in Python using Pywr to mimic the functionality of WQSAM, a water quality model whose use is established in South Africa. As in WQSAM, Pywr-WQ produces water quality predictions using flow data as an input to a calibrated model.

Ongoing water quality management in the catchment will need careful management if water quality is to be maintained. All scenarios where areas under land uses of mining, urbanization, or cultivated agriculture were expanded resulted in decreased water quality. This was particularly the case when simulating the impacts of mining. Climate change resulted in decreased flows, with accompanying minor changes to water quality. The only scenario with clearly improved water quality was found where less mining was simulated.

All the models that were used were calibrated on observed water quality data that reflect water management and environmental practices of the past approximately 25 years. Applying these calibrations to scenarios assessed here has resulted in decreased water quality. However, while it might not be possible to decrease the area of land used for a particular purpose, it may be possible to improve the water quality by better management of the resource than existed in the past.

There are various mechanisms available for water resource management in the different sectors, but they come down to the general recommendation that contaminated water should not be released to a water resource, which includes both the surface and groundwater. Secondly, any effluent that is released be appropriately treated before release. Management of the impacts of the various sectors will improve Vaal and Grootdraai Dam water quality.

DSS USER MANUAL

A Decision Support System (DSS) was produced in order that users might experiment with the models that were generated during the project. A user manual to the system is included. Although the modelling in the project was done using Pywr and Pywr-WQ, the DSS was produced as a WQSAM model that is accessed within SPATSIM. This approach was selected so that users who are not comfortable with running a model from scripts would be able to access the DSS comfortably. Datasets used in the DSS were generated using Pywr and Pywr-WQ and ported to WQSAM for a more familiar menu-based user interface.

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Reference Group	Affiliation
Eunice Ubomba-Jaswa	Water Research Commission (Research Manager)
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ACRONYMS & ABBREVIATIONS

CMA	Catchment Management Agency
COD	Chemical oxygen demand
DEM	Digital Elevation Model
DSS	Decision support system
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
ERWAT	Ekurhuleni Water Care Company
GIS	Geographic Information System
GWF	Ground Water Flow
IF	Interflow
IWR	Institute for Water Research, Rhodes University
JET	Just Energy Transition
JSON	Java Script Object Notation
PAIA	Promotion of Access to Information Application
Pywr	Water resource network modelling library in Python
Pywr-WQ	Water quality models in Pywr following WQSAM methods
QGIS	Quantum GIS
RQIS	Resource Quality Information Services
RQO	Resource Quality Objective
SF	Surface Flow
SPATSIM	Spatial and Time Series Information Modelling
TDS	Total Dissolved Solids
VRESAP	Vaal River Eastern Sub-System Augmentation Project
WMS	Water Management System
WQSAM	Water Quality Systems Assessment Model
WRC	Water Research Commission
WReMP	Water Resources Modelling Platform
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model
WR2012	Water Resources of South Africa, 2012 Study
WUL	Water Use License
WWTW	Wastewater Treatment Works

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

The Vaal River catchment in general and the Grootdraai Dam catchment in particular, play an important role in the social-economic prosperity of South Africa. The catchment supports many industries and activities such as manufacturing, mining, agriculture, tourism, and petro-chemicals considered to be critical to socio-economic development of South Africa. Many of the industries and bulk and non-bulk water users rely on raw water from the Grootdraai Dam catchment to sustain their operations. However, over the years, water quality within the catchment has been found to vary both spatially and temporally. The causes of the observed changes in water quality in the catchment are diverse, including both non-point sources such as run-off from agricultural farmlands and point sources such as discharges of poorly treated or untreated effluents from municipal wastewater treatment works (WWTWs). Poorly decommissioned and abandoned mines within the catchment are also key contributors to deteriorating water quality within the catchment. The observed changing water quality is further compounded by variable and changing climate, land use changes, lack of collective effort by both users and regulators to reverse the trajectories and a lack of predictive tools to assist regulators and users to take effective collective actions based on informed scenario analyses of current and future trends.

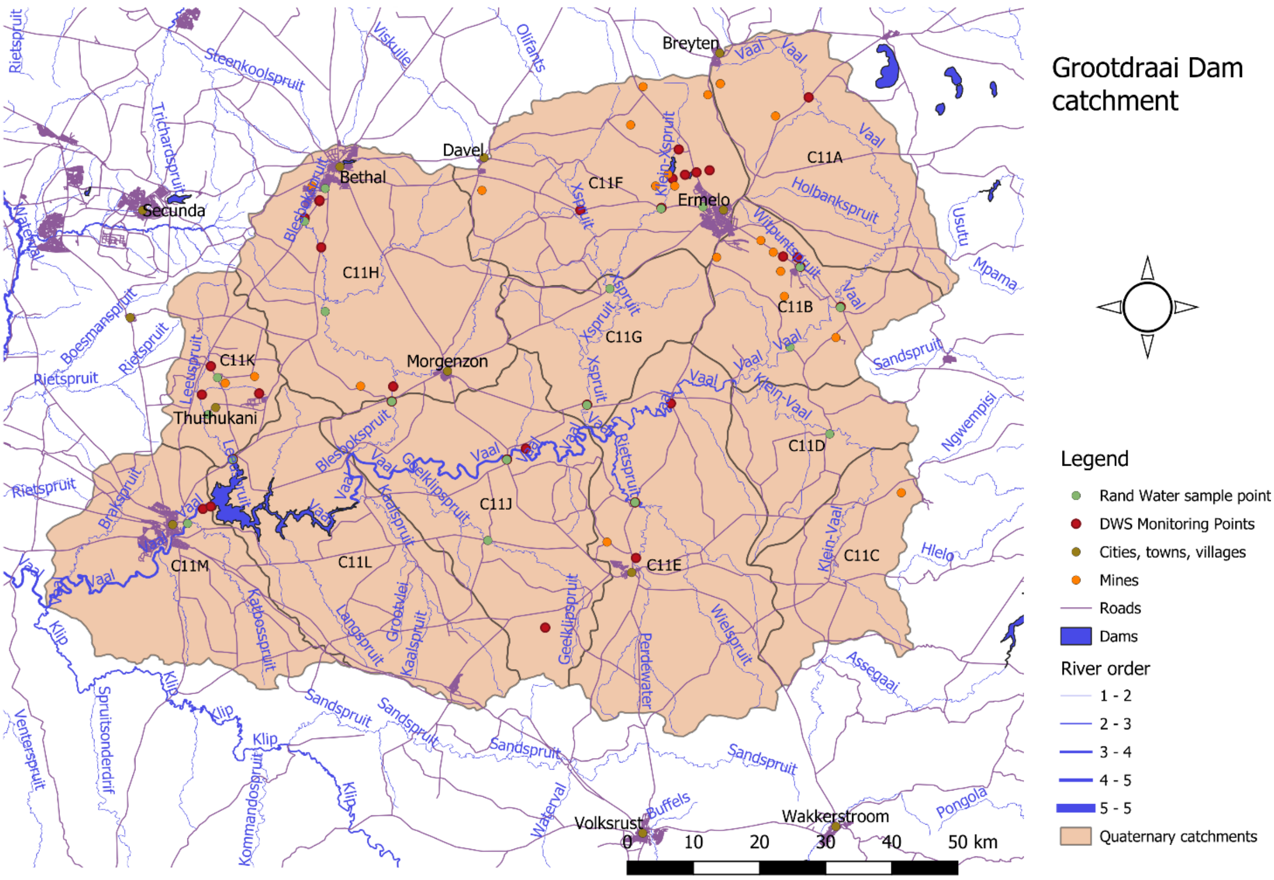


Figure 1-1 Map of the Grootdraai Dam catchment showing rivers, towns, water quality monitoring sites, and mine locations.

The Grootdraai Dam lies on the upper Vaal River close to Standerton (see Figure 1-1). The dam was completed in 1982, and was built primarily to supply water to Sasol's coal-to-liquid plant in Secunda (DWAF, 2009a). However, other water users use water from the dam, and in particular Eskom generates a significant amount of the country's electricity in the catchment (Tutuka, Majuba, and Camden power stations are all in the catchment, as are a number of active and defunct coal mines).

The catchment contains the upper Vaal River and its tributaries, the Leeuspruit, the Blesbokspruit, the Tweefontein Spruit, the Witpuntspruit, the Holbankspruit, the Onverwagspruit, the Klein Vaal River, the Vaalbankspruit, the Rietspruit, the Krogspruit, the Geelklipspruit, the Kaalspruit, the Langspruit, the Katbosspruit, and their tributaries and some smaller streams. The catchment can receive inflows from the Heyshoop and Zaaihoek transfer schemes, with transfers being done in accordance with operating rules. Water can also be transferred out of the catchment to the Vaal-Olifants transfer scheme.

Standerton, at the lower end of the catchment, is the largest town in the catchment. Ermelo, upstream of Standerton, is another significant settlement, and the catchment also contains the smaller settlements of Daggakraal, Volksrust, Kriel, Thuthukani, Camden and Amersfoort. Secunda and the Sasol coal-to-liquid plant, and associated coal mines, are out of the catchment to the north of Standerton.

Land use in the catchment is dominated by coal mining, power generation, and agriculture (DWAF, 2009a, 2009b). Legal irrigation of agriculture takes place, but a proportion of irrigation is illegal which puts stress on the water resources (DWAF, 2009b). The extent of agriculture may also indicate the potential for nutrient loss from soil or fertilized fields to groundwater or rivers. Non-point agricultural nutrient pollution which threatens Grootdraai Dam water quality was established by Ncube (2015), and Ntshalintshali (2019) noted that Vaal River water leaving the Vaal Dam, approximately 90km downstream of Grootdraai Dam, had higher nutrient levels. There is also the potential for pesticide or herbicide impacts where these are used. Decant from active and defunct mines is another potential impact on water quality in the catchment (DWAF, 2009a, DWAF, 2009b).

Water quality in the middle and lower Vaal system is anchored by having good water quality water in the upper Vaal River, specifically in the Grootdraai and Vaal Dams (DWAF, 2009b). Water users of Grootdraai Dam, who produce a significant quantity of hydrocarbons, fertilizers and other chemicals, and electricity for the country also have an interest in clean water from the Grootdraai Dam. However, although DWAF (2009a, 2009b) report favourably on water quality in Grootdraai Dam, du Plessis et al. (2015) report on several threats to water quality in the system.

Water quality in the catchment will need careful management given some of the land uses in the catchment. Since the dam was commissioned, power generation has increased and the size of Secunda on the margin of the catchment has increased. Although water demand increased since dam commissioning, it is now in decline and predicted to decrease further (A. Surendra, Operations Manager, Eskom, pers. comm., DWS, 2018). Tutuka is scheduled for decommissioning from 2035, Majuba from 2046, and Camden was scheduled for decommissioning from 2020, which should decrease water used in power generation (DMRE, 2019). Camden was not decommissioned to schedule, and it seems likely that given Eskom's power generation issues at the time of writing, these dates may be further delayed (Ting and Byrne, 2020, Myllyvirta and Kelly, 2023). Sasol-Secunda's water use is predicted to increase in the future (DWS, 2018).

Both power generation and the Sasol coal-to-liquid plant consume coal, and many coal mines are present in the catchment. Issues related to the threat to freshwater resources posed by coal mining are well known (e.g. see McCarthy, 2011). In addition to the potential for acidification, salinization, and metal solubilization associated with coal-related acid mine drainage and decant, other threats to water quality may be posed as a result of the combustion or gasification of coal in the catchment. These include rain acidification and the potential for heavy metal contamination (Mphepya et al., 2004, Munawer, 2018, Kok et al., 2021). In this regard, coal combustion in South Africa has been found to be a significant source of mercury in freshwater systems (Dabrowski et al., 2008).

Du Plessis et al. (2015) looked at water quality in the catchment in light of the domestic use water quality guidelines, and found several problem areas. Most notably, they found intolerable levels of alkalinity, of COD, of phosphate and of ammonia. A number of other water quality parameters are elevated above ideal levels.

DWAF (2009b) list Grootdraai Dam as being oligotrophic, while DWS water quality data show the amount of phosphate and total phosphorus at levels that indicate a risk of shifting to a higher trophic level.

The number of operational and defunct coal mines in the Grootdraai catchment will need to be carefully managed to avoid a threat to water quality as a result of pyrite oxidation and consequent acid mine drainage (DWAF, 2009b). There are 21 coal mines or pits across the catchment, and these have, for the most part, been assessed as posing a high or very high threat to surface water resources (WRC, 2017). No other mineral is mined in the catchment.

Maintenance of water quality in the system is heavily dependent on the transfer of clean water into the system via the various interbasin transfers. Decreasing water quality in the Heyshope Dam, the source of one of transfer schemes, is a concern in this regard (DWAF, 2009b).

From DWS data, although salinity levels appear to have increased over the monitored period, the median salinity remains at an ideal level. The majority of individual ions that were monitored are likewise ideal. Median sulphate levels are also ideal, but an increasing trend with time is apparent. Phosphate levels are often high, and total phosphate levels are also high, which constitutes a eutrophication risk. Another major water quality issue at this point is high alkalinity, which is at the upper end of the acceptable class. Finally, spatial variation in water quality data across the catchment is high.

Ongoing management of water quality in the catchment will require engaging with a number of stakeholders if it is to be successful. Stakeholders in the catchment have water requirements in terms of quantity and quality for industry, mining, irrigation and abstraction for domestic use. Simultaneously, many of these uses come with consequences for water quality in terms of return flows from facilities managed by them, as well as abstraction of water reducing the capacity of the system to dilute other pollutants.

1.2 CATCHMENT OVERVIEW

The Grootdraai Dam Catchment is situated in Mpumalanga province (Figure 1-2) in the north-east section of the Upper Vaal Catchment, South Africa. The catchment experiences intense anthropogenic impacts, including industry, urbanization, agriculture and mining. The Grootdraai Dam Catchment encompasses twelve quaternary catchments.

Figure 1-3 shows the elevation of the Grootdraai Catchment, with elevation between 1500 m and 2000 m and decreasing from East to West. Figure 1-4 shows the soil types of the catchment, with loamy sand to sandy loam soil dominating the north-east, sandy loam soil in the central and southern regions, and sandy clay to clay soil dominating in the west. Figure 1-5 shows the distribution of land use in the catchment. The catchment is dominated by cultivated land (43%), and other categories (including grassland, shrubland, barren land, and wetlands) make up 54% of the land cover. Urban areas account for 1.8%, water bodies 0.7%, and mining areas 0.3% of the land in the catchment.

Annual rainfall in the catchment varies from 633 mm to 765 mm (Bailey and Pitman, 2015). Agriculture accounts for the most land use, with maize, livestock and chicken production significant. The WRC mine water atlas indicates that there are 21 mines in the catchment, all of which are coal mines (WRC, 2017). Standerton was in the second largest municipality, Lekwa, with 119669 people counted in the 2022 census (StatsSA, 2024). The largest municipality, Msukalikwa, contained Ermelo and other smaller towns and had 199314 people counted in the 2022 census (StatsSA, 2024). Both municipalities had significant rural populations.

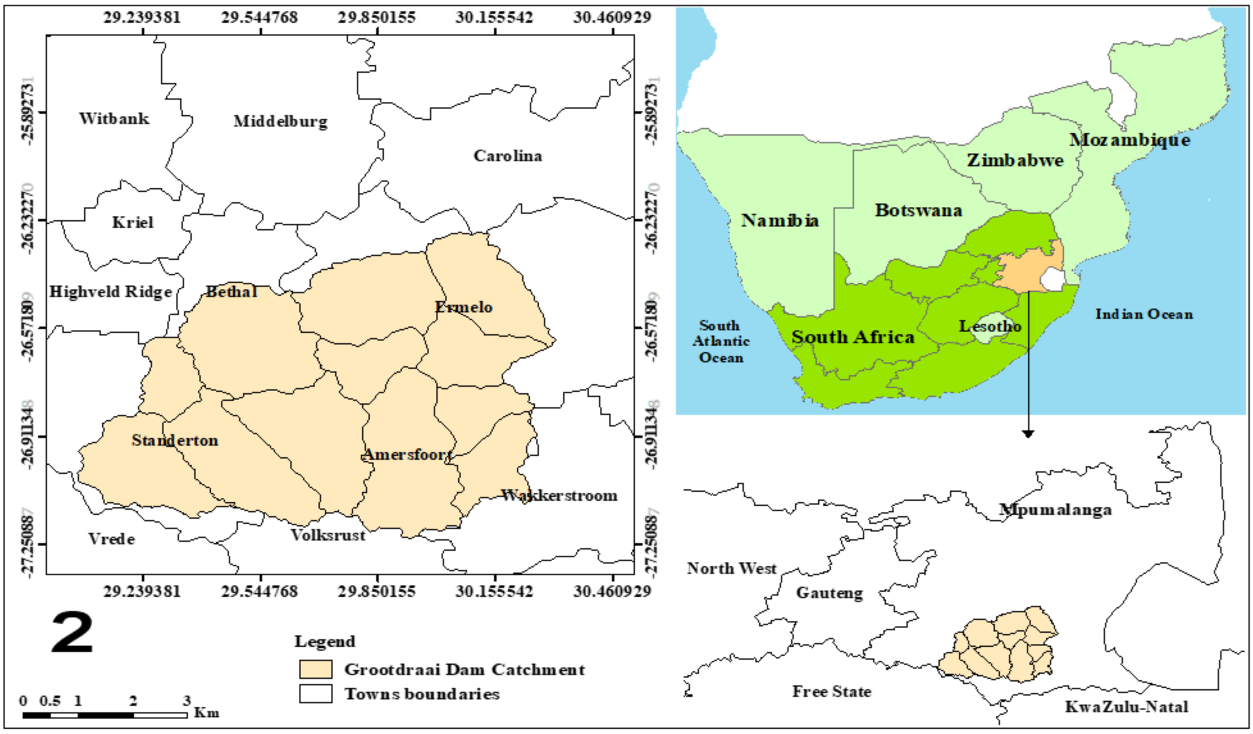


Figure 1-2 Grootdraai Dam catchment location

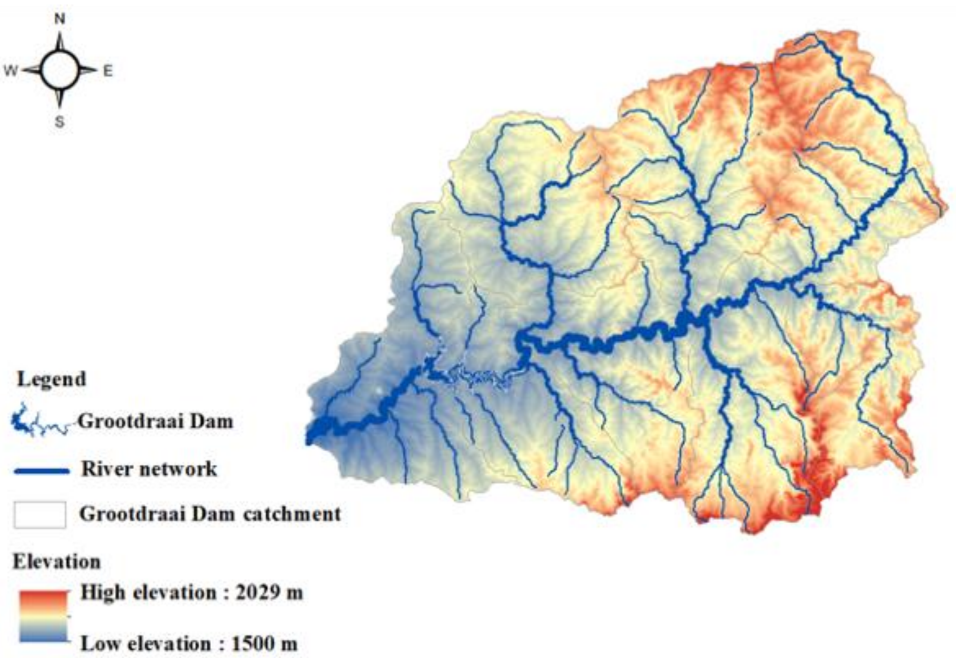


Figure 1-3 Grootdraai Dam catchment elevation map

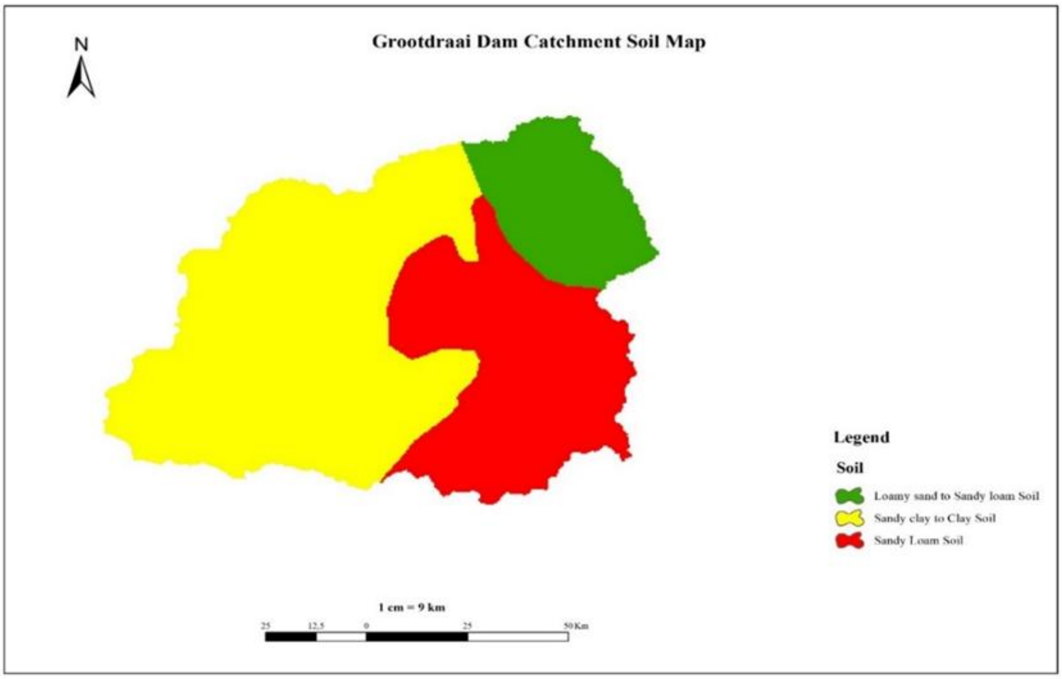


Figure 1-4 Soil type map of the Grootdraai catchment

1.3 PROJECT AIMS

The following were the aims of the project:

1. The overall objective is to predict current and future water quality changes in the Grootdraai catchment because of various activities both (present and planned) as well as varying scenarios that are likely to occur. The following are the sub-objectives:
2. Identify potential solutions and determine actions that should be prioritised in order to reduce potential impacts as a result of quality deterioration.
3. Identify all man-made and naturally occurring current and potential future sources of pollution in the catchment.
4. Establish the short- and long-term drivers of water quality deterioration in the catchment.
5. Develop a predictive tool which can inform what the status of water quality will be in the future.
6. Identify potential solutions to address quality in the short and long term.

1.4 SCOPE AND LIMITATIONS

The model was calibrated using observed data, the most recent of which is from 2010. This is a function of using hydrological data from the WRC's WR2012 project. This may limit the capacity of the model to produce predictions of more recent water quality trends. This is particularly the case when attempting to predict the result of climate change based on a model calibrated on a system not in that process.

The number of scenarios that could be assessed was necessarily limited. The consequence of this was there are more management options that are not examined. However, the scenarios that were assessed indicate how several significant impacts on water quality affect water quality at the dam, and the results allow some confidence in predicting whether selected management methods might result improve or reduce water quality.

Wet deposition of aerosols, leading to increases in sulphate levels and acidity, are known from sites with industrial influence, including inside the Grootdraai Dam catchment (Mphepya et al., 2004, Kok et al., 2021). The effect of such wet deposition is acidified rainfall with relatively high levels of sulphate and nitrate. Unfortunately we were not able to obtain enough data on this, and as a result were not able to directly address its influence in the models except as a non-point data source. In that role the influence of aerosolic deposition is conflated with the other land use types present.

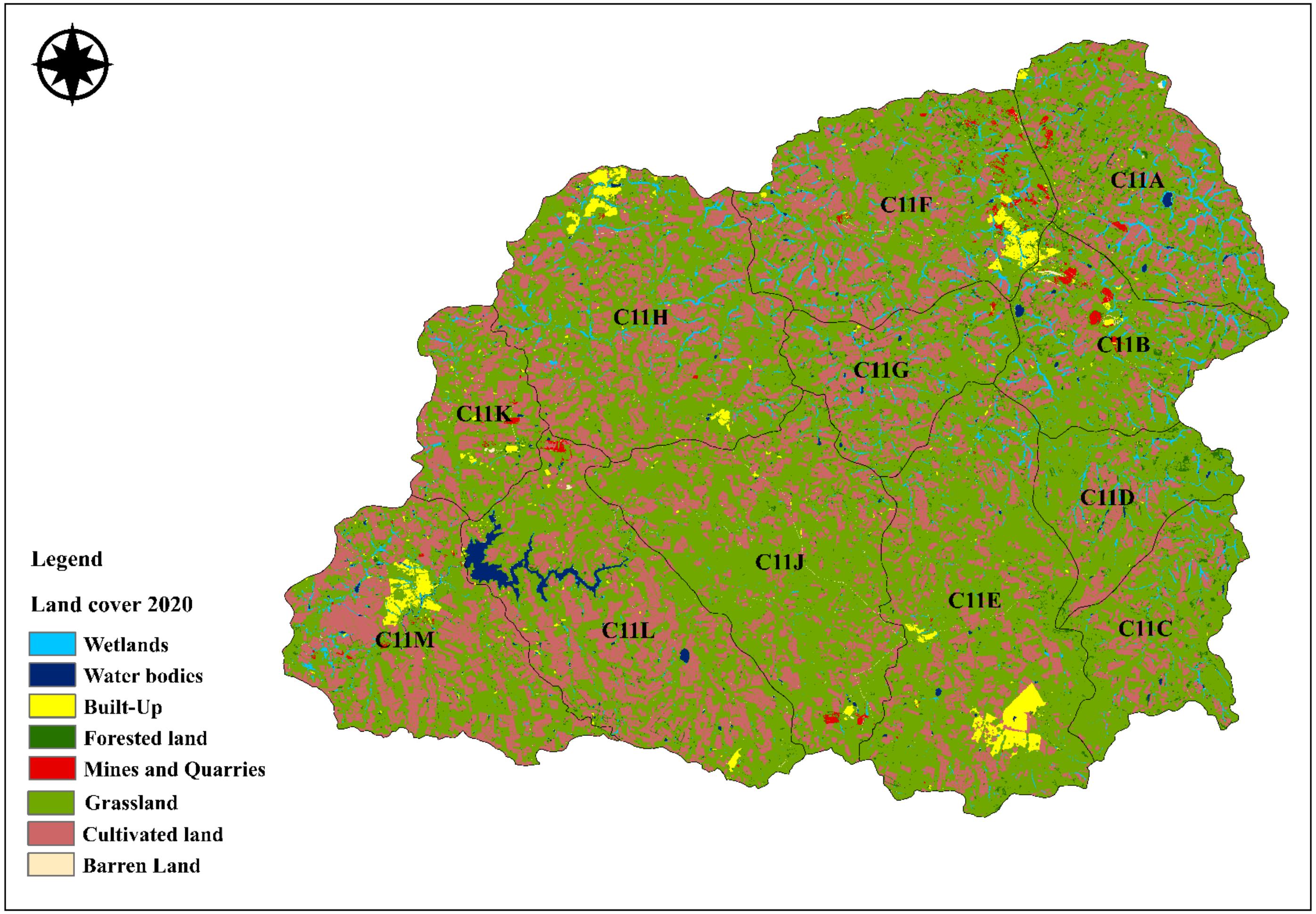


Figure 1-5 Land use map of the Grootdraai Dam catchment.

CHAPTER 2: METHODS

2.1 DATA

This project aims to produce a model of water quality in the catchment. If the model is to be reliable, it will need enough data for full calibration of the model. With this in mind, flow and water quality data, as well as other spatial data were collected for the catchment as listed below.

2.1.1 Water quantity and flow

The water quality model also needs flow data to enable the water quality model to run. Water quantity models were developed using Pywr calibrated against a yield data for the upper Vaal catchment which was available from a prior project (Aurecon, 2020), and, after disaggregation to daily flows, was suitable for use in the water quality model. Further details of the approach used are provided in Hughes and Slaughter (2015, 2016) and Slaughter et al. (2015).

Predictions of yields under climate change taken from Aurecon (2020) underlie the climate change water quality modelling undertaken here.

2.1.2 Water quality

Water quality data were sourced from the DWS WMS (Water Management System) database for all monitored points in the catchment above Grootdraai Dam. In this way, 45344 water quality records from in-stream and end-of-pipe sources were collected. Monitoring point details and locations are listed in Table 2-1, and presented in Figure 1-1.

Table 2-1 DWS monitoring points in the Grootdraai Dam catchment with data sourced for this project.

ID	Name	Latitude	Longitude	Type
177959	Blesbokspruit at R38 Bridge Goedehoop (GDDC17)	-26.56639	29.44556	Instream
177958	Blesbokspruit D/S of Bethal Sewage Works at Pieksdal (GDDC16)	-26.52667	29.42306	Instream
100001042	Brummerspruit at N17 D/S Ermelo S/W	-26.51278	29.90806	Instream
90587	C1H005 Welbedacht 382 is on Leeuspruit (see C1H044 for Flow)"	-26.85431	29.32528	Instream
90588	C1H006 Rietvley 488 is on Blesbokspruit	-26.77581	29.54144	Instream
90589	C1H007Q01 Vaal River at Goedgeluk/Bloukop	-26.84000	29.72361	Instream
90599	C1H019Q01 Grootdraai Dam on Vaal River: Downstream Weir	-26.92194	29.28472	Instream
90603	C1H027Q01 Tweefontein Spruit at Tweefontein	-26.78028	29.80694	Instream
90604	C1R001Q01 Vaalbank 476 Ir – Vaal Dam on Vaalrivier: near Dam Wall"	-26.88340	28.11670	Instream
90612	C1R002Q01 Grootdraai Dam – Grootdraai Dam on Vaalrivier: near Dam Wall	-26.91870	29.29530	Instream
177942	Douglas Dam at Outflow (GDDC05)	-26.46778	29.94000	Instream
177940	GDDC04 Douglas Dam Inflow at N11 Bridge	-26.46444	29.95556	Instream
177943	GDDC06 Spruit at Old Spitzkop	-26.46167	29.97333	Instream

ID	Name	Latitude	Longitude	Type
177956	GDDC15 Blesbokspruit 150 is @ R38 Bridge Topfontein on Blesbokspruit Tributary	-26.50250	29.44333	Instream
100000505	Human Spruit Upstream Van Heerden	-26.50333	29.44306	Instream
100000503	Humanspruit at Delta Farm House	-26.50333	29.44306	Instream
177946	Humanspruit Downstream of Delta Mine at R29/N2 Bridge (GDDC08)	-26.57889	30.07333	Instream
100000504	Humanspruit Next to Rail Line	-26.50333	29.44356	Instream
177960	Leeuspruit Downstream of New Denmark Colliery (GDDC18)	-26.72806	29.29556	Instream
100001044	Rietspruit at N11 Tapfontein Bridge Between Ermelo and Amersfoort	-26.91306	29.87222	Instream
177935	VS1 Vaal River Origin at N17 Bridge (GDDC01)	-26.36250	30.10806	Instream
177949	VS2 Vaal River at R29/N2 Bridge at Camden (GDDC10)	-26.64722	30.15167	Instream
177951	VS2-3 Blesbok Spruit at R39 Bridge Rietvley (GDDC12)	-26.75556	29.54333	Instream
177962	VS2-4 Leeuspruit at R39 Welbedacht Bridge (GDDC19)"	-26.85417	29.32528	Instream
100001098	VS3 Vaal River on N11 Bridge to Amersfoort	-26.77861	29.92083	Instream
177950	VS4 GDDC11 Vaal River at R35 Bloukop Bridge	-26.85472	29.69806	Instream
177938	Willem Brumer Dam Wall/Outflow (GDDC03)	-26.47306	29.92306	Instream
177936	Willem Brummer Dam (C1)	-26.43333	29.93139	Instream
100001099	Winkelhaak 431 is at N17 Bridge on Tweefontein Spruit	-26.51583	29.79778	Instream
177947	Witpuntspruit at R29/N2 Camden Bridge (GDDC09)	-26.59278	30.09694	Instream
100000507	Witpuntspruit at Usutu Mine	-26.58000	30.09278	Instream
178890	Eskom Majuba WWTW Effluent to Geelklipspruit	-27.08333	29.75000	WWTW
177963	GDDC21 Amersfoort – Final Effluent at Amersfoort Wastewater Treatment Works	-26.98861	29.87333	WWTW
178902	Thuthukane S/W F/E to Leeuspruit	-26.76667	29.28333	WWTW
178907	Tutuka S/W to Leeuspruit	-26.76500	29.36111	WWTW

Rand Water were approached to supply water quality data collected by them. This necessitated the submission of a formal Promotion of Access to Information (PAIA) request for water quality data from the catchment as Rand Water do not release full datasets otherwise (Rand Water do release quarterly seasonal composite data on the web, but their sampled data, collected at monthly intervals, requires a PAIA request). These data add a further 7679 water quality records to the water quality data available. Rand Water sampling points are listed in Table 2-2 and presented in Figure 1-1.

Table 2-2 Rand Water sample points in the Grootdraai Dam catchment that contributed data to this project.

Sample point	Description	Latitude	Longitude	Type
VE	Vaal River @ Ermelo	-26.64818	30.15120	Instream
WITPUNTSPRUIT	Witpuntspruit @ N2 near Camden	-26.59340	30.09635	Instream
VAAL-DS_WITPT	Vaal River Downstream of Witpuntspruit	-26.70205	30.08280	Instream
VKV	Klein Vaal River @ Goedehoop	-26.82015	30.13665	Instream
VRA	Rietspruit below Amersfoort	-26.91308	29.87200	Instream
VKK	Brummerspruit below Ermelo	-26.51392	29.90747	Instream
VKR	Tweefontein @ Riverside	-26.62272	29.83778	Instream
VK	Brummerspruit before Vaal River	-26.78088	29.80670	Instream
VAS	Vaal River above Standerton	-26.85518	29.69767	Instream
VGK	Geelklipspruit below Amersfoort	-26.96488	29.671967	Instream
VBB	Blesbokspruit below Bethal	-26.53110	29.42285	Instream
VBS	Blesbokspruit @ Skaapkraal	-26.65372	29.45093	Instream
VB	Blesbokspruit @ Vaal River Confluence	-26.77597	29.54142	Instream
ND-LEEU	Leeuspruit @ New Denmark Colliery	-26.85462	29.32540	Instream
VS	Vaal River @ Standerton	-26.94182	29.26392	Instream
S-BETHAL	Bethal Sewage Works	-26.48637	29.45093	WWTW
S-ESW	Ermelo Sewage Works	-26.51132	29.96438	WWTW
S-TUTU	Tutukani Sewage Works	-26.79368	29.29190	WWTW
S-ND-SOUTH	New Denmark Colliery – South Shaft	-26.74352	29.30453	WWTW

The types of data in the DWS and Rand Water databases varies, as do the sampling frequencies. However, both data sets had basic water quality parameters, major salts, plant nutrients, and some data on metals or other elements beyond the major salts, as well as bacterial counts. Sample points are more densely distributed in the upper Vaal around Ermelo, around Bethal, and around Thuthukani, and are regularly spaced along the Vaal channel.

2.1.3 Spatial

In order that the results of modelled water quality may be considered in the light of potential water quality threats, a number of spatial datasets were obtained. The spatial arrangement of the various water-related aspects contributes to the water quality model configuration. The data used to define the spatial relations between stressors and water quality changes are given in Table 2-3. These data should represent major water quality threats or considerations in the study region.

Table 2-3 Project spatial data sources.

Dataset	Source
Flow	Rand Water Vaal Dam Water Quality Model (Aurecon, 2020)
Water quality	Rand Water, Department of Water and Sanitation
Rand Water monitoring points	Rand Water
DWS monitoring points	Department of Water and Sanitation
Rivers	Department of Water and Sanitation
Dams	Department of Water and Sanitation
Catchments	Department of Water and Sanitation
Roads	OpenStreetMap
Places	OpenStreetMap
Borders	GADM global boundary database
Mines	WRC South African Mine Water Atlas (WRC, 2017)
Land Use	DEFF South African National Land Cover 2013 and 2020 datasets

Mines present in the catchment are taken from WRC's mine water atlas and are as in Table 2-4. Note that one mine might own several of the collieries listed, so the list does not refer to the number of registered companies.

Table 2-4 Mines in the Grootdraai Dam catchment after WRC (2017)

Mine Name	Latitude	Longitude
Vlakfontein Mine	-26.388	30.063
Mooifontein-Sterkfontein	-26.344	29.988
Umlabu Colliery	-26.359	29.971
Sara Buffels	-26.348	29.883
Kriel Colliery Block F	-26.4	29.866
Mooifontein-Sterkfontein	-26.344	29.988
Wesselton II	-26.467	29.917
Golfview Mine	-26.483	29.9
Wesselton II	-26.483	29.926
Remhoogte	-26.489	29.664
Sterkfontein	-26.483	29.433
Penumbra Coal Mining (Pty) Ltd	-26.58	29.983
Usutu Colliery	-26.557	30.043
eMalahleni	-26.573	30.06
Camden	-26.599	30.07
Mooiplaats Colliery	-26.633	30.075
Overvaal	-26.689	30.145
Leiden	-26.9	30.234
Amersfoort	-26.967	29.834
Syferfontein Colliery	-26.755	29.499
New Denmark Colliery	-26.742	29.355
Eastside Colliery	-26.751	29.315

2.2 STAKEHOLDER INTERACTION

2.2.1 Inception workshop

As an initial phase to engaging stakeholders, the project team approached a range of stakeholders with the goal of identifying other stakeholders for invitation to a workshop to introduce the project. Other than stakeholders identified in this fashion, web searches were undertaken for known organizations that may have an interest in water quality in the catchment. Organizations approached in this manner included local water stakeholders (DWS, Rand Water, ERWAT), consultants, mines, electricity generators, other industries, local and national government, research organizations, and universities. In the end, 136 potential stakeholders from 53 organizations were invited. In the end, 29 stakeholders, drawn mostly from the Department of Water and Sanitation and Sasol, attended the physical meeting, with approximately 16 more online. The workshop was held on 15 July 2022.

As part of the workshop, various stakeholders presented on the current project, aspects of catchment water management history and potential developments, water quality and water quality management in the catchment, and a presentation of a water quality model DSS developed for the Vaal Barrage region as example of what might be achieved in the current project.

2.2.2 Scenario workshop

The same group of stakeholders that was invited to the inception workshop was invited to a workshop to discuss the likely scenarios for future development in the catchment with the aims of formulating likely, plausible scenarios for exploration by means of water quality modelling to assess what the likely impact of future catchment land use and management or development scenarios on water quality in water leaving the catchment.

Although a large number of invitations were sent out to the same representatives of local water stakeholders (DWS, Rand Water, ERWAT), consultants, mines, electricity generators, other industries, local and national government, research organizations, and universities, attendance was limited, and in the end, eight stakeholders were physically present, with two more attending online.

During the meeting, the current state and noted trends were reviewed, and potential development and other scenarios were presented and discussed. Likely scenarios that were discussed related to climate, power station closure, coal mining in the catchment, wastewater management, interbasin transfers, extent and types of agriculture, and other potential events. The aim of the workshop was to generate a ranked list of potentials scenarios ranked by likelihood. These could then be used as scenarios for exploration using water quality modelling for the catchment.

2.3 WATER QUALITY MODEL

2.3.1 General modelling approach

The Water Quality Systems Assessment Model (WQSAM) was developed to fill gaps within water quality modelling specific to South Africa. WQSAM was developed to integrate closely with routinely used and established water allocation models in South Africa, such as the Water Resources Yield Model (WRYM), Water Resources Modelling Platform (WReMP) and Water Resources Planning Model (WRPM).

Figure 2-1 below shows the conceptual tiered structure of WQSAM. WQSAM is run within the modelling framework SPATSIM (Spatial Time Series and Information Modelling). SPATSIM allows a GIS-like representation of a catchment, stores modelling data, such as timeseries and parameter data, and models, such as WQSAM, can be run from within SPATSIM. As shown in Figure 2-1 below, within the representation of a catchment using WQSAM, the system representation of the underlying quantity model (WRYM, WRPM, etc.) will be replicated in WQSAM (tier A). The flows from the quantity model will then be brought into SPATSIM to allow these flows to drive water quality simulations in WQSAM. As shown in tier B, WQSAM includes a monthly-to-daily flow disaggregation facility for incremental (natural) flow. This is because while the quantity models are generally run at a monthly time step, WQSAM requires flows at a daily time step to adequately represent the temporal variation in water quality. The daily incremental flows are then further separated into flow fractions (tier C), namely surface flow, interflow, and groundwater flow. This is because these flow fractions typically have very different water quality signatures. In WQSAM, water quality signatures are applied to these flow fractions to represent non-point water quality loads into the system. Tier D represents the monthly-to-daily disaggregation of modified flows. Finally, water quality simulation processes are represented in Tier E.

WQSAM has already been applied to the Upper Vaal catchment, including the Grootdraai Catchment, in a previous project. Within that project, WQSAM integrated with a WRPM representation of the Upper Vaal, i.e. flow simulations from the WRPM were brought into WQSAM to drive water quality simulations. The Upper Vaal catchment is a relatively large catchment, and the WRPM representation of the Upper Vaal was lumped, i.e. it did not represent the catchment in high spatial detail. While this relatively crude level of spatial detail was appropriate for representing the entire Upper Vaal catchment, the present study focuses on the Grootdraai Catchment as one of the sub-catchments of the Upper Vaal catchment.

