DYNAMIC SYSTEM WATER BALANCE MODEL (DYWABM) ENHANCEMENTS: CLIMATE CHANGE AND WATER QUALITY RISKS USING STEVE TSHWETE LOCAL MUNICIPALITY (STLM) AS A CASE STUDY AREA

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

The provision of secure, reliable, affordable and equitable water services while meeting ecosystem requirements is one of the most significant and ever-present challenges. This is particularly so with the rapid urbanisation, increasing demand for food, expansion of mines and industry, deteriorating water infrastructure and intermittent energy supply. Managing water resource systems within the hydrological cycle with multiple pressures from various anthropogenic activities, climate change-induced risks, and uncertainty requires models that can use large data sets implement feedback loops and learning algorithms for the these changing conditions. A linear approach to solving water-related problems leads to transfer of risks and costs from one user/sector/place to another which is not in line with principles of sustainable development and equitable access to water resources. A dynamic system water balance model (DyWaBM) developed on the Kgetlengrivier Local Municipality in the North West Province of South Africa was applied on a more complex water supply system in the Steve Tshwete Local Municipality (STLM) in the Mpumalanga Province of South Africa to enhance its capabilities on water quality and climate change risks. It works with operational time scales, testing interventions that can affect water security on a day-to-day basis. On this study the basic water system configuration for STLM was developed using baseline data which included land use, water resources, bulk water supply and wastewater infrastructure. System components were identified in Google Earth Pro and confirmed through ground truthing. System and sub-system network models were developed to describe the movement of water and its storage/retention through the various interconnected features. The baseline data is presented in **Chapter 2** of this document.

Anthropogenic activities in the study area were mapped. These activities, which include agriculture, mining, processing of minerals, other industrial activities, thermal power stations, human settlements (including unplanned settlements), and water and wastewater treatment plants, are major water quality drivers. Process diagrams were developed for coal mines, thermal power stations and industry as sources of pollution. These activities have significant negative impacts on the quality of the water resource. Data for 2017-2020 revealed the extent of water pollution at STLM water quality monitoring points. Presence of sulphates in raw water and final treated water point to challenges in dealing with this parameter. In most of the water treatment plants (WTPs), turbidity was found to be above the recommended limits. Data for bulk supply reservoirs showed that sulphates were mostly above the South African National Standards (SANS) recommended values. High concentrations of Manganese were observed in most of the reservoirs. The microbiological parameters revealed that all investigated samples were completely free from *E. Coli* and total and faecal coliforms. There was evidence of microbial pollution from farming activities and septic sources at some drinking water points. Physicochemical and biological parameters at selected drinking water supply points were above the permissible levels. Mhluzi, Eastdene, Rockdale 236 and Dennesig draw drinking water from Vaalbank WTP, which obtains its water from Middelburg Dam. This dam is situated downstream of coal fields, thermal power stations, wastewater treatment plants (WWTPs) and settlements, which might be the source of high sulphate, total coliforms and heterotrophic bacteria and plate counts (HPC). The impacts of WWTPs as sources of pollution were evaluated by analysing historical and current data from sampling points for each plant. The pH values indicated slightly acidic water. There were high total dissolved solids (TDS) for untreated and treated wastewater for some samples. Discharged effluent did not comply with the limits recommended by the Department of Water and Sanitation (DWS) for most physico-chemical parameters. Analysis of available data informed the water quality methodology formulated for the DyWaBM. The existing water quality monitoring system falls far short of the requirements for implementing and testing of this methodology. The water quality methodology is presented in **Chapter 3** of this document.

High priority monitoring points were identified for implementation. The municipality wants to obtain support in implementing technologies for near-real time monitoring and resources to improve sampling and testing. Electronic inline monitoring systems can measure parameters such as Ammonium, Chloride, and Nitrate, Temperature, pH, Rhodamine, Total Algae (Chlorophyll + Phycocyanin and Phycoerythrin) Turbidity, Dissolved Oxygen, Conductivity, Salinity, Specific Conductivity, Total Dissolved Solids and Total Suspended Solids. Critical parameters can be selected for monitoring.

Climate patterns were obtained from analysis of data on the historical and projected future climate. The Global Precipitation Climatology Centre (GPCC), Climatic Research Unit gridded Time Series (CRU TS) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) data sets were selected for historical long-term and short term (recent climate) analysis of precipitation, maximum temperature, minimum temperature, and potential evapotranspiration. The 1931-2060 climate was drier than the 1961-1990 and 1991-2020 climates. Mean annual precipitation (MAP) for most sub-catchments decreased by about -29 mm between the 1931-1960 and 1961-1990 climates. It decreased by about -21 mm between the 1961-1990 and 1991-2020 climates; however, for B12D and B12E, MAP increased. For all sub-catchments with the Coordinated Regional Downscaling Experiment (CORDEX) hind-cast period 1971 to 2000, maximum temperature was generally highest in October and lowest in June to August while minimum temperature was lowest in June to August. In daily management of water resources, the observed parameter values already reflect changing climate and so do weather and seasonal climate forecasting parameters. A methodology for assessing impact of climate change risks was developed for the DyWaBM considering rainfall, temperature, and evaporation. These parameters are relevant for estimating water available from rainfall and stormwater harvesting, analysing water quality, and assessing storage conditions and pollution risks. CORDEX RCP4.5 and RCP8.5 climate model scenarios were applied as median and middle third extents of daily data. Average conditions for periods of ten years 2021-2030, 2031-2040 and 2041-2050 time horizons were adopted. While these global data sets are useful, the existing network of climate monitoring stations (rainfall, evaporation, and temperature) falls far short of the requirements for implementing and testing this methodology. The climate change methodology is presented in **Chapter 4** of this document.

The input data requirements for implementation of the water quality methodologies in the DyWaBM were specified. The results from evaluation of the adequacy of the existing monitoring of water levels, flow rates, water quality and climatic parameters are presented in **Chapter 5** of this document. Gap filling methods and improvements to the monitoring system are recommended.

The enhanced DyWaBM was set up for quaternary catchments B12A, B12B, B12D and B12E which fall within the STLM, but due to inadequate monitoring data detailed tests were conducted on B12A only. The model was run on a daily time-step with results producing summarised results for each month to formulate and test interventions. The model tracked several indices including measures of access to available water resource as days at the minimum and maximum levels of supply, supply/demand ratios, etc. Resource yield was assigned to supply areas and changes in yield through improving the water mix were tested.