This project therefore requires a representation of the Grootdraai Catchment that is of higher spatial detail than that provided by the WRPM representation mentioned above. This requirement presents a challenge in terms of allocation modelling. The water allocation models used in South Africa, including the WRPM, are proprietary "black-box" models, and limited people have an understanding of how to set them up and run them. This study could therefore not apply any of the allocation models mentioned above to represent the Grootdraai catchment in greater spatial detail.

To represent flow in the Grootdraai, the present study used Pywr (Tomlinson et al., 2020). Pywr is a generalised network resource allocation model used to evaluate or identify infrastructure, environmental or institutional interventions related to water supply. The advantages of Pywr include that it is free, open source and highly extendable.

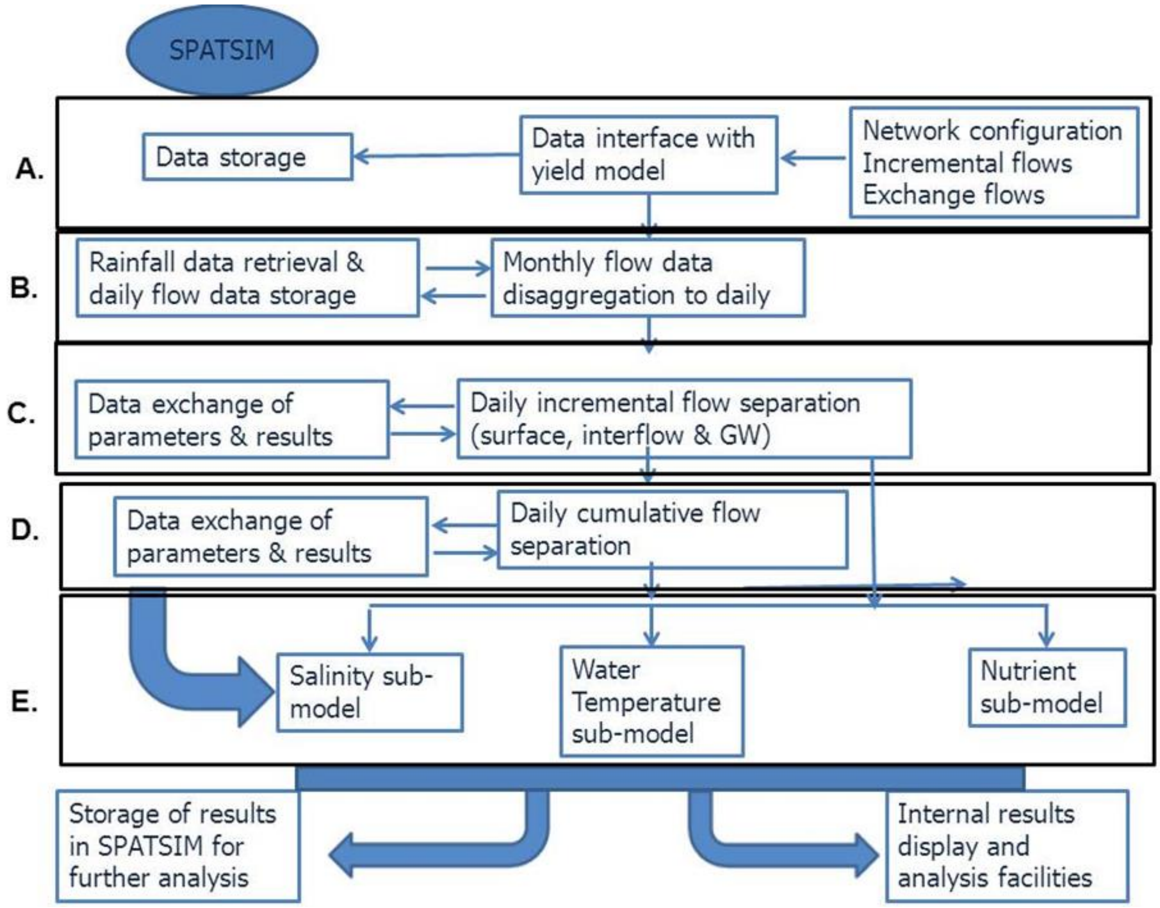


Figure 2-1 Conceptual representation of the model components in the Water Quality Systems Assessment Model (WQSAM): A) Input of WReMP output data and storage to the modelling framework Spatial Time Series and Information Modelling (SPATSIM) system, and replication of the nodal structure from the Water Resources Modelling Platform (WReMP) to WQSAM and SPATSIM; B) Disaggregation of simulated monthly incremental flow to daily and storage to SPATSIM; C) Base flow separation of simulated daily incremental flow to the flow components surface water flow, interflow and ground water flow; D) disaggregation of monthly cumulative flows to daily; E) Water quality modelling components for salinity, water temperature and nutrients.

The use of Pywr in combination with WQSAM represents a dramatic change in the traditional approach under which WQSAM has been applied to previous catchments. Therefore, a large section of this report is dedicated to the approach used to set up the Pywr model.

2.3.2 Water quantity Pywr model

2.3.2.1 Grootdraai Dam catchment representation in Pywr

Introduction

The WRPM representation of the Grootdraai Catchment was not in a sufficient fine spatial scale to use in the present project (see Figure 2-2). The catchment was therefore represented in a finer spatial scale in Pywr. Pywr is a generalised network resource allocation model used to evaluate or identify infrastructure, environmental or institutional interventions related to water supply. The advantages of Pywr include that it is free, open source and highly extendable.

WRPM system structure

As shown in Figure 2-2, the catchment is represented in too coarse a fashion for adequate catchment water quality modelling. The approach taken in this project to develop a more distributed representation of the Grootdraai Catchment was to arrange nodes and links to be representative of the catchment at a quaternary catchment level, with links representing river reaches and nodes representing where these reaches join, areas of storage, and points of modelling interest (areas in the reach that experience return flows or abstraction, or locations of water quality monitoring gauges).

Broad conceptual process followed

Figure 2-3 shows the process followed in restructuring the Grootdraai system in Pywr. The initial restructuring of the model was based on re-distribution of runoff (incremental flow) to a quaternary level. To assist this process, various data for the catchment were consulted, including soils, land cover, elevation and rainfall distribution (see Chapter 2).

The WRPM model structure shown in Figure 2-2 was replicated in the online version of Pywr (waterstrategy.org). Using the redistributed runoff, additional inflow nodes were added to the model, along with appropriate link nodes. The return flows in the model were then related with actual effluent inflows where possible by consulting DWS and Rand Water monitoring points.

The model was downloaded from Waterstrategy.org in the form of a JSON file. Data, parameters, and recorders were then added to the model using a Python script. The model was set to read in model driving data (natural inflows, abstractions, return flows, etc.). The model simulations of flow were then compared to those of the WRPM to ensure that the two models simulated broadly the same flow.

Figure 2-4 shows the model structure implemented in the online version of Pywr at www.WaterStrategy.org.

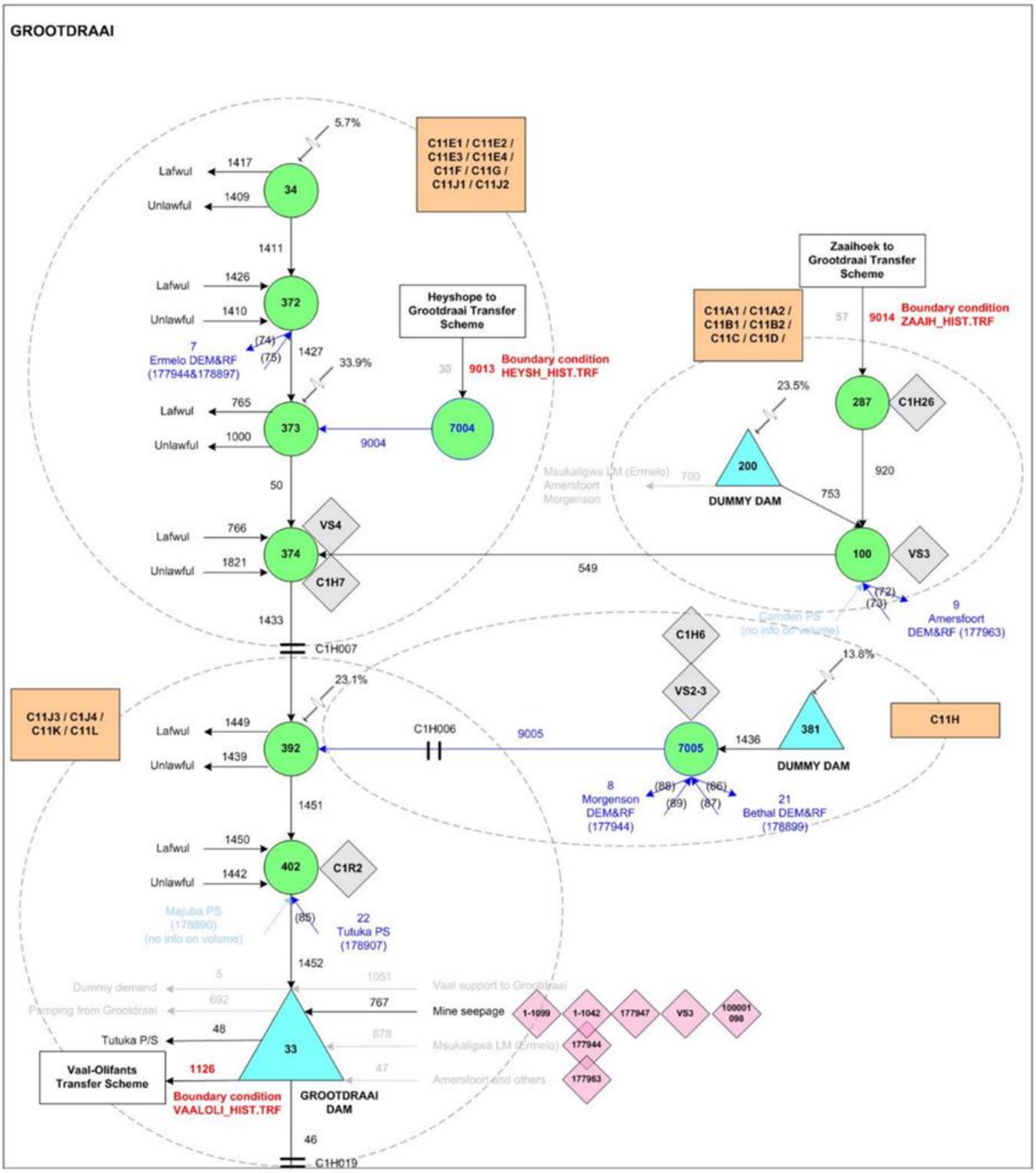


Figure 2-2 System structure of the Grootdraai Dam catchment used in the Water Resources Planning Model (figure from Aurecon, 2020).

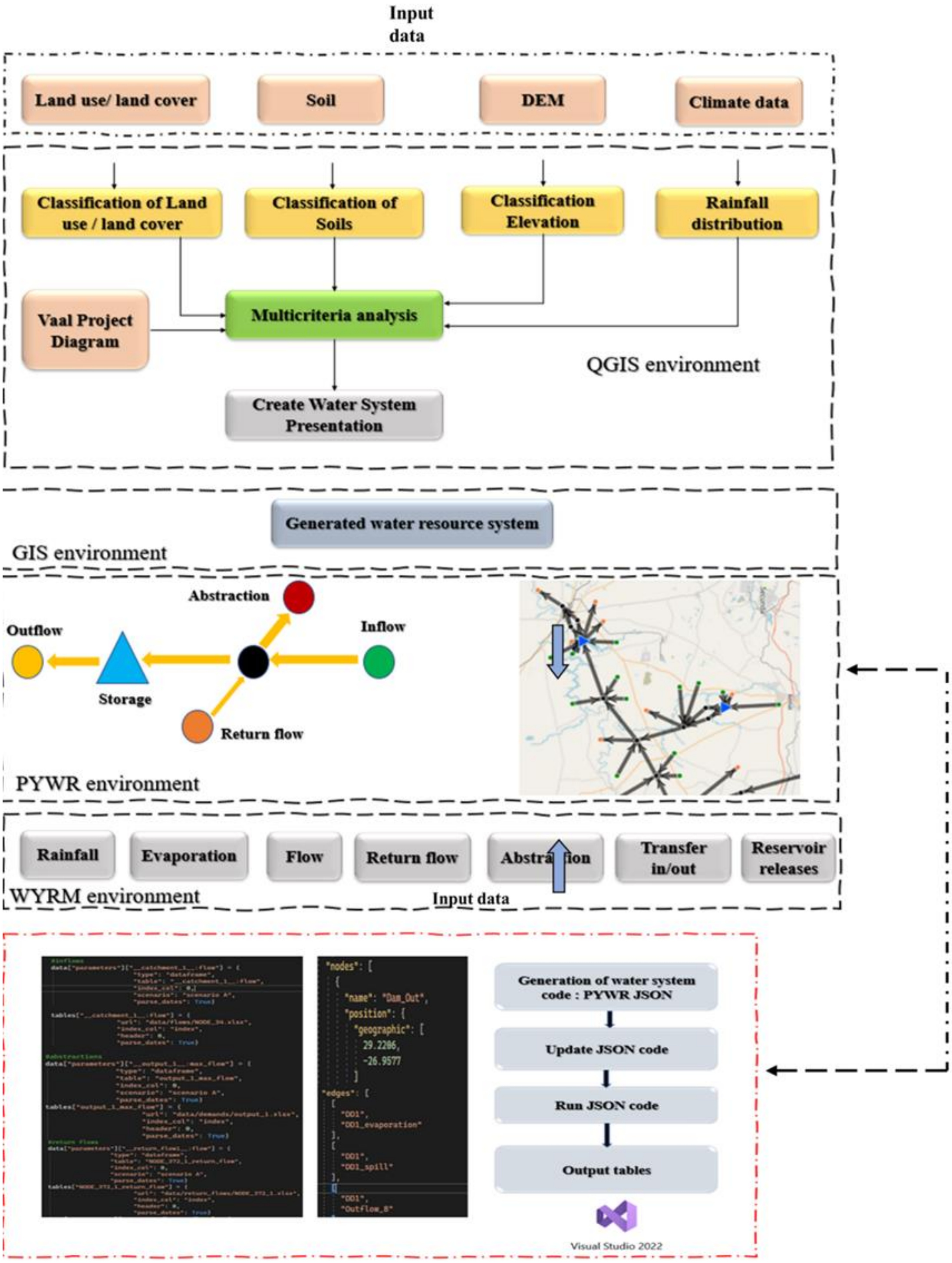


Figure 2-3 Conceptual framework for the production of the water allocation model for Grootdraai Dam Catchment in Pywr.

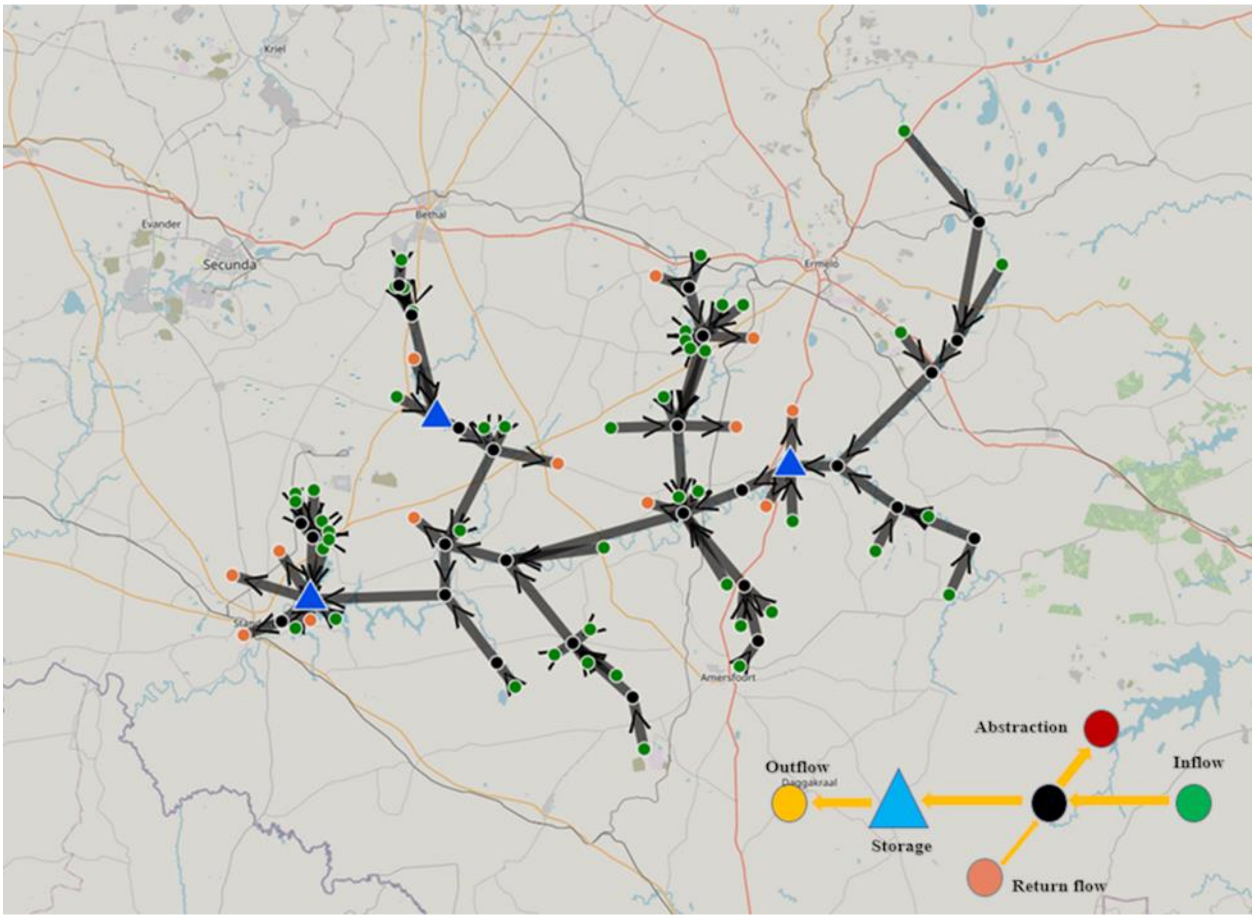


Figure 2-4 Screenshot of the Pywr model for the Grootdraai Dam catchment.

2.3.2.2 Redistribution of incremental flows

Monthly incremental flows for the Grootdraai Catchment were disaggregated to daily in a previous project, using the lumped representation shown in Figure 2-2 (Aurecon, 2020). These daily incremental flows with a lumped distribution were redistributed to a quaternary level in this project.

As mentioned in the previous section, various data for the catchment, including land use, soils, elevation, and rainfall distribution were used to redistribute the lumped natural flow from the WRPM model to a more distributed quaternary catchment level in Pywr. Table 2-5 below shows the percentage of total natural flow for the catchment assigned to each quaternary catchment.

Table 2-5 Redistribution of natural flows to a more distributed model of the Grootdraai Catchment

Runoff distribution node	Node position in catchment	Surface of sub-quaternary catchment (km^2)	Surface ratio (%)	Runoff distributed fraction (%)
11	C11J	1002	0.28	9.65
8	C11F	930	0.26	8.96
9	C11G	432	0.12	4.16
10	C11E	1156	0.33	11.13
1	C11A	721	0.35	8.15
2	C11B	535	0.25	6.06
4	C11C	449	0.22	5.08
3	C11D	372	0.18	4.21
6	C11L	948	0.41	9.56
5	C11K	340	0.15	3.43
7	C11J	1002	0.44	10.11

2.3.2.3 Associating model return flows with return flow gauges

Table 2-6 below shows the association between model return flows and actual monitored effluents according to DWS and Rand Water data where possible. The WRPM systems diagram (Figure 2-2) indicated these monitoring points in some cases.

Table 2-6 Association between model return flows and Department of Water and Sanitation or Rand Water return flow monitoring gauges

Model return flow	Quaternary catchment	Average return flow (cumecs)	Gauge	Description
RR_6	C11K	0.003		Denmark Colliery effluent
RR_7	C11K	0.016	178902	Rand Water TUTU
RR_8	C11K	0.031	178907	Tutuka S/W to Leeuspruit
RR_9	C11L	0.011	1-1042/177963	Mine seepage
RR_11	C11H	0.153	177944	Ermelo S/W Final Effluent to Klein Drinkwater Spruit (GDDC07)
RR_12	C11H	0.006	178899	Blesbokspruit 150 IS Bethal – Final Effluent at Bethal Wastewater T W to Blesbokspruit
RR_4	C11J	0.034	178890	Eskom Majuba Blesboks WWTW Effluent to Geelklipspruit
RR_5	C11J	0.007		
RR_1	C11F	0.001		Lawful leakage
RR_2	C11F	0.002		Unlawful leakage
RR_3	C11F	0.105	177944/177897	Ermelo S/W Final Effluent to Klein Drinkwater Spruit (GDDC07)/SESW
RR_10	C11G	0.0013	177963	GDDC21 Amersfoort – Final Effluent at Amersfoort Wastewater Treatment Works

2.3.2.4 Final model structure

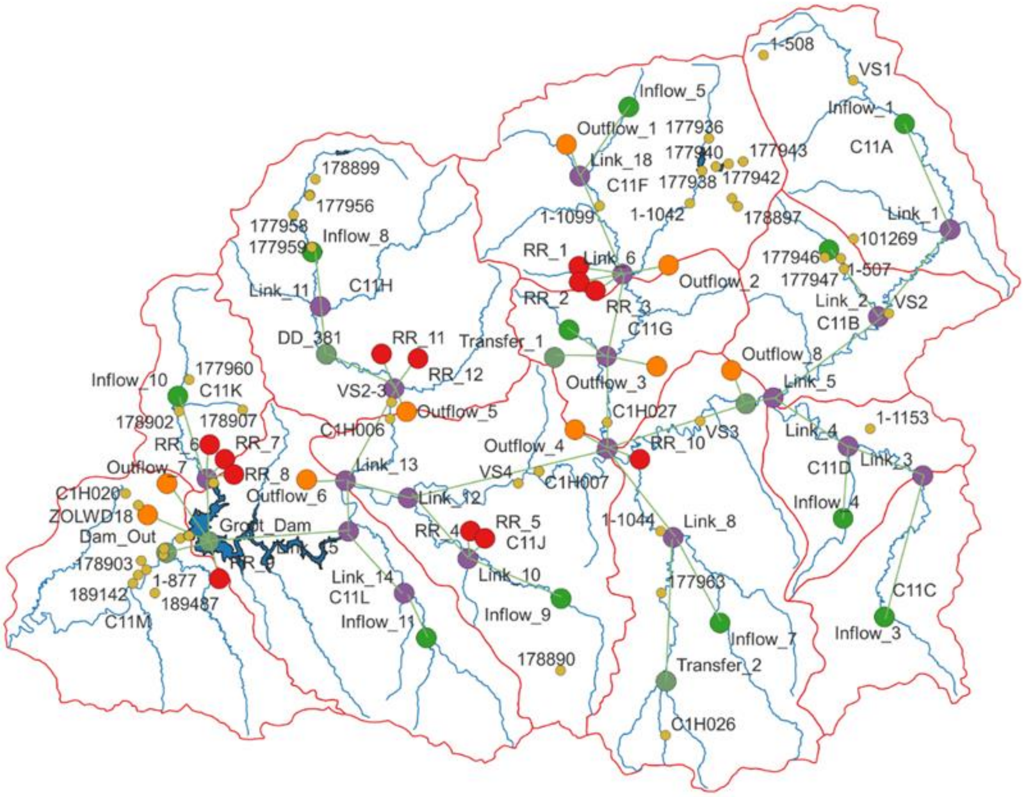


Figure 2-5 Final model structure as implemented in Pywr. Green: runoff/inflow; red: return flow; orange: abstraction; purple: linked nodes; beige: DWS gauges.

Figure 2-5 shows the final model structure represented in Pywr. The figure shows that inflows are represented at a quaternary level. The green, orange, red, black and blue points represent natural inflow, abstractions, return flows and storage, respectively. The catchment also receives input of flow from two transfers (two additional green points) and loses flow from one transfer (one orange point).

2.3.3 Water quality modelling with WQSAM/Pywr-WQ

2.3.3.1 Extracting flows from Pywr for WQSAM/Pywr-WQ

Flow rate units in Pywr are set according to the timestep of the model. So, for example, if a weekly time-step Pywr model is established, the flow unit would be Million m^3/week. The Pywr model established for the Grootdraai Dam was a daily-time-step model. Therefore, the unit rate of flow used was Mm^3/day. However, WQSAM uses flow rates of m^3/sec. Therefore, all flows extracted from Pywr needed to be converted to m^3/sec. Python scripts were used to extract flows from Pywr and to covert the flows into m^3/sec.

The Pywr scripts created text files in a “continuous text” format that SPATSIM can recognise, with the name each file corresponding to the name of the Pywr, and WQSAM, node. Creation of flow input files in this way allows the mass import of data into SPATSIM. Table 2-7 below shows a summary of the flows extracted from Pywr for mass import into SPATSIM.

Table 2-7 Categories of flows extracted from Pywr for input into WQSAM/Pywr-WQ

Type of flow	Description
Daily incremental flow	Natural flows into the catchment
Daily cumulative flow	Modified flows in the river reach
Daily inflows	Modified flows entering each model node
Daily outflows	Modified flows exiting each model node
Daily abstractions	Flows abstracted at demand nodes
Daily return flows	Effluent flows returned at return flow nodes
Daily storage	Storage at storage nodes
Daily transfers in	Transfers of flow into some nodes
Daily transfers out	Transfers of flow out of some nodes
Daily rainfall	Localised rainfall contributing to the storage of storage nodes
Daily evaporation	Evaporation representing loss of water at storage nodes

2.3.3.2 Establishment of a SPATSIM application for running the WQSAM model

The node-link structure used in the Pywr yield model was replicated in a SPATSIM application (Spatial Time Series and Information Modelling), so that WQSAM methods could be used in this environment (Figure 2-6). This duplicate model structure allows for interfacing between the Pywr water quantity model, the WQSAM water quality model, and finally the Pywr-WQ water quality model.

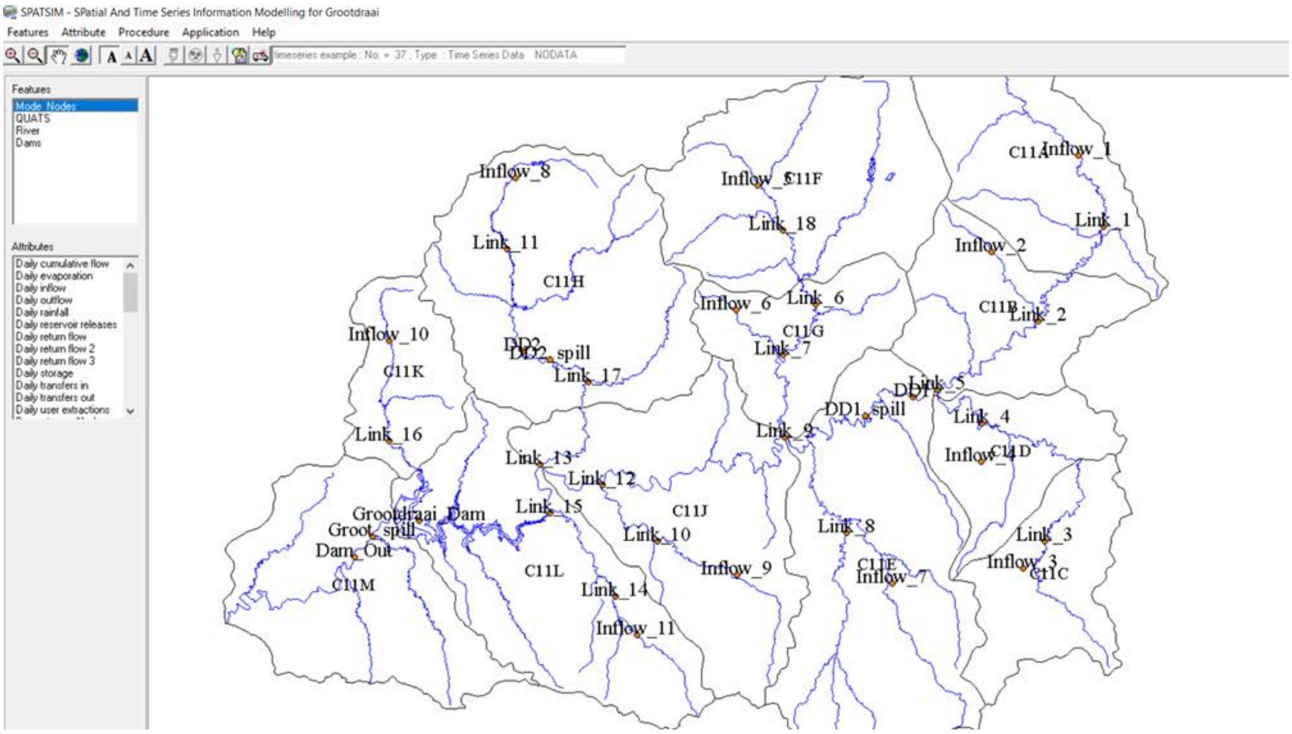


Figure 2-6 Screenshot of SPATSIM application for the Grootdraai Dam catchment.

2.3.3.3 Separating incremental flow fractions

Daily incremental flows were disaggregated in WQSAM to the surface flow, interflow, and groundwater flow fractions. This is undertaken so the water qualities of each fraction can be managed separately. Within the disaggregation process, default alpha and beta parameter values of 0.95 and 0.5 were implemented, respectively. Figure 2-7 below shows a screenshot of WQSAM in which the flow separation process in implemented.

2.3.3.4 Implementation of the Pywr-WQ model

The central water quality modelling framework planned for this project was WQSAM, a water quality model applied using a SPATSIM application. However, as modelling proceeded, use of the WQSAM model was found to not be possible. As Pywr had already been applied in water yield modelling to enable water quantity modelling at a higher resolution than was available from the Aurecon (2020) model, a water quality model, Pywr-WQ, was developed in the same environment.

The Pywr-WQ model functions as a dynamic extension of the Pywr model, integrating water quality mechanisms and principles drawn from the well-established WQSAM model. The Pywr-WQ model is seamlessly linked to the open-source Python water resources (Pywr) model.

Within this model, WQSAM was leveraged for the purpose of flow component separation, enabling the distinction between surface flow, interflow, and groundwater flow. The outcomes derived from this process were subsequently integrated into the Pywr-WQ model. It is imperative to underscore that the Pywr-WQ model faithfully adheres to the same rigorous calibration methods as those meticulously employed in WQSAM. These methods encompass the meticulous characterization of both point and diffuse sources for an array of water quality variables, ranging from essential nutrients to various salts, including the assessment of total dissolved solids (TDS).

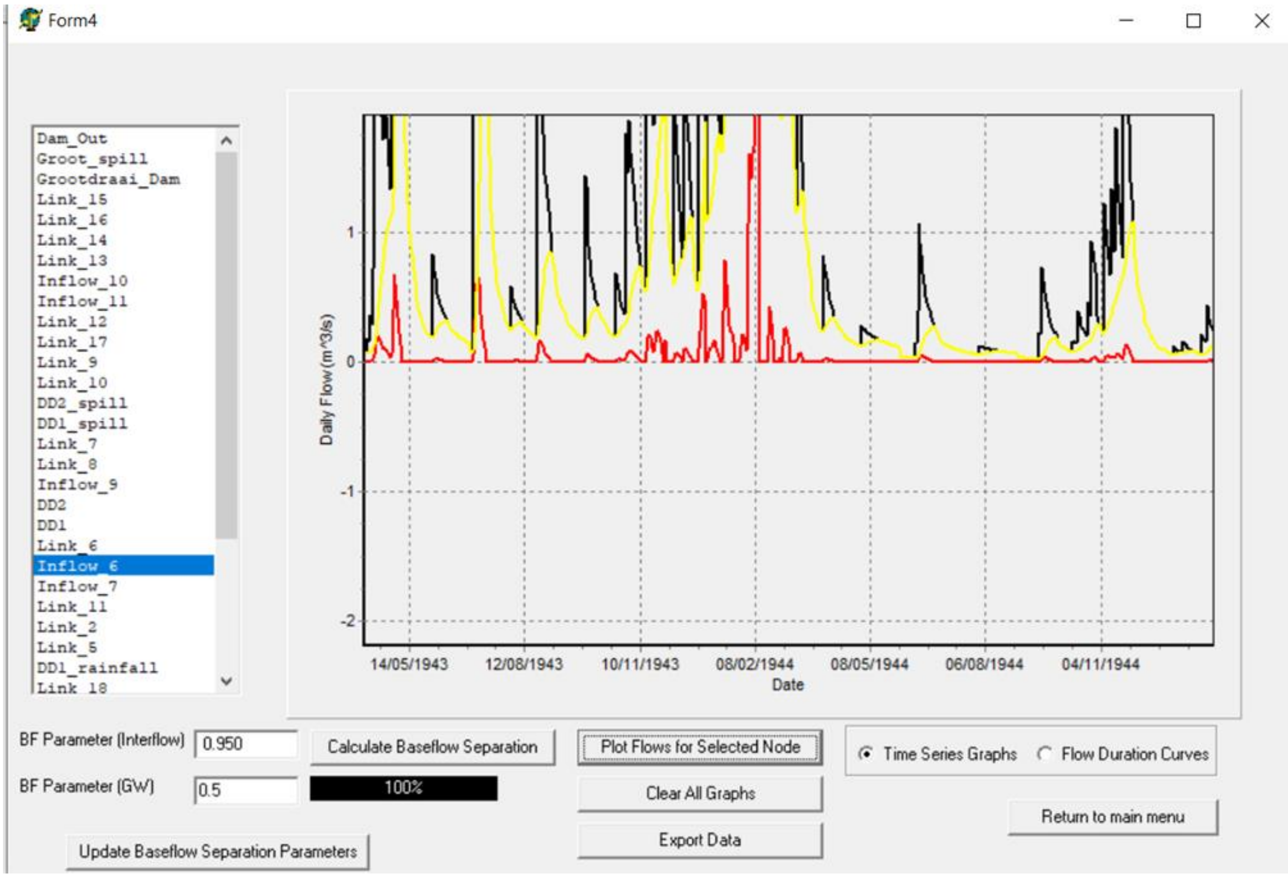


Figure 2-7 A screenshot of the WQSAM hydro pre-processor module for separating incremental flow fractions.

2.3.3.5 Importing observed water quality data

DWS and Rand Water instream water quality gauges were examined and matched to nodes in Pywr-WQ according to geographical position. To do this, the nodes were mapped together with the gauging points in GIS (see Figure 2-5). Table 2-8 shows the matching between water quality monitoring points and nodes in WQSAM. Water quality data for the gauging points was in a CSV format. Python scripts were used to extract water quality monitoring data into a format for mass import into Pywr-WQ.

Table 2-8 Matching between instream water quality monitoring points and Pywr-WQ model nodes within the Grootdraai Dam catchment

Model node	DWS station	n
Link_4	1-1153	125
Inflow_1	VS1	201
Link_2	VS2	252
Inflow_2	177947	218
Inflow_5	1-1042	197
Link_7	C1H027	1067
Link_9	C1H007	2573
Inflow_8	177956	204
Link_17	C1H006	1947
Link_16	VS2-4	236
Grootdraai_Dam	C1R002	2893

2.3.3.6 Model calibration for historical conditions

The Pywr-WQ model was calibrated for historical conditions for the period 1920 to 2010. Instream water quality simulations were compared to observed data for the gauges shown in Table 2-8. Water quality signatures assigned to return flows were guided by effluent water quality monitoring data for the gauges shown in Table 2-6. The water quality variables that were simulated are:

- Total dissolved solids (TDS)
- Sulphate
- Nitrate and nitrite nitrogen
- Ammonium nitrogen
- Phosphate phosphorus
- Fluoride
- Potassium
- Magnesium
- Sodium
- Chloride

These comprise the major plants nutrients, likely to reflect nutrient loading owing to wastewater and potential agricultural runoff, and several major ionic groups, as well as total dissolved solids, which were the genesis of this project. The model does not simulate other important water quality parameters, such as pH, which may be of significance in the catchment. If sufficient metal data were available for calibration, adding selected metals to the model, particularly in assessing mining impacts, would be desirable. Modules were written to extend WQSAM (Slaughter et al., 2018), and these could potentially be included if data for calibration were available.

2.3.3.7 Investigation of scenarios

Once the WQSAM model has been sufficiently calibrated against historical conditions, various scenarios will be investigated in the parameterised model. These arise from the stakeholder engagement process and include

- Changes in land use (in particular mining, irrigated or intensive agriculture, and urban size)
- Climate change scenario
- Changes in water use

CHAPTER 3: RESULTS-STAKEHOLDER INTERACTION

3.1 INCEPTION WORKSHOP

As an initial phase to engaging stakeholders, the project team approached a range of stakeholders with the goal of identifying other stakeholders for invitation to a workshop to introduce the project. Other than stakeholders identified in this fashion, web searches were undertaken for known organizations that may have an interest in water quality in the catchment. Organizations approached in this manner included local water stakeholders (DWS, Rand Water, ERWAT), consultants, mines, electricity generators, other industries, local and national government, research organizations, and universities. In the end, 136 potential stakeholders from 53 organizations were invited. In the end, 29 stakeholders, drawn mostly from the Department of Water and Sanitation and Sasol, attended the physical meeting, with approximately 16 more online.

A major function of the inception workshop was to introduce stakeholders to the study and to the potential of the WQSAM water quality and its utility. An explicit aim of the project is work towards having a stakeholder-led programme of water quality management, and in order to achieve the stakeholder need to understand what impacts water quality across the catchment, and to identify their potential role in managing water quality. Accordingly, the nature of the catchment, and the importance of water to electricity generation, mining and agriculture in the catchment were noted, as was the need for adequate clean water for Sasol's coal-to-fuel plant at Secunda, just outside the catchment. Some attention was paid to identified threats to water quality in the catchment, and identified spatial and temporal trends in water quality across the catchment.

Historical developments in the upper Vaal River catchment in general and the Grootdraai catchment in particular were presented so as to show what potential stresses on water quality were present over time. Transfers were a part of this, and the extent of the capacity for transfers highlighted to show how these could be used to control flow and to ameliorate water quality changes. Changes in water quality with time and location revealed that anthropogenic change is present, but also that some changes in water quality seem to be a function of non-anthropogenic "background" water quality, possibly driven by geology or another catchment-specific phenomenon.

As an example of how the WQSAM water quality model could contribute to planning of water quality in the catchment, a decision support system that linked water use license emittance conditions with instream water quality targets was demonstrated. The DSS, which used WQSAM to model water quality in a catchment as complex and challenged as the middle Vaal River in the Vaal Barrage area, was successfully used to model a range of water quality parameters, and to relate these to specified instream water quality targets (these were originally envisaged as RQOs, but any user defined targets could be chosen) and then calculate the proportion of times that any water quality parameter might exceed the specified target. This allowed stakeholders to explore a tool capable of supporting stakeholder-led water quality scenario analysis.

The workshop was used to present information on two water quality monitoring networks in the Grootdraai Dam catchment. The two networks, run by DWS and Rand Water, monitor a number of water quality parameters regularly at a number of sampling sites throughout the catchment. Major water quality parameters such as pH, salinity, major plant nutrients and major ions were collected by both, but otherwise they varied in what parameters were collected. Both identified mining impact and sewage discharge as major threats to water quality in the region. Finally, other organizations also collect data at varying scales and frequencies, and with differing goals.

This workshop was a success in that attendance, both physical and online, was good, and stakeholders were drawn from a number of different sectors. In this sense, the workshop established a solid base to further interaction with catchment stakeholders. Unfortunately, representatives of the municipal sector did not participate, although several were invited.

3.2 SCENARIO WORKSHOP

On 27 March 2023 a workshop was held where stakeholders were invited to provide input to developing suitable scenarios that will be used in assessing how management strategies might impact on water quality throughout the catchment and in Grootdraai Dam. Those invited include the same group that were invited to the inception workshop, the project reference group, identified municipal stakeholders, and other stakeholders that had been identified in the interim.

The discussion opened with a presentation on the catchment, and the steadily degrading water quality that threatened water users. In considering potential scenarios, the following possible trends were considered:

Climate change: Remilekun et al. (2021) predict precipitation reductions for the Vaal catchment ranging from 0.4 to 30% for Representative Concentration Pathways (RCPs) 4.5 and 8.5 by the end of the century. Decreased rainfall will impact on land uses to some extent, and is liable to lead to decreased water quantity and quality.

Power station closure: The Eskom IRP (2019) indicates that Komati Power Station is currently scheduled for decommissioning. In this catchment, Camden Power Station is scheduled for decommissioning starting in 2020. Other catchment power stations are scheduled to commence decommissioning in 2035 and 2046. The Eskom Just Energy Transition (JET) is an Eskom programme aiming to reach net zero emissions by 2050 (Eskom, 2023). JET is supported by a World Bank loan (497 million $) supporting the transition of Komati from coal to alternative energy. Beyond this, there are pledges of $8.5-billion for transition of power generation in South Africa away from coal.

Mining changes: Coal currently generates the great majority of South Africa's electricity, as well as being used in steel and cement production, among other areas (Merven et al., 2021). However, concern about climate change is bringing pressure on the continued use of coal. Even if coal use in South Africa continues, carbon border taxes and other instruments are likely to penalize ongoing coal consumption, and mining is liable to decrease. Ongoing management or closure of coal mines has consequences for water quality in the catchment (McCarthy, 2011).