Observed water abstraction data showed that water demand far exceeds the water resource available for B12A. Hendrina settlement has about 10% of the total population of B12A has a higher supply/demand index than Kwazamokuhle settlement with about 90% of the population. For some months the maximum supply level for Hendrina exceeded its water demand. With the RCP8.5 (most unlikely) scenario model results showed a higher opportunity for improving the available water resource from rainwater harvesting than the RCP4.5 (likely) scenario using the resource as a percentage of demand as the indicator, but when using supply as a percentage of demand, maximum water supply level, minimum water supply level as indicators, the RCP8.5 (most unlikely) scenario presents a lower opportunity of improving water supply levels with rainwater harvesting than the RCP4.5 (likely) scenario. These results reflected supply constraints in the system. Updated network models and results are presented in **Chapter 6** of this document.

The STLM is concerned that flow into its main source of water Middelburg Dam is polluted by upstream activities and the quality of raw water is exceeding the treatment capacities of its plants. It wants to convene a workshop with stakeholders to initiate a project to improve monitoring of flow and quality of water in the dam catchment and obtain commitment from stakeholders to avoid polluting the streams and implement interventions such as retention and pre-treatment. The municipality also wants to improve supply of water to communities in terms of quality and quantity, reduce periods of low/no supply and avoid under and over-supply. Improving water security involves work in monitoring and implementation of investments to improve quality and quality of water and critical points in the system. This means new jobs within the STLM, mines, power stations and industry.

The project investigated the application of dynamic system principles to management of water resource systems at daily, weekly, and monthly time scales. These are operational time scales where people make decisions which respond to and also affect the performance of the system. The DyWaBM provides information on resource availability and quality in advance and allows water resource system managers and operators to review the impact of interventions on water security in the STLM. The development of this software application to provide information of resource availability and quality status of a water source, would be of great assistance to local municipalities in South Africa and beyond.

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ACRONYMS & ABBREVIATIONS

ACRONYM/ABBREVIATION	DESCRIPTION
ARD	Acid Rock Drainage
BH	Borehole
BOD	Biochemical Oxygen Demand
CBD	Central Business District
CHIRPS	Climate Hazards Center InfraRed Precipitation with Station data
COD	Chemical Oxygen Demand
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRU	Climate Research Unit University of East Anglia
CRUTS	Climatic Research Unit gridded Time Series
CV	Coefficient of Variation
DFFE	Department of Forestry, Fisheries and the Environment
DJF	December-January-February
DMS	Density Medium Separation
DO	Dissolved Oxygen
DWS	Department of Water and Sanitation
DyWaBM	Dynamic Water Balance Model
EC	Electric Conductivity
ENSO	El Niño Southern Oscillation
FCB	Faecal Coliform Bacteria
FOSS-LGD	Framework Open Source Software to Analyze Large Gridded Data
GIS	Geographical Information System
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
GWPSA	Global Water Partnership Southern Africa
HPC	Heterotrophic Bacteria and Plate Counts
IMESA	Institute of Municipal Engineering of Southern Africa
IPCC	Intergovernmental Panel on Climate Change
IQS	Incident Qualification System
ITCZ	Intertropical Convergence Zone
KLM	Kgetlengrivier Local Municipality
MAP	Mean Annual Precipitation
M-K S	Mann-Kendall Statistic
NACOF	National Climate Outlook Forum
NDJ	November-December-January
NETCDF	Network Common Data Form
NFEPA	National Ecosystem Ecosystem Priority Areas
NOAA CPC GEFS	National Oceanic and Atmospheric Administration Climate Prediction Centre Global Ensemble Forecast System

ACRONYM/ABBREVIATION	DESCRIPTION
NOAA CPC GFS	National Oceanic and Atmospheric Administration Climate Prediction Centre Global Forecast System
OND	October-November-December
PS	Power Station/Pump Station
QGIS	Quantum Geographic Information System
RCP	Representative Concentration Pathway
SADC	Southern African Development Community
SANBI	South African National Biodiversity Institute
SANS	South African National Standards
SARCOF	Southern Africa Regional Climate Outlook Forum
SAWS	South Africa Weather Services
SST	Sea Surface Temperature
STLM	Steve Tshwete Local Municipality
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TOD	Total Oxygen Demand
TS	Time-series
WAL	Waste Authorisation license
WISA	Water Institute of Southern Africa
WMO	World Meteorological Organization
WQI	Water Quality Index
WRNA	WR Nyabeze and Associates
WSA	Water Services Authority
WSP	Water Services Provider
WTP	Water Treatment Plant
WUL	Water Use Licence
WWTP	Wastewater Treatment Plant

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CHAPTER 1: INTRODUCTION

1.1 Project background

The provision of secure, reliable, affordable and equitable water services while meeting ecosystem requirements is one of the most significant and ever-present challenges. This is particularly so with the rapid urbanisation, increasing demand for food, expansion of mines and industry, deteriorating water infrastructure and intermittent energy supply. From 2016 to 2018, WRNA, in collaboration with the University of Johannesburg, conducted research on a project entitled "Development and application of a dynamic water balance model (DyWaBM) to evaluate possible interventions to improve water security in Kgetlengrivier Local Municipality". Funds were obtained from the Water Research Commission under Project K5/2531. The Kgetlengrivier Local Municipality (KLM) provided a relatively simple case study area to develop and test the dynamic system model concepts and evaluate possible interventions to improve water security. It involved an area of about 5259 km^2 with a total population of about 51,049 (StatsSA, 2011). For the KLM case study, the model was set up for 4 water supply systems, each with 2 to 3 sub-zones and was run from July 2017 to April 2018. Results showed that two water supply systems had monthly supply/demand ratios of between 77% and 95%, while the other two were between 24% and 46%. The monthly supply/demand ratio of the three water supply systems was less than 15%. Using the daily supply/daily demand ratios, it was shown that the KLM frequently suffers days of complete supply failure. When applied with actual experience within and across zones, the principle of equity within water use categories revealed significant inequities. Rainwater harvesting and the re-use of treated wastewater and groundwater could increase yield, reduce demand in well-serviced areas, and release water for poorly served areas. New bulk water meters were installed to improve monitoring, and the model was successfully applied to improve daily operations. The study proved that the model concept has practical potential.