Water contamination and wastewater treatment: Anecdotal reports of sewerage leakage to freshwater systems were made in the inception workshop. Inspection of 2021 Green Drop scores reveal that Mkusalikwa, Pixley ka Seme and Govan Mbeki district municipalities had scores of approximately 20%, leading the Regulator to express concern about the overall poor state of wastewater services at all systems and the consequential impact on respective water resources (DWS, 2022). Scores in this range indicate a critical state, that needs urgent intervention for all aspects of the wastewater services business.

Interbasin transfers and input water quantity and quality: Water entering the catchments via the Heyshope and Zaaihoek transfer schemes adds water to support flow in the some of the rivers above the Grootdraai Dam. Added water brings a certain water quality to the system. In the past, that has been good, but the increase in coal mining in the source region threatens the quality of input water (DWAF, 2009) and hence the quality of water downstream in the Grootdraai Dam catchment.

Agriculture: The greatest land user in this catchment is agriculture, which has been accused of illegal water abstraction and well as contributing to nutrient contamination in the upper Vaal. While potentially significant, the impact of agriculture on Vaal water has not been clearly quantified.

Other: Other things may lead to water quality degradation, including population change (by growth and/or urbanization), the state of the economy nationally or locally, and the quality of governance of management. The impact of these on water quality is not direct, but changes can lead to change through other actors of processes.

Having viewed a presentation on the above topics, stakeholders reviewed these, submitted any other potential water quality impacts, in finally, ranked the importance of identified trends. Major trends that were identified are presented below.

Agriculture was found to be a significant but largely unquantified factor in water quality in the catchment. Some stakeholders felt that nutrient input from agriculture was likely to be high, while others considered wastewater from WWTW may be more significant. End-of-pipe data from WWTW should help to resolve this. During the workshop, specific likely impacts as a result of intense chicken farming in the catchment, and the operation of abattoirs, were raised. All agricultural inputs were liable to be modelled as non-point or diffuse inputs as no point source or end-of-pipe data on agricultural inputs was available. As a result, these could not be easily distinguished from each other, or from leaking wastewater pipes, which are also reported in the catchment.

Population trends may have significant impacts on water quality. The population in South Africa is still growing, and trends like immigration and urbanization also modify population changes. Population in the catchment has grown, driven mostly by agriculture and mining. Population growth can have multiple effects such as land use change, resource use increase, and wastewater and other waste production increases. Population size may also decrease consequent on closure or mines or power stations. Population size is therefore a cross-cutting impact, as it may be induced or reversed by other catchment scenarios.

Climate change will impact the catchment to a greater or lesser extent. Remilekun et al. (2021) predict minor to more significant precipitation reductions in the future, which will affect the amount of water available to end users, as well as the freshwater resource dilution capacity. It is possible that overall precipitation will not change, but its timing might, and it is generally agreed that intensity of precipitation-related events will increase. Changes in seasonality will have a significant impact on the resource. A drought, which has not occurred recently, would have a severe impact on the catchment. Likewise, the impact of flooding would be severe.

Municipal impacts owing largely to WWTW management and operation were highlighted as a potentially problematic scenario. That significant nutrient contamination of the upper Vaal river is established (du Plessis et al., 2015), as is the generally very bad Green Drop score awarded to the municipalities. Green Drop scores are penalized by factors other than effluent quality, and theoretically, a negative Green Drop score could result from failure in reporting, or failure to implement particular approached to management, rather than as a result of effluent quality. However, inspection of the WWTW's Wastewater Risk Rating reveals this to be bad where the Green Drop Scores are bad. End-of-pipe assessments of effluent quality should indicate the extent of municipal contribution to nutrient contamination in the catchment, although this will not account for leakage from broken pipes reported from the catchment. Although not explicitly considered as part of this scenario, bacterial contamination is likely to accompany nutrient contamination from WWTW. Municipal impacts could be improved by better management. They will in all likelihood respond to population size in the area.

The power stations in the catchment will be due for closure when their design life is exceeded. As these are all coal-fired turbines, international pressure may force accelerated closure to curtail greenhouse gas production. Closure and shutdown of power stations themselves are not anticipated to result in major direct water quality impacts. As the sites are connected to the power grid, power stations are liable to be replaced by alternative power sources following Eskom's Just Energy Transition. The coal mines that supplied the power stations will need a new market, or be forced to close. Therefore indirect, knock-on impacts owing to job losses, with potential population impacts, are plausible, as are reduced impacts of mining as the demand for coal dries up.

The state of the economy and governance/management were two general impacts that may have consequences for water quality in the catchment. Where governance and the economy are both good, water quality impacts are not anticipated. This could be at a national level, but at local level it is the economy/governance of sectors, for example agriculture or the municipal sector, that may have negative effects and result in these acting as cross-cutting impacts across other identified scenarios.

The workshop had limited attendance, but those who were present were for the most part actively engaged and contributed substantially to scenario assessment and discussion.

CHAPTER 4: RESULTS-MODEL CALIBRATION

4.1 YIELD MODELLING

4.1.1 Model calibration

The daily model simulations of storage by the Pywr were compared with the monthly simulations of the WRPM model for the Grootdraai Dam. As shown in Figure 4-1 below, there was a good match between the two models. Where they occur, differences can be attributed to the difference in time step between the two models (the WRPM was run at a monthly time step, whereas the Pywr was run at a daily time step), and the fact that the Pywr model has a more distributed structure.

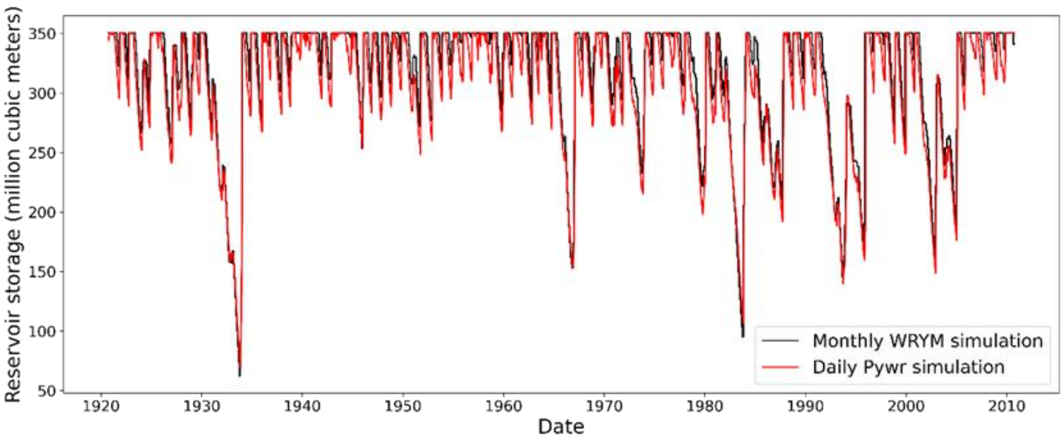


Figure 4-1 D

4.2 WATER QUALITY MODELLING

4.2.1 Calibration

Figures showing calibrated model outputs compared with observed data for various water quality parameters at the Grootdraai Dam are presented below in Figure 4-2 and Figure 4-3. As inspection of these figures reveals, the Pywr-WQ model is largely capable of modelling water quality under the flow regime of 1920 to 2010.

While the water quality model fits were generally good, several of the modelled variable showed a slight tendency to over simulate the parameter at lower levels, often but not always accompanied by under simulation at higher levels. This is most apparent in the model for chloride (Figure 4-3), but is also present to some extent in the modelled results for sodium, magnesium, and to a lesser extent, sulphate. Other ion models, for example potassium and calcium provide a better simulation of observed data across the full extent of values.

Modelled TDS data have a generally good fit to the observed data, albeit with some overestimation of very values. As TDS is a highly significant water quality variable in the context of this catchment a good TDS model is important for modelling of water quality scenarios.

Nutrient model fits were in general good (Figure 4-2), and did not display the tendency to mis-estimate extreme values in this way. As with TDS, nutrient levels have been identified water quality issues in this catchment, and reliable models are important for scenario analysis.

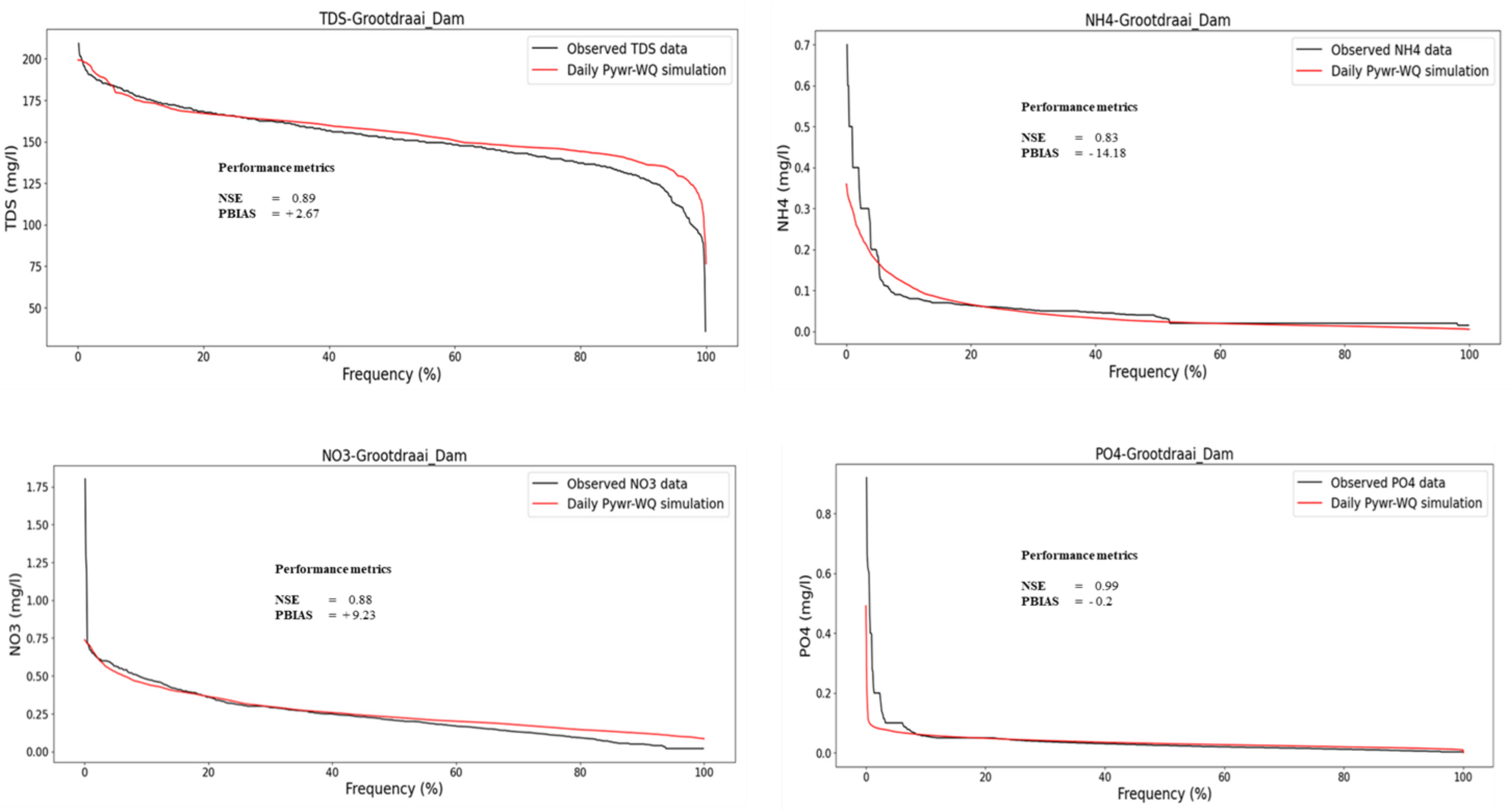


Figure 4-2 Calibration of the Pywr-WQ model for nutrients and total dissolved solids within the Grootdraai Dam catchment under the historical baseline scenario.

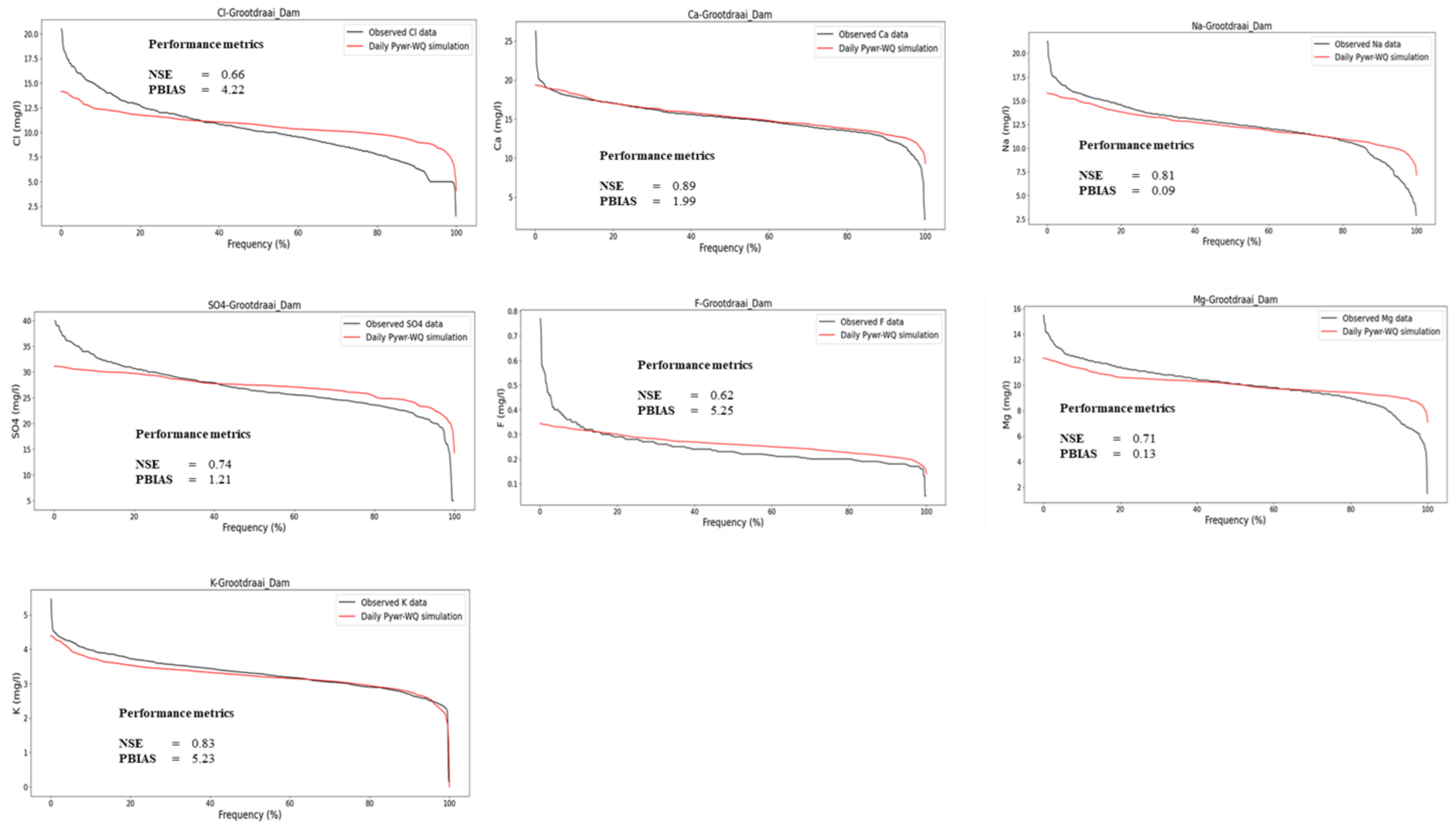


Figure 4-3 Calibration of the Pywr-WQ model for a range of inorganic ions within the Grootdraai Dam catchment under the historical baseline scenario.

CHAPTER 5: RESULTS-SCENARIOS AND LAND USE CHANGES

5.1 INTRODUCTION

The water quality modelling approach adopted here uses observed data and flow to simulate water quality in a catchment. Where point source data are used, they can be included as inputs in the model. Non-point source, or diffuse inputs to the model are more difficult to simulate. The latter are included using a combination of calibration and expert knowledge. However, Slaughter and Mantel (2017) used a multiple regression approach to assess the link between calibrated nutrient signatures in incremental flows and land use, and they found that, particularly at higher nutrient signatures, that land uses could be correlated with modelled nutrient levels.

Cultivated land is a land that has been found to modify riverine nutrient levels, and is the context of the Grootdraai Dam catchment, may lead to changes in nutrients entering the dam. Cultivated land is more likely to be fertilized and irrigated, both of which may act to transport nutrients to rivers.

Slaughter and Mantel's (2017) work assessed the link between modelled nutrient levels and land uses, but a link between water quality and other land uses is likely other cases. For example, the strong link between acid mine drainage, leading to levels of acidity (unless treated), potential for metal loading, and high loads of sulphate and TDS, and gold and coal mining in South Africa (McCarthy, 2011). Coal mining is well established in the Grootdraai Dam catchment (WRC, 2017), and areas of land used for mining may be found to be associated with sulphates and salt in rivers. If the association is clear, then predictions of the effect of changing mining in the catchment and its consequent impact on water can be made.

Another land use that may be associated with changes in water quality relates to urbanization. Urbanization has myriad impacts on surface water. Wastewater released from a Wastewater Treatment Works (WWTW) is a well-known impact, but this usually a point source, and can be modelled by explicit inclusion into the model. However, other diffuse sources, such as runoff, can contaminate surface water, and may be related to the area of urban land. The Grootdraai Dam catchment has been reported to have extensive wastewater spills, and these too will constitute a diffuse nutrient source.

This chapter describes establishing the relation between various land uses and aspects of water quality using a multiple regression after Slaughter and Mantel (2017), then using this relation to predict what changes to land use in the catchment might have. This allows the exploration of several scenarios that relate to land uses in the catchment.

5.2 DEVELOPMENT OF LAND COVER MODEL

Water quantity and quality data from 1920 to 2010 were extracted from the calibrated Aurecon (2020) model, then rescaled from monthly to daily timestep. Pywr-WQ was calibrated against the imported water quality data.

The modelling process concentrated on nutrients linked to non-point source loads, particularly nitrite/nitrate nitrogen (NO_2+NO_3-N), ammonium nitrogen (NH_4-N), and phosphate phosphorus (PO_4-P). Additionally, the investigation encompassed other water quality variables pertinent to catchment land uses including sulphate (SO_4), calcium (Ca), and salinity (as TDS).

National land cover data for the years 2013 and 2020 were downloaded from the South African National Landcover dataset [https://egis.environment.gov.za]. The land cover dataset was clipped to each quaternary catchment and the areas under each land cover class computed. The original dataset contained 42 land cover classes which were reclassified into 8 categories for the present study (Table 5-1). The reclassification was done to avoid any uncertainty resulting from the use of a large amount of land cover classes during statistical analysis. In addition, the inclusion of so many categories can influence water quality model accuracy (Slaughter and Mantel, 2017). The reclassified data are presented in Figure 5-1. This study investigated the relationship between land cover and non-point source loads considering all land cover within quaternary catchments in a similar way to the study by Slaughter and Mantel (2017).

Table 5-1 Grouping land cover categories from the 2020 South African National Land Cover dataset into more representative land cover categories for the purpose of the current study.

Code	Param	Grouped land cover category	Original land cover classes
A	α	Barren land	Barren land (natural rock surfaces); barren land (dry pans); barren land (eroded lands); barren land (bare river bed materials); barren land (other bare).
B	β	Urban/ Built-Up	Urban/built-up (residential formal tree); urban/built-up (residential formal bush); urban/built-up (residential formal low vegetation); urban/built-up (residential formal bare); urban/built-up (residential formal grass combination); urban/built-up (industrial); urban/built-up (roads and rails).
C	γ	Cultivated land	Cultivated land (commercial permanent orchards); cultivated land (commercial annual crops pivot irrigated); cultivated land (commercial annual crops non-pivot irrigated); cultivated land (commercial annual crops rain fed / dryland); cultivated land (fallow land) and old field (e.g. trees, bush, grass, bare).
D	δ	Forested land	Forested land (contiguous forest); forested land (dense forest and woodland); forested land (open plantation forest); forested land (temporary unplanted forest).
E	ε	Grassland	Grassland (natural grassland).
F	ζ	Mines and Quarries	Mines and quarries (mines, extraction pits)
G	η	Waterbodies	Waterbodies (natural rivers); waterbodies (natural pans); waterbodies (artificial dams).
H	θ	Wetlands	Wetlands (herbaceous wetlands)

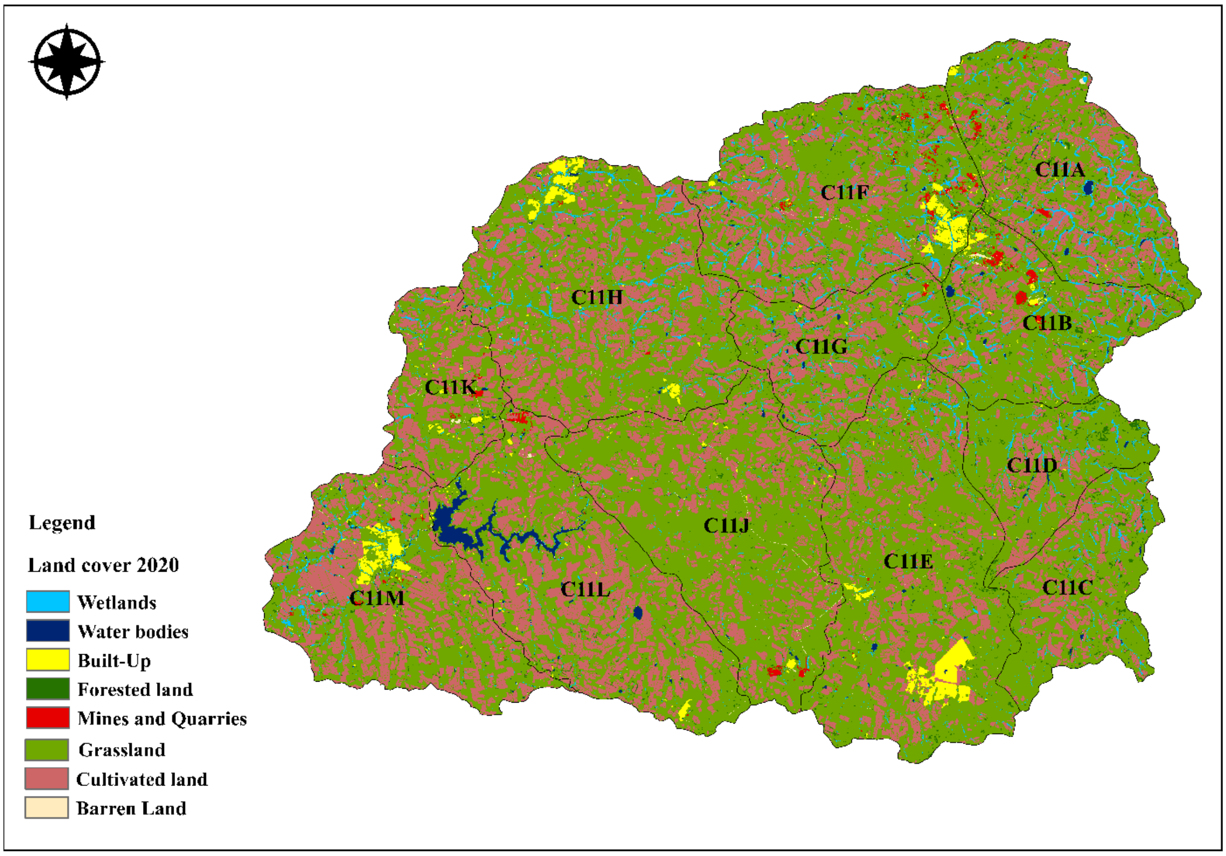


Figure 5-1 Reclassified land cover of the Grootdraai Dam catchment.

Multiple regression was employed to investigate the relationships between surface flow nutrient water quality signatures (SF_N) and land cover components associated with nutrient content. Similarly, this analytical approach was extended to elucidate the links between groundwater flow salt water quality signatures ($GWF_{\text{salts and TDS}}$) and land cover attributes, particularly in the context of likely salts and salinity considerations. The distribution of land cover types within each quaternary catchment was investigated in terms of their proportional representation in relation to the total area. This approach aligns with the approach by Slaughter and Mantel (2017). The multiple regression models were conducted using Python, with regression equations with the general form of:

$$SF_N = (\alpha \times A) + (\beta \times B) + (\gamma \times C) + (\delta \times D) + (\varepsilon \times E) + (\zeta \times F) + (\eta \times G) + (\theta \times H) \quad \text{Eq. 1}$$

$$GWF_{\text{salts+TDS}} = (\alpha \times A) + (\beta \times B) + (\gamma \times C) + (\delta \times D) + (\varepsilon \times E) + (\zeta \times F) + (\eta \times G) + (\theta \times H) \quad \text{Eq. 2}$$

A-H represent the land cover categories mentioned earlier, as fractions of the total area (see Table 5-1), and α-θ represents the regression parameters applied to respective land cover categories. The Chi-square statistic was used as a goodness-of-fit statistic for each regression. The method evaluated the best values for the regression parameters through minimizing the sum of the Chi-square parameter. Regression coefficients were forced to be greater than zero, on the assumption that none of the land cover categories would act as nutrient, salts, or salinity sinks. These calculations were undertaken using the SciPy library (Virtanen et al., 2020).

The modelled rate of change of land area under a particular land use was defined by assessing, for each quaternary catchment, the rate of change of particular land use types between the 2013 and 2020 land use classification exercises [https://egis.environment.gov.za]. This provided an annual rate of change for each land use type that could be applied to predict land use changes over any particular time frame, after which the multiple regression model could be applied to the changed land use areas to predict water quality changes owing to land use scenarios. Two time frames were adopted for this: a medium and long term assessment predicting the effects of land use related diffuse water quality changes at 2050 and 2099 respectively.

5.2.1 Results of the multiple regression analysis

The regression coefficients from the multiple regression analyses on surface flow nutrients and salts in groundwater are presented below in Table 5-2 and Table 5-3. The size of the regression coefficient indicates the extent of land use and its effect on salts or nutrients at Grootdraai Dam in each particular quaternary catchment. So, for example, the α listed for catchment C11A is zero for both nutrients and salts, indicating that the contribution of areas classified as barren land was low with respect to the water quality parameters. In this case, barren land is rare and no relationship can be established. However, γ is greater for C11A, though the extent varies between nutrients, and it remains significant in driving salt levels. γ is the correlation coefficient for cultivated land (Table 5-1), and cultivated land is common in this and other catchments in this study (Figure 5-1). The size of the correlation coefficient indicates how strongly this land use contributes to water quality at Grootdraai Dam. The results indicate that different nutrient groups are affected differently by the extent of cultivated land, and that salt levels also respond to cultivated land area.

Table 5-2 Multiple regression coefficients for nutrients in surface flow in each quaternary catchment (see Eq. 1).

Parameters	NO_2-N + NO_3-N	NH_4-N	PO_4-P
C11 A			
α	0.00	0.00	0.00
β	1.05	0.00	0.16
γ	5.22	1.72	0.29
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	5.56	2.80	7.97
η	0.00	0.00	0.00
θ	0.00	0.00	0.00
C11 B			
α	0.00	0.00	0.00
β	6.47	9.57	4.70
γ	0.00	0.00	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	2.47	10	5.49
η	0.00	0.00	0.00
θ	6.21	5.18	1.34
C11 C			
α	0.00	0.00	0.00
β	20.83	0.10	20.83
γ	0.14	1.07	0.136
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	0.00	0.00	0.00
η	0.00	0.00	0.00
θ	0.00	0.00	0.00
C11 D			
α	0.66	3.56	34.72
β	0.00	0.00	0.00
γ	0.42	1.78	0.13

Parameters	**NO_2-N + NO_3-N**	**NH_4-N**	**PO_4-P**
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	0.89	5.59	151.51
η	0.00	0.00	0.00
θ	0.00	0.00	0.00
C11 F			
α	0.00	0.00	0.00
β	12.79	11.38	2.66
γ	0.00	0.00	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	2.91	8.63	9.56
η	0.00	0.00	0.00
θ	3.42	2.40	1.16
C11 G			
α	0.00	0.00	0.00
β	9.76	4.76	11.19
γ	0.15	0.17	0.21
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	0.00	0.00	0.00
η	0.00	0.00	0.00
θ	0.00	0.00	0.00
C11 L			
α	0.00	0.00	0.00
β	0.00	0.00	0.00
γ	1.05	1.10	0.02
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	0.00	0.00	0.00
η	0.88	1.07	0.25
θ	0.00	0.00	0.00
C11 E			
α	0.00	0.00	0.00
β	7.10	0.00	0.00
γ	2.29	0.61	3.1
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	2.49	0.56	19.67
η	0.00	0.00	0.00
θ	0.00	0.00	0.00
C11 J			
α	0.00	0.00	0.00
β	0.00	0.00	0.00
γ	0.61	0.61	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	0.00	0.00	3.54
η	0.00	0.00	0.00
θ	0.56	0.56	0.56

Parameters	NO_2-N + NO_3-N	NH_4-N	PO_4-P
C11 H			
α	0.00	0.00	0.00
β	4.00	23.87	0.40
γ	0.00	0.00	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	5.86	4.17	2974.10
η	0.00	0.00	0.00
θ	0.00	0.00	0.00
C11 K			
α	0.00	0.00	0.00
β	18.30	25.84	8.35
γ	0.00	0.00	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	30.80	16.02	14.10
η	0.00	0.00	0.00
θ	0.00	0.00	0.00

Although results vary between quaternary catchments, nutrient levels in quaternary catchments seem to response generally to the extent of land either occupied by urban land, cultivated land, and land used for mining and quarrying (regression correlation coefficients β, γ, and ζ) (Table 5-2). In all cases, this relationship is positive, indicating that increased nutrients associated with these land uses is common, and that increases in land under these three uses would increase nutrients at Grootdraai Dam. The variation between catchments will result from different extents and practices in catchments.

Table 5-3 Multiple regression coefficients for salts in groundwater flow in selected quaternary catchments (see Eq. 2).

Parameters	TDS	SO_4	Ca
C11 A			
α	0.00	0.00	0.00
β	200.61	58.50	35.00
γ	689.20	120.00	80.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	17514.97	400.00	988.02
η	0.00	0.00	0.00
θ	0.00	0.00	0.00
C11 B			
α	0.00	0.00	0.00
β	49638.00	45000.00	330.00
γ	0.00	0.00	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	27000.00	15000.00	500.00
η	0.00	0.00	0.00
θ	17800.00	13000.00	850.00
C11 F			
α	0.00	0.00	0.00
β	14300.00	1800.00	420.00

Parameters	TDS	SO_4	Ca
γ	0.00	0.00	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	70000.00	6000.00	1119.56
η	0.00	0.00	0.00
θ	6376.00	1400.00	600.00
C11 K			
α	0.00	0.00	0.00
β	15500.00	4500.00	560.76
γ	0.00	0.00	0.00
δ	0.00	0.00	0.00
ε	0.00	0.00	0.00
ζ	45833.34	10000.00	2432.04
η	0.00	0.00	0.00
θ	0.00	0.00	0.00

Selected catchments were assessed to determine how much land uses contributed to salt exports (Table 5-3). The catchments chosen were those with significant salt exports in the Grootdraai Dam catchment. Salts assessed were TDS for overall salinity loads, sulphate for its association with acid mine drainage in the South African context (McCarthy, 2011), and calcium for its association with liming methods for acid mine drainage treatment (Vellemu et al., 2018). Again, there were differences between quaternary catchments, but salt loading was most associated with land used for urban areas, mines and quarries, and in some catchments, herbaceous wetlands (correlation coefficients β, ζ, θ). The association of freshwater salinity with runoff from urban areas and mining is to be expected. However, the reason for the link between salinity and herbaceous wetlands in C11B and C11F (but not C11A and C11K) is not clear. Other catchments have wetlands, but they are not associated with salinity in the same way. C11B and C11F have a relatively higher level of urbanization (Ermelo) and a high level of mining. At this point it seems likely that either: the land classification algorithm has classified effluent discharge sites as herbaceous wetlands; or, release of wastewater from pipe leakages, which has been reported from the region, has stimulated wetland formation. However, it is not clear why this is not reported from the other catchments that were assessed.

To validate the accuracy of the multiple regression results, a comparison was carried out between the SF_N and $GWF_{salts\ and\ TDS}$ values obtained through the multiple regression and those derived from the calibration of the Pywr-WQ model using observed data. To achieve this, the SF_N and $GWF_{salts\ and\ TDS}$ values determined from the multiple regression were integrated into the Pywr-WQ model setup for the Grootdraai dam catchment. The multiple regression model outputs were then compared to the Pywr-WQ model outputs that had been calibrated against observed data using the Nash-Sutcliffe Efficiency (NSE). To visually represent these comparative results, Figure 5-2 illustrates frequency distributions that highlight the agreement between the SF_N and $GWF_{salts\ and\ TDS}$ values obtained from the multiple regression and those from the Pywr-WQ model calibration against observed data.

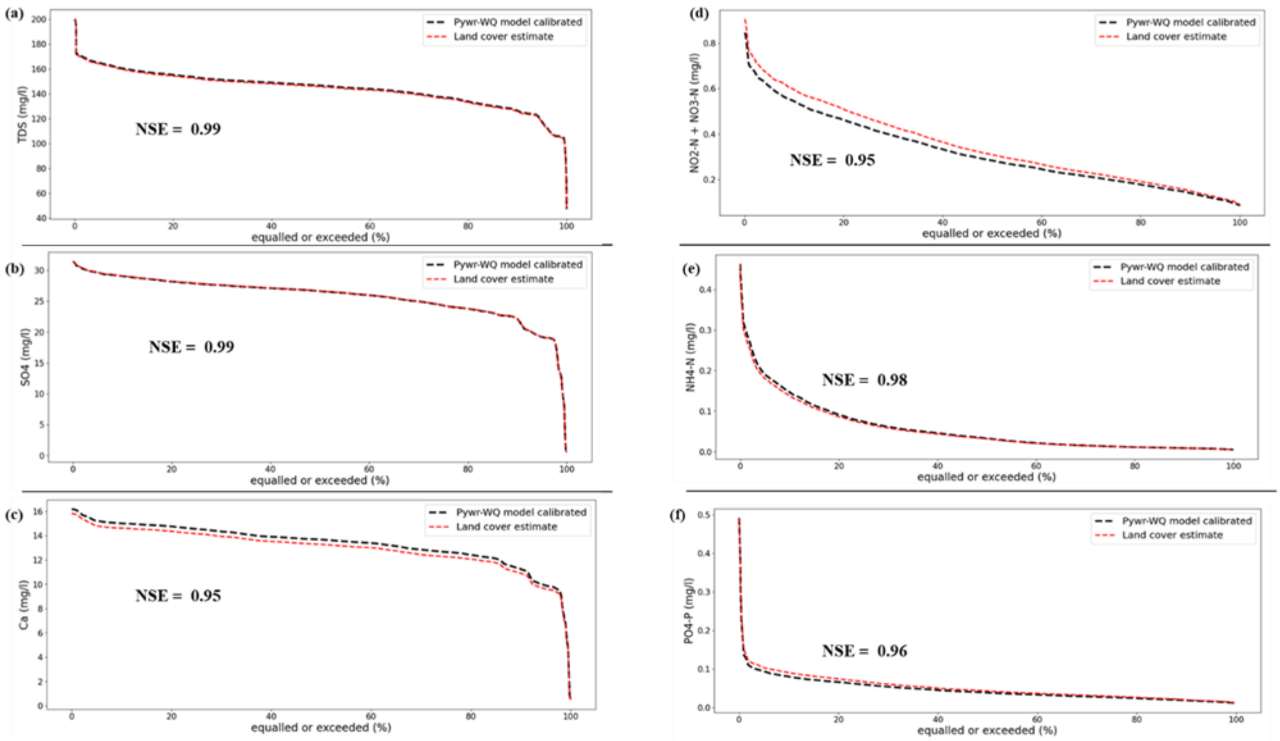


Figure 5-2 Frequency distributions of surface flow nutrient concentrations (SF_N) and groundwater flow salts and salinity concentrations ($GWF_{salts\ and\ TDS}$), as estimated through multiple regression, and the corresponding SF_N and $GWF_{salts\ and\ TDS}$ estimated by calibration of the Pywr-WQ model to observed data for the Grootdraai Dam Catchment.

5.2.2 Land cover scenarios

The amount of change in land cover classes over time that is predicted based on the 2013-2020 rates of change are presented in Table 5-4. Rates of change for each quaternary catchment differ, and these are also presented. These are the land areas that underlie predictions of changes in water quality derived using the multiple regression model based on changes in land use. Changes are presented as results after two time frames: medium term, or change at 2050, and long term, or change by 2099. These longer time frames were chosen so that even minor changes would become apparent to users. Shorter term predictions are presented in chapter 8.

Table 5-4 Predictions of land cover class area changes based on the 2013-2020 rate of change. Areas for urban land, cultivated land and mining land cover per quaternary catchment were assessed.

Land cover classes	Growth rate per year (%)	Current 2020	Medium-term 2050 (%)	Long term 2099 (%)
C11A				
Urban (built-up)	0.04	0.64	1.84	3.80
Cultivated land	0.42	42.44	55.04	75.62
Mines	0.03	0.33	1.23	2.70
C11B				
Urban (built-up)	0.03	1.58	2.48	3.95
Cultivated land	0.4	36.77	48.77	68.37
Mines	0.001	1.82	1.85	1.90
C11C				
Urban (built-up)	0.02	0.18	0.78	1.76
Cultivated land	0.5	38.35	53.35	77.85
Mines	0.001	0.033	0.06	0.11
C11D				
Urban (built-up)	0.02	0.24	0.84	1.82
Cultivated land	0.46	36.55	50.35	72.89
Mines	0.001	0.004	0.03	0.08
C11F				
Urban (built-up)	0.1	3.0	6.00	10.90
Cultivated land	0.4	44.59	56.59	76.19
Mines	0.05	0.92	2.42	4.87
C11G				
Urban (built-up)	0.03	0.42	1.32	2.79
Cultivated land	0.5	50.65	65.65	90.15
Mines	0.001	0.13	0.16	0.21
C11E				
Urban (built-up)	0.1	4.0	7.00	11.90
Cultivated land	0.3	34.25	43.25	57.95
Mines	0.01	0.031	0.33	0.82
C11H				
Urban (built-up)	0.1	2.45	5.45	10.35
Cultivated land	0.3	45.23	54.23	68.93
Mines	0.01	0.011	0.31	0.80
C11L				
Urban (built-up)	0.04	0.75	1.95	3.91
Cultivated land	0.2	47.66	53.66	63.46
Mines	0.01	0.186	0.49	0.98
C11J				
Urban (built-up)	0.02	0.40	1.00	1.98
Cultivated land	0.3	36.73	45.73	60.43
Mines	0.02	0.31	0.91	1.89
C11K				
Urban (built-up)	0.04	1.30	2.50	4.46
Cultivated land	0.3	48.78	57.78	72.48
Mines	0.04	0.3	1.50	3.46

5.2.2.1 Increase in urban areas scenario

Figure 5-3 and Figure 5-4 showed nutrients in surface waters simulated for increased urban growth scenario in the medium and long term. The plots show firstly that an increase in urban land leads to an increase in nutrients at Grootdraai Dam. This is particularly so for nitrate/nitrite and phosphate, but for ammonium the increase is barely apparent. The results from medium and long term results are similar in these plots, because temporal variation is present.

The nutrient simulations do increase the risk of eutrophication in Grootdraai Dam with urban growth. This is of particular concern in light of reported high phosphate levels, and well as reported wastewater leakages in the catchment.

When assessing the impact of increased urban areas on water quality, other land use categories were also modified. Therefore, these factors may contribute to the changes observed at Grootdraai Dam.