Managing water within the hydrological cycle where multiple pressures from anthropogenic activities, climate change-induced risks, and uncertainty requires models to implement feedback and learning algorithms for changing conditions and use large data sets. Steve Tshwete Local Municipality (STLM) has industry, mines, power stations, urbanisation and agriculture. Thus, water demand is much higher, and pollution control is a major issue. This study provided an opportunity to demonstrate that the model can be applied to more complex water supply systems. The STLM covers an area of approximately 3,976.42 km^2, it has a population of 229,831 in 2011 (StatsSA, 2011) and is estimated to have gone up to 278,749 by 2016 (Statistics South Africa, 2017). The main users of water are domestic, industrial and mining. About 11.3 Million m^3/year is registered for domestic abstraction. The municipality has extensive water and sanitation backlogs. The STLM obtains its water from four dams, namely Middelburg (yield 11.3 Million m^3), Witbank (yield 28.1 Million m^3), Athlone (yield 0.219 Million m^3), and Pienaar (yield 0.999 Million m^3). There are three main water treatment plants (WTPs) namely Vaalkop WTP (capacity of 16.06 Million m^3/year), Kruger WTP (capacity of 2.19 Million m^3/year) and Hendrina WTP (capacity of 2.0 Million m^3/year),. Severe water quality problems are experienced due to pollution from coal mining activities. Pollutants such as arsenic, barium, cadmium, chromium, iron, lead, vanadium, manganese, mercury and sulphates are associated with mining activities. The discharge of treated, partly treated and untreated effluents from mines, power stations (coal fired-water cooled), industries and sewage treatment plants, combined with seepage of acidic mine drainage from several active and abandoned coal mines, contribute nutrients, salts and metal ions and microbial contaminants to the river system. Reclamation and use of mine water are being encouraged to reduce pollution levels. Anglo-American, BHP, Middelburg and Shanduka Mines have been treating mine water. Kanhym feedlot uses approximately 0.22 Million m^3/year from the Boskrans Wastewater Treatment Plant (WWTP). Columbus stainless steel uses raw water from the Middleburg dam (0.37 Million m^3/year) and treated sewerage effluent from the Boskrans WWTP (0.22 Million m^3/year). Middleburg ferrochrome utilizes 0.24 Million m^3/year of potable water supplied by the local municipality and approximately 0.19 Million m^3/year of treated sewerage water. The Boskrans WWTP has a capacity of 10.95 Million m^3/year. NDM's Water Master Plan (2017) mentions that High water losses and poor sewage treatment are major challenges for STLM. According to the DWS, the projected water demand for the low and high growth scenarios is 15.50 Million m^3/year and 16.99 Million m^3/year, respectively. In both scenarios, water demand exceeds available yield without factoring in the impact of climate change. The water-food-energy nexus plays out in the STLM as runoff from this area feeds into the Loskop Dam, a water source for the 1900 ha Loskop irrigation scheme. With intermittent energy supply, increasing quantities of effluent and declining river flows driven by escalating demands for water, water quality problems now occur more frequently (Bruwer and Ashton (1989), Ashton and Dabrowski (2011)). Variable and changing hydro-climatic conditions, increasing water demand and pollution pose serious risks to consistently meeting current and future water needs.

The degradation of the quality of water in rivers, dams, and groundwater in South Africa is posing serious threats to river ecosystems and human health, and if the current trend is allowed to continue, regional and international conflicts may arise in the future. Using a dynamic systems approach, this project enables the research team to investigate solutions for transitioning to 'water-sensitive' settlements within a cyclic water economy. A linear approach to solving water-related problems leads to the transfer of the issues from one user/sector/place to another, which is transfers responsibilities, costs and risks and this is sustainable. The development of the water quality component and the capability to test climate scenarios were important enhancements for the DyWaBM.

1.2 Project aims

The following were the aims of the project:

1) To enhance the GIS and Schematisation components of the DyWABM by delineating the STLM into supply area into water supply zones, define the water supply system network components, connectivity and constraints
2) To enhance the DyWaBM to track the quality of water and evaluate its impact on different users, including the ecology
3) To enhance the DyWaBM to incorporate climate change scenarios and evaluate risks to quantity and quality of water
4) To evaluate the adequacy of the existing monitoring system for application of the DyWaBM
5) To develop the DyWaBM for the STLM water supply system and make recommendations on to improve water security

1.3 About the DyWaBM

The Dynamic Water Balance Model (DyWaBM) is a computer simulation model which applies system dynamics principles to obtain continuous water balance information at finer spatial and temporal scales than the existing tools. Its main purpose is to better understand interrelationships, behaviour, complexities and problems within a water supply system for baseline conditions and as they evolve over time. The spatial context of the DyWaBM evolves around 3 core elements: catchments, aquifers and rivers. Other elements associated with these core elements may include precipitation, streamflow, storage, infiltration, evaporation, water conveyance, water treatment, water use, and water reuse. The model tracks water movement within a network of elements such as water sources, sources of pollution, routes for water and waste conveyance, storage and treatment infrastructure, water users, etc.

The current version of the DyWaBM consists of a GIS sub-model implemented in a network sub-model built in Microsoft Point and a computation sub-model using Microsoft Excel spreadsheet with visualisation capabilities. The model can be driven by historical (observed) and forecast data. Input data includes time series data, initial values, lower and upper limits, water demand, population and production data and various coefficients. Forecast rainfall is one of the important input parameters, and it is at a daily time scale. Flow rates in streams and conveyance systems are calculated as volumes per second.

The output comprises tables and graphs of indices derived for observed and future scenarios showing the following:

- Yield from each source per day versus total daily demand – adequacy of water resource
- Yield from available per day from each alternative source of water
- Yield available per day for each sub-zone from each source
- Water supplied to each sub-zone per day as percentage of daily demand – measure of deficit experienced
- Maximum daily supply level and days at maximum supply for each sub-zone
- Minimum supply level and days at minimum supply for each sub-zone
- Number of days supplied from rainfall harvesting with available storage
- Days and maximum water supply level with rainwater harvesting
- Number of days when water is available from rainwater harvesting

With output at a daily time-step, the DyWaBM describes the extent of a challenge, and possible interventions can be identified, tested, and evaluated in terms of potential impact on defined users, including the ecology. It implements water balance assessments at the demand/consumption point instead of the conventional practice of assessing water balance at the source.

Indices are applied to evaluate different conditions a month in advance (i.e. whether a supply deficit or surplus is to be anticipated) for simple and indeterminate networks based on the current state and defined future conditions while considering system features and constraints. The DyWaBM is not all about formulating equations. It's about allowing model users to intuitively understand complex systems, the relationships between parameters and system behaviour, and test possible solutions. Simulations are performed for system components, obtaining daily values for a month using the mathematical formulations. Previous runs can be used to determine possible changes to the system components characteristics and relationships. This may involve the following:

- Changing equations
- Changing parameter values
- Introducing new elements/connectivity
- Implementing forecasting procedure
- Implementing of learning algorithms

Typical modelling steps are as follows:

- Defining water supply zones and sub-zones
- Defining the water supply system network components, connectivity and constraints
- Formulating equations
- Obtaining results for each sub-zone and zone from automated simulation runs with new data or when scenarios are activated.