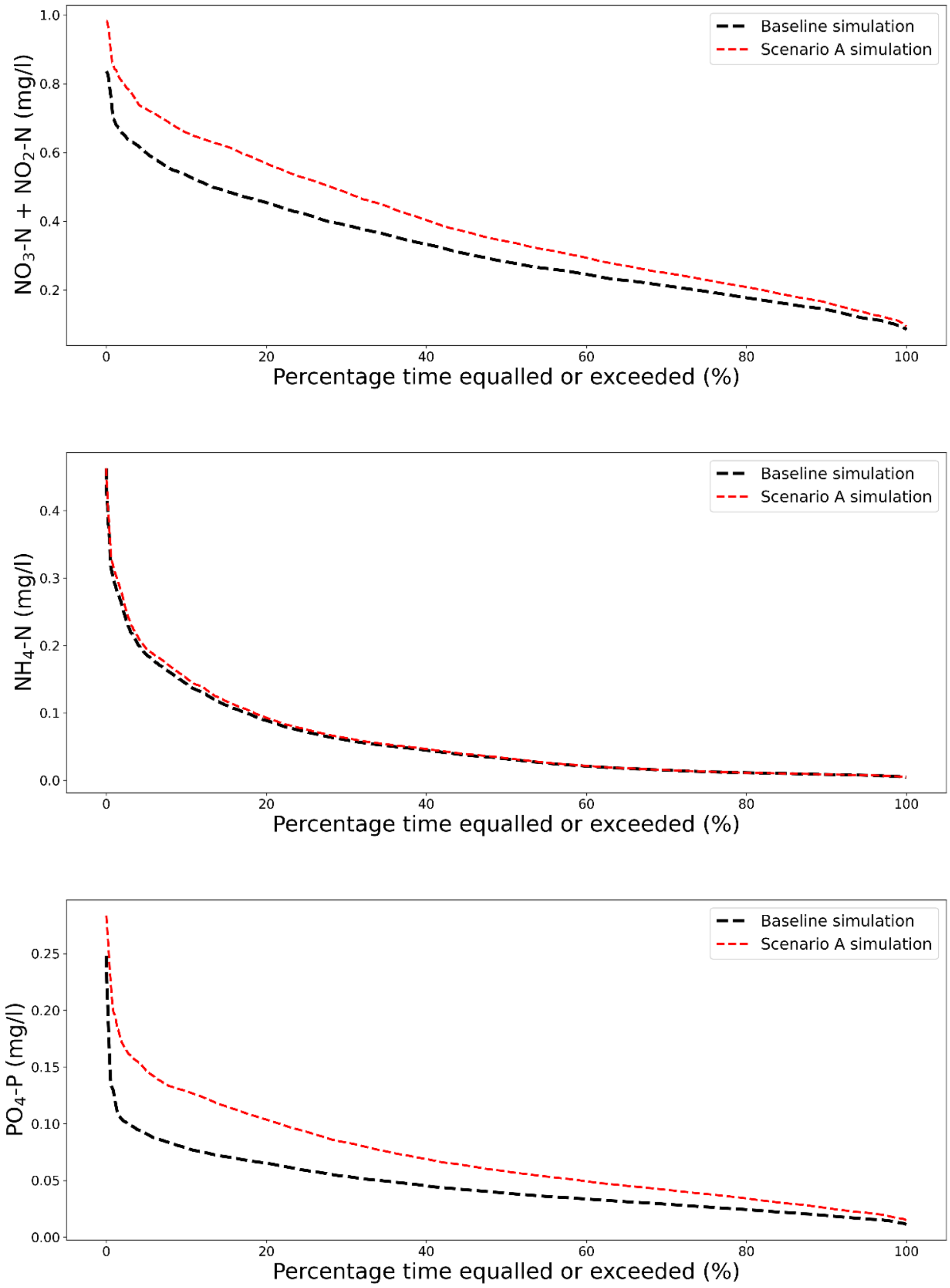


Figure 5-3 Concentration duration curves for nutrients at Grootdraai Dam simulated under increased urban areas by multiple regression in the medium term (2020-2050).

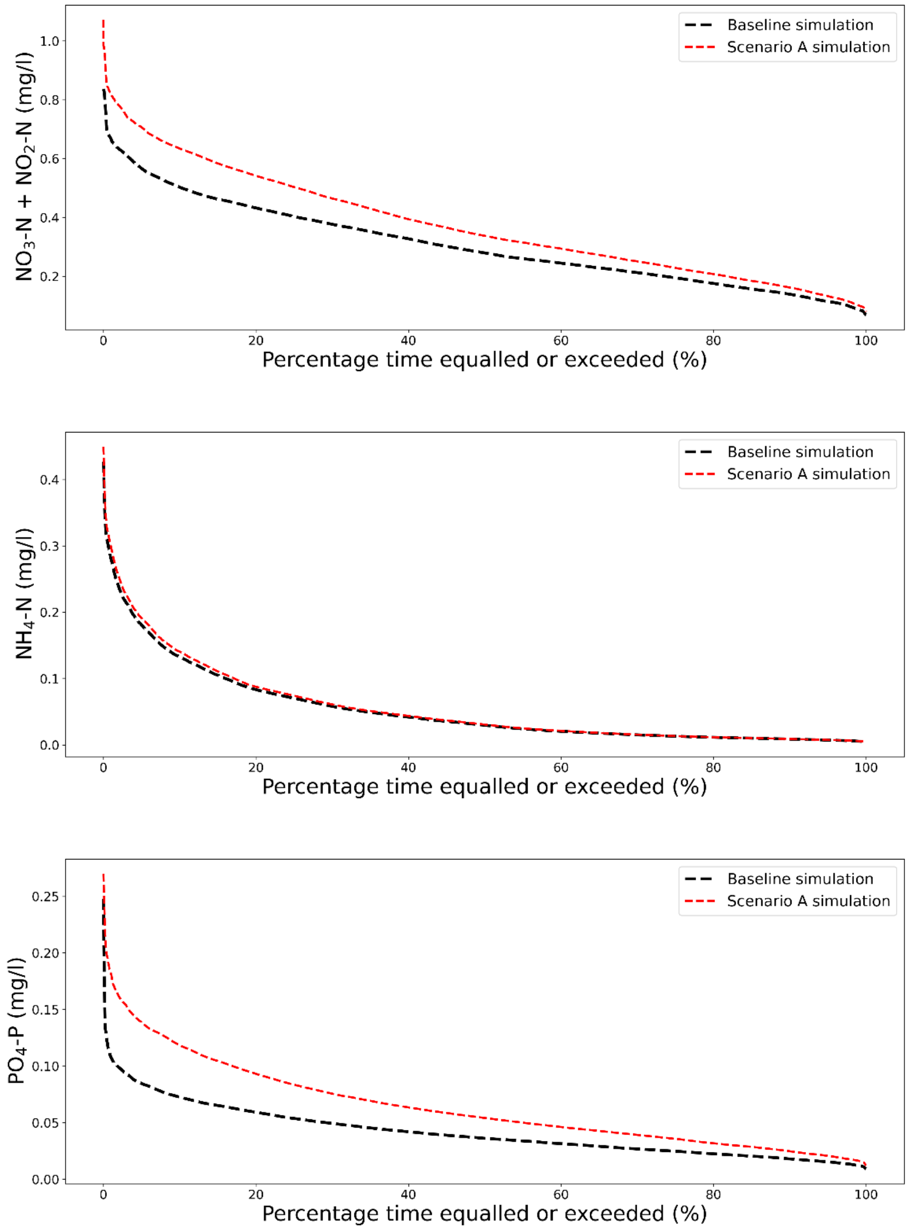


Figure 5-4 Concentration duration curves for nutrients at Grootdraai Dam simulated under increased urban areas by multiple regression in the long term (2020-2099).

Simulated increases in urban also led to increased levels of selected salts in the medium and long term (Figure 5-5 and Figure 5-6). These salts include those associated with mining, but also combined salinity. All showed an increase, but the figures from salinity simulations indicate that the increases in salinity are due to other ions, and, although sulphate and calcium increased, those increases do not account for the increase in salinity. This also suggests that salinity increases as a result of urban growth are not a function of mining increases. Salinity increases in the long term are greater than seen on the medium term.

Increased salinity at Grootdraai Dam as seen in these simulations is of concern as salinity in the catchment was one of the reasons for this study. The graphs highlight a notable influence of increased urban areas on these salts, possibly correlated with the coefficients assigned to urban areas, where it ranks as the second land use class with high β values. One must note that while the rise in urban areas may contribute to the elevated levels of salts, it does not necessarily imply that urban areas are the sole factor influencing these concentrations. Although other land use types may not be experiencing an increase, they could still contribute to the elevated levels, highlighting the complex nature of these influences.

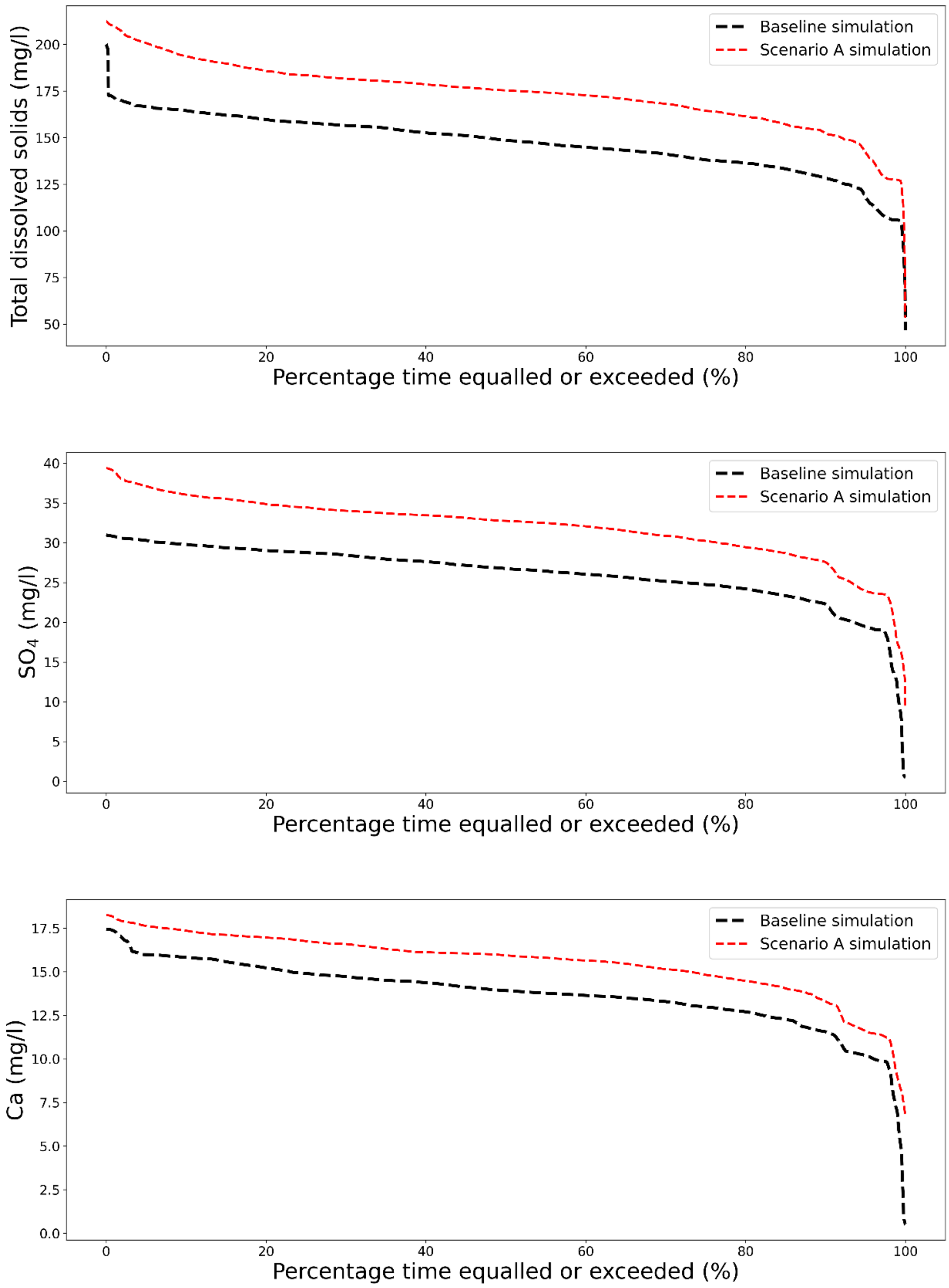


Figure 5-5 Concentration duration curves for selected salts at Grootdraai Dam simulated under increased urban areas by multiple regression in the medium term (2020-2050).

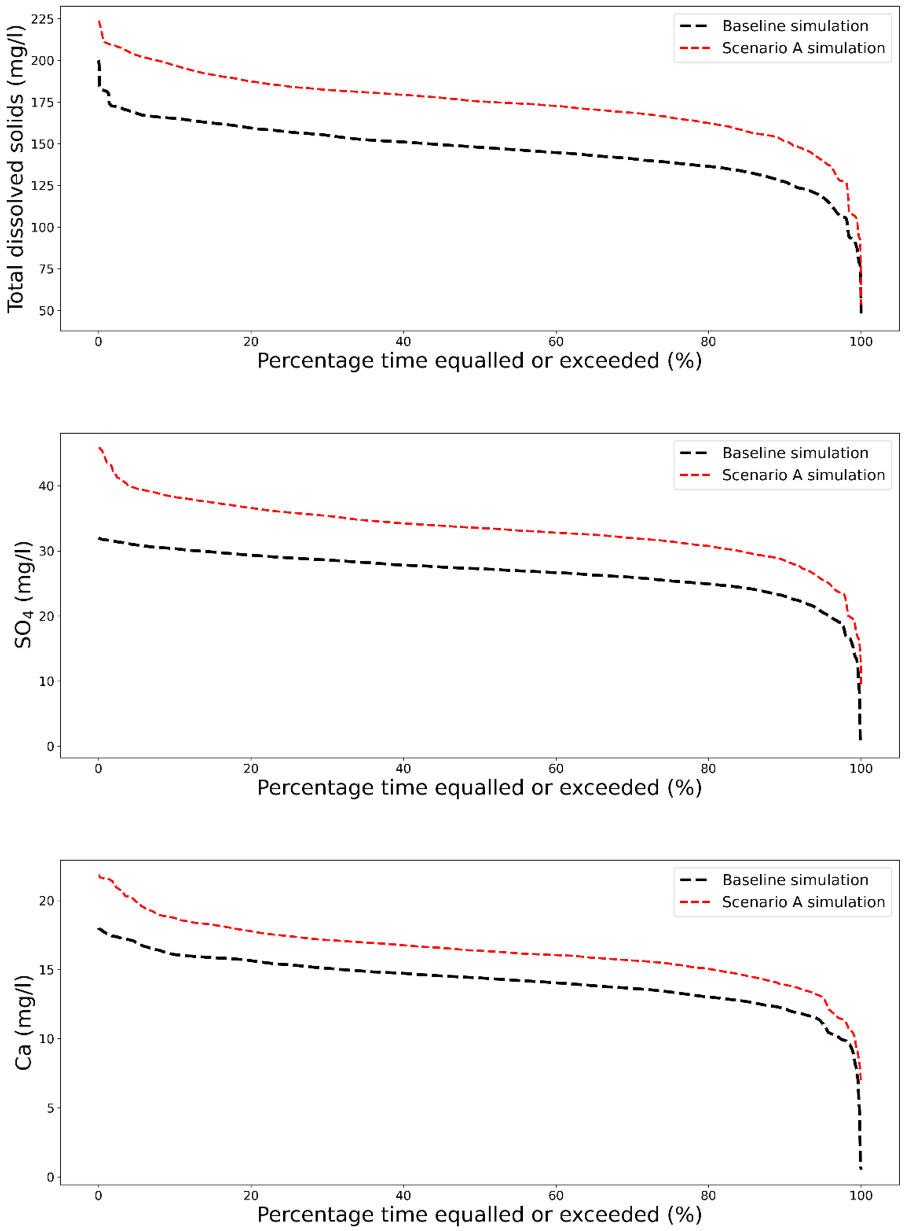
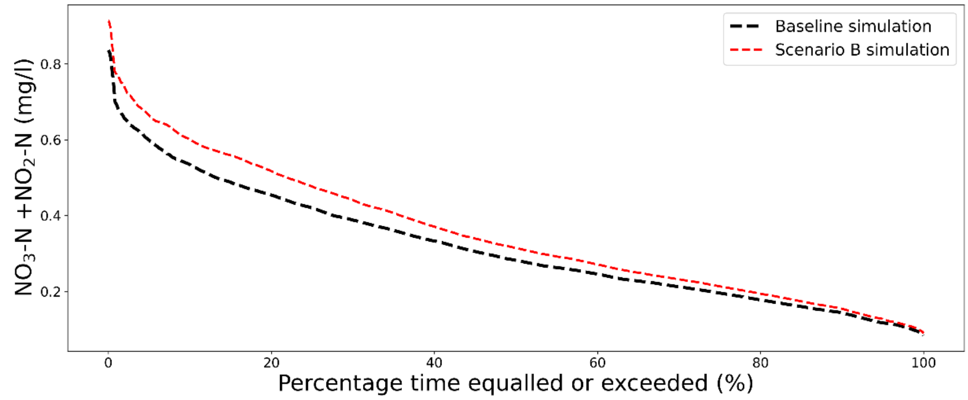


Figure 5-6 Concentration duration curves for selected salts at Grootdraai Dam simulated under increased urban areas by multiple regression in the long term (2020-2099).

5.2.2.2 Increase in cultivated land scenario

Figure 5-7 and Figure 5-8 show nutrients at Grootdraai Dam as the result of a simulated increase in cultivated land in the catchment in the medium and long term respectively. The plots show an increase in both nitrate/nitrite and phosphate at both time scales, with the increase in phosphate being most pronounced. The baseline and simulated nitrate/nitrite show concentrations that vary fairly evenly, with the baseline and simulated phosphate levels being mostly on the lower side, but a small percentage of samples having very high phosphate concentrations. It is probably worth considering that a generic RQO ideal class upper limit is 0.005 mg/l, which is lower than all of nearly all concentrations in the baseline and simulated data.



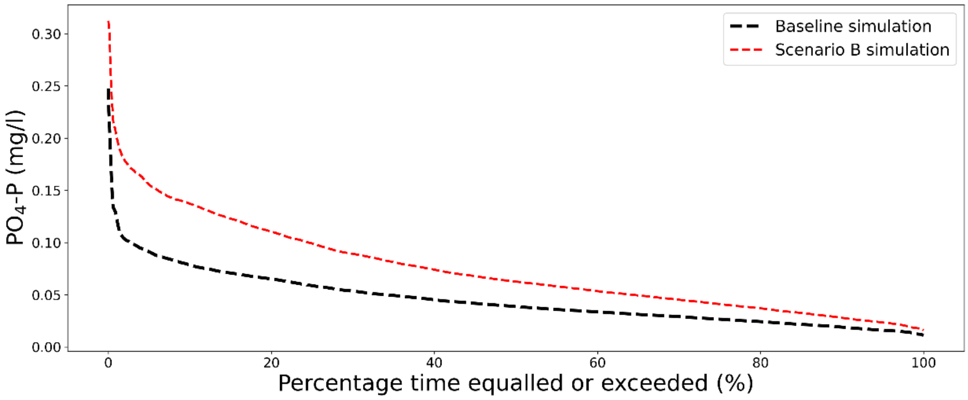


Figure 5-7 Concentration duration curves for nutrients at Grootdraai Dam simulated under increased cultivated areas by multiple regression in the medium term (2020-2050). Ammonium is not presented as it was indistinguishable from the baseline.

As with the risk of eutrophication with urban growth, there is likewise a threat that increased nutrient released from cultivated land may threaten the trophic status of Grootdraai Dam. While eutrophication may occur in response to any nutrient, freshwater systems are in general considered phosphate-limited (Smith et al., 1999), and therefore it is of concern that phosphate has greater increases. Against the observed general decrease in phosphate levels in South Africa (Griffin, 2017), levels seem likely to remain high in this catchment with consequent threat to Grootdraai Dam water quality.

Although changes in urban areas may not be easily stopped, they are an area where management intervention may have potential in reducing their impacts on water resources. Green Drop scores for the municipalities in the Grootdraai Dam catchment are around 20% or below, and wastewater treatment works have been identified as critical and in need of intervention (DWS, 2023). Municipalities have been exposed to legal action has a result of wastewater leakage (Carnie, 2023). If wastewater plants were properly run and effluents appropriately handled, a significant amount of the nutrient and salt impacts of urban lands could be reduced. Proper waste management can act to minimise the effects of urban expansion.

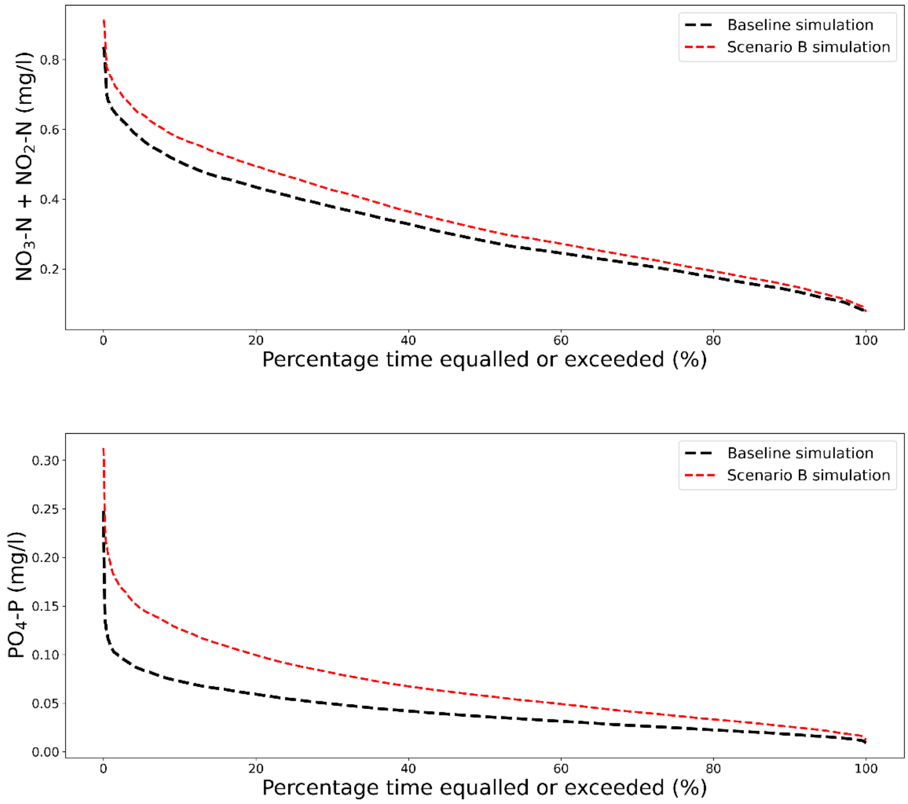


Figure 5-8 Concentration duration curves for nutrients at Grootdraai Dam simulated under increased cultivated areas by multiple regression in the medium term (2020-2050). Ammonium is not presented as it was indistinguishable from the baseline.

5.2.2.3 Increase in mining areas scenario

The outcomes of simulated increases in area mined on nutrients in the Grootdraai Dam catchment in the medium and long term are presented below (Figure 5-9 and Figure 5-10). The simulation assumes that mine type and practices from the calibration data set remain the same, which in this catchment means coal mining only. The simulations presented below will likely not apply if another mine type is assessed, and that mine management practices continue as in the past.

The trends observed in nutrient approximate those from the simulations of increased cultivated land: nitrate/nitrite results from baseline and simulations show a regular rate of change from high to low levels, with simulations showing a slight increase in nitrate/nitrite; and phosphate varying less, except for a small fraction with significantly higher levels. In comparison with DWS generic RQOs, phosphate baselines, and even more, simulations are worryingly high and exceed tolerable levels, while nitrate/nitrite levels remain at ideal levels throughout. As a result, the same worries of phosphate-led eutrophication remain when increased mining is simulated.

Medium and long term nutrient simulations return similar outcomes with respect to nutrients.

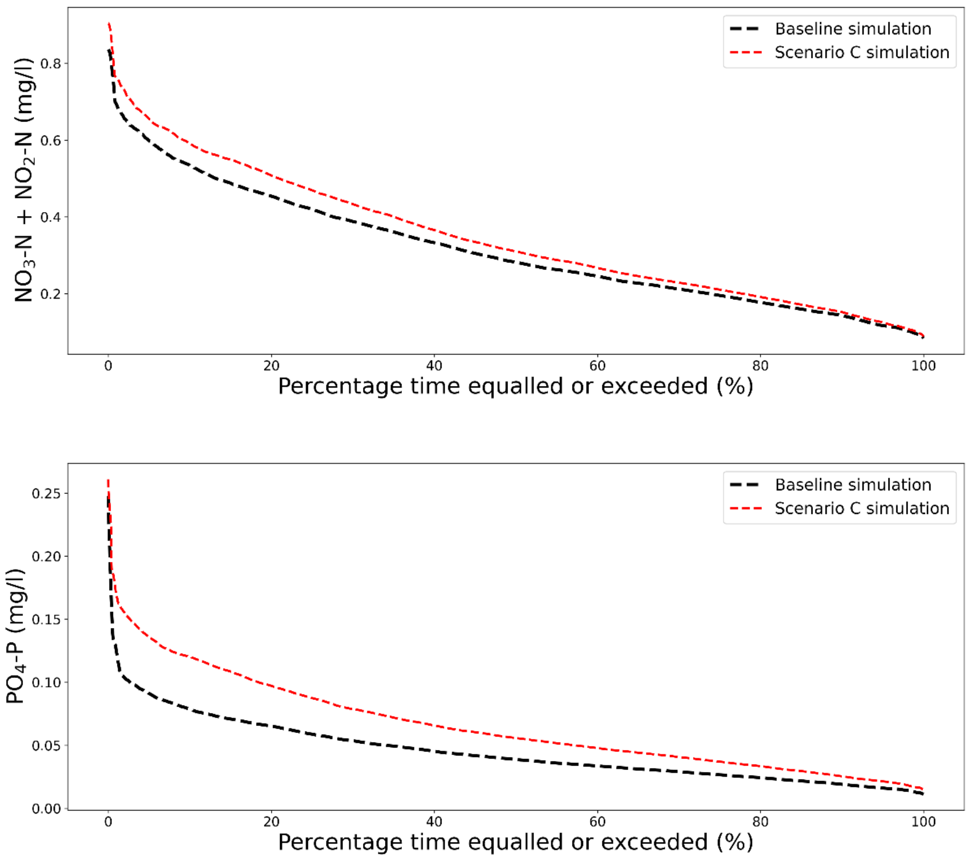


Figure 5-9 Concentration duration curves for nutrients at Grootdraai Dam simulated under increased mining areas by multiple regression in the medium term (2020-2050). Ammonium is not presented as it was indistinguishable from the baseline.

That an increase in cultivated land leads to an increase in freshwater is easily explained by increased fertilizer use, for example, or increased irrigation, an increase in mining resulting in increased nutrients is less clear. Nitrate/nitrite and phosphate levels are not commonly linked to mining, unlike certain mining related salts, and coal mining has no intrinsic link to nutrient via the geology. It is not known how mining leads to these increases. One can posit that mining may concentrate workers in an area, leading to increased wastewater production and thereby nutrient loading, but for now this remains a hypothesis.

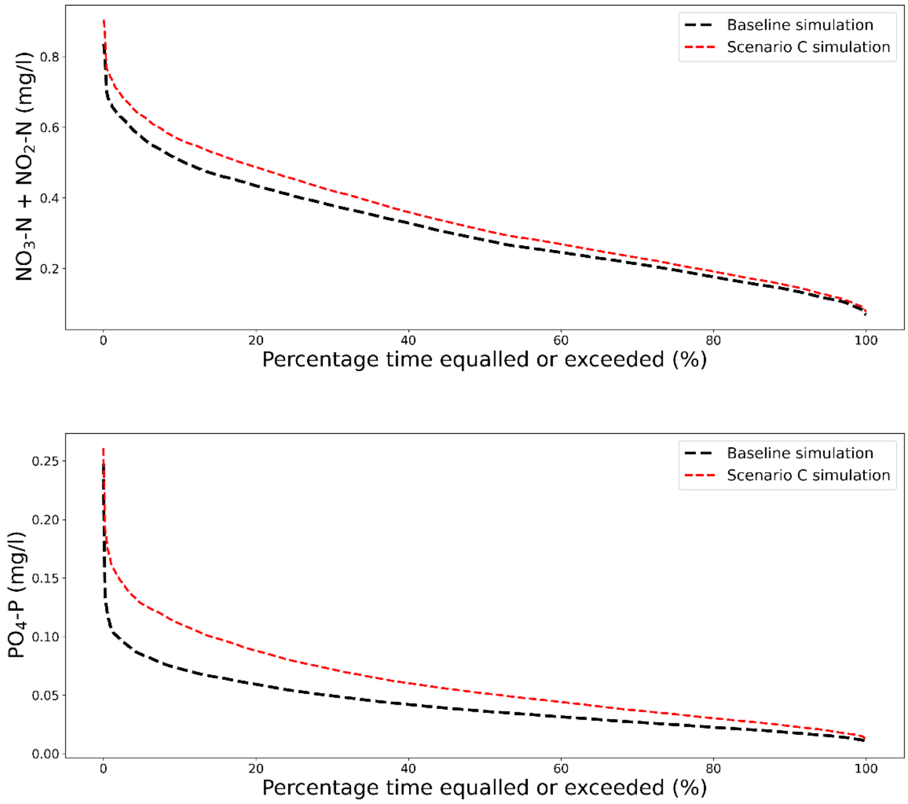


Figure 5-10 Concentration duration curves for nutrients at Grootdraai Dam simulated under increased mining areas by multiple regression in the long term (2020-2099). Ammonium is not presented as it was indistinguishable from the baseline.

Changes in selected salts under simulated increased mining in the Grootdraai Dam catchment in the medium and long term are presented below in Figure 5-11 and Figure 5-12. As might be expected, increased mining in the catchment resulted in large increases in salinity in the Grootdraai Dam in both time frames. The salts that were selected for this modelling procedure include sulphate, anticipated as sulphate is generated from pyrites as acid mine drainage is formed in South African coal mines (McCarthy, 2011), and calcium which is introduced during the liming process when acid mine drainage is treated (Akcil and Koldas, 2006). Simulated salinity increases were not due to these salts alone, although both showed significant increases under increased mining scenarios, and other ions contribute to the majority of salinity increases.

Atmospheric deposition of sulphates and other ions is well known following fossil fuel combustion in South Africa (Mompati et al., 2022), and deposition of sulphates has been recorded from the Grootdraai Dam catchment itself (Mphepya et al., 2004). As such, it is known that burning fossil fuels in the catchment increases soil and therefore water salt levels. There is therefore a fraction of the apparent mining impact that is due to electricity generation. We unable to quantify the importance of aerosolic deposition, and so this is not specifically modelled here.

Taking DWS generic RQOs as a guideline, the salinity and calcium levels under increased mining would be classed as acceptable, and sulphate as ideal. However, this needs to be considered in the light of the rationale for this project, that increasing salinity in the catchment might threaten the use of the water. In circumstances where salinity is already an issue, any increases in salinity are to be avoided.

The same caveat that arose in recommendations about increasing salinity as a result of urban impact apply here. Mine water needs either to be isolated from the catchment, or treated in such a way that salinity is dealt with. Simply liming acidified mine water and returning it to the catchment, either as surface water or groundwater, will lead to further salinization.

If mines are to be closed, the process needs to follow DWS Best Practice Guidelines for closure of mines and specifically minimising impacts on water resources (DWAF, 2008a, 2008b). Proper closure can remove the impacts associated with coal mining. However, simply leaving the mine with no water management will allow mining-related impacts to continue.

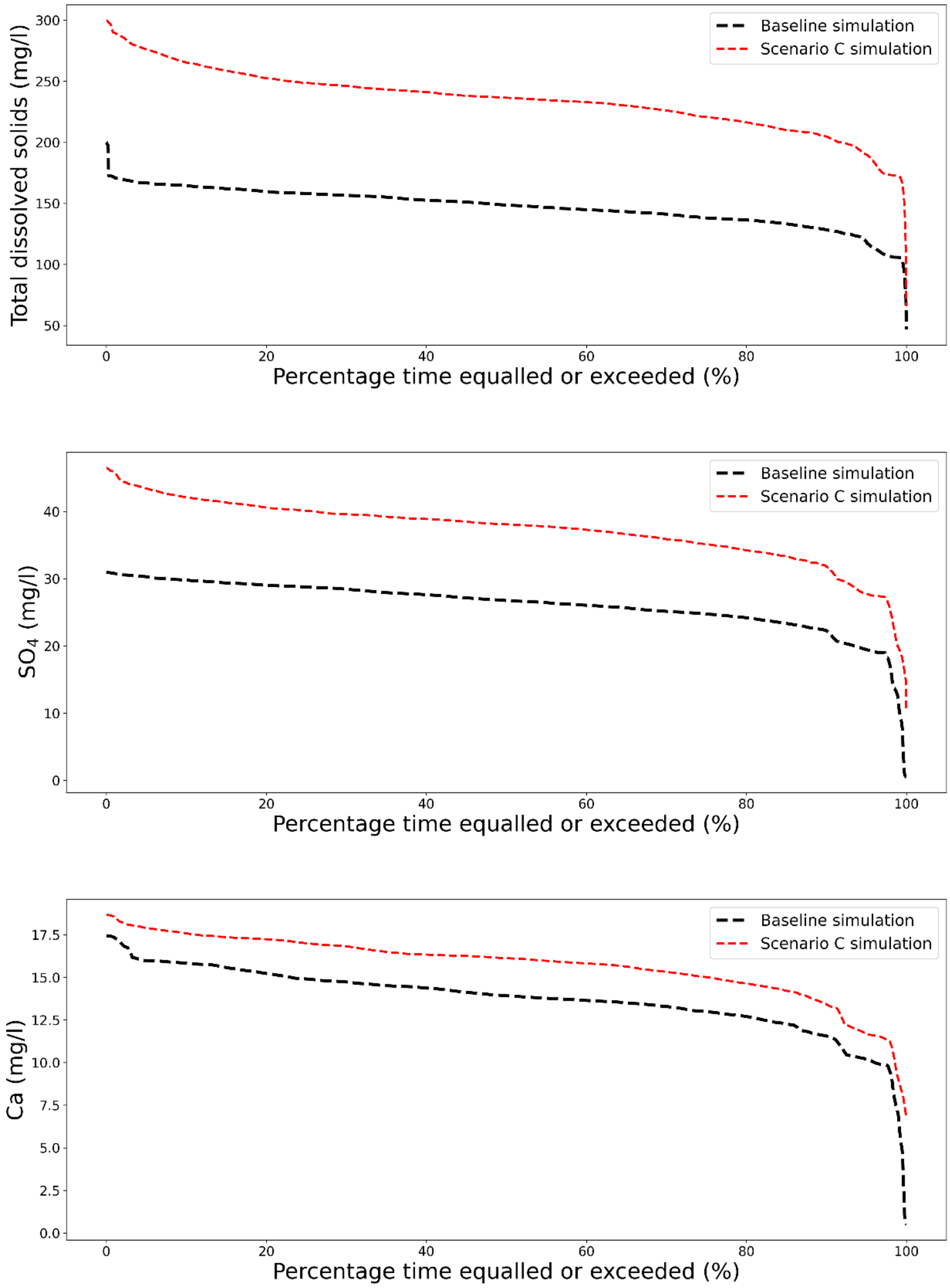


Figure 5-11 Concentration duration curves for selected salts at Grootdraai Dam simulated under increased mining areas by multiple regression in the medium term (2020-2050).

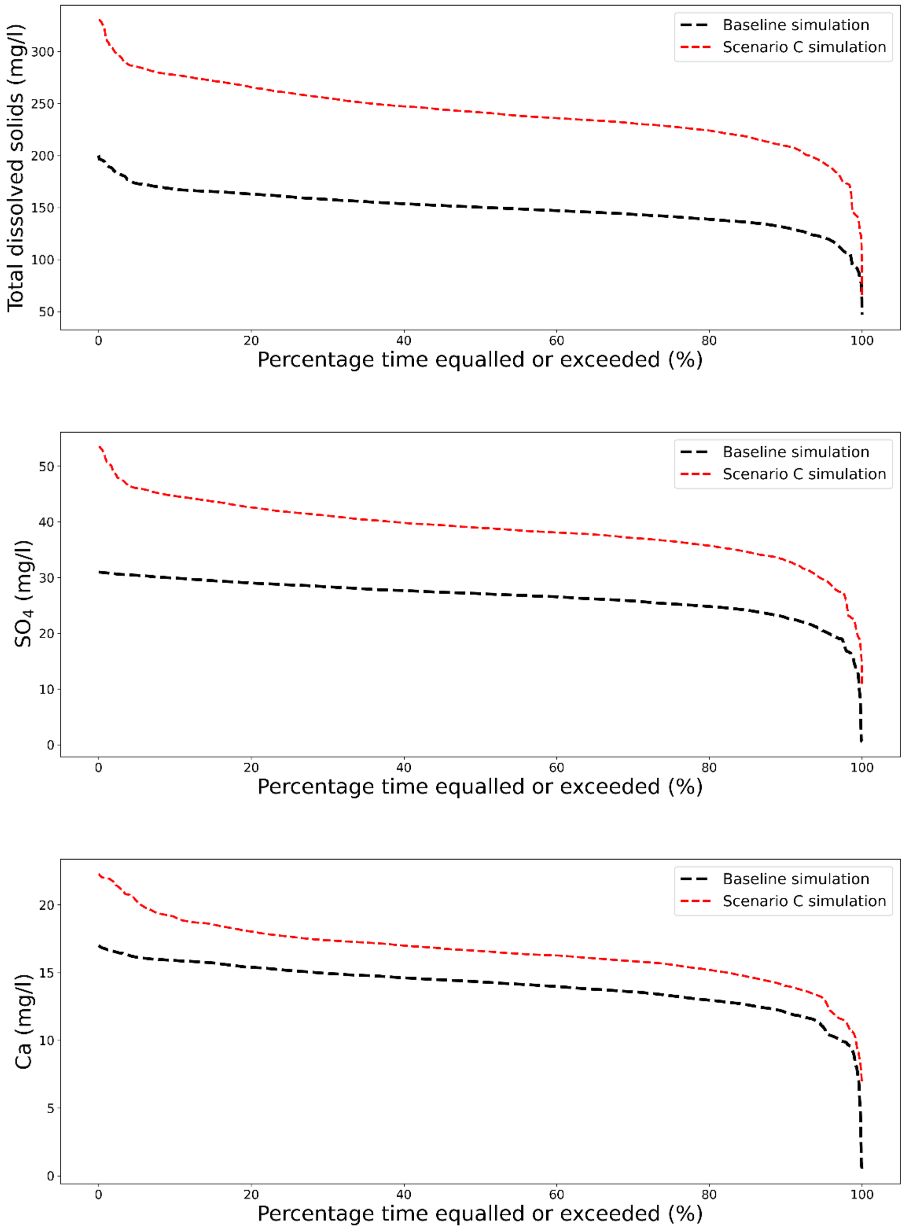


Figure 5-12 Concentration duration curves for selected salts at Grootdraai Dam simulated under increased mining areas by multiple regression in the long term (2020-2099).

5.2.2.4 Overall land use changes

These scenarios indicate in general that an increase in land in urban areas, land used for mining, and cultivated land has negative effects on water quality, and that the longer the increase happens, the greater the effect. However, there are nuances in the different scenarios. Firstly, that an increase in nutrients in surface flows occurs, but is not very large compared to the baseline scenario. Secondly, that increased groundwater salts under the scenarios assessed may be limited (e.g. urban increases by 2050), but may also be large, and will need to be managed.

It is important to consider that all scenarios assume that land use impacts are the same as were present in the calibration dataset, and therefore that with improved management in the future, the predicted impacts may be limited. In earlier calibration data, these assumptions are liable to be somewhat unrealistic. However, these model outcomes do illustrate what may happen if management practices do not change.

Non-point agricultural nutrient pollution which threatens Grootdraai Dam water quality was established by Ncube (2015), and Ntshalintshali (2019) noted that Vaal River water leaving the upper Vaal had higher nutrient levels. In the context of a 0.3% increase in cultivated land cover, higher values of nitrate/nitrite and ammonium loads were found compared to mining and urban land cover scenarios in the medium and long-term. The cultivated scenario indicated a significant potential for nutrient loss from soil or fertilized fields to rivers for 2050 and 2099 time frames. The main sources of inorganic nitrogen that enter aquatic systems are surface runoff from the surrounding catchment area, as well as the discharge of effluent streams containing human and animal excrement, agricultural fertilizers, and organic industrial wastes (DWAF, 1996).

The modelling process, involving assessing the impact of a moderate increase in urban land cover, revealed a notable elevation in phosphate concentrations during both wet and dry seasons in the medium and long term. This trend was observed in comparison to the cultivated land scenario. These findings provide valuable insights into the primary sources of phosphate within the study area, addressing the question of whether the predominant origin of phosphate is derived from wastewater treatment works (WWTW) or agricultural leaching. The notion of phosphate leaching from the soil remains a potential contributor through surface runoff. However, the compelling evidence of consistently elevated phosphate levels in urban land cover suggests an alternative source, potentially arising from damaged or compromised wastewater pipes.

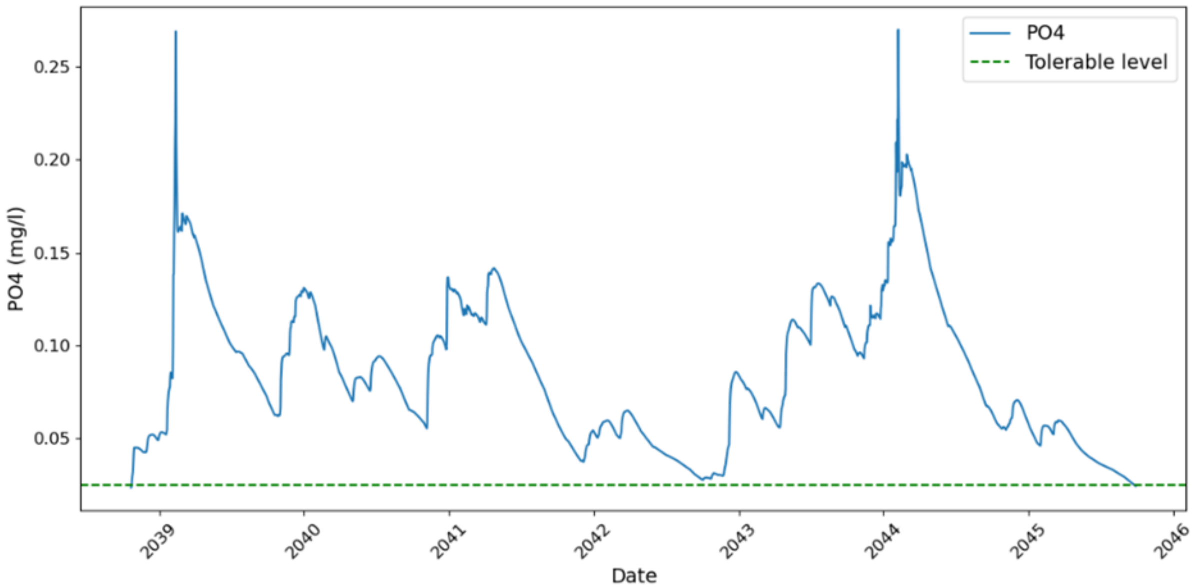


Figure 5-13 Variations in phosphate concentrations within Grootdraai Dam, illustrated in the context of a moderate increase in urban land cover, reveal instances of the high consecutive exceedances relative to RQOs.

Coal is consumed by both power generation and the Sasol coal-to-liquid plant, and there are many coal mines in the Grootdraai Dam catchment. The impact of coal mining on freshwater resources is a well-known issue (McCarthy, 2011). Coal-related acid mine drainage and decant have the potential to cause acidification, salinization, and metal solubilization, which can threaten water quality. A previous study demonstrated that the number of operational and defunct coal mines in the Grootdraai catchment will need to be carefully managed to avoid a threat to water quality as a result of pyrite oxidation and consequent acid mine drainage (DWAF, 2009b). Here, a moderate increase of 0.015% in mining land cover showed higher values of sulphate, calcium, salinity and phosphate loads comparing to urban and cultivated land cover scenarios for medium and long-term. The mining scenario indicated a significant potential loss for salts from soil to rivers for 2050 and 2099 time frames. Tutuka power station is scheduled for decommissioning from 2035, Majuba from 2046, and Camden was scheduled for decommissioning from 2020 (DMRE, 2019). However, a moderate increase of 0.015% in coal mining land area that supplied the power stations demonstrated significant changes in salinity (i.e. sulphate, calcium and total dissolved solids) and phosphate. The increase in phosphate levels may stimulate growth of aquatic plants and algae. The accumulation of salts in water here is due to the continuous addition of salts from both natural and human-made sources (e.g. coal mines, lack of wastewater treatment and wastewater pipes leakage).

According to DWS (2016), the resources quality objectives (RQOs) stated that for Grootdraai Dam located in resources unit (RU)10, the average phosphate phosphorus level should not exceed 0.02 mg/l, but the medium and long-term phosphate phosphorus levels showed an average value that ranges from 0.06 to 0.07 mg/l within 2050 and 2099 horizons (medium and long-term) under cultivated areas increase scenario.

Phosphate tends to promote the likelihood of algal and other plant growth. Furthermore, the lithological characteristics of the Grootdraai Dam catchment may contribute to the mobilization of salts such as total dissolved solids, sulphate, and calcium to groundwater, and that explains the high groundwater flow signatures given to salts during water quality simulation for mining scenario for medium and long-term. In addition, clay soil type is the most dominant comparing to sandy and loamy soils, where clay is known of its ability to absorb and store water, contaminated water with high salinity and salts level results in increasing the probability of groundwater contamination. The RQOs stated numerical limitation for the 95th percentile of salinity level is 191.1 mg/l for Grootdraai Dam. The model predicted that medium and long-term levels showed a shift in total dissolved solids level ranging 198.9 mg/l and 285.5 mg/l. This may result in riverine biodiversity loss such that the original biota are replaced by more salt-tolerant species, with consequent effects on community structure and microbial and ecological processes. The sub-catchments selected for mining land cover scenario assessment (i.e. C11A, C11B, C11F and C11K) revealed concerning fluctuation in salts levels in the medium and long-term (Table 5-5).

Table 5-5 Salinity results for sub-catchments for medium and long-term presented in means and standard deviation under an increase in mining.

		C11A	C11B	C11F	C11K
Medium term (2050)					
TDS		368.6 ± 160.3	1846.7 ± 856.5	1538.8 ± 670.6	474.9 ± 186.9
SO_4	mg/l	113.4 ± 50.2	1375.9 ± 650.8	190.9 ± 89.9	106.9 ± 45.7
Ca		35.1 ± 12.8	30.2 ± 3.4	63.2 ± 23.6	20.3 ± 9.8
Long term (2099)					
TDS		544.8 ± 246.1	1840.1 ± 859.9	2720.0 ± 1241.9	848.6 ± 387.2
SO_4	mg/l	116.6 ± 52.2	1369.2 ± 652.1	291.5 ± 138.8	187.7 ± 89.4
Ca		44.9 ± 17.7	30.2 ± 4.3	81.8 ± 32.8	40.1 ± 20.4

Other ions beyond sulphate and calcium will make up the remainder of salts making up the total salinity. Sulphate and calcium were chosen because of their known association with acid mine drainage in South Africa and liming treatment respectively. These results highlight how significantly mining contributes to salinity in C11B, but relatively less in the other catchments assessed.

CHAPTER 6: RESULTS-CLIMATE CHANGE SCENARIOS

6.1 INTRODUCTION

That climate change is happening is well established, and will continue. South Africa has been judged to be highly vulnerable to climate change, owing to a high reliance on rain-fed agriculture and low adaptive capacity (World Bank 2021). In general, temperatures across the country are rising, and, while less pronounced, climate related changes in water quantity and quality are anticipated (World Bank 2021). Increased temperatures will have consequent evapotranspirative changes, which may impact already dry soil inordinately (World Bank 2021).

A planning exercise undertaken for Mpumalanga climate risks identified the following water related risks (DEA and GIZ 2015):

- Decreased water availability as a result of changed rainfall and evapotranspiration.
- High flow and low flow period timing changes.
- Higher flood incidence.
- Decreased water quality owing to higher runoff and temperature changes.

Climate related changes on water can therefore have an effect and water quantity and water quality. An effect not explicitly addressed by DEA and GIZ (2015) is potential changes to the diluent capacity of a water resource when the quantity and timing of water availability changes. Another system effect of erosion and scouring following intensive flow that is addressed is the potential of increased dam siltation resulting in reducing system storage.

This broad framework will be used in assessing flow and quality changes in the Grootdraai Dam catchment.

Climate change effects assessment for the upper Vaal was undertaken as part of a prior project (Aurecon, 2020). Yield data from that dataset was suitable for use in the water quality model, after disaggregation to daily flows. Further details of the approach used are provided in Hughes and Slaughter (2015, 2016) and Slaughter et al. (2015). Daily flow data are then used in the calibrated Pywr-WQ model to generate water quality predictions under conditions of climate change.

6.2 CLIMATE CHANGE FLOW DATASET

Baseline flow data consistently exhibited substantially higher annual flow values when compared to the climate change flow data ($p < 0.001$). Annual flows of both data sets are depicted in Figure 6-1. The climate change dataset tends to exhibit lower mean and 95th percentile values in comparison to the baseline dataset, with reductions of approximately 2.9% and 10.4%, respectively.

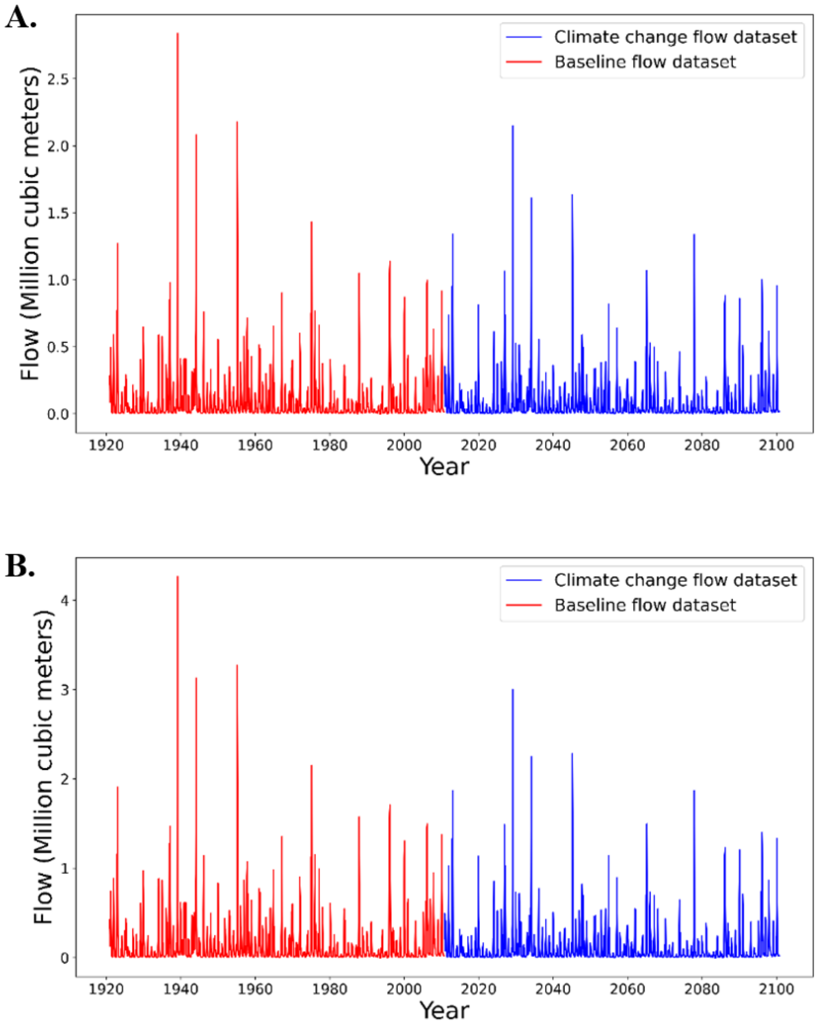


Figure 6-1 Variation in annual average flow within the Grootdraai Dam Catchment plotted against time (2010-2099). Figure A illustrates the annual average flow variation at quaternary catchment C11A, situated in the upstream area, while figure B depicts the annual average flow variation at quaternary catchment C11L, positioned in the downstream area of the Grootdraai Dam Catchment.

There are several assumptions related to the water quality modelling process:

- The water temperature during the climate change scenario is assumed to remain the same as in the calibrated setup (baseline scenario).
- Continuous changes in land use within the region, driven by climate change adaptation and shifts in the South African economy, are hypothesized to have an insignificant impact on the future hydrological responses of the Grootdraai Dam Catchment.
- It is assumed that there will be no increase in water demand from water users, leading to decreased freshwater flows. This increase in demand could potentially result in higher pollutant concentrations and the deterioration of river water quality.
- Water supply from the Grootdraai Dam remains consistently available when the dam's water level is at or below 90% of its capacity.

6.2.1 Flood extreme events

The analytical approach used three distinct distributions – Generalized Extreme Value (GEV) (Hosking et al., 1985), Gumbel (Gumbel, 1935), and Log Normal (Crow and Shimizu, 1987) as potential fits for the climate change flow data. The primary objective of this procedure was to identify the most suitable distribution capable of capturing the underlying patterns within the dataset. The selection of distributions, a crucial aspect of the analysis, enabled the determination of average flows associated with specific return periods. These average flows, corresponding to predefined return periods, were subsequently utilized as thresholds for assessing flood extreme events.

A quantile analysis was then undertaken, focusing on four chosen return periods categorized as exceptional, very abnormal, abnormal, and normal. The flood flow data for each return period was extracted using HyfranPLUS (El Adlouni and Bobée, 2011). These return periods were determined based on the magnitude of flood events (Hangnon et al., 2015). Each category corresponded to specific return period thresholds: exceptional was a 50-year return period; very abnormal was a 20-year return period; abnormal was an 8-year return period; and normal was a 2-year return period.

For each return period, flood flow data was computed using a peak coefficient, which represents the ratio of the maximum flow to average flow. The peak coefficient was derived from the climate change flow dataset and applied to calculate the flood flow by multiplying it by the average flow obtained from the quantile analysis for each selected return period.

To ensure scientific rigor, a series of statistical assessments were conducted to determine whether the sample's distribution adhered to a specific distributions. Evaluation criteria included the Kolmogorov-Smirnov test (Massey, 1951) and chi-square test (Tallarida et al., 1987) for validation. Furthermore, the flood hydrograph for each return period was generated using the time of concentration formula, employing empirical equations commonly utilized in South Africa, as exemplified by previous studies (e.g. Gericke and Smithers, 2016; Kirpich, 1940; USBR, 1973).

The flow data quantiles extracted from the application of lognormal distribution law for specific return periods that refer to a certain flood characteristic (e.g. exceptional, very abnormal, abnormal and normal) are presented in Table 6-1.

Table 6-1 Flood flows for various return periods for assessment of the climate change scenario using a lognormal flow distribution within the Grootdraai Dam.

Return period (years)	Average flow (m^3/s)	Peak coefficient	Maximum flow (m^3/s)
50	4.73	24.61	125.43
20	3.44	24.61	91.22
8	2.34	24.61	62.05
2	0.96	24.61	25.45

6.2.2 Drought extreme events

The analysis computed drought thresholds of 80% frequency of the monthly duration curves. This approach involved determining a threshold value for each month that is exceeded by the climate change flow dataset 80% of the time. The selection of the 80% frequency is based on its common use in drought studies (e.g. Van Loon, 2013) and its relevance for capturing important drought characteristics. The choice of this percentile aligns with the broader range of percentiles (ranging from the 70% to the 95% frequencies) that have been widely employed in the assessment of perennial river droughts. To enhance the robustness of the discrete monthly threshold values, a smoothing technique was applied. This involved employing a centred moving average over a 10-day window, aimed at preventing the emergence of a staircase pattern in the data and thereby ensuring more realistic representations of drought characteristics. This approach has been employed in many previous studies (Gustard and Demuth, 2008; Hortness, 2006; Pyrce, 2004). The flow characteristic extracted from the monthly DC80% serves as a significant threshold flow, given its representation of extreme low-water levels (Figure 6-2).

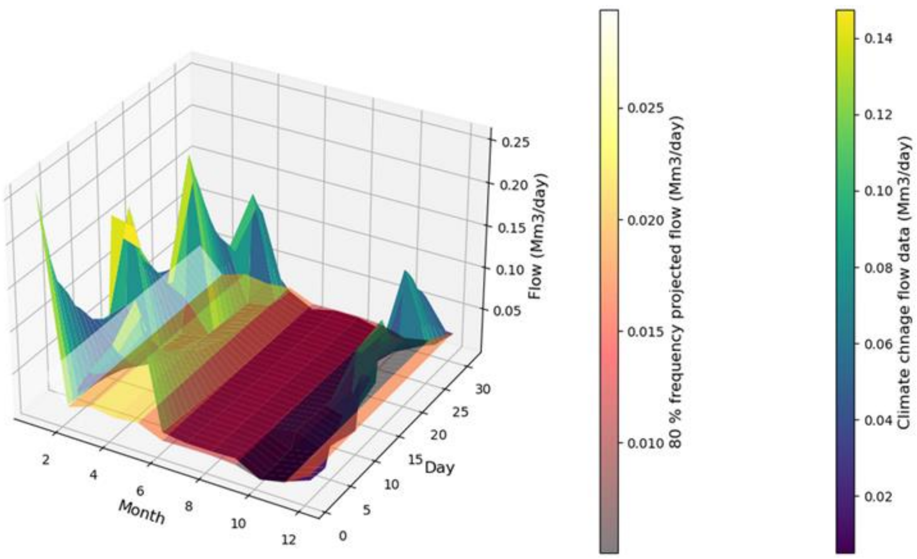


Figure 6-2 Deficit volumes and durations as a function of 80% frequency low-water thresholds – Grootdraai Dam in 2080 (long-term).

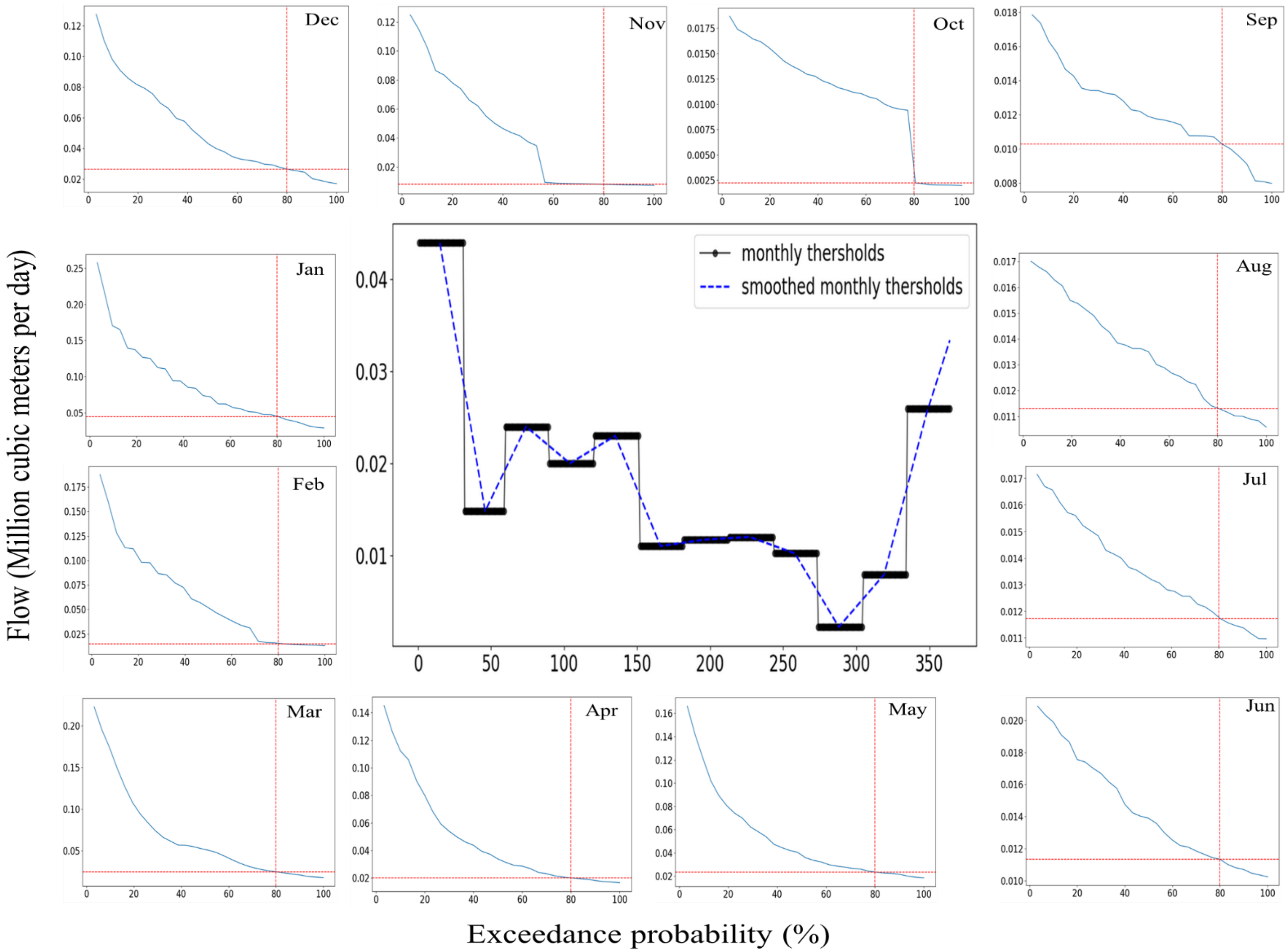


Figure 6-3 Derivation of smoothed monthly threshold level from monthly duration curves (example with climate change flow data for the year 2080).

6.3 CLIMATE CHANGE SCENARIO SIMULATION

Figure 6-4 and Figure 6-5 depict the temporal distribution of nutrient and salts concentrations before and after climate change scenario prepared using the calibrated Pywr-WQ model. Figure 6-6 and Figure 6-7 are concentration exceedance curves for the same data. These figures enable us to understand how nutrient and salts concentrations vary in frequency in both scenarios.

Throughout the duration curves, notable patterns emerge in the behaviour of various water quality variables. These patterns can be attributed to the complex interactions within the Grootdraai Dam catchment and the specific dynamics influenced by the climate change scenario. Notably, we observe that certain variables exhibit an increase in concentration over time under climate change, others remain relatively close to the baseline scenario simulations, and yet others demonstrate a decrease.

Specifically, salts such as chloride, sulphate, and magnesium experience a decrease over time relative to the baseline simulations. All major plant nutrients also show a decrease in response to climate change. The mechanisms leading to these changes are not known. However, it is of interest that sulphate concentrations show a decrease with climate change-sulphate is associated with coal mining in South Africa (McCarthy, 2011) and coal mining is prevalent in this catchment. The decrease in nutrients results in lower eutrophication risks under climate change conditions (provided other constraints are constant).

Conversely, variables like fluoride, potassium, sodium, and total dissolved solids exhibit an increase when compared to the baseline scenario. Again the mechanisms behind these changes is not known, but can relate to precipitation patterns, soil leaching, runoff formulation and return flows, and more. The increased salinity under climate change is a concern, as this will have implications for future water use in the catchment. Increased sodium and salinity has negative implications for the use of Grootdraai Dam water for irrigation (Grattan and Oster, 2003).

Several other water quality parameters, such as nitrates and ammonium, as well as salts like calcium, maintain close similarities to the baseline scenario.

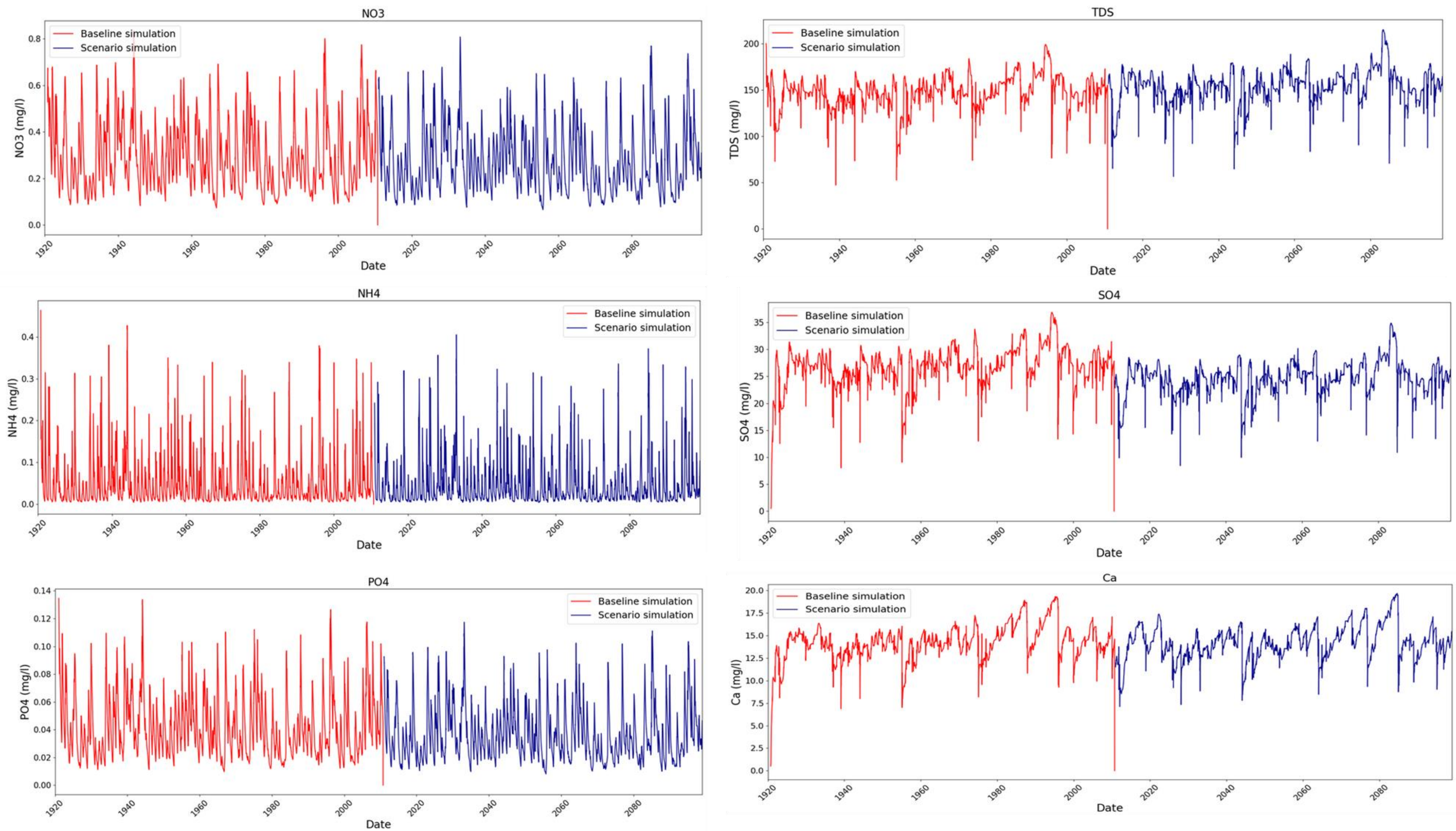


Figure 6-4 Temporal distributions of nutrient and some salt concentrations for the climate change scenario generated by the calibrated Pywr-WQ model.

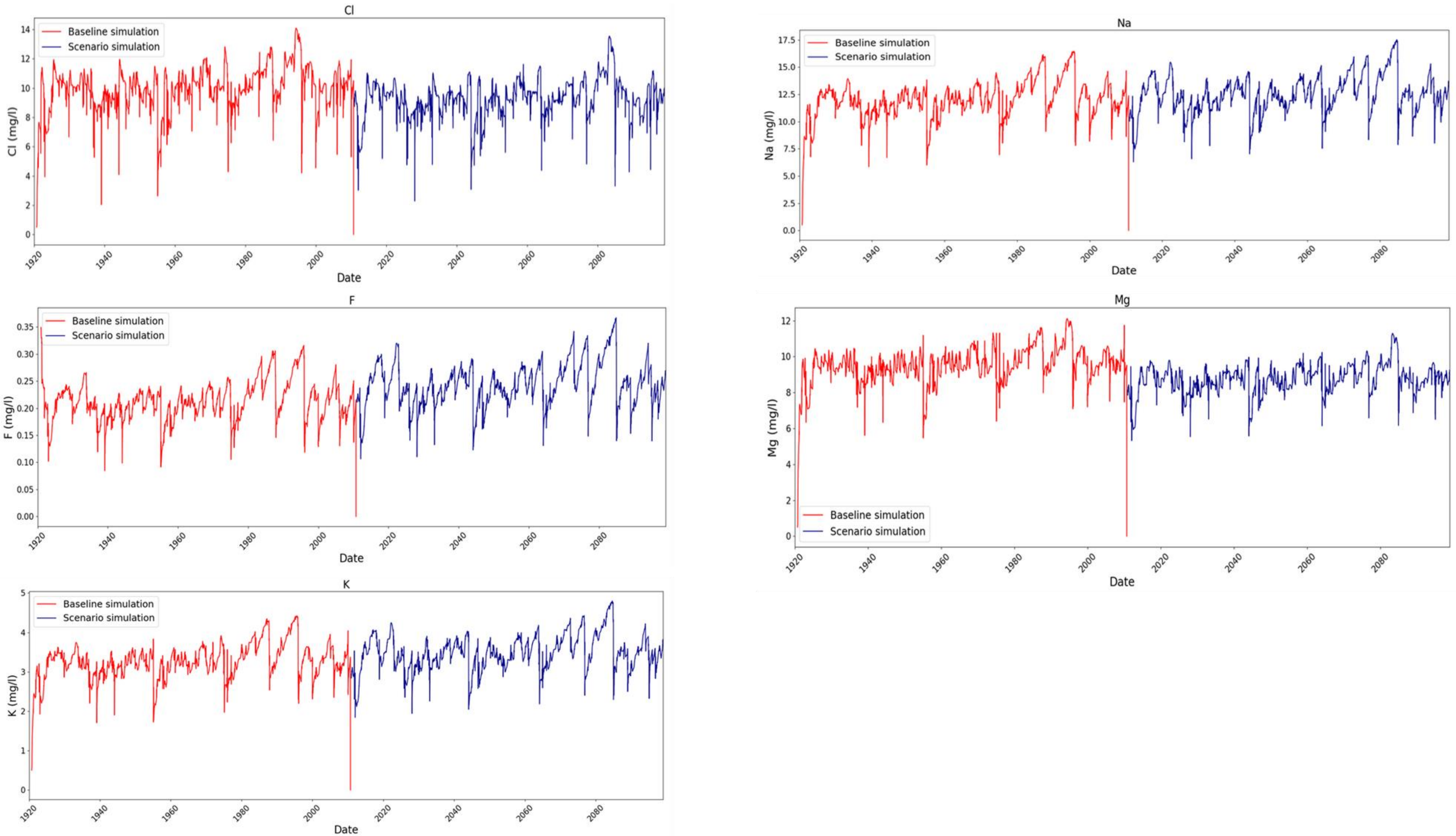


Figure 6-5 Temporal distributions of remaining salt concentrations for the climate change scenario generated by the calibrated Pywr-WQ model.

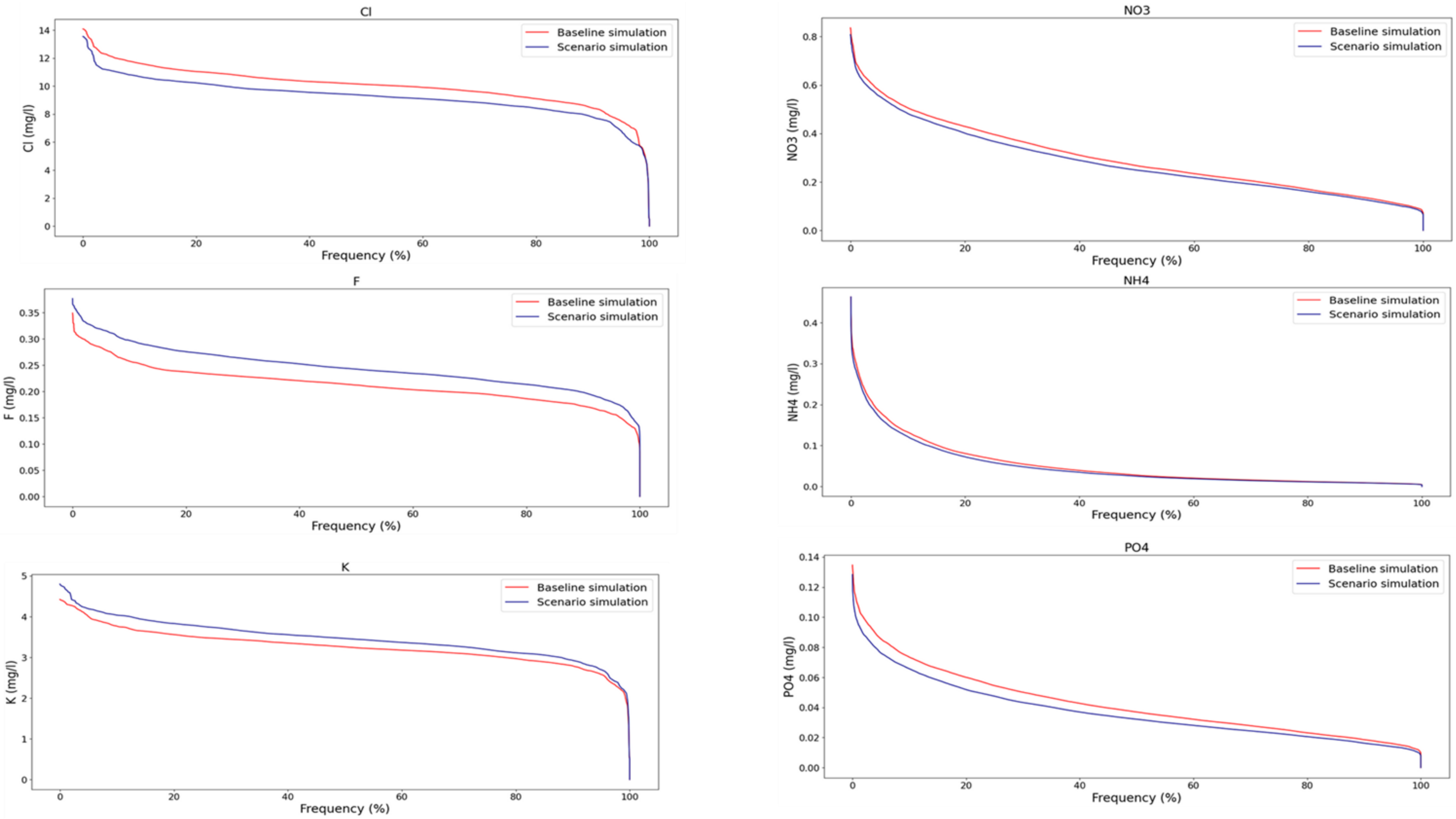


Figure 6-6 Concentration exceedance curves of nutrients and some salt concentrations for the climate change scenario generated by the calibrated Pywr-WQ model.

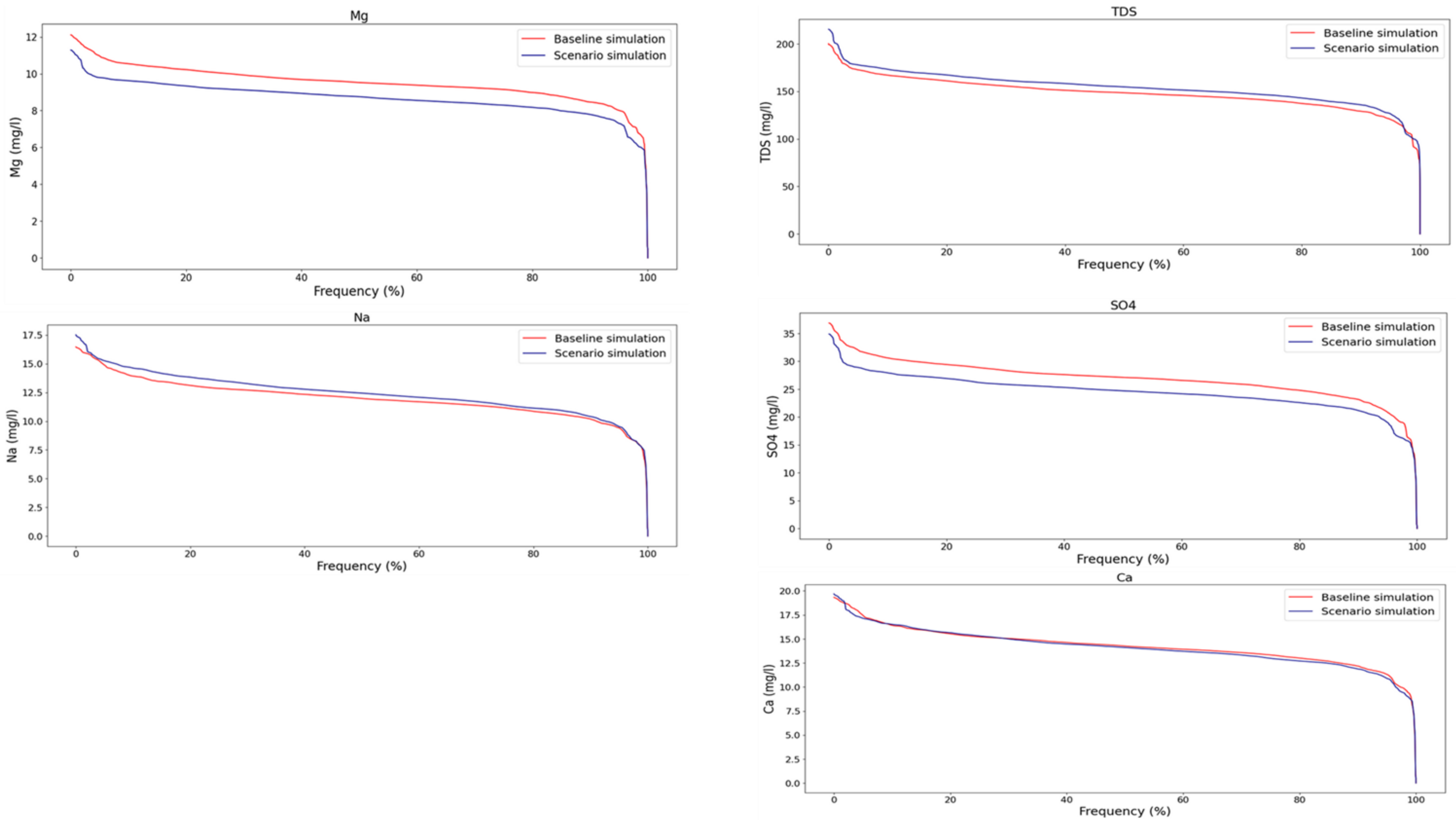


Figure 6-7 Concentration exceedance curves of remaining salt concentrations for the climate change scenario generated by the calibrated Pywr-WQ model.

6.3.1 Water quality simulations during flood and drought events

While climate changes may lead to general changes in water quality, other climate-related changes such as a higher incidence and intensity of droughts and floods is predicted (World Bank, 2021). General water quality changes in Grootdraai Dam water quality in response to predicted climate change are presented above in 6.3. Here we will specifically consider the likely impacts of droughts and floods.

Figure 6-8 and Figure 6-9 depict simulations using the Pywr-WQ model of temporal nutrient and salts dynamics within the Grootdraai Dam under flood events in the medium and long term. Conversely, Figure 6 12 and Figure 6 13 illustrate temporal simulations of salts and nutrient concentration during drought episodes in the medium and long term within the Grootdraai Dam.

Figure 6-8 and Figure 6-9 present specific flood episodes occurring within both medium and long-term contexts. In particular, the medium-term flood event spans from 11/02/2044 to 20/02/2044, while the long-term flood event occurs between 01/01/2085 and 09/01/2085. These specific flood events were chosen based on computed flood thresholds (Table 6-2), utilizing the threshold corresponding to a 2-year return period, which is characteristic of normal flood events. The figures provide a broader time perspective, incorporating days preceding and following the flood episodes. This approach was intentionally adopted to facilitate a more comprehensive examination of the influence of floods on water quality variables. The decision to extend the temporal scope is informed by the operational characteristics of the Pywr-WQ model, which functions on a daily time step. In contrast, flood events are inherently dynamic, with durations ranging from 2 to 72 hours. Attempting to illustrate the hourly variations of these variables during a flood would not align with the model's daily time scale. Hence, presenting data encompassing both pre-flood and post-flood periods is a more suitable means to gain a holistic understanding of how floods impact water quality.

During the flood event, we observed a substantial increase in nutrient levels, specifically nitrate, ammonium, and phosphate. In contrast, the concentrations of salts like sulphate, calcium, and total dissolved solids (TDS) also rose, following an initial decrease, but this increase occurred more slowly. These changed levels can be explained by the loading and movement of these substances through runoff processes, including potential hydraulic erosion.

Table 6-2 presents flood flow data obtained by applying an exceptional flood threshold to the climate change dataset. This application led to the emergence of exceedance events that occurred throughout the simulation period.

Table 6-2 An example of application of flood threshold (exceptional flood) over the climate change dataset within the Grootdraai Dam.

Flood event	Flood flow (m^3/s)	Flood event	Flood thresholds (m^3/s)
13/02/2028	167.00	27/11/2076	142.25
11/02/2044	177.09	01/01/2085	139.875
14/02/2064	162.35	27/01/2099	178.62

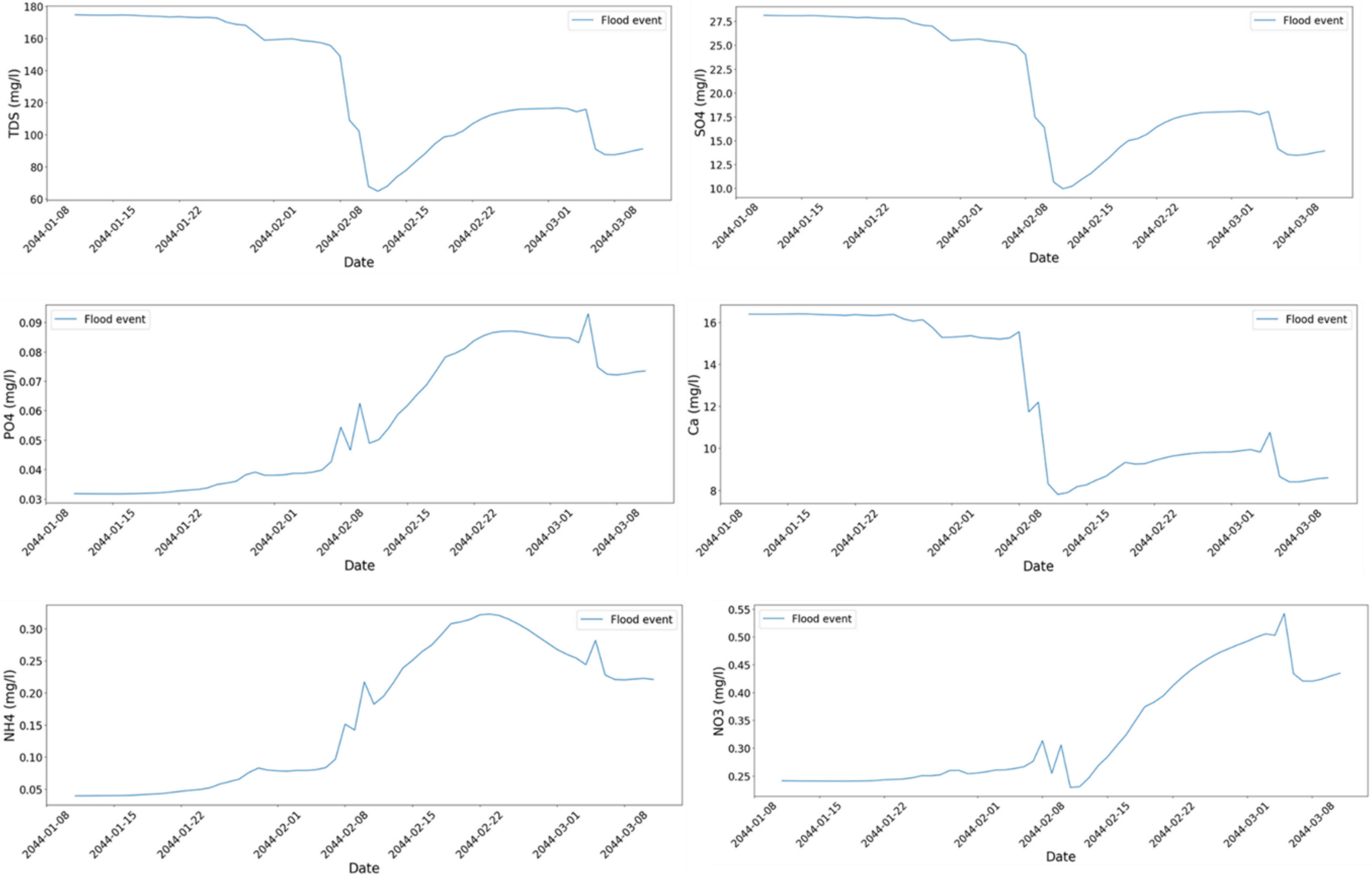


Figure 6-8 Simulation of nutrient and salts during normal (rp = 2 years) flood events in Grootdraai Dam for medium-term.