The DyWaBM produces results at a daily time-step. Weekly and monthly reports can be produced for decision support.

1.4 Purpose of this document

The following documents were produced on this study:

1) Project Inception Report (Deliverable 1)
2) Water system configuration and baseline data (Deliverable 2)
3) Water quality methodology and baseline data (Deliverable 3)
4) Climate change and risks methodology and baseline data (Deliverable 4)and
5) Status of monitoring system and recommendations (Deliverable 5)

The purpose of this document is to present results from deliverables 2 to 5 above, final results from model runs, the updated DyWaBM procedure, outline the capacity building activities undertaken and provide an indication of further research work required

CHAPTER 2: BASELINE DATA AND DYWABM WATER SYSTEM CONFIGURATION

2.1 Introduction

This chapter is focused on baseline information for setting up the DyWaBM for the STLM water supply system. It describes (a) the procedure implemented in delineating the STLM into GIS elements for the DyWaBM and presents the results and (b) the procedure implemented in defining the DyWaBM water supply system network components, connectivity and constraints. The basic water system configuration developed is presented.

2.2 Selection of study area

Readily available data was used to quickly obtain an overview the main features and decide how best to align administrative and water resource management spatial frameworks as data sources for the DyWaBM and engagement with water resources and water supply managers on model outputs. This was also critical for access to data, the involvement staff from STLM and other stakeholders. The study area was defined as the area bounded by quaternary catchments B12A to B12E in the Upper Olifants Catchment as shown in **Figure 2.1**. About 93% of the study area is within STLM and covers 56% of STLM. In practical terms data collection and review covered most of the upper Olifants River catchment. The study area is part of the Mpumalanga Highveld where several rivers and streams originate. This region is known for high annual rainfall (714 mm) and high-water table. A significant portion of its runoff drains to pans, reducing the total runoff draining into dams. For example it is estimated that while the total catchment area for Middelburg dam is 1576 km^2, its effective drainage area is about 1401 km^2.

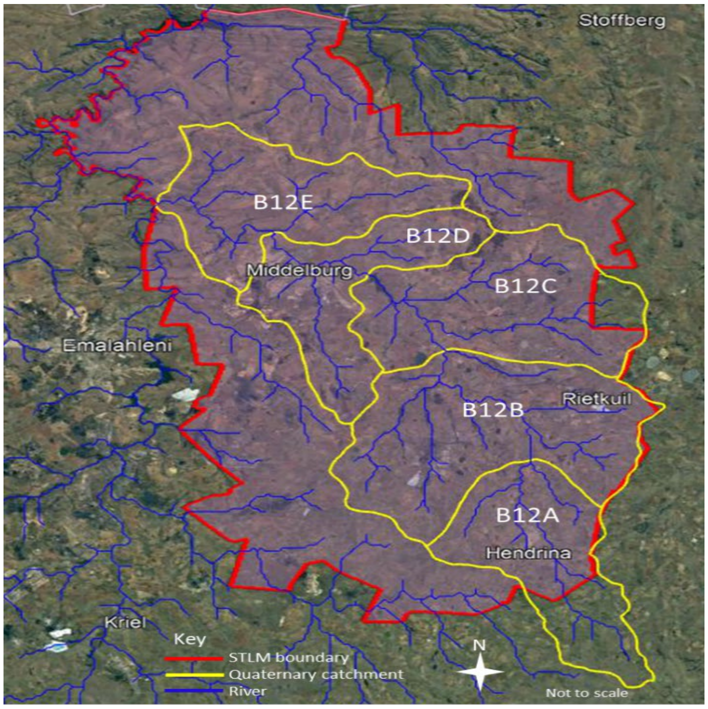


Figure 2.1: Study area

2.3 Land use

The main land use features are Farms, Industry, Mines, Power stations and Settlements.

2.3.1 Farms

Cadastral maps produced by the Surveyor General were reviewed online (https://csggis.drdlr.gov.za/psv/). Parent farm data was found to be relevant for the study. The available data set has 159 parent farms and 14 more were added as best estimates from Google Earth Pro (labelled X1 to X14) to have complete coverage of the study area. More up to date data was obtained from the Surveyor General. Farms are important sources of water, users of water and sources of pollutants. They may also provide primary treatment of water. The map in **Figure 2.2** was plotted in Quantum Geographic Information System (QGIS).

STLM has a range of agricultural activities, including animal grazing, feedlots, land cultivation and poultry production. Cattle farming occurs extensively throughout the municipality. The Southern and flatter parts are under crop production, including maize, soybeans, sorghum and potatoes. The mountainous northwestern region is predominantly under game farming. Irrigation is practised between Komati and Pullens Hope and between Pullens Hope and the N4. Deciduous fruits and horticulture are clustered north from the N4 towards KwaMakalane and even up to Doornkop (STLM, 2019).

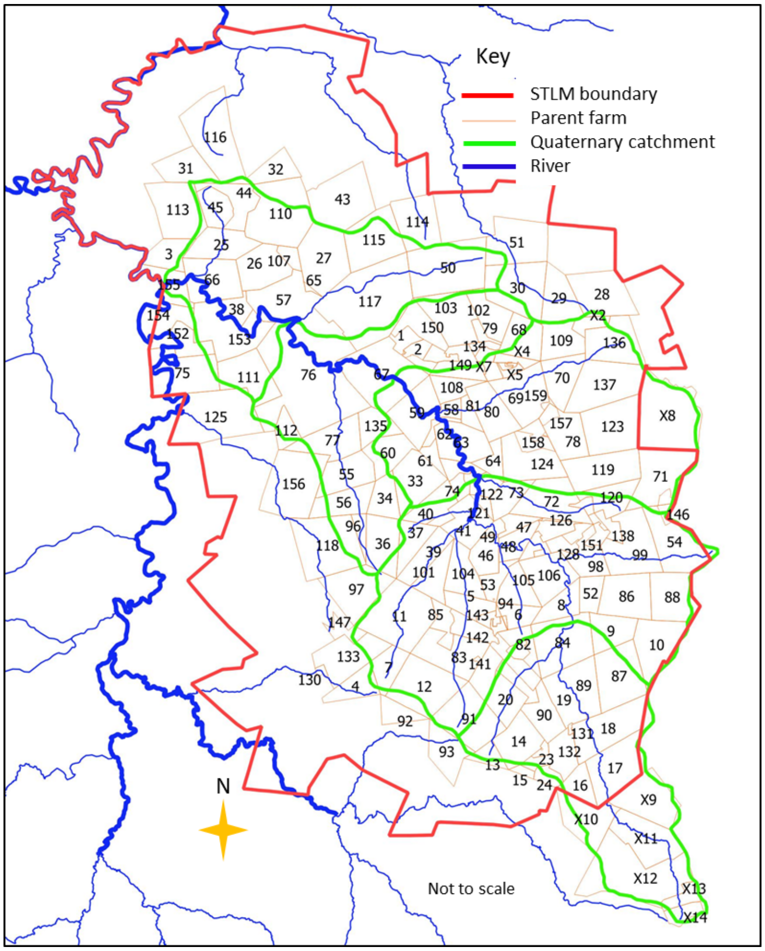


Figure 2.2: Cadastral data – Parent farms

2.3.2 Industry, mines and power stations

Four major industries, 25 mines and 2 power stations were identified and digitised on Google Earth Pro. The locality is shown in **Figure 2.3**. Some of the more commonly known mines are as follows:

- (i) 1 and 2 – Hakhano coal mine,
- (ii) 4 – Graspan-Elandspruit-Yoctolux colliery complex,
- (iii) 5 and 6 – Shanduka Townlands colliery,
- (iv) 16 – Woestaleen colliery and
- (v) 23 – Optimum coal mine

The Wescoal mining complex, associated with a water reclamation, is outside the study area. Mines are important water users and sources of pollutants and can be water sources. Columbus Stainless Steel is industry 2.

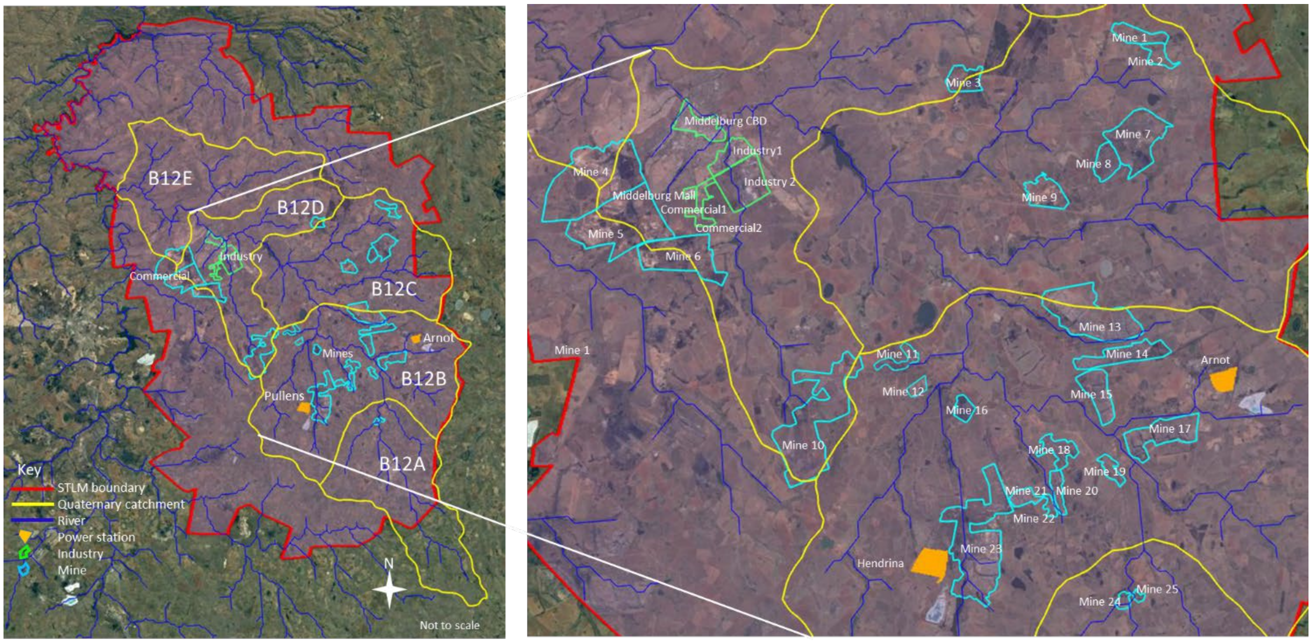


Figure 2.3: Google Earth – Industries, mines and power stations

2.3.3 Settlements

Six relatively large settlements identified on Google Earth Pro are shown in **Figure 2.4**. The largest settlement is Middelburg town, which is divided into 17 water supply areas following development boundaries and refined by topography and water courses.

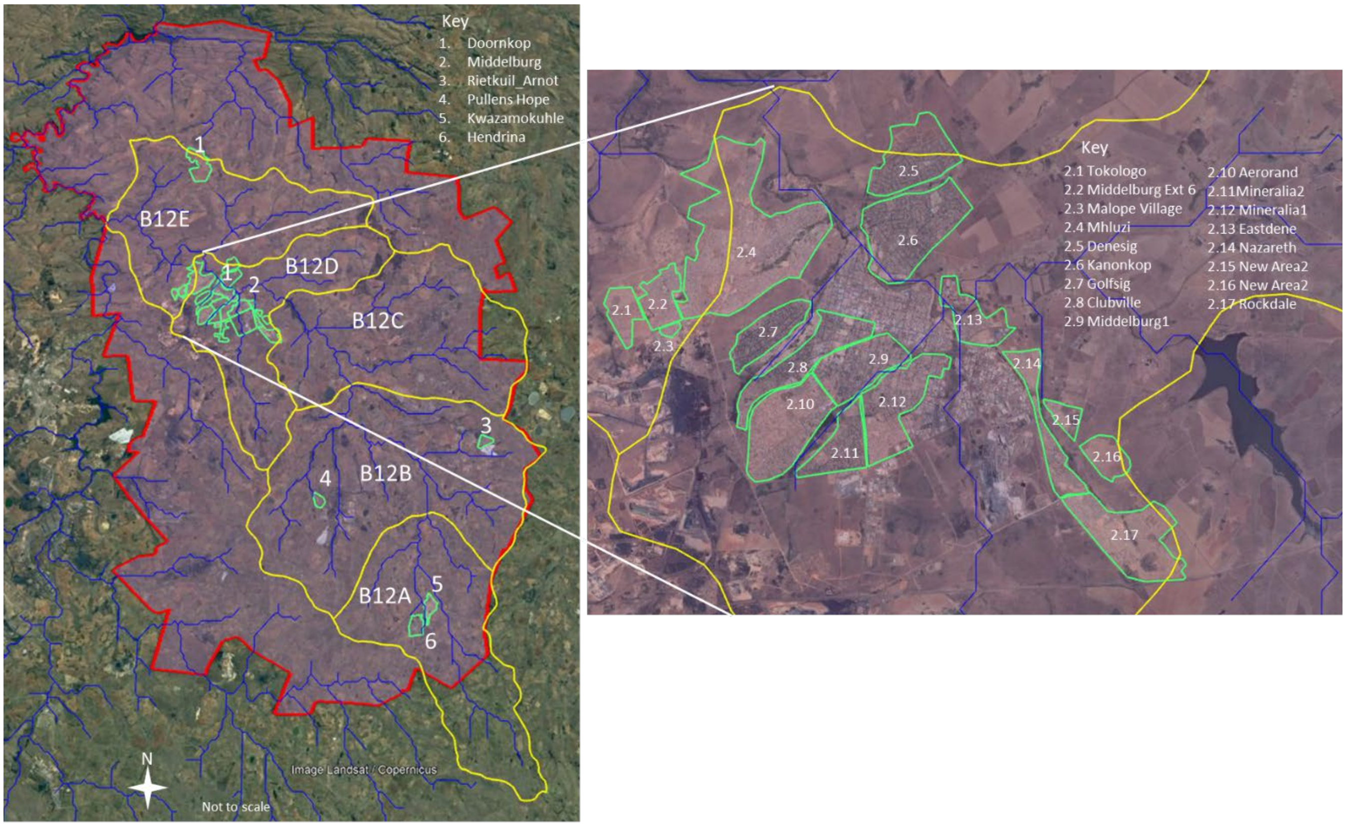


Figure 2.4: Google Earth – Settlements

Water supply zones and sub-zones wild be defined based on existing studies and analysis of the emerging system network. Demand centres will be determined and elevation data will be extracted from Google Earth.

2.4 Water resources

The main features are catchments, rivers, dams, rainfall stations, flow gauging stations and water quality monitoring points

2.4.1 Catchments, rivers and dams

The following four datasets for rivers were reviewed:

- (i) DWS primary and secondary rivers
- (ii) DWS IQS 1:500 000 rivers
- (iii) SANBI NFEPA rivers (2011) and
- (iv) Hydrosheds Africa HydroRivers version 10

The Hydrosheds data set was the best option regarding coverage and accuracy. The fields and stream numbering are also relevant for this study; therefore, they were adopted. The HYRIV_ID field can be used as the association field. Each river or river section can be associated with its catchment area. The DyWaBM associates a dam with a river/river section. A dam has inflow and outflow nodes in river/river section areas. There is no limit to the number of dams we can associate with a river/river section. Most of the dams in the study area are associated with mines and farms. Arnot and Hendrina power stations have ash dams. The river network and dams identified by Google Earth Pro are shown in **Figure 2.5**.

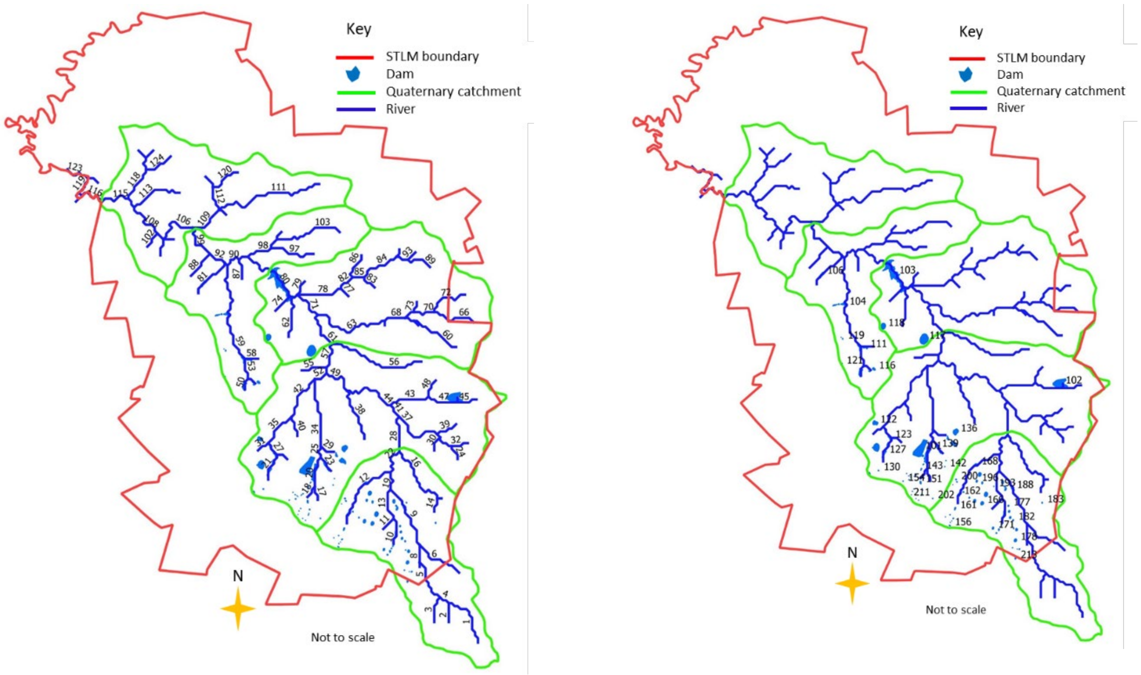


Figure 2.5: C**atchments, rivers and dams**

2.4.2 Rainfall stations and flow gauging stations

The study area has only two flow gauging stations. Station B1H012 is upstream of Middelburg Dam, and B1H015 Is just downstream of the dam. The flow monitoring stations have been open since 1978. The DWS monitors water levels in Middelburg Dam. Twenty-one rainfall stations were identified from the SAWS database. The location of the identified rainfall and flow monitoring stations is shown in **Figure 2.6**. While only two of them are open, it is still possible to get observed and forecast data from internet sources such as Yr, SAT24 and JAXA and for forecasts, SADC Climate Services, NOAA CPC GEFS and NOAA CPC GFS.