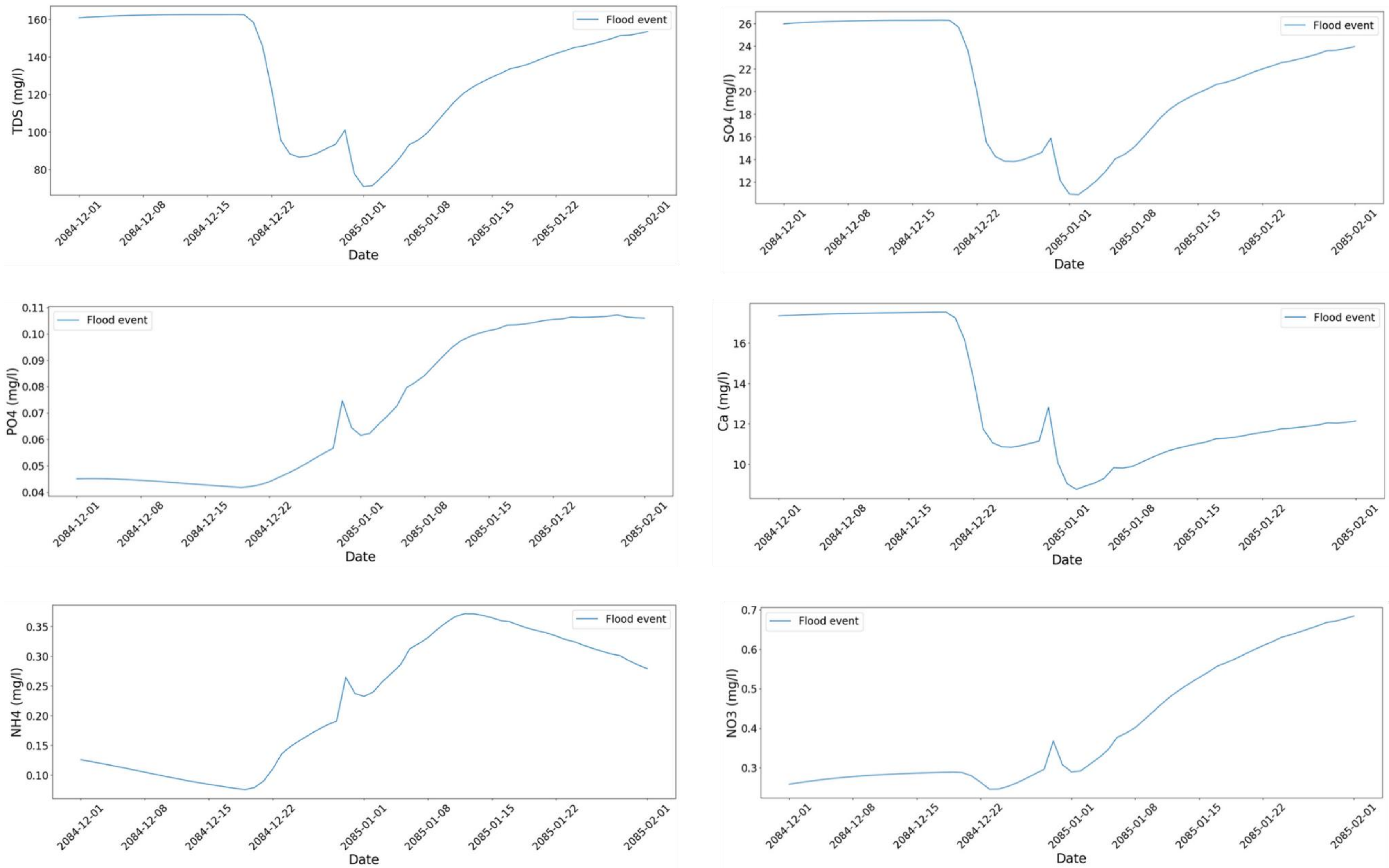


Figure 6-9 Simulation of nutrients and salts during normal (rp = 2 years) flood events in Grootdraai Dam for long-term.

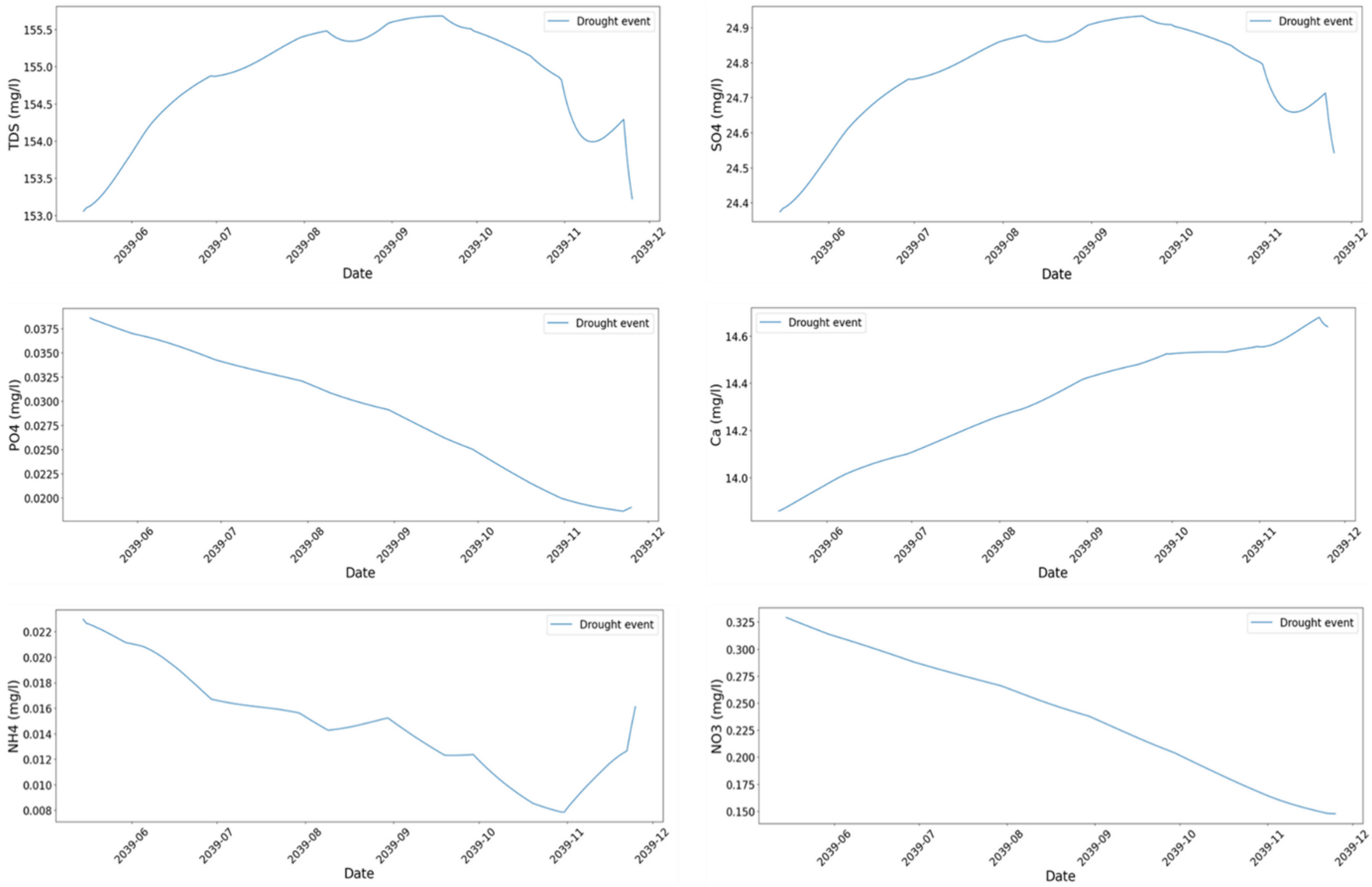


Figure 6-10 Simulation of nutrients and salts levels during drought episodes in Grootdraai Dam in the medium term.

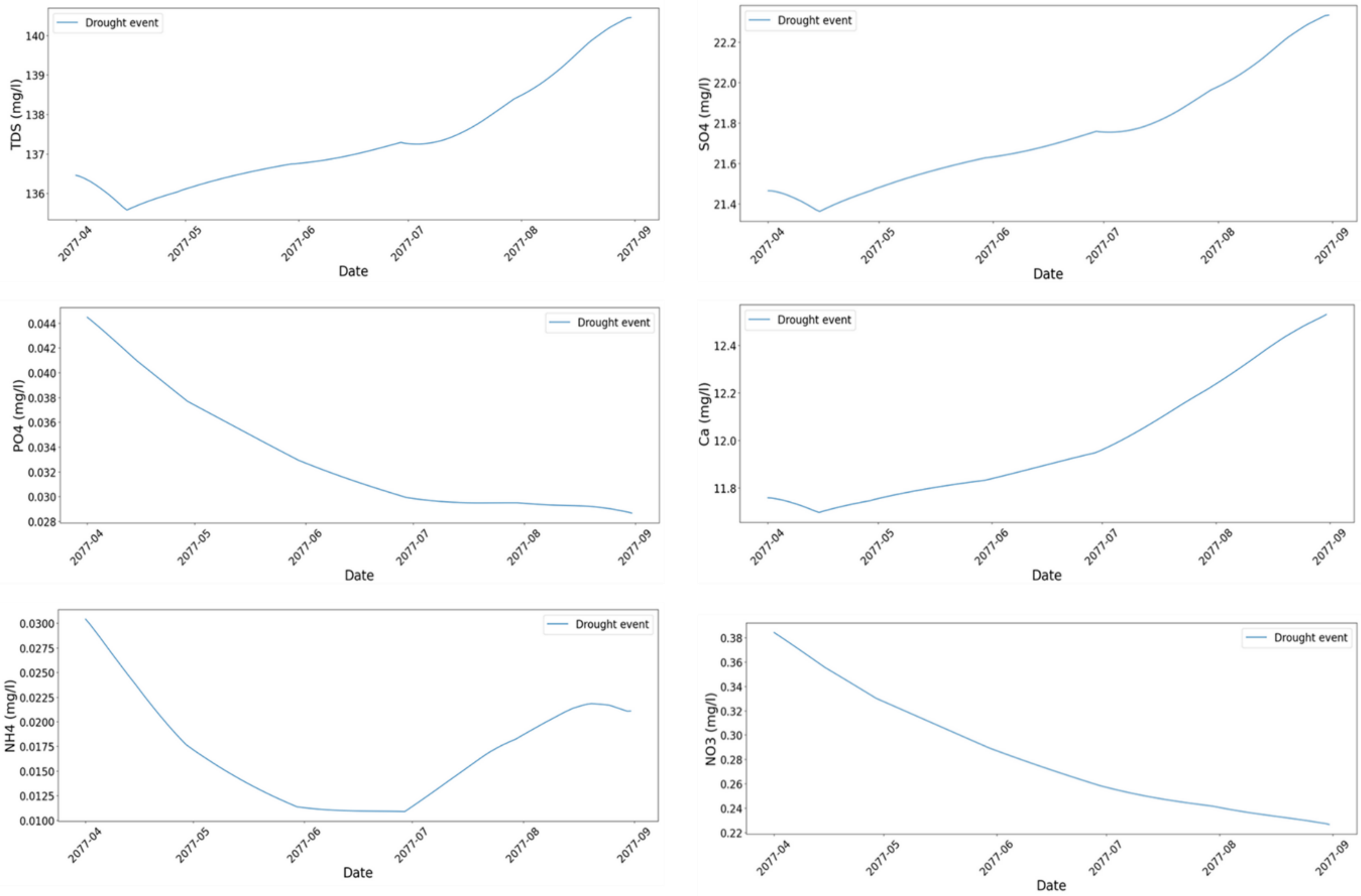


Figure 6-11 Simulation of nutrient and salts levels during drought episodes in Grootdraai Dam in the long-term.

Figure 6-12 showed the flood hydrograph over base time of the flood episodes for different flood thresholds.

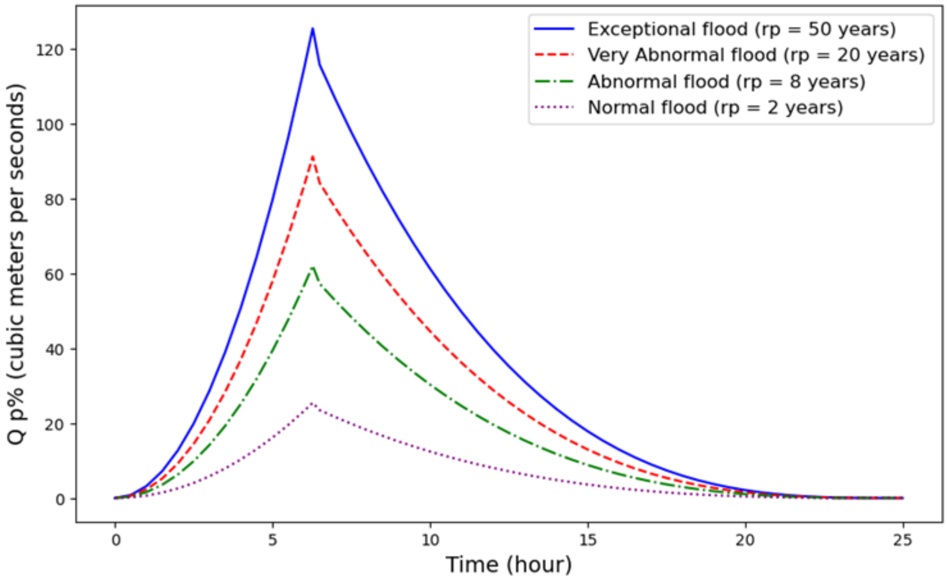


Figure 6-12 Flood hydrograph for different return period characterized with different flood severity during full flood episode (rising and falling) within the Grootdraai Dam.

Figure 6-10 and Figure 6-11 depict how salt and nutrient dynamics unfold during drought episodes in Grootdraai Dam in the medium and long term. To provide a more detailed insight, these figures focus on specific drought periods: one spanning from 01/07/2039 to 05/11/2039 in the medium term, and another from 01/05/2077 to 31/08/2077 in the long term. These chosen dates encapsulate the essence of consecutive drought phenomena, with each spanning a more than 100 day period, specifically 118 and 122 days.

In the medium term, there is a distinct pattern of changes in various water quality parameters during a drought. Salts like total dissolved solids, sulphate, and calcium show a distinct increase in concentrations from the onset of the drought event. This surge culminates in peak values, after which a gradual decline ensues, ultimately leading to the conclusion of the drought event. On the other hand, nutrients such as phosphate, ammonium and nitrate/nitrite decrease, with decreasing runoff playing a crucial role in this phenomenon.

Drought episodes typically result in reduced runoff, which, in turn, affects the mobilization of pollutants from the soil to the river system. In the long-term context, the scenario is characterized by a different set of dynamics. Salts like total dissolved solids, sulphate, and calcium display a gradual increase over time. This rise may be attributed to the dam's reduced capacity to dilute these pollutants during extended drought episodes. Additionally, nutrients like phosphate and nitrate/nitrite follow a pattern of gradual decrease, primarily due to the limited capacity for mobilizing these pollutants via runoff, and possibly biological uptake. However, ammonium has a distinctive trend, featuring three stages of decrease followed by a plateau, and eventually an increase. This phenomenon implies a fluctuation in the dam's capacity to effectively dilute pollutants during prolonged drought episodes, reflecting the complexities of the environmental dynamics at play.

CHAPTER 7: RESULTS: MIXED WATER USE CHANGES

7.1 INTRODUCTION

This chapter assesses the effects on water quality of a realistic, or plausible, mixed use model of future water quality. The model contains ongoing climate change with some mine closure (consequent on reduced coal use for power generation under Eskom's Just Energy Transition programme (Secretariat JETP, 2022)), and anticipated future increases in water use for the Sasol-Secunda coal-to-liquids complex. This approach assesses the impact of reduced dilution capacity, and it also assesses the effect of likely future water use change. Changes in urban water use, or changes in irrigated agriculture could also make up part of this abstraction under this model, if the water is taken from Grootdraai Dam.

The same configuration used for the Pywr-WQ model in a climate change context (discussed in chapter 6) was applied to evaluate the influence of mining closure on water quality in the Grootdraai Dam catchment on future water quality.

Sasol-Secunda is permitted to draw water from Grootdraai Dam only when the reservoir's capacity reaches a threshold of 90%, although this threshold is not always definite (Stone, 2009). Recent communication from Sasol indicates that the new threshold for water abstraction applied by Sasol-Secunda is 75%. There are expectations of increased water demand in the future from Sasol-Secunda (DWS, 2018).

To address this, the configuration file was modified to account for two distinct scenarios, each involving different long-term rates of growth in Sasol-Secunda's water demand, specifically, growth rates of 5% and 70%. The rationale for selecting these increase rates is to mirror a highly probable increase rate in water abstraction represented by a 5% increase, and a significantly less likely occurrence of a 70% increase rate in abstraction from Grootdraai Dam. The model setup remained consistent with the climate condition scenario, utilizing the climate change flow dataset and the same calibrated parameters for certain quaternary catchments. The mining closure scenario was also examined within the selected highly impacted quaternary catchments (C11A, C11B, C11F, C11K), with a focus on evaluating key water quality parameters such as total dissolved solids, sulphate, and calcium, all of which are of particular significance in mining regions. The adjustments made to the non-point source nodes were limited to the selected quaternary catchments due to their concentration of mining activities. Non-point source nodes in the remaining quaternary catchments retained their original values from the calibrated configuration file. Changes were only made to the non-point source nodes' signatures in the specified quaternary catchments to reflect the closure of mining activities.

This approach involved revisiting the calibrated parameters for surface flow (SF salts), interflow (IF salts), and groundwater flow (GWF salts). The quaternary catchments with the lowest signatures for total dissolved solids, sulphate, and calcium were identified, and their respective water quality signatures were then applied to the quaternary catchments under consideration (C11A, C11B, C11F, and C11K). The modelling process is illustrated in Figure 7-1.

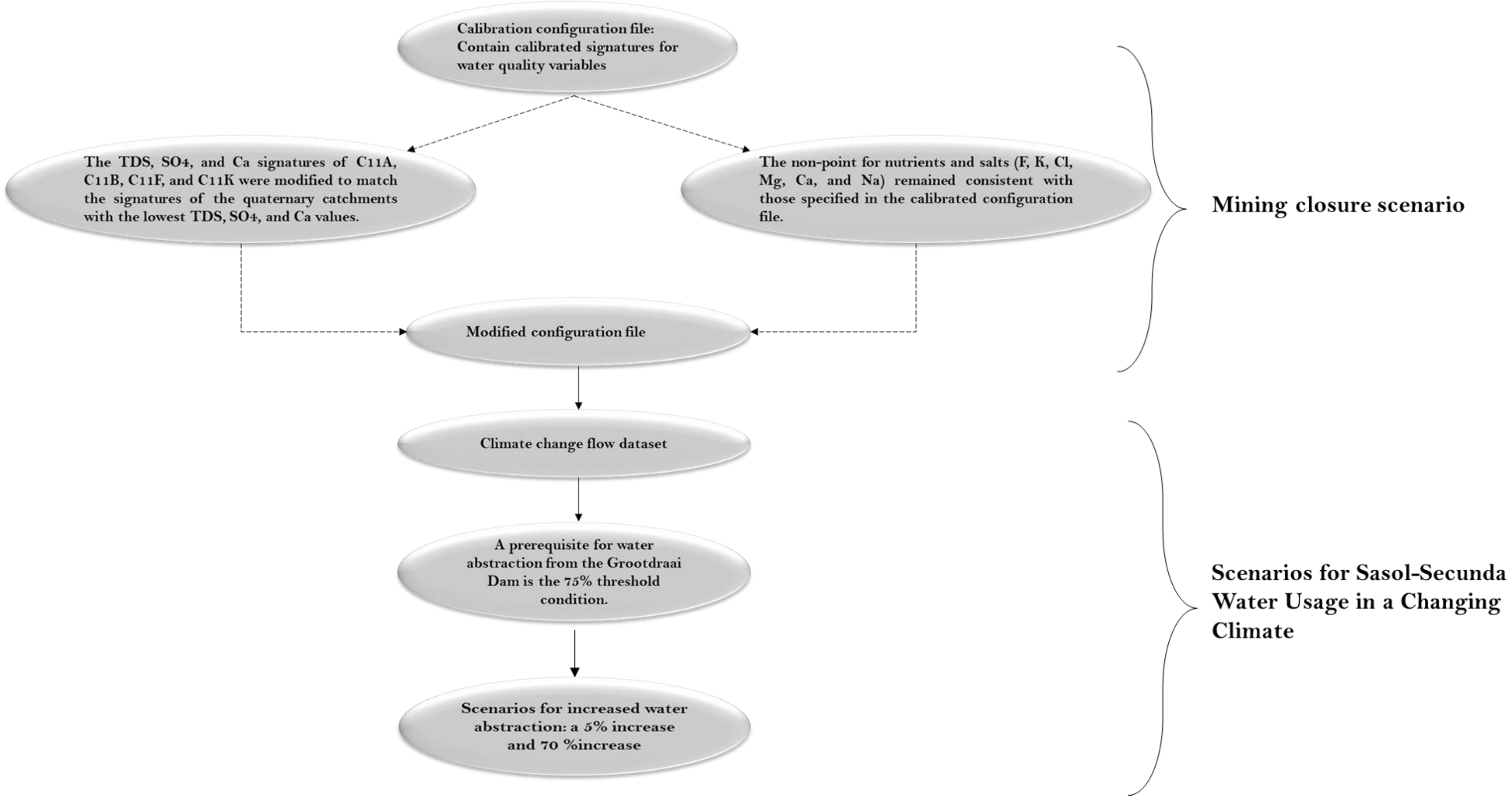


Figure 7-1 Modelling process under climate change scenario, mining closure, and water abstraction increase scenarios by Sasol-Secunda and other water users for water quality at the Grootdraai Dam.

7.2 SASOL-SECUNDA ABSTRACTION

Figure 7-2 illustrates water abstraction from Grootdraai Dam under the 75% capacity threshold. This figure demonstrates that if the capacity of the Grootdraai Dam falls below 75% of its full capacity, there will be no water abstraction by Sasol-Secunda. Conversely, when the dam's capacity exceeds 75% of its full capacity, Sasol-Secunda will have the capability to extract water to meet its demand from the Grootdraai Dam.

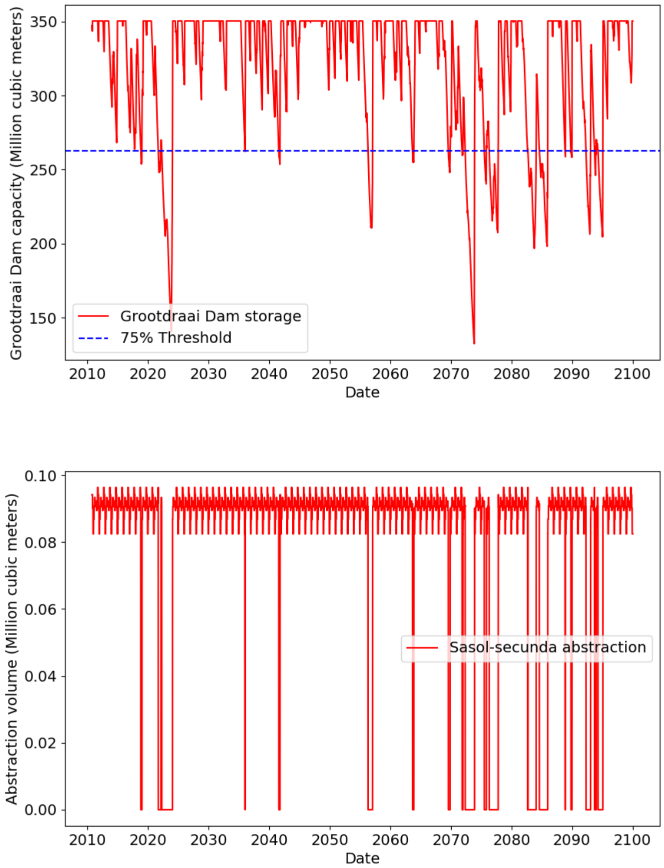


Figure 7-2 Sasol-Secunda abstraction volumes, contingent on adherence to the 75% operating rule. According to this rule, abstraction occurs when the dam's capacity reaches or exceeds 75% of its full capacity. If the storage falls below 262.5 Mm^3, abstraction resumes, exhibiting varying volumes depending on the abstraction.

Figure 7-3 depicts two distinct increased abstraction scenarios at the Grootdraai Dam. One represents an increase abstraction of 5%, and the other represents increased abstraction of 70% over the long term. Figure 7-3 illustrates the abstracted volume under these applied scenarios.

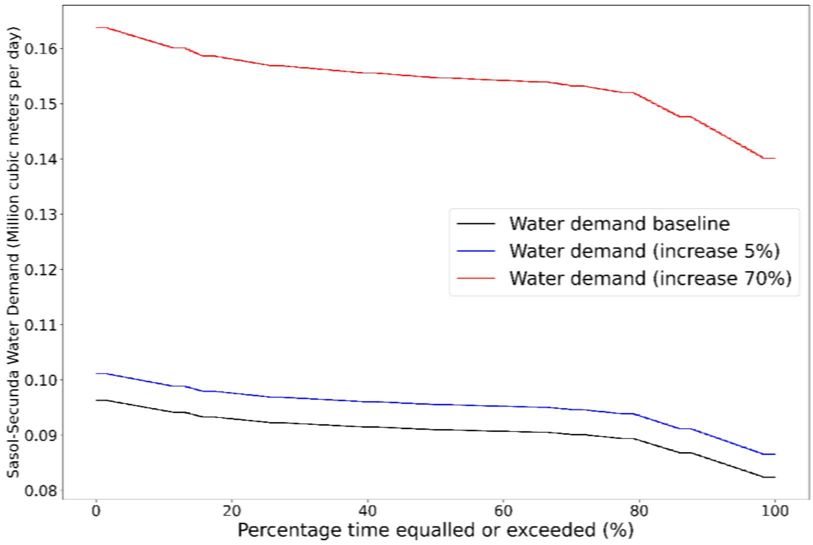


Figure 7-3 Sasol-Secunda water demand shown as frequency distributions across varied abstraction rates of 5% and 70%.

7.3 WATER QUALITY PARAMETERS UNDER MINING CLOSURE

Table 7-1 shows the water quality signatures given for each inflow node located with the selected quaternary catchments C11A, C11B, C11F and C11K, respectively.

Table 7-1 Non-point source salt signatures for each flow component (surface flow SF, interflow IF and groundwater GF). Units are mg/l.

	TDS			Sulphate			Calcium		
Node	SF	IF	GF	SF	IF	GF	SF	IF	GF
Inflow 1	13	50	279	8	11.2	18.7	4	7.5	13
Inflow 2	13	50	279	8	11.2	18.7	4	7.5	13
Inflow 3	13	50	279	8	11.2	18.7	4	7.5	13
Inflow 10	13	50	279	8	11.2	18.7	4	7.5	13

The quality signatures for the selected quaternary catchments that are highly impacted by mining match the signatures of the lowest impacted quaternary catchment within the Grootdraai Dam catchment.

7.4 WATER USE INCREASE SCENARIOS

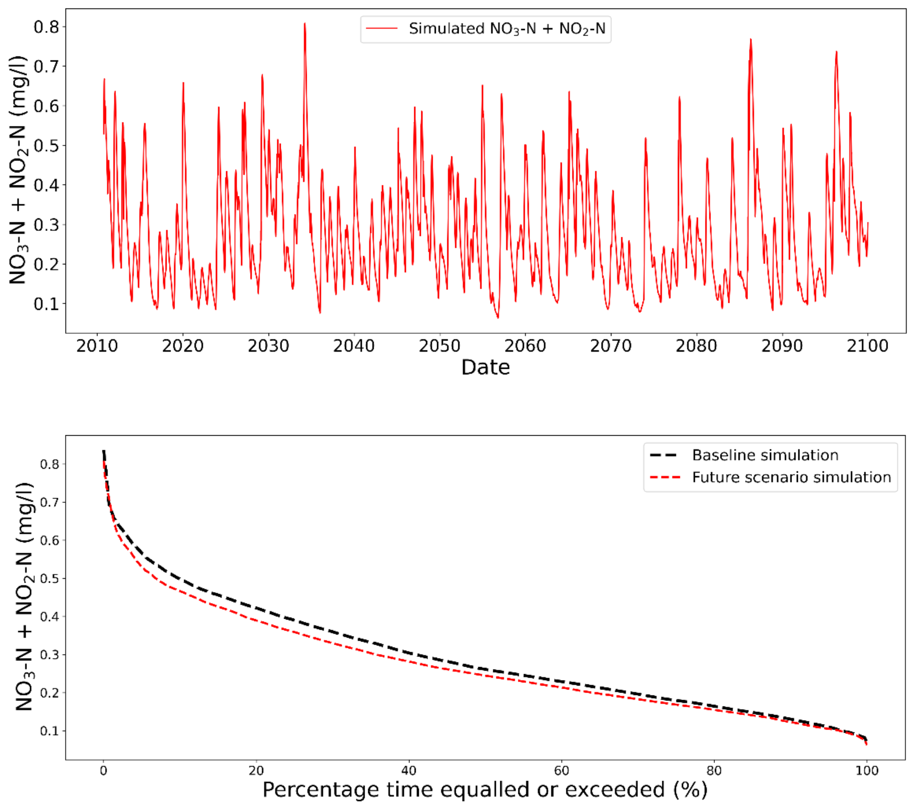


Figure 7-4 The daily variation of nitrate/nitrite over the long term is depicted in the future scenario simulation, presented as a time series distribution over long-term (2010-99). A comparison between the future scenarios simulation and baseline simulation is illustrated through frequency distributions for the Grootdraai Dam. The applied 5% and 70% increase in water abstraction under changing climate and mines closure yielded identical output referred to as future scenario simulation.

Figure 7-4 presents the daily variation of nitrate/nitrite levels over the long term within the Grootdraai Dam. It displays the time series distribution and compares future scenario simulations with baseline simulations using frequency distributions. Interestingly, simulations under scenarios mines closure, climate change and 5% or 70% increase in water abstraction yielded identical outputs, indicating no variation in nitrate/nitrite levels between the two simulations. It is also of note that the predicted changes show a decrease in nitrate/nitrite compared to baseline data. Climate change was found to indicate a decrease in nitrate/nitrite on its own.

Figure 7-5 presents the daily variation of ammonium levels over the long term within the Grootdraai Dam. It displays the time series distribution and compares future scenario simulations with baseline simulations using frequency distributions. Interestingly, simulations under scenarios with mines closure, climate change and 5% or 70% increase in water abstraction yielded identical outputs, in the same way as was observed for nitrate/nitrite. The same observations as to decreased levels of this nutrient apply-climate change alone is able to account for the change.

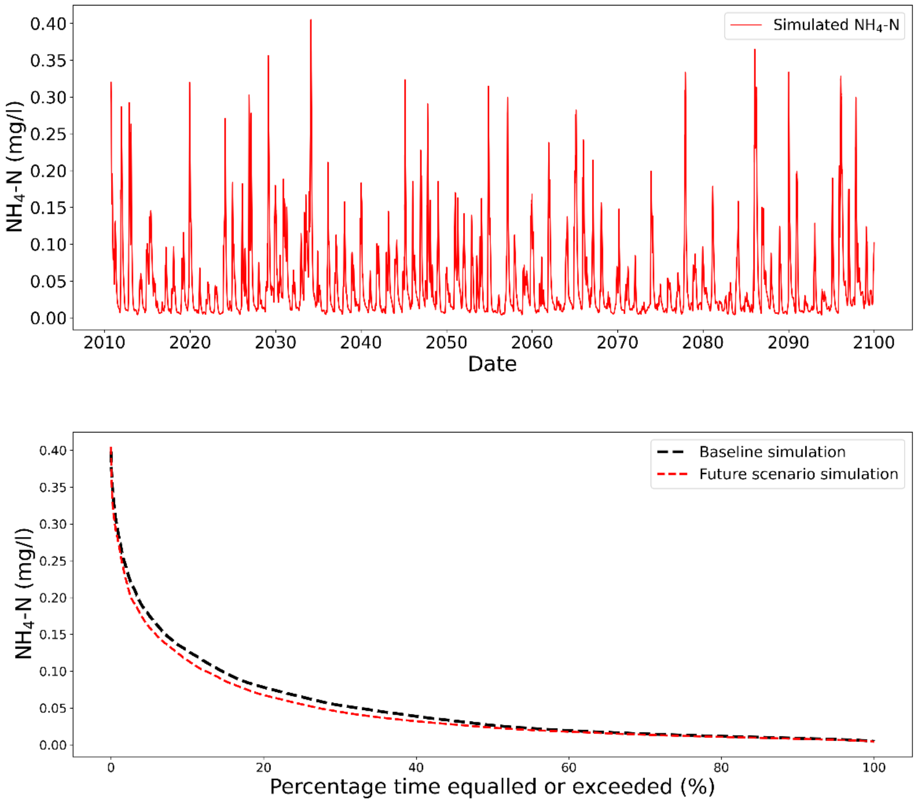
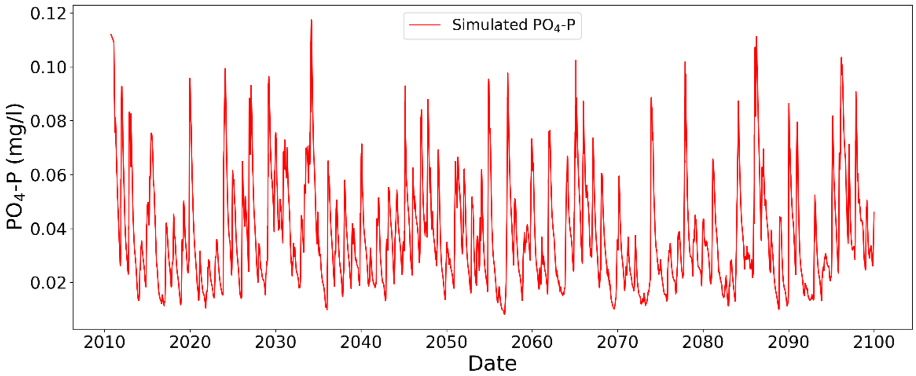


Figure 7-5 The daily variation of ammonium over the long term is depicted in the future scenario simulation, presented as a time series distribution over long-term (2010-99). A comparison between the future scenarios simulation and baseline simulation is illustrated through frequency distributions for the Grootdraai Dam. The applied 5% and 70% increase in water abstraction under changing climate and mines closure yielded identical outputs.

Figure 7 6 presents the daily variation of phosphate levels over the long term within the Grootdraai Dam. It displays the time series distribution and compares future scenario simulations with baseline simulations using frequency distributions. Interestingly, simulations of mines closure, climate change and 5% to 70% increase in water abstraction yielded identical outputs, indicating no variation in phosphate levels between the two simulations. Like the other nutrients assessed in this chapter, the outcome of all scenarios is a decrease in phosphate levels. As climate change predicts this outcome alone, it may be function of changing future flows alone. Nevertheless, even increasing abstraction by 70% in this scenario does not outweigh the effects of other scenario components, and water quality is improved.



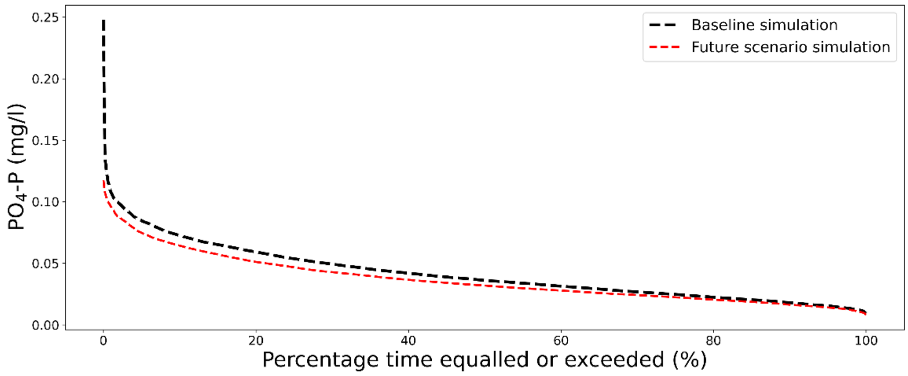


Figure 7-6 The daily variation of phosphate over the long term is depicted in the mixed use simulation, presented as a time series distribution over long-term (2010-99). A comparison between the future scenarios simulation and baseline simulation is illustrated through frequency distributions for the Grootdraai Dam. The applied 5% and 70% increase in water abstraction under changing climate and mines closure yielded identical output referred to as future scenario simulation.

Figure 7-7 shows the frequency distribution of changes in the mining-linked water quality parameters dissolved solids, sulphate and calcium in the future mixed use simulation under a 5% increase in abstraction. Figure 7-8 shows the same set of water quality parameters for the mixed use scenario with a 70% increase in abstraction. Like the nutrient simulations presented above, there is little difference between the two abstraction scenarios- that is to say, within the range of parameters assessed here, the degree of abstraction of water from Grootdraai Dam had little impact on the water quality in the dam. Dilution was not, within the ranges of parameters assessed, a significant means of water quality maintenance in Grootdraai Dam.

The other significant observation from these figures relates to the response of the three identified mining-associated water quality parameters to the mixed use scenarios. Although, as noted, the effects of different abstraction rates was limited, a comparison with the baseline establishes a significant increase in water quality after climate change and a cessation of mining. Modelled climate change had little impact on calcium, and caused a small increase in TDS. Climate change did result in a decrease in sulphate levels, but not to the extent observed in Figure 7-7 and Figure 7-8. The conclusion is therefore that closure of mines resulted in a decrease in salinity, sulphate and calcium, largely driven by mining related water quality parameters. This forces one to acknowledge that one method of addressing catchment water quality issues is to remove drainage water from coal mines from circulation, or to treat mine water is a manner that does not allow for increased sulphate and calcium levels.

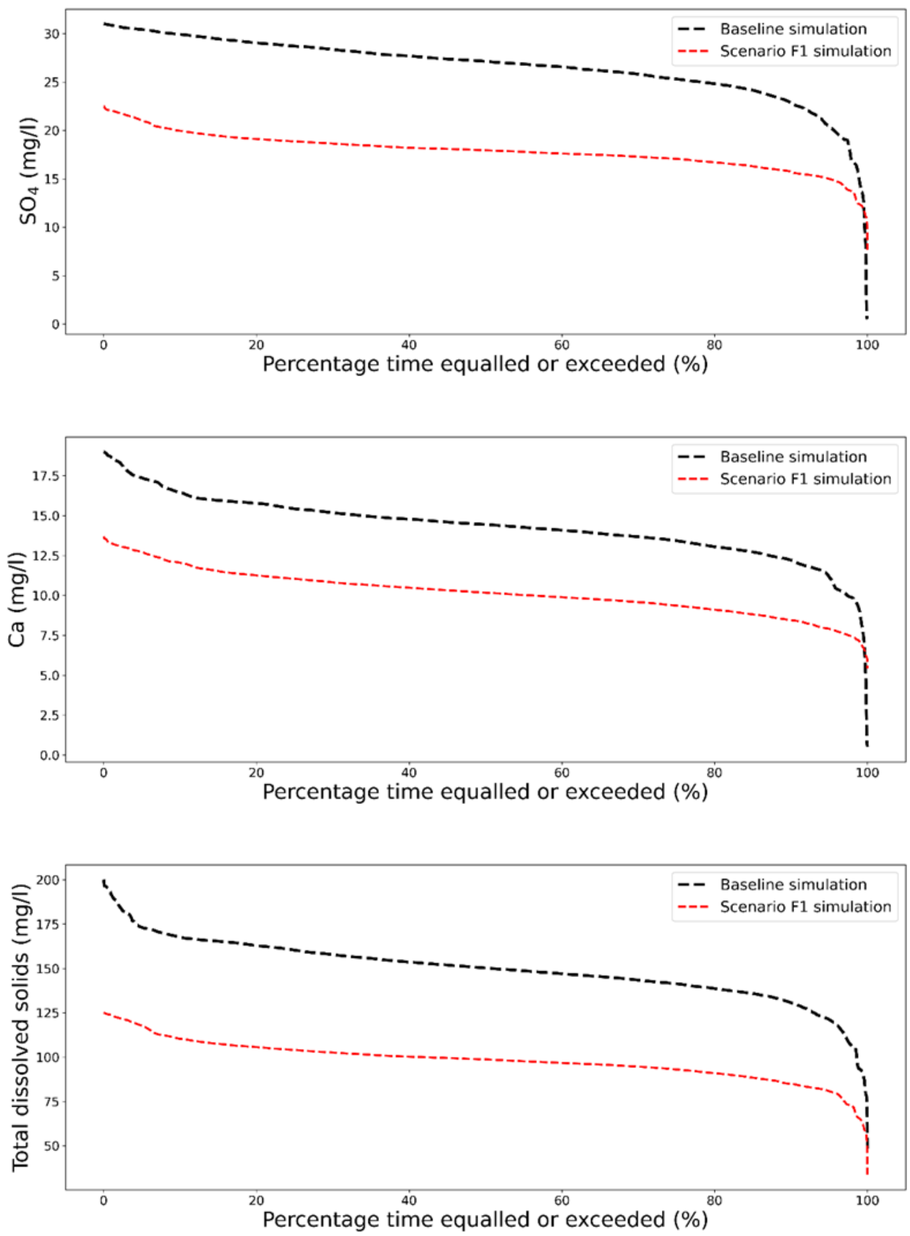


Figure 7-7 A comparison between frequency distributions of mining-related indicators after simulation of an increase of 5% in water abstraction, mines closure, and changing climate and baseline simulation at the Grootdraai Dam over the long-term (2010-99).