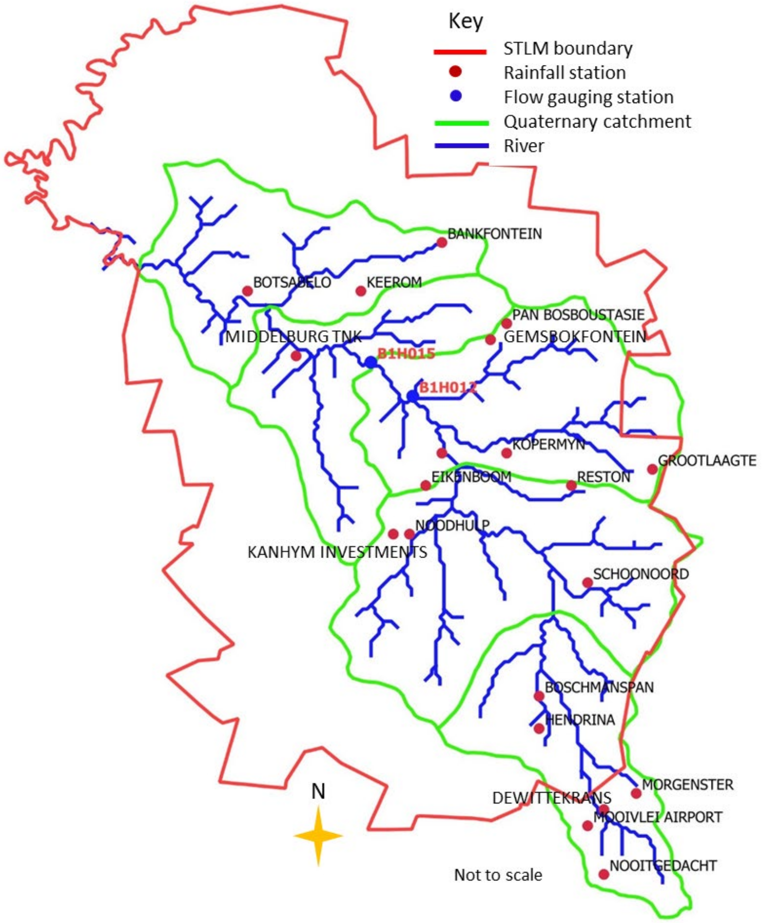


Figure 2.6: Rainfall and flow monitoring stations

2.4.3 Water quality

Water in the system contains a wide range of physical, chemical and biological materials in solution or suspension. Physical materials include silt and clay. Biological materials include algae and plants. Chemicals include calcium, magnesium, iron, nitrogen, phosphorous and manganese. Waste from domestic, agricultural, industrial, energy, and mining activities affects water's physical, chemical and biological characteristics. Within a system, water is used, polluted, treated, re-used, passed on, returned, or transferred to other systems. The condition or quality of the water describes its chemical, physical, and biological characteristics concerning the suitability of its use for a particular purpose. STLM water and wastewater treatment plants are also included as monitoring/sampling points. Water quality monitoring is generally done for compliance requirements associated with discharge permits. Some of the variables of concern are Suspended Solids, COD, Nitrates, Free and Saline Ammonia, Ortho-phosphates, pH and faecal coliforms.

The DyWaBM is data-driven and water quality data is one of the drivers. Therefore, it is very important to get a firm grasp on monitoring and confirm how data will be obtained. A planned site visit was rescheduled because of a strike in STLM. Several engagements were done with major water users and information was obtained on wastewater discharge and water quality monitoring points. Existing water quality monitoring points were compared with monitoring requirements to drive the DyWaBM. The site visits also established the following:

(a) status of monitoring point (active/closed)
(b) parameters being monitored and frequency of monitoring
(c) who conducts the monitoring (names of people and contact information)
(d) how monitoring is done (this will help us figure out how the data will be fed into the model)

2.5 Bulk water and wastewater infrastructure

The main features are diversion/abstraction infrastructure, pumping stations, raw water mains, water treatment plants, treated water mains, reservoirs, bulk distribution pipelines bulk wastewater mains and wastewater treatment plants. This includes reservoirs and pumps for raw water and treated water as well as points for wastewater.

2.5.1 Schemes operated by STLM

The schematic diagrams for the Middleburg-Mhuzi and Hendrina-Kwazamokuhle water supply systems obtained from the Nkangala District Water Serviced Development Plan (undated) are shown in **Figure 2.7** and **Figure 2.8**. The diagrams were redrawn with DyWaBM network elements.