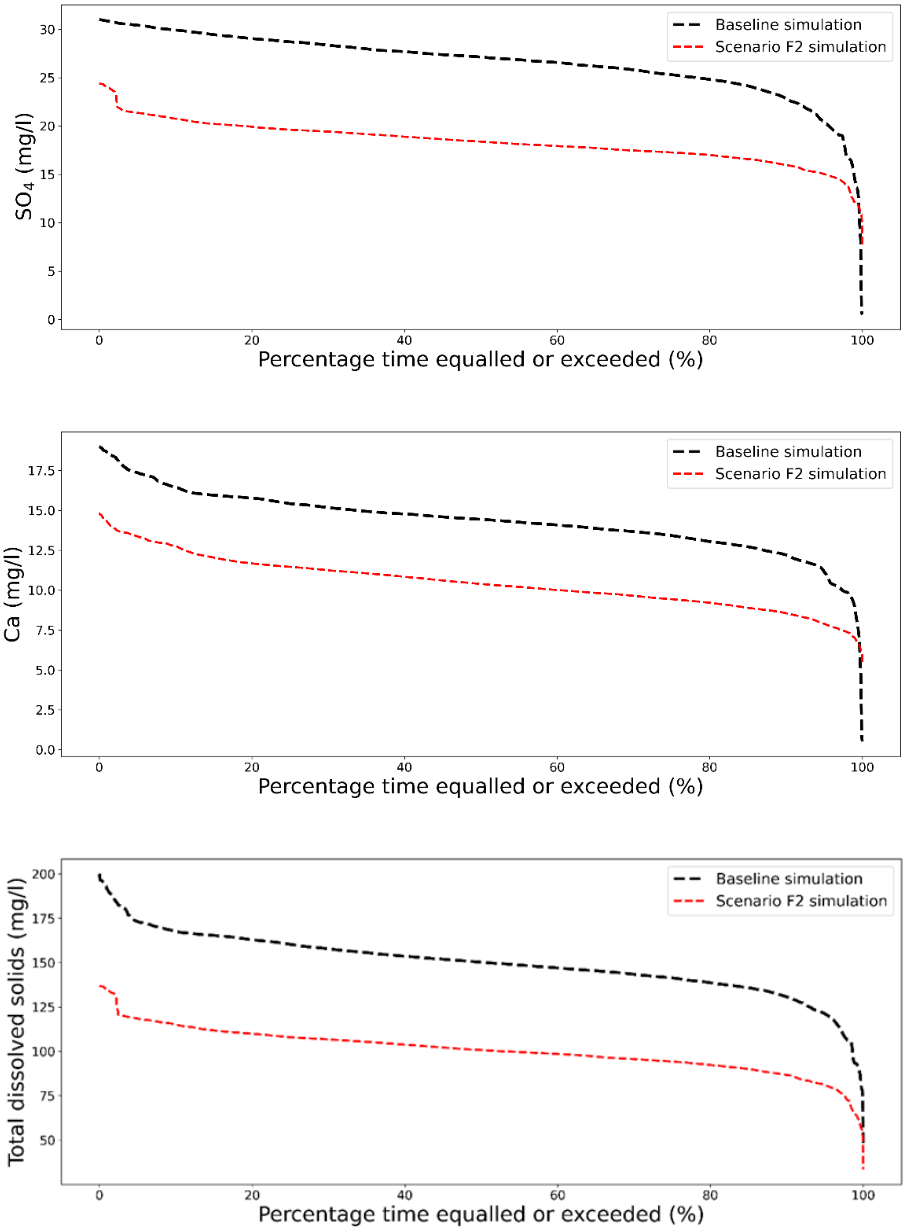


Figure 7-8 A comparison between frequency distributions of mining-related indicators after simulation of an increase of 70% in water abstraction, mines closure, and changing climate and baseline simulation at the Grootdraai Dam over the long-term (2010-99).

Cessation of mining was included in the model largely by limiting known mining impacts (salinity, sulphate, and calcium) in the model. It is therefore not a surprise that these show a clear response to the mixed use scenarios. Other ions were also modelled in the simulations. The responses of these, as with nutrients, is more of a simulation of their response to climate change and abstraction scenarios.

Figure 7-9 shows the response of sodium, potassium and fluoride ions to largely climate change and several abstraction scenarios. All show a slight increase in the future, much as they do under a pure climate change scenario. As was found for other mixed use scenarios, the difference in future water quality levels between a 5% and 70% abstraction growth scenario was, from the viewpoint of these water quality parameters, not distinguishable.

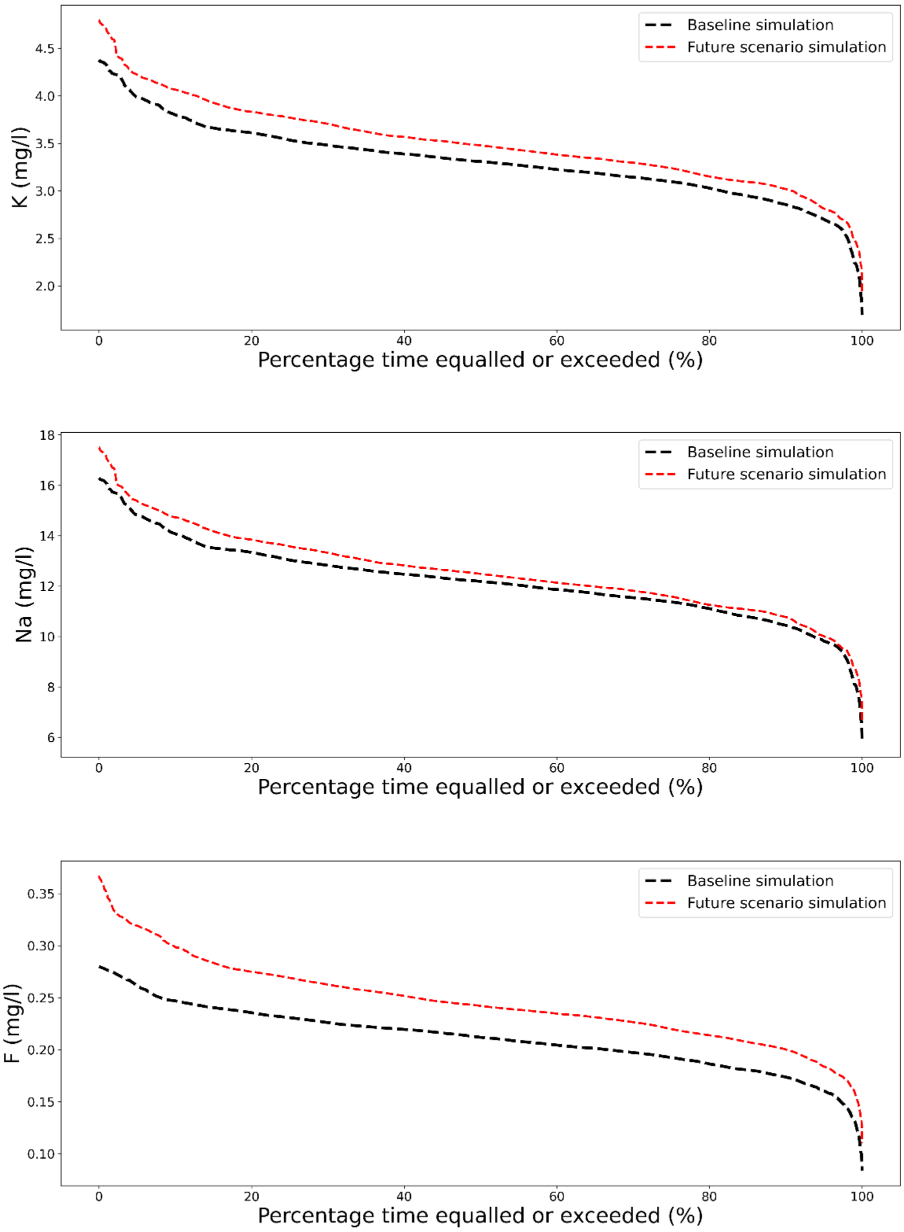


Figure 7-9 A comparison between the mixed use scenario's simulation and baseline simulation is illustrated through frequency distributions for the Grootdraai Dam for potassium, sodium, and fluoride. The applied 5% and 70% increase in water abstraction under changing climate and mines closure yielded identical output referred to as future scenario simulation.

Figure 7-10 shows the changes in magnesium and chloride under mixed use scenarios compared with baseline levels. In both cases the mixed use scenarios show improved water quality compared to the baseline, and in both cases these largely reflect the changes anticipated under climate change. Again, in both the difference in abstraction scenarios are not perceptible, and within the ranges assessed, abstraction from Grootdraai Dam seems to have had no effect on water quality.

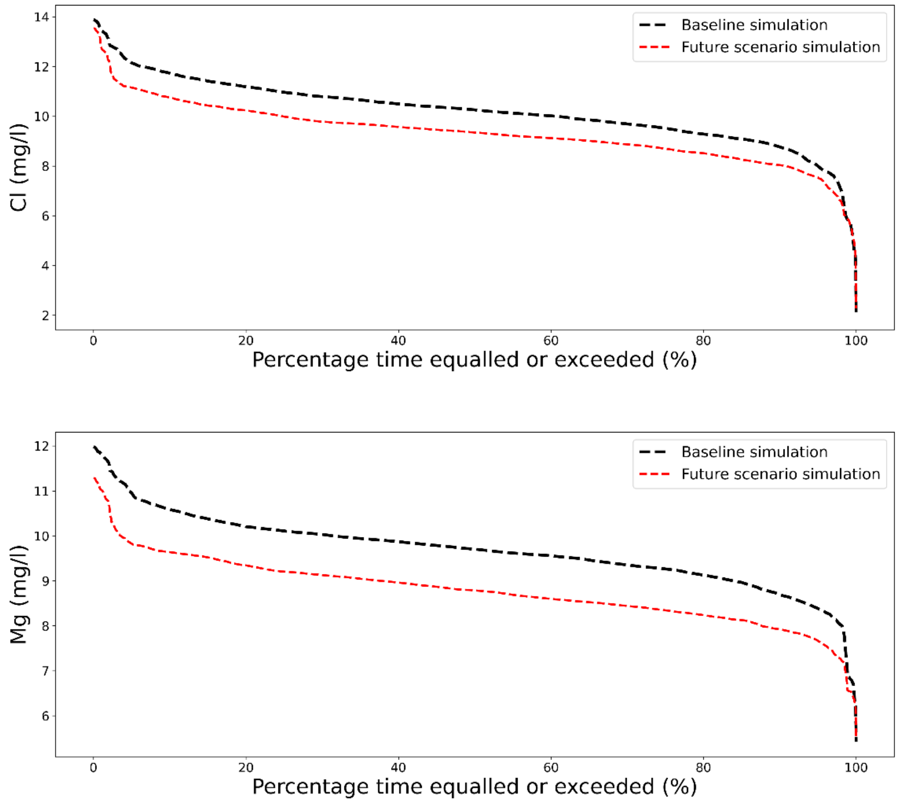


Figure 7-10 A comparison between the mixed use scenarios simulation and baseline simulation is illustrated through frequency distributions for the Grootdraai Dam for chloride and magnesium. The applied 5% and 70% increase in water abstraction yielded identical outputs.

Overall, the combined results of the mixed use scenarios have a number of valuable outcomes for management of the catchment. Firstly, the majority of simulations reflect the anticipated outcome of climate change. While this varies between elements, in general a relatively small change is expected, and, in many cases, change due to climate change in the absence of other impacts can improve water quality. Secondly, in all cases, the difference between a 5% and a 70% increase in abstraction has an imperceptible effect on water quality, and it appear that within the ranges tested that abstraction from Grootdraai Dam has no perceptible impact on water quality. The third major conclusion is that control of water from mines has major implications for catchment and dam salinity. This is the largest of the anticipated changes, and can potentially lead to large improvements in salinity. It is important though that mine water be managed correctly. Treating mine water with lime, which is common in South Africa (McCarthy, 2011), raises the pH, but does not appreciably impact the sulphate, and adds calcium with the calcium oxides and hydroxides that make up the lime (Akcil and Koldas, 2006). Using liming to treat mine water contributes to salinity, and it is important that the added salinity associated with mine water and limed mine water be isolated from the catchment. It is likewise important that mine water be isolated from seeping into the groundwater or interflow fraction.

CHAPTER 8: RESULTS: SHORT TERM OUTCOMES

8.1 INTRODUCTION

The modelling time frames that have been presented here have been medium to long term. This facilitates distinguishing between model results and makes the eventual trend clear. However, such broad time frames may obscure what the shorter term implications of the results presented here. This chapter contains model predictions for 5, 10, and 20 year time frames after modelling start (Table 8-1). Predictions are grouped according to whether they refer to major plant nutrients or to salts. Data are presented classified according to Rand Water's (2020) classification scheme as this classified more compounds than current RQOs for this site did (DWS, 2016.).

8.2 NUTRIENTS

Increased mining results in nitrate/nitrate concentrations trended from tolerable levels towards increasingly acceptable in Grootdraai Dam. Conversely, increased urban land results in a persistent challenge, with nitrate/nitrite concentrations remaining largely unacceptable over the next 5 to 20 years. Increased cultivated land results in Grootdraai Dam water being poised for a gradual shift towards improved conditions. Climate change introduces a distinctive pattern, where a substantial decline in unacceptable nitrate/nitrite levels is anticipated, accompanied by an increase in acceptability and tolerability. The mixed use scenario results in a relatively stable state in Grootdraai Dam nitrate/nitrite levels, with a consistent balance between acceptable, tolerable, and unacceptable nitrate/nitrite levels.

Mining increases imply improved ammonium levels, with an initial high percentage of compliance and an improvement over the coming years. Urban increase results in a relatively stable distribution, maintaining a balance between acceptable and ideal water quality classifications. Cultivated areas Increase displays a trend indicating a gradual increase in compliance percentages. Climate change results in a balance between ideal and acceptable classes. Lastly, the mixed use scenario results in fluctuations between ideal and acceptable classifications at Grootdraai Dam.

Mining land increases result in slight improvement in phosphate at Grootdraai Dam, as more samples are classified as ideal in this scenario. Urban land increases maintain a balanced range between ideal and acceptable classifications. Cultivated land improves phosphate levels slightly in the medium term. Climate change results in a slight shift in phosphate samples from ideal to acceptable. Finally, the mixed use scenario has phosphate compliance percentages oscillating between ideal and acceptable.

8.3 SALTS

The mining land increase scenario leads to salinization of water, both from a TDS and sulphate point of view. Increased urban land leads to changes in water classification, though no clear trend from a short to medium term view point. The climate change model in the shorter term does not change water quality from acceptable. Finally, in the short to medium term, the mixed effects model sees salinity and sulphate levels fluctuating between ideal and acceptable.

Table 8-1 Classification of modelled data from 5, 10, and 20 years after modelling began as a percentage of data. Data are classified using Rand Water's (2020) scheme for this catchment as this provides classes for more paramaters than RQO (DWS, 2016). Only classified data are presented. Blue is ideal, green acceptable, yellow tolerable, and red intolerable.

Node description	Years	Nitrate/nitrite (NO_3 + NO_2-N)			Ammonium (NH_4 - N)		Phosphate (PO_4 - P)		Salinity (TDS)		Sulphate (SO_4)		
Grootdraai_Dam Node	Mining increase												
	5	18.2	44.4	37.4	32.2	67.8	46.1	53.9	27.5	72.5	38.3	56.8	4.9
	10	34.4	42.7	22.9	43.1	56.9	41.6	58.4	14.4	85.6	67.3	29.9	2.5
	20	39.3	39.6	21.1	40.7	59.4	36.7	63.3	8.7	91.3	71.3	27.4	1.3
	Urban increase												
	5	13.7	41.1	45.2	31.7	68.3	48.8	51.2	78	22	20.6	73.8	5.6
	10	28.5	42.3	29.2	42.4	57.6	45.3	54.7	85.2	14.8	22.1	75	2.9
	20	33.07	38.4	28.5	40	60	43.1	56.9	89.6	10.4	17.9	80.6	1.5
	Cultivated land increase												
	5	17.1	44.3	38.6	32.4	67.6	50.1	49.9					
	10	33.3	42.9	23.8	43.5	56.5	46.7	53.3					
	20	38.4	39.8	22	41	59	43.5	56.5					
	Climate change												
	5	9.7	65.3	25	42.1	57.9	17.6	82.4					
	10	14	49.5	37	57.8	42.2	27.2	72.8	100		100		
	20	9.9	43.1	47	59.2	40.8	26.2	73.8					
	Mixed use scenario with 70% abstraction increase												
	5	8	26	66	40.8	59.2	84.3	15.7	75.9	24.1	100		
	10	12	38	50	57	43	74	26	44.9	55.1	91.7		8.3
	20	10	43	47	41.1	58.9	74.5	25.5	47	53	95.2		4.8

CHAPTER 9: DSS USER MANUAL

9.1 A BRIEF OVERVIEW OF THE LINK BETWEEN PYWR, SPATSIM, WQSAM AND THE DSS

This section aims to provide a simplified explanation of the connection between the Decision Support System (DSS), the Python water resources (Pywr) model, SPATSIM, and the Water Quality Systems Assessment Model (WQSAM). The Pywr model simulates the flow in the Grootdraai Dam catchment, incorporating monthly incremental flow generated by a hydrology model (i.e. the Pitman model). This natural flow is then disaggregated to monthly timestep following the approach detailed by Slaughter et al. (2015). During the conversion it is converted from m^3/s to Mm^3/day. It is then integrated into the Pywr model at incremental flow nodes marked with "Inflow_" in Figure 9-1.

The Pywr model, with data on daily abstractions, return flows, and reservoir operations, enables the simulation of daily flow. The generated flows are fed into SPATSIM, which also features 'Nodes' mirroring the system structure of the Pywr model (refer to Figure 4 and Figure 5). These Nodes have attributes corresponding to Pywr model flows, such as daily estimates of return flows, abstractions, reservoir releases, storages, and inflow flows. Examining the list of nodes in the water quality modelling screen of the DSS (Figure 11) demonstrates this distributed structure.

WQSAM reads the Node attributes from SPATSIM, requiring additional attributes related to daily flows and water quality. Under the Node feature in SPATSIM, various attributes pertain to daily flows, daily reservoirs storages, daily reservoir releases, water quality parameters, observed water quality, and simulated water quality. Essentially, SPATSIM acts as a central repository, facilitating data exchange between WQSAM, the DSS, and the Python water resources (Pywr) model.

The “Inflow_” nodes are essentially nodes that receive incremental “natural” flow. The model user can only change non-point inputs of water quality loads at these nodes. In this project, it is recommended that model user should not change any of the calibrated parameters for the “Inflow_” nodes.

The "DD" nodes serve as dummy dam nodes, consolidating various distributed water storages in a quaternary catchment into a single "dummy dam" for simplicity. Another type of node, often labelled with the prefix "Link_", denotes links within the quaternary catchments and positions where mostly observed data are available for comparing model simulations to actual water quality data. These nodes may also encompass points of wastewater discharge, directly associated with Resources Quality Objectives (RQOs). The fourth type of node signifies dams, with one dam situated at the catchment level, specifically the Grootdraai Dam.

Emphasizing the flow directionality of the Grootdraai Dam System in the Decision Support System (DSS), Figure 9-1 illustrates the flow direction via arrows connecting the nodes.

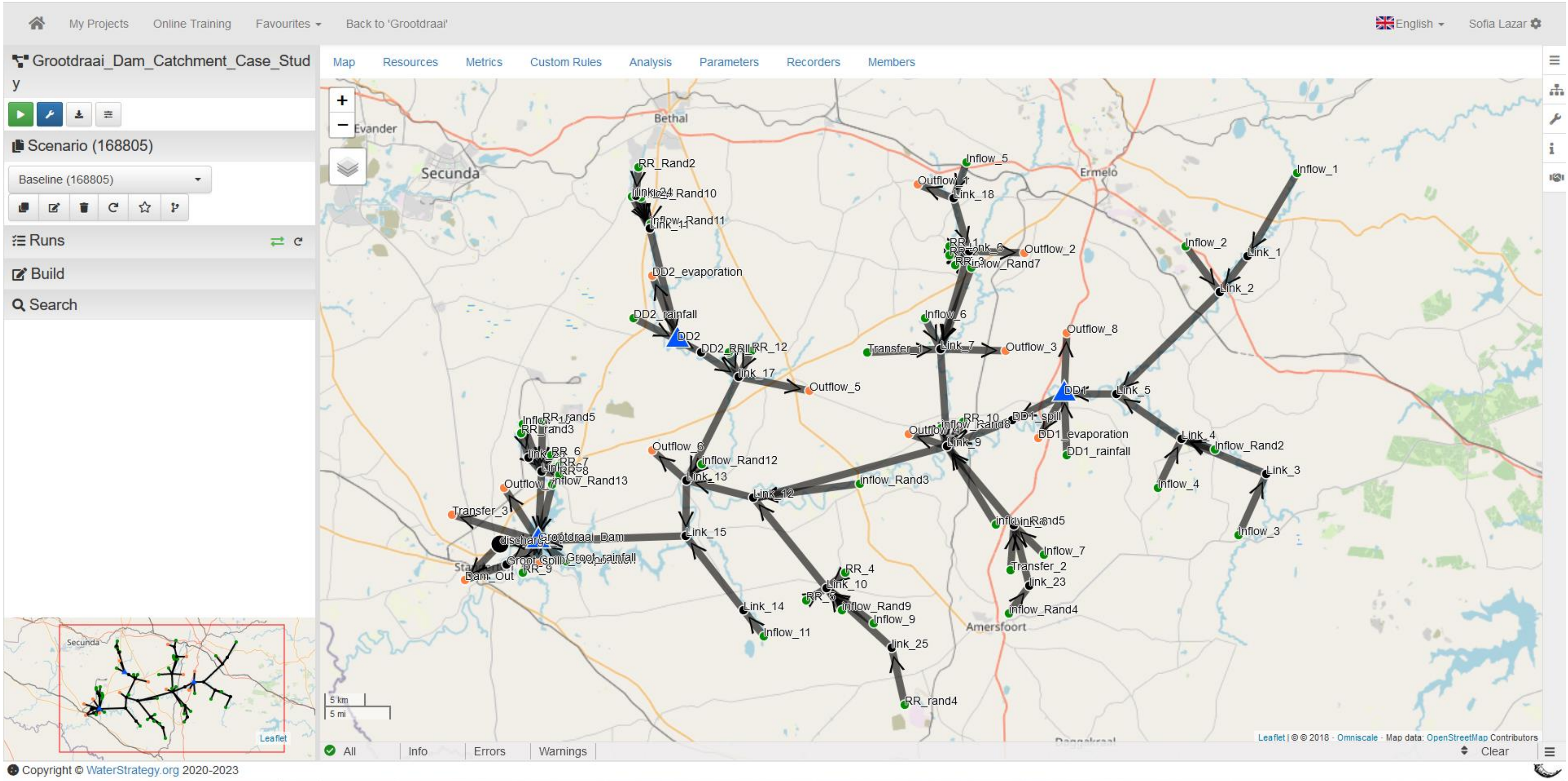


Figure 9-1 Systems diagram of the Grootdraai Dam catchment showing modelled nodes within WaterStrategy.org environment.

9.2 OPENING INVESTIGATED SCENARIOS APPLICATION IN SPATSIM

Upon installing SPATSIM through this link <https://www.ru.ac.za/iwr/research/software/spatsim/>, an icon, as illustrated in Figure 9-2, will be visible on user's computer desktop.

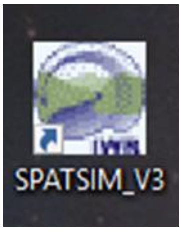


Figure 9-2 SPATSIM icon on computer desktop.

The SPATSIM launch screen, depicted in Figure 9-3, will be displayed. To execute SPATSIM with the designated scenario application, select the desired option and click the 'Select' button. It's worth noting that the scenarios explored in this project can be found under "Grootdraai_XX_scenario", where "XX" varies depending on the specific scenario, such as increase in mining (+0.015%), urban (+0.05%), cultivated (+0.3%) areas and climate change, and Future3 (climate change + Sasol-Secunda abstraction 70% + mining closure).

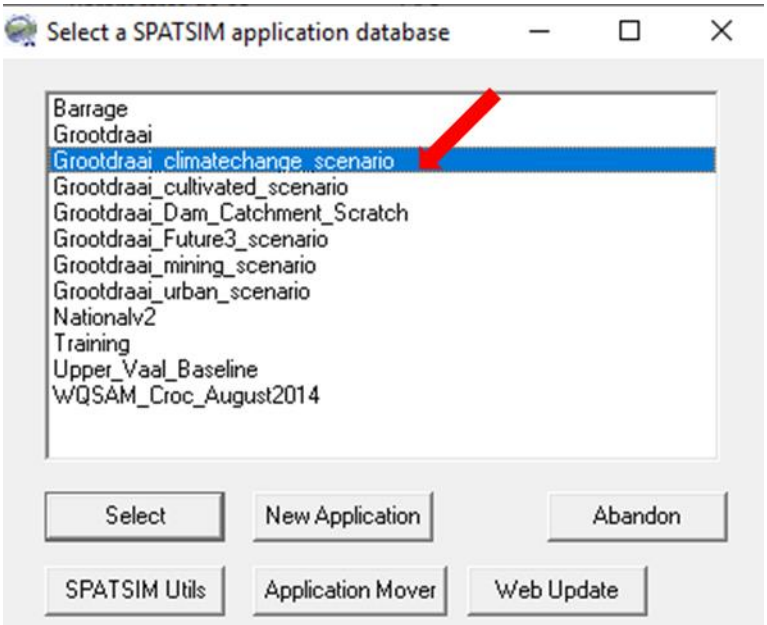


Figure 9-3 SPATSIM launch screen displays the available applications. To initiate the scenarios application, select "Grootdraai_XX_scenario", where "XX" corresponds to the different investigated scenarios, and then click the 'Select' button.

Upon opening SPATSIM, the selected scenario application will be displayed, as illustrated in Figure 9-4. The main screen exhibits geographic features associated with shape files, presented in the top left-hand box. The chosen scenario application comes preloaded with added features. Various features, such as the 'Node' feature, may possess multiple attributes crucial for simulating the water quality of the scenario, as detailed in the left-hand lower box. Figure 9-5 showcases the user's ability to toggle labels for different features, adjust their size, zoom in and out, and pan to different areas.

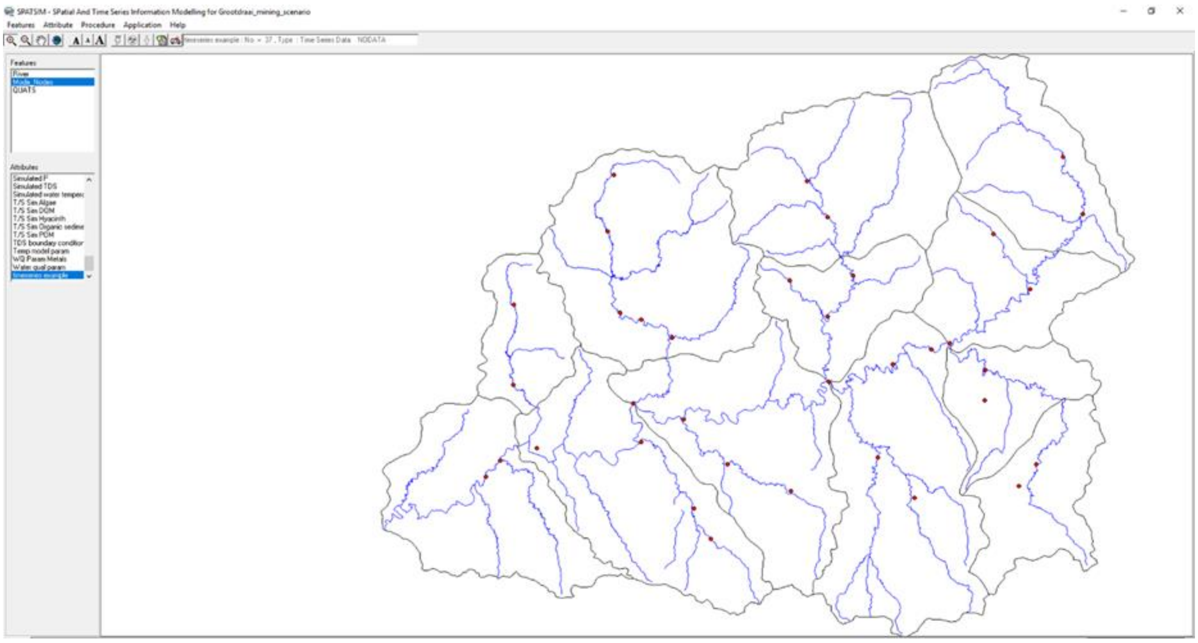


Figure 9-4 SPATSIM application showing the Grootdraai chosen scenario application.

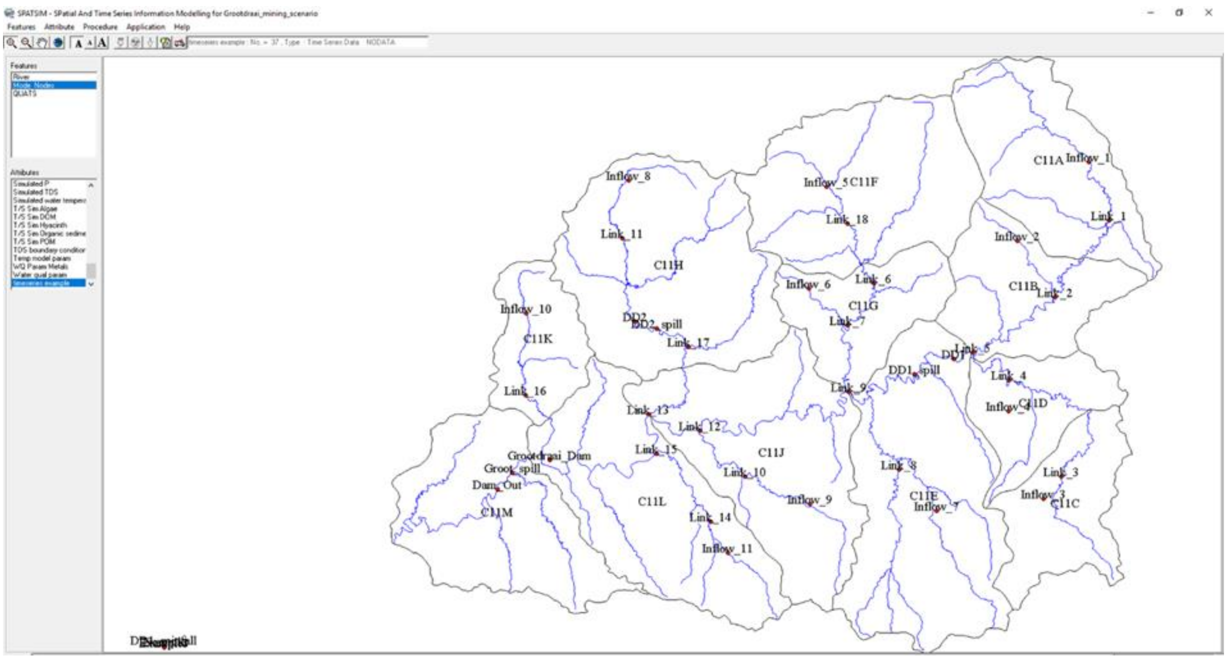


Figure 9-5 Grootdraai scenario application in SPATSIM showing labels for the 'Node' and 'Catchments' features.

9.3 GROOTDRAAI SCENARIOS DSS

Within SPATSIM, the user can initiate the DSS by navigating to 'Application' → 'Run Process' → 'Directly', as depicted in Figure 9-6. Subsequently, the user will be presented with a list of available models, as illustrated in the left-hand image of Figure 9-7. To launch the DSS, simply double-click on 'Barrage Water Quality DSS linked to RQOs'.

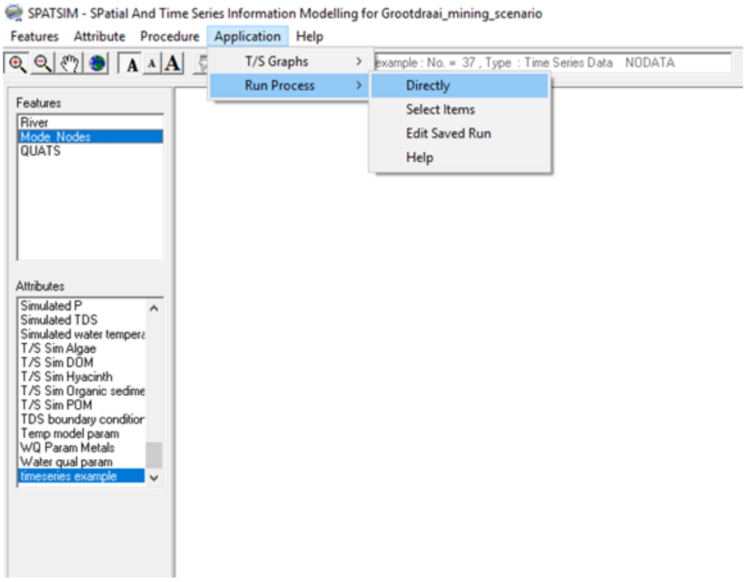


Figure 9-6 Process for running a model from within SPATSIM.

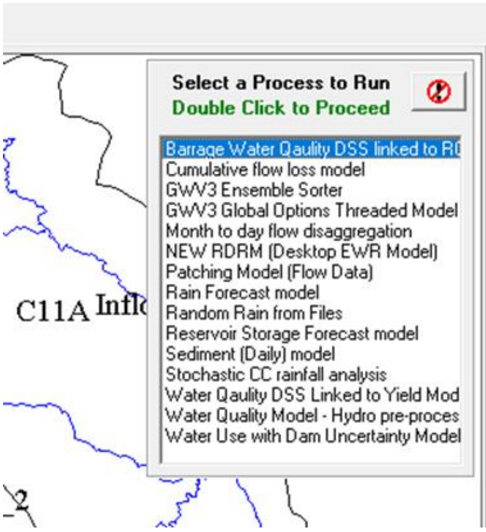


Figure 9-7 Executing the Grootdraai scenarios DSS involves choosing to run a model directly from SPATSIM, following the instructions in Figure 9-6. Subsequently, the user should select 'Barrage Water Quality DSS linked to RQOs' and double-click to initiate the process.

The Grootdraai scenarios DSS launch screen, as shown in Figure 9-8, should appear. The latest DSS run will be the second in the list. To run the DSS, select the second run, click ‘Read Data’ and then ‘Run Model’. Subsequently, another window will be appeared (Figure 9-9), this window contains three options that will guide the model user through the decision system.

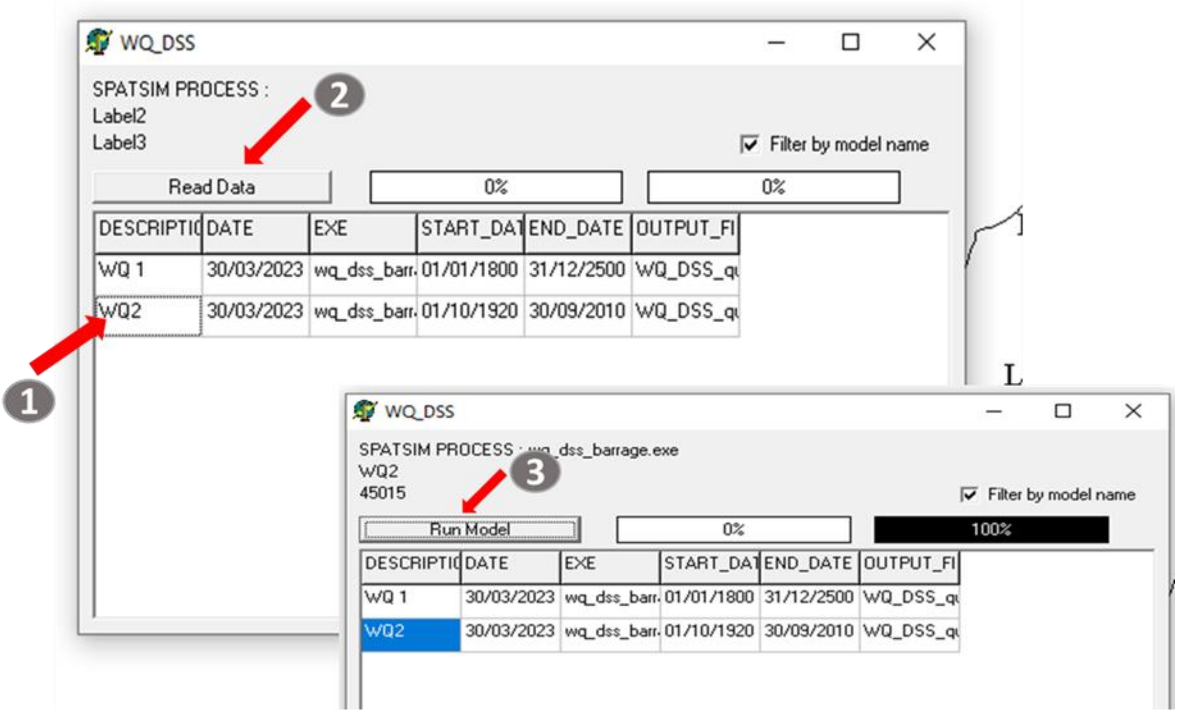


Figure 9-8 The launch screen of the Grootdraai scenarios DSS displays various model runs. To initiate the latest DSS, select the second option in the list, click 'Read Data' and then proceed with 'Run Model'.

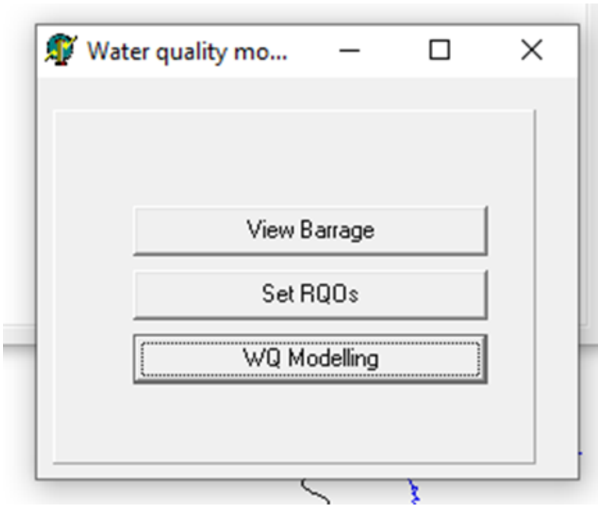


Figure 9-9 The features screen of the DSS offers various functions. Users can utilize 'Set RQOs' to establish RQOs for different positions in the catchment. Additionally, 'WQ Modelling' allows for the configuration of pollutant loads and the visualization of model simulations concerning RQOs for various nodes in the catchment.

9.4 EXPLORING THE GROOTDRAAI SCENARIOS (DSS)

Selecting the 'Set RQOs' button will prompt the display of the interface depicted in Figure 9-10. This window enables users to establish Resources Quality Objectives (RQOs) for any nodes, providing the utmost flexibility for exploring the investigated scenarios involving potential changes to RQOs. To define RQOs for a specific node and water quality variable, simply click on the desired node from the left-hand list. Subsequently, input a numerical limit and 95th percentile for the targeted water quality variable, and then click 'Save RQOs for Node' prior to exiting the screen.

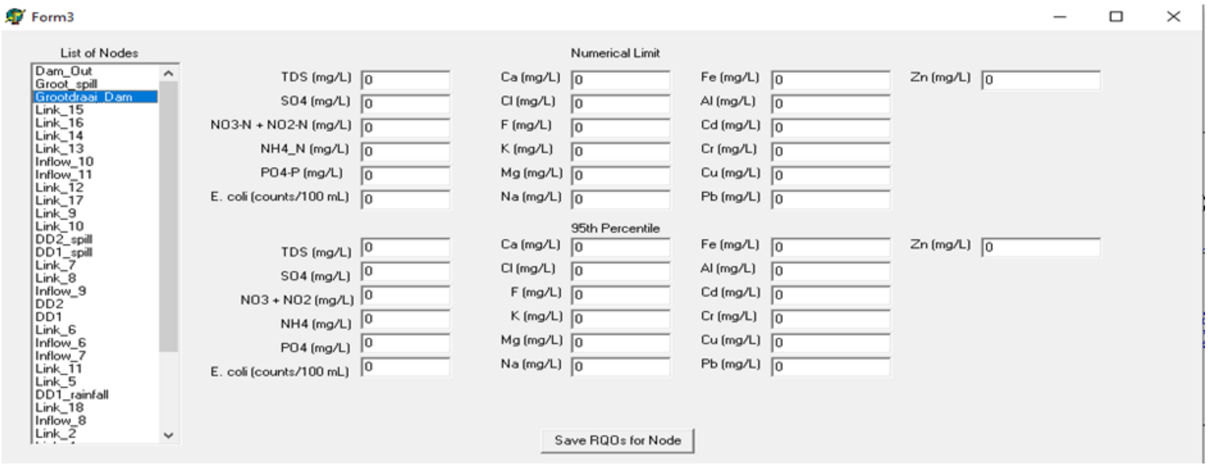


Figure 9-10 Interface designed for configuring Resources Quality Objectives (RQOs) for various modelled nodes. Access this screen by selecting the 'Set RQOs' button. Each node allows the establishment of two RQOs: a numerical limit and a 95th percentile.