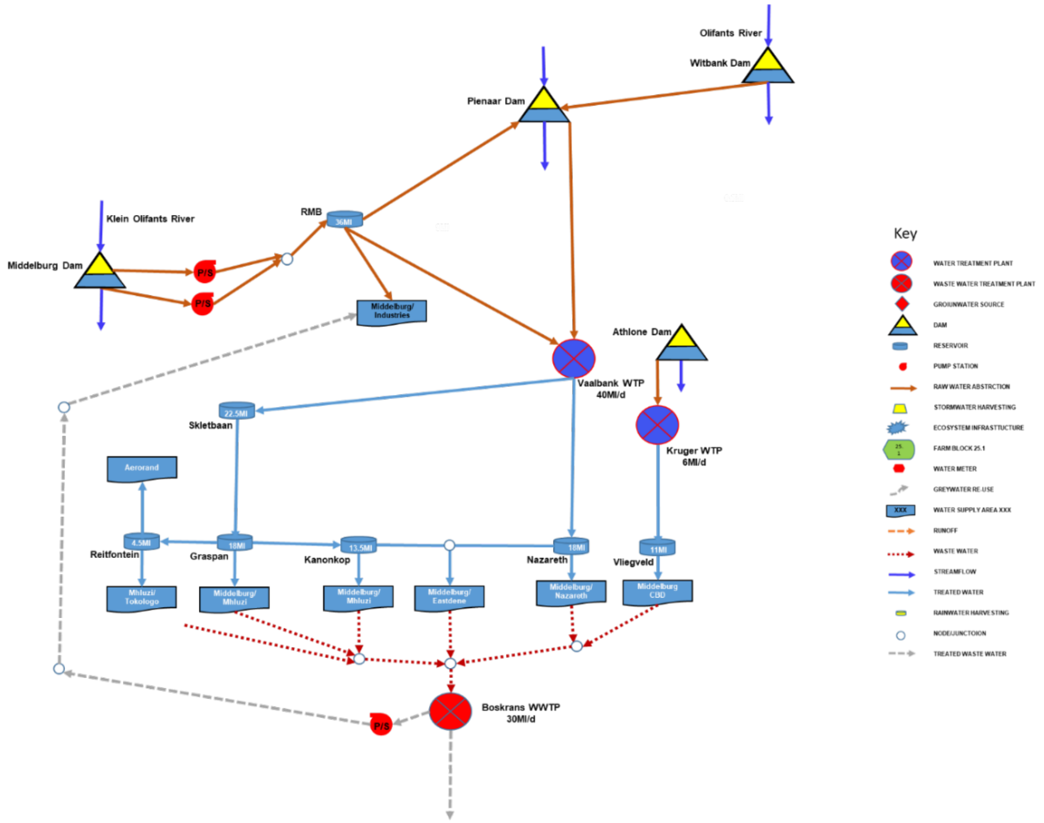


Figure 2.7: Middleburg-Mhuzi water supply system

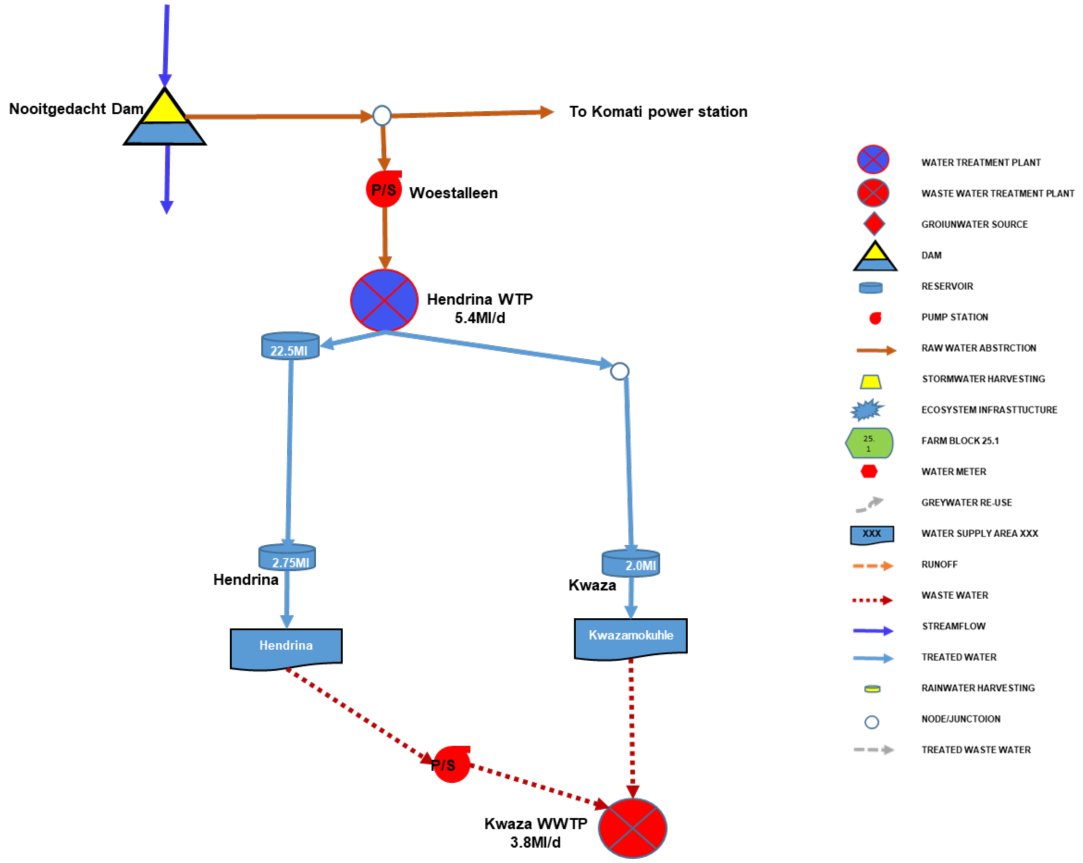


Figure 2.8: Hendrina – Kwazamokuhle water supply system

(a) Sources of water

Middelburg is supplied with water from the Middelburg Dam situated on the Klein Olifants River. The dam can supply 36 438 m^3/day. A raw water pump station at Witbank dam and a pipeline from Witbank dam to the Pienaars dam supply additional water to the Middelburg-Mhuzi water supply system. The yield from the main dams is as follows:

(i) Middelburg – 11.3 Million m^3
(ii) Athlone – 0.219 Million m^3
(iii) Pienaar – 0.999 Million m^3 and
(iv) Witbank – 28.1 Million m^3,

(b) Water and sanitation services

The STLM covers an area of approximately 3,976.42 km^2, with a population of 229,831 in 2011 (StatsSA, 2011) and is estimated to have gone up to 278,749 by 2016 (Statistics South Africa, 2017). A projected growth rate is 4.38% and by 2040, it is estimated the population may be 646 637 (STLM 2019). According to the StatsSA, 2016 Community Survey, 81.9% of households had access to potable water (household connections and communal stands) and 85.4% had flush and chemical toilets. Most rural households utilize boreholes (41.1%) and water tankers (10.1%) as water sources, while 39.7% obtained water from a regional/ local water scheme operated by a municipality or other water services provider. The municipality has extensive water and sanitation backlogs. Water demand is growing; the main water users are industry, mines, power stations, and urban and agricultural users. About 11.3 Million m^3/year is registered for domestic abstraction. Kanhym feedlot uses approximately 0.22 Million m^3/year from the Boskrans wastewater treatment plant (WWTP). Columbus Stainless Steel uses raw water from the Middleburg dam (0.37 Million m^3/year) and treated sewerage effluent from the Boskrans WWTP (0.22 Million m^3/year). Middleburg ferrochrome utilizes 0.24 Million m^3/year of potable water supplied by the local municipality and approximately 0.19 Million m^3/year of treated sewerage water. According to the DWS the projected water demand for the low and high growth scenarios is 15.50 Million m^3/year and 16.99 Million m^3/year, respectively. Both scenarios, water demand exceeds available yield without factoring in climate change impacts. The water-food-energy nexus plays out in the STLM as runoff from this area feeds into the Loskop Dam, a water source for the 1900 ha Loskop irrigation scheme. With intermittent energy supply, increasing quantities of effluent and declining river flows driven by escalating demands for water, water quality problems now occur more frequently (Bruwer and Ashton (1989), Ashton and Dabrowski (2011)). Variable and changing hydro-climatic conditions, increasing water demand and pollution pose serious risks to consistently meeting current and future water needs. Nkangala District Municipality's Water Master Plan (2017) mentions that high water losses and poor sewage treatment are major challenges for STLM.

(c) Water and wastewater treatment infrastructure

There are two water treatment plants (WTP) servicing the Middelburg – Mhluzi water supply area, namely Vaalkop WTP (capacity of 16.06 Million m^3/year) and Kruger WTP (capacity of 2.19 Million m^3/year). Reclamation and use of mine water is being encouraged to cut back on pollution levels. Anglo-American, BHP, Middelburg and Shanduka Mines have been treating mine water. Boskrans wastewater treatment plant (WWTP) has a treatment capacity of 10.95 Million m^3/year, and the Kwazamokhule WWTP has a treatment capacity 1.4 Million m^3/year.

(d) Water quality

Severe water quality problems are experienced due to pollution from coal mining activities. Pollutants such arsenic, barium, cadmium, chromium, iron, lead, vanadium, manganese, mercury and sulphates are associated with mining activities. The discharge of treated, partly treated and untreated effluents from mines, power stations (coal fired-water cooled), industries and sewage treatment plants, combined with seepage of acidic mine drainage from several active and abandoned coal mines, contribute nutrients, salts and metal ions and microbial contaminants to the river system. The degradation quality of water in rivers, dams