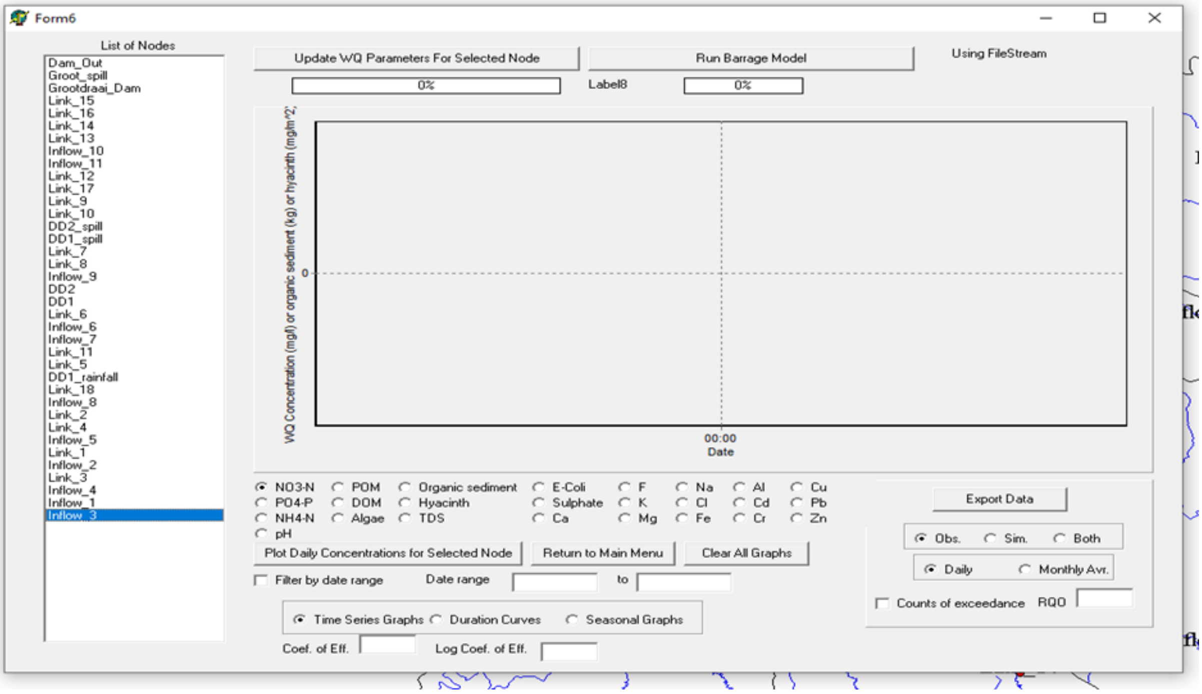


Figure 9-11 Access the water quality modelling screen of the Grootdraai scenarios DSS by clicking on the 'WQ Modelling button'.

The majority of functionality of the DSS is in the water quality modelling screen, as shown in Figure 9-11, which can be accessed by clicking on the 'WQ Modelling' button. This screen allows point- and non-point pollutant inputs to be changed for different parts of the catchment.

In Figure 9-12, a procedure is depicted where users can choose the node of interest from the left-hand list. By selecting the button corresponding to the desired water quality variable at the panel's bottom, users can visualize simulations across the entire period or opt for a specific subset. Moreover, the 'filter by date range' option empowers users to refine simulations to specific start and end dates.

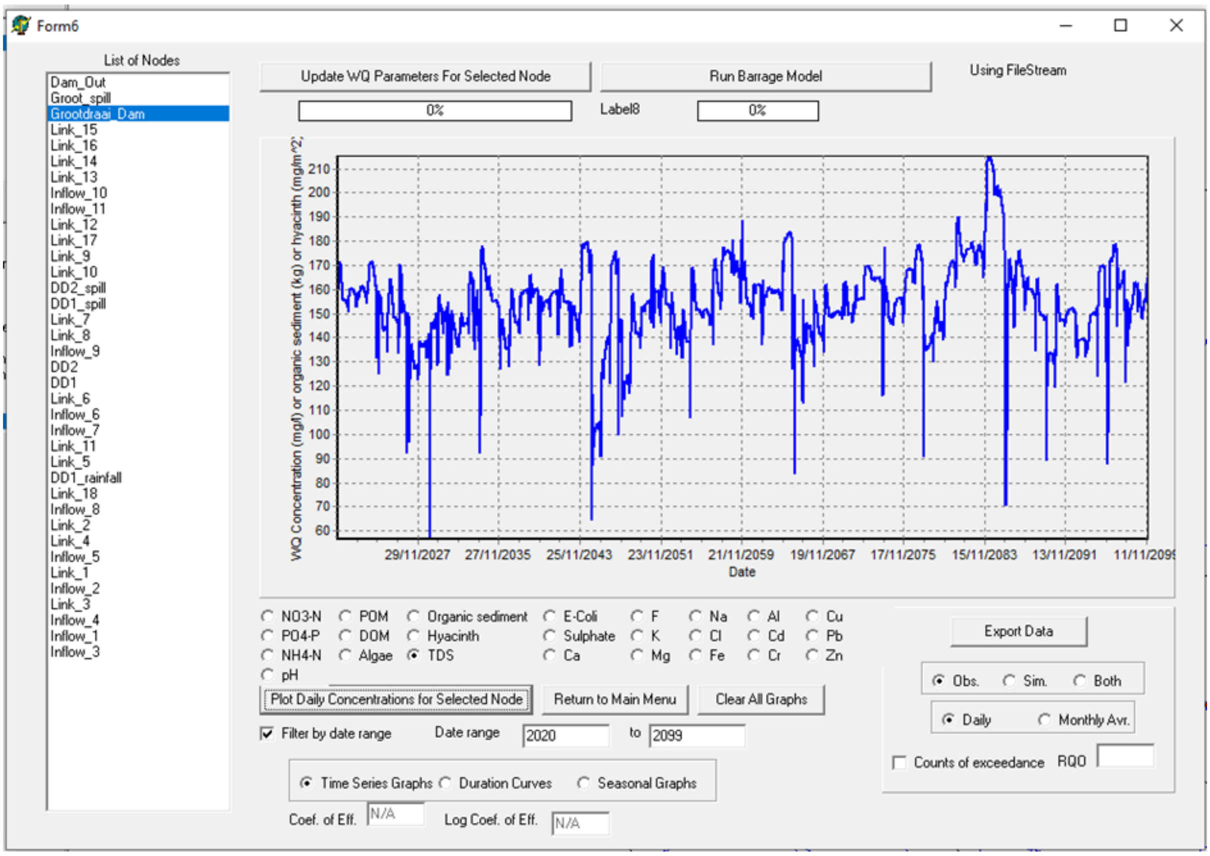


Figure 9-12 Water quality modelling screen of the Grootdraai Dam DSS showing simulations of TDS for the Grootdraai Dam for 2020-2099 as a time series.

Model simulations can also be displayed as frequency distributions by selecting the ‘Duration Curves’ button at the bottom of the panel instead of the ‘Time Series Graphs’ button. The simulation under climate change scenario, shown as the blue line in Figure 9-13. By plotting as a frequency distribution, the model user can also view the RQOs for a particular node (if set) for comparison against RQOs. For example, the numerical limit and 95th percentile for the Grootdraai Dam node are shown as the yellow and red lines in Figure 9-13, respectively.

Note

The user of the model is advised against executing the water quality model, specifically refraining from selecting or clicking on the button labelled "Run Barrage Model" and the button "Update WQ Parameters for Selected Node" depicted in Figure 9-14.

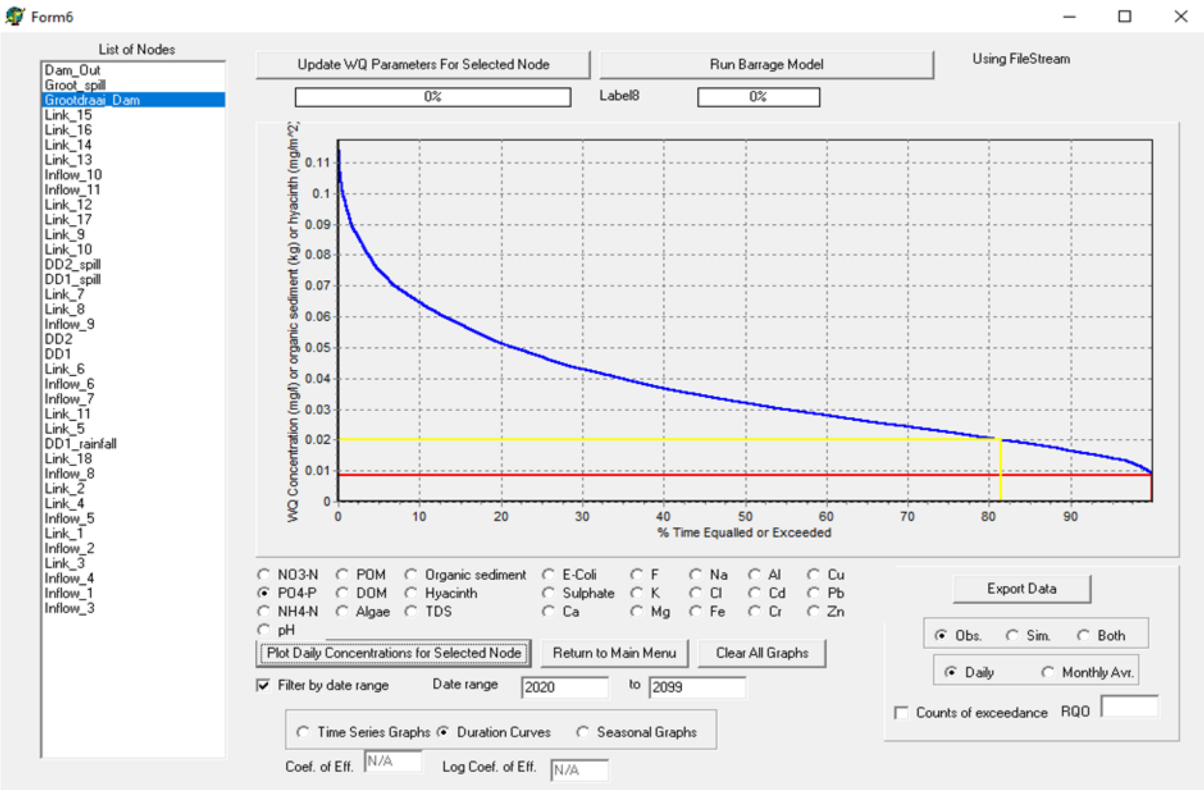


Figure 9-13 Water quality modelling screen of the Grootdraai Dam DSS showing simulations of phosphate under climate change scenario for the Grootdraai Dam node for 2020-2099 as frequency distributions or concentration-exceedance curve. The numerical limit and the 95th percentile data utilized for this node were chosen from DWS (2016).

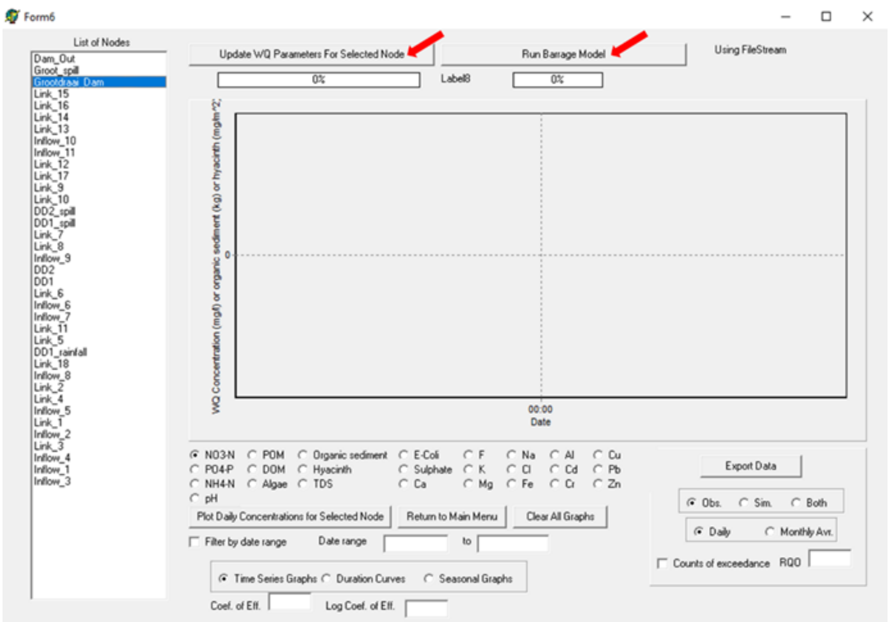


Figure 9-14 Screen showing Grootdraai DSS within SPATSIM.

9.5 EXAMPLES OF ALTERNATIVE SCENARIOS EXPLORED

9.5.1 Investigating the effects of increasing mining areas in the Grootdraai Dam Catchment (GDC)

The impact of expanding mining areas on water quality in the catchment can be examined in the DSS by selecting the application labelled "Grootdraai_mining_scenario," as illustrated in Figure 9-15.

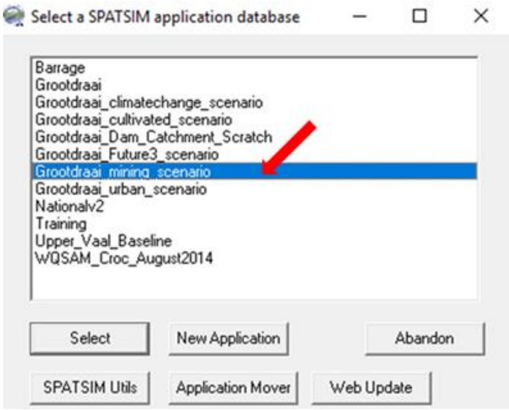


Figure 9-15 The SPATSIM launch screen exhibits the mining scenario application, indicating an increase of 0.015% in mining areas.

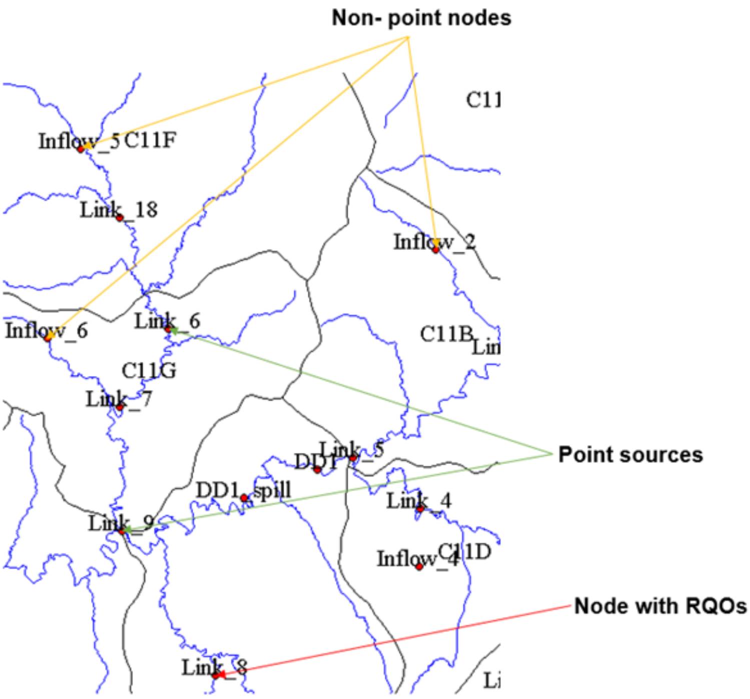


Figure 9-16 Screenshot of the Grootdraai Dam catchment highlighting specific nodes chosen to demonstrate the application of the DSS in examining alterations in upstream pollutant loads. Nodes such as Inflow_5, Inflow_6, and Inflow_2 represent incremental (natural) flow. Link_6 and Link_9 are nodes involving return flow, while Link_3 serves as the node for comparing simulated water quality against the RQOs (Rand Water, 2022).

Illustrated in Figure 9-16, the quaternary catchments C11F, C11G, and C11B serve as upstream tributary catchments for the Grootdraai Dam. In this context, nodes such as Inflow_5, Inflow_6, and Inflow_2 represent points of incremental (natural) flow, encompassing parameters for non-point source loads of water quality variables. Nodes Link_6 and Link_9 are associated with return flow, while Link_8 within the catchment contains simulated data.

The model user can examine the simulated water quality at Link_8 to evaluate the impacts of the point source upstream at this location. In Figure 9-17, by plotting the frequency distributions for Total Dissolved Solids (TDS) at Link_8, one can observe the RQOs established at Schulpspruit where this point is located. It becomes evident that the simulated water quality surpasses the numerical limit of RQOs under tolerable levels (Rand Water, 2022), for 55% of the time.

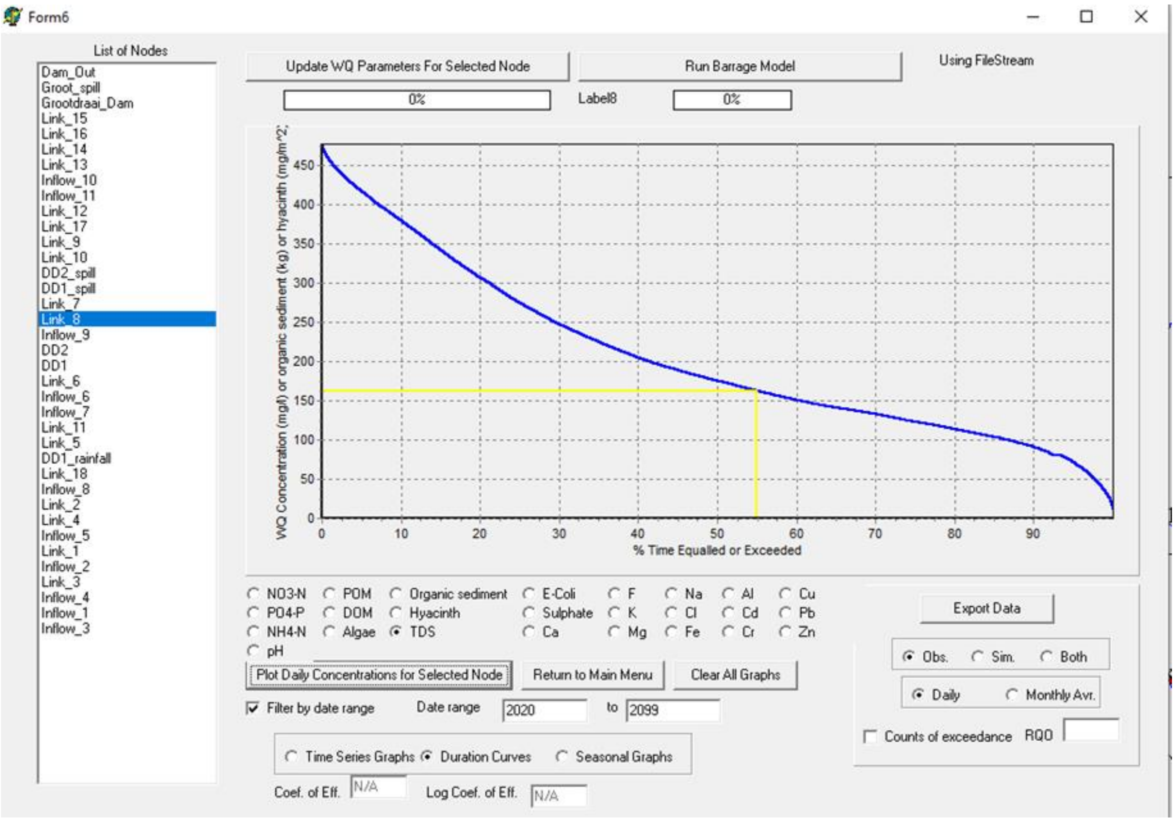


Figure 9-17 Model simulated TDS at Link_8 in the Grootdraai Dam catchment as plotted as a frequency distribution/concentration exceedance plot, shown in relation to the RQOs at this node (Rand Water, 2022).

9.5.2 Investigating the effects of increasing urban areas in the Grootdraai Dam Catchment

The impact of expanding mining areas on water quality in the catchment can be examined in the DSS by selecting the application labelled "Grootdraai_urban_scenario," as illustrated in Figure 9-18.

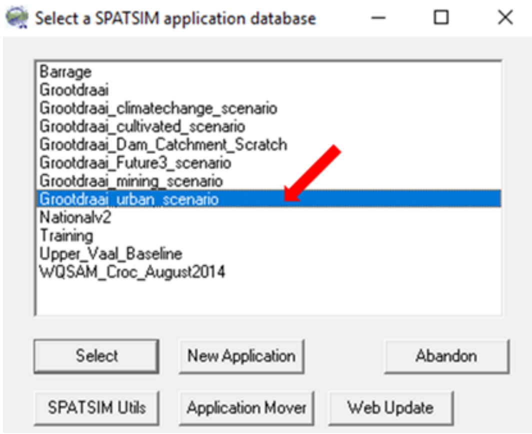


Figure 9-18 The SPATSIM launch screen selecting the urban scenario application, indicating an increase of 0.05% in urban areas.

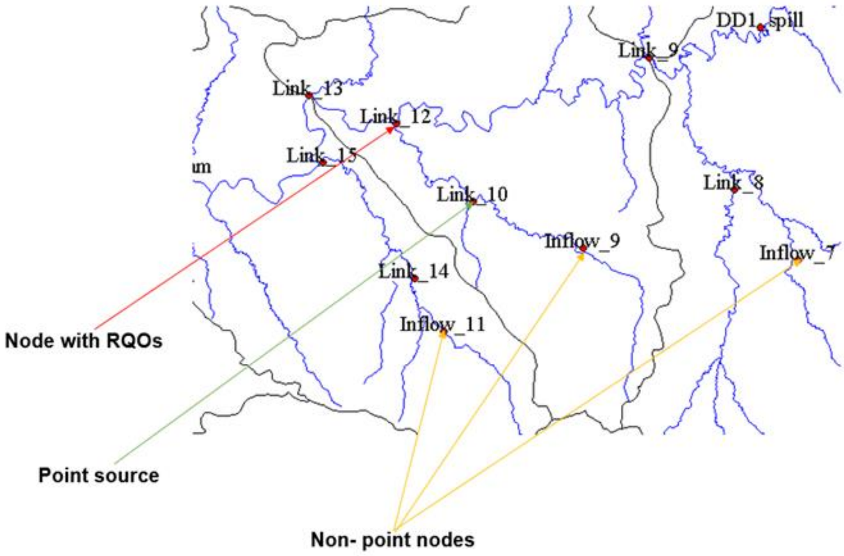


Figure 9-19 Screenshot of the Grootdraai Dam catchment highlighting specific nodes chosen to demonstrate the application of the DSS in examining alterations in upstream pollutant loads. Nodes such as Inflow_11, Inflow_9, and Inflow_7 represent incremental (natural) flow. Link_10 is a node involving return flow, while Link_12 serves as the node for comparing simulated water quality against the RQO (Rand Water, 2022).

Illustrated in Figure 9-19, the quaternary catchments C11L, C11G, and C11E serve as upstream tributary catchments for the Grootdraai Dam. In this context, nodes such as Inflow_11, Inflow_9, and Inflow_7 represent points of incremental (natural) flow, encompassing parameters for non-point source loads of water quality variables. Node Link_10 is associated with return flow, while Link_12 within the catchment contains simulated data.

The model user can examine the simulated water quality at Link_12 to evaluate the impacts of the point source upstream at this location. In Figure 9-20, by plotting the frequency distributions for ammonium (NH_4) at Link_12, one can observe the RQOs established at Schulpspruit where this point is located. It becomes evident that the simulated water quality surpasses the numerical limit of RQOs under tolerable levels (Rand Water, 2022) for 45% of the time.

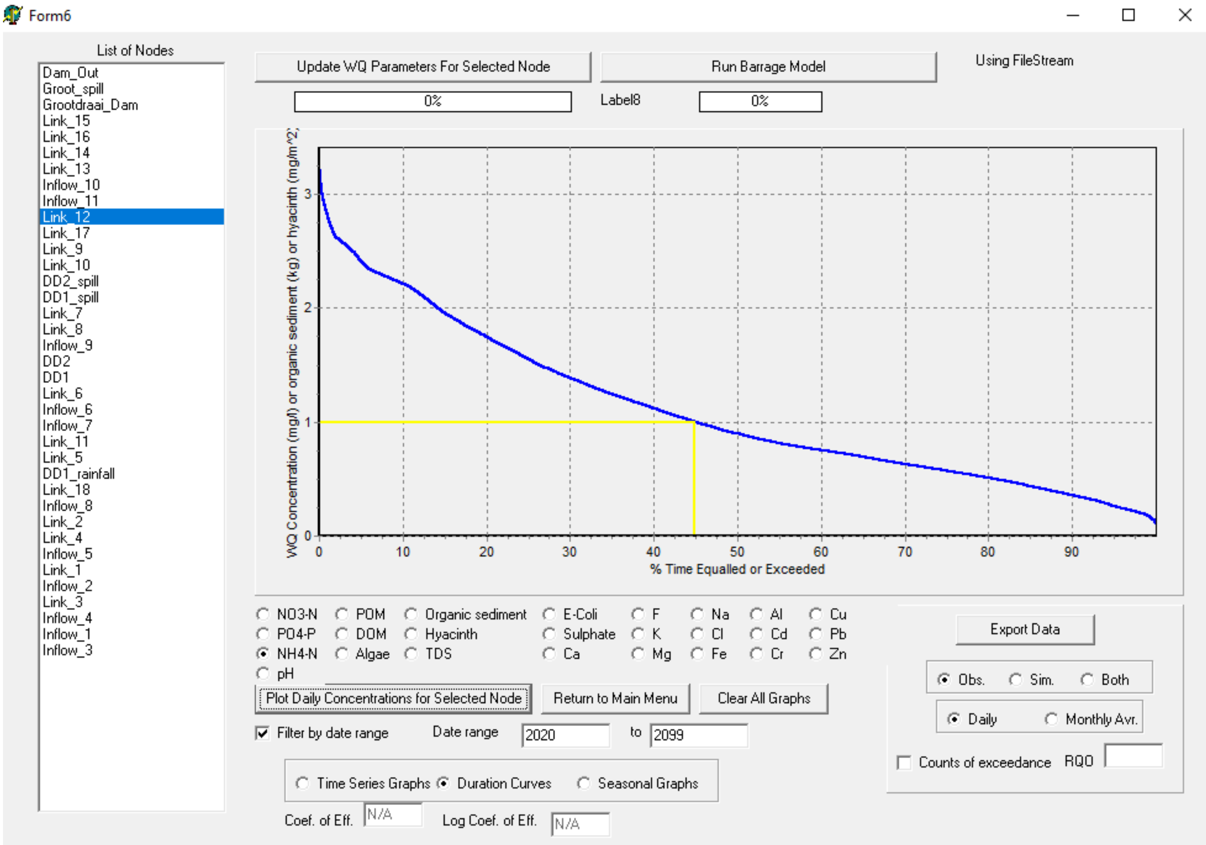


Figure 9-20 Model simulated ammonium at Link_12 in the Grootdraai Dam catchment as a frequency distribution//concentration exceedance plot, shown in relation to the RQOs at this node (Rand Water, 2022).

9.5.3 Investigating the effects of closing mining operations, while allowing an abstraction by Sasol-Secunda of 70% above current, under changing climatic conditions in the Grootdraai Dam Catchment.

The impact of expanding mining areas on water quality in the catchment can be examined in the DSS by selecting the application labelled "Grootdraai_Future3_scenario," as illustrated in Figure 9-21.

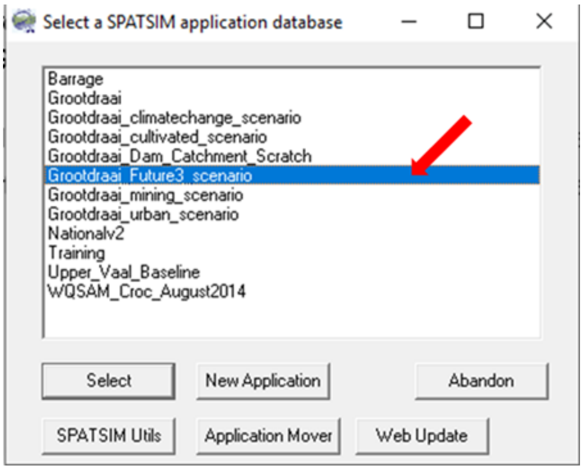


Figure 9-21 The SPATSIM launch screen displays the future3 scenario application, signalling the closure of mines and a 70% increase in water demand at the abstraction level from the Dam to Sasol-Secunda, amidst changing climatic conditions.

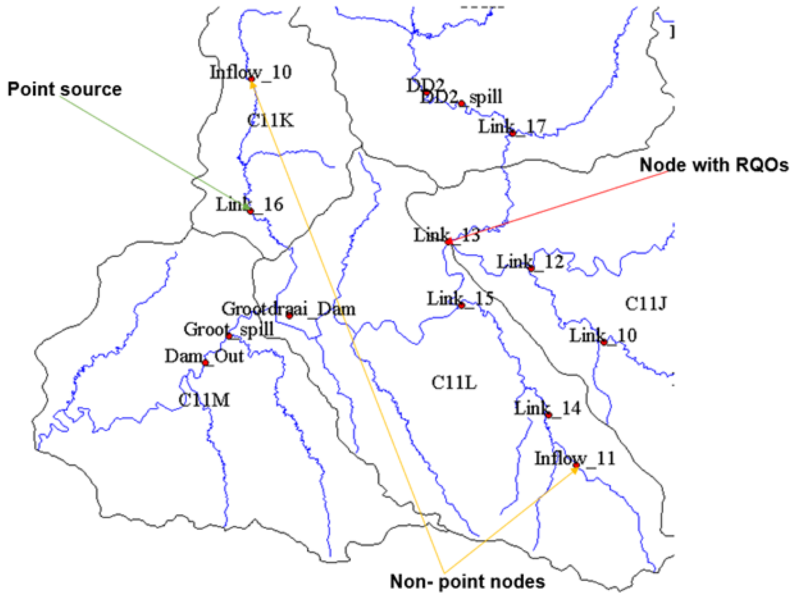


Figure 9-22 Screenshot of the Grootdraai Dam catchment highlighting specific nodes chosen to demonstrate the application of the DSS in examining alterations in upstream pollutant loads. Nodes such as Inflow_10 and Inflow_11 represent incremental (natural) flow. Link_16 is a node involving return flow, while Link_13 serves as the node for comparing simulated water quality against the RQO (Rand Water, 2022).

Illustrated in Figure 9-22, the quaternary catchments C11K, C11L, and C11J serve as upstream tributary catchments for the Grootdraai Dam. In this context, nodes such as Inflow_10 and Inflow_11 represent points of incremental (natural) flow, encompassing parameters for non-point source loads of water quality variables. Node Link_16 is associated with return flow, while Link_13 within the catchment contains simulated data.

The model user can examine the simulated water quality at Link_13 to evaluate the impacts of closing mines and increasing water abstraction under changing conditions at this location. In Figure 9-23, by plotting the frequency distributions for sulphate (SO_4) at Link_13, one can observe the RQOs established at Majuba where this point is located. It becomes evident that the simulated water quality surpasses the numerical limit of RQOs under tolerable levels (Rand Water, 2022) for 15% of the time.

The model user has the option to incorporate water quality guidelines specific to the Grootdraai Dam catchment from The Rand Water, accessible at www.reservoir.co.za. These guidelines encompass numerical limits across various categories, ranging from ideal to unacceptable, and can be inputted into the DSS, as illustrated in Figure 9-10. However, it's noteworthy that the existing water quality guidelines might be considered limiting, as they provide numerical limits for only seven water quality variables, including TDS, sulphate, chloride, fluoride, and nutrients.

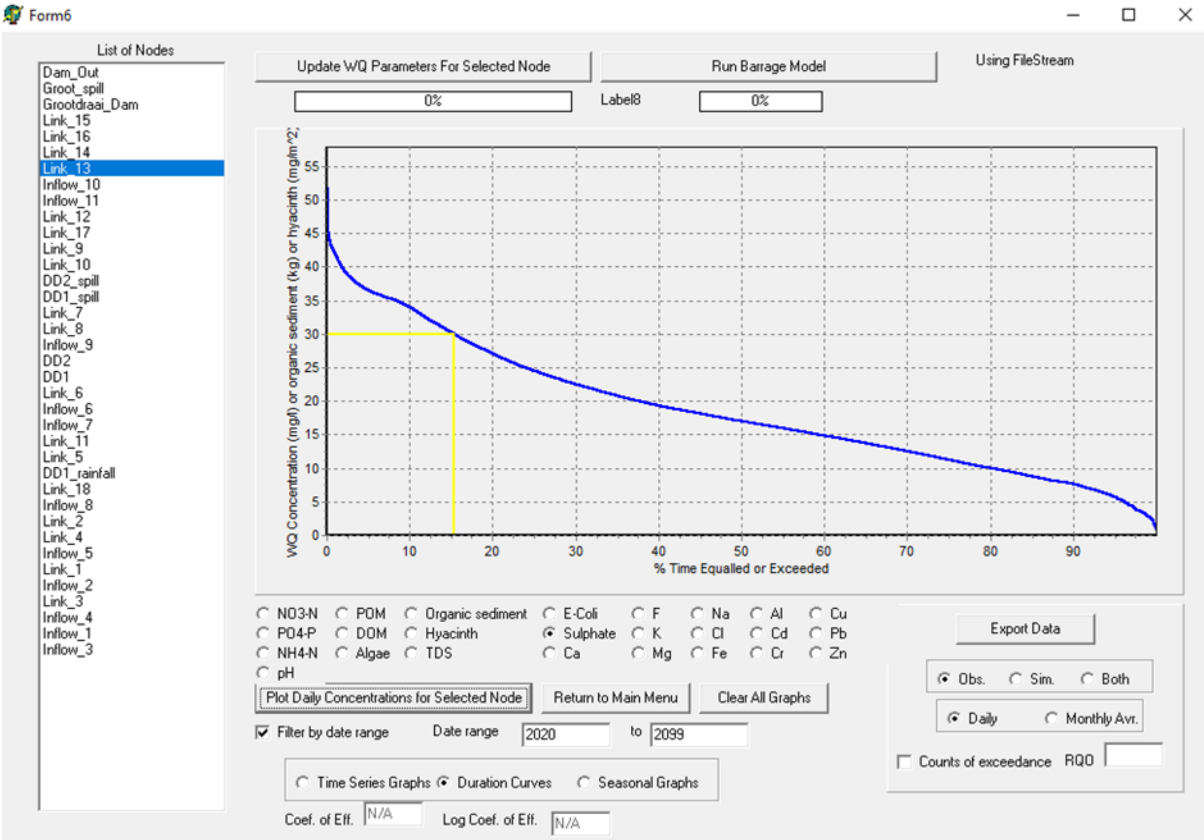


Figure 9-23 Model simulated sulphate at Link_13 in the Grootdraai Dam catchment shown as a frequency distribution/concentration exceedance curve, shown in relation to the RQOs at this node (Rand Water, 2022).

CHAPTER 10: CONCLUSIONS & RECOMMENDATIONS

10.1 CONCLUSIONS

Pywr proved a useful framework for generating yield models in a catchment in the South African context. Pywr-WQ, a water quality model that uses the same processes as the proven and established WQSAM model, was also capable of water quality modelling in the Grootdraai Dam. An output from this project is therefore a high resolution yield model for the catchment, as well as a high resolution, calibrated water quality model for the catchment.

Stakeholder engagement processes gave a few potential scenarios for the catchment. The scenarios were engaged with using the calibrated water quality model. Changes to flow and water quality as a result of climate change were also assessed. Several mixed use models were run in an attempt to assess the impact of plausible future scenarios.

If the water quality from this catchment is to be maintained at a level where it can continue to be used without treatment, the catchment will need to be carefully managed. Based on the results of the scenarios assessed, many changes to the catchment will have negative impacts on water quality in the catchment, and this will then impact water quality leaving the catchment. This decrease in water quality will have cost implications when future water users need to treat water before it can be used.

When water quality is simulated based on the calibrated water quality model applied to predicted flows under climate change, future water quality is seen to decrease, with increases, albeit small, in nutrients and salt levels. As climate change is already under way, these water quality changes are likely and are liable to continue. The negative effects of floods and droughts also need to be factored in. Climate change is not something managers can change, however. Future water users will have to devise methods for ongoing adaptation and use of the water in order that industry, agriculture, etc. can continue, and domestic demand can be satisfied.

Scenarios that were assessed indicated that increases in mining, cultivated agriculture, and land used for urban uses have negative connotations for water quality in Grootdraai Dam. The model predicts decreases in water quality in response to increases in three land uses: mining, cultivated agriculture, and urban settlements. That conclusion is of itself not surprising-all these land uses have been found to be associated with decreased water quality in the past (DWA, 2011; Griffin et al., 2014). It may not be practical to limit the growth of urban space and cultivated land, as these are largely a function of population size. However, coal mining may decrease into the future under the Just Energy Transition (Secretariat JETP, 2022).

Given the potential negative effect of mining on water quality, it is important that management limit this through limiting coal mine exposure to sensitive water resources. Examples of this include the wetland complex around Chrissiesmeer on the border of the catchment east of Ermelo, and the source waters of the transfers into the catchments. Coal mining has commenced at Heyshope Dam, which is a concern for water entering the system via the transfer scheme. Nevertheless, water entering from the dam was generally of ideal, or at worst acceptable, quality.

In this light it bears worth to consider the results of the mixed use models, where the model assesses a scenario that on the surface is arguably realistic, or plausible: a future where coal mining is reduced, where climate change continues, and where abstraction of water increases, and consequently dilution capacity is reduced. The results from these simulations, where abstraction only was varied, was a marked improvement in water quality. Ongoing climate change and varied abstraction did not have a major impact on the water quality improvement that reducing mining had.

While mine closure in the immediate or shorter term might not be practical, better water management practices on mines may be. Improved water and environmental management by all stakeholders in urban, agricultural and mining sectors can improve the quality of water discharged from them. In this way improved management can address the negative effects that these different land uses may have on water resources. For example, control of mine water so that any water released is not acid or saline (i.e. not liming), or contaminated with metals, will greatly reduce the impact of mining on water resources. Likewise, maintenance and proper operation of wastewater treatment works will act to reduce the impact of urban areas on water resources. The agricultural sector can ensure that river banks are uncultivated and undisturbed, that irrigation and fertilization methods are appropriate and minimize runoff to surface or groundwater, that agricultural wastes are properly disposed of or reused, and any other tools or methods to limit water resource contamination. In general all sectors need to limit nutrient or salt loss to surface or groundwater, and to ensure that any released effluents are of an appropriate quality.

It may be possible to release water via the transfer schemes should droughts prove too severe in order that flow be maintained to Grootdraai Dam. The transfer schemes could also be used to provide flushing flows should water quality drop too low, in a similar way to the use downstream of Vaal Dam water to control Vaal Barrage salinity (Tempelhoff et al., 2007). Water for flow in the upper catchment might also be provided via the Vaal River Eastern Sub-System Augmentation Project (VRESAP).

It is important to bear in mind that these results have been derived based on the calibrated link between past water quality and areas of land linked to a particular use. Therefore, to a certain extent, the water quality model calibration reflects land use practices from the past. Therefore, if water impacts are limited through management decisions, then the decrease in water quality associated. The model by its nature assumes that management practices of the calibration data set will continue into the future. If better water management is instituted, then the predicted implications of these models need not happen and the decreasing trend in water quality could be reversed.

10.2 RECOMMENDATIONS

Future research should adopt a comprehensive approach to address key assumptions in this study. Firstly, future research could explore the phased closure of mining operations, studying the individual contributions of different mining sites to changes in salt levels. Moreover, research could explore the continuous drainage of salts from mining areas over time, considering the gradual reduction of salt levels. A developed version of Pywr-WQ model that incorporates progressive shifts from initial salt signatures to recommended salt signatures would facilitate a more realistic representation of salt concentration changes over time.

The land use change models are based on a multiple regression model that is calibrated on modelled data from 1920 to 2010. As a result, the multiple regression model reflects land use patterns and practices during that period, along with its reflection in changing water quality. As changing current land use patterns and practices may fall outside that historic envelope, it is recommended that the model be updated with more current data when that is available in order to improve the reliability of its predictions.

Ongoing engagement with stakeholders can provide valuable insights and data related to mining closures, post-closure practices, and the broader impact of mining closure on water quality. Likewise, ongoing engagement regards power station operation, wastewater treatment works operation, catchment agricultural practices, and so on will inform management and application of the model.

An area that may be valuable for discussion and engagement would relate to changes in management of many sectors that might decrease the impact of that sector on water quality. Improved water management in this way would entail sector-specific engagement, and could entail the use of established methods. Here, management of closed or unused mines could have an impact equivalent the modelled reduction in mining. Engagement of other stakeholders will have value too. For example, the Lekwa Local Municipality was fined R70 million in 2023 for raw sewage leakage (Carnie, 2023), and the environmental costs and water quality impacts of this are enormous. Municipal stakeholders or others could have input on how to manage this problem.

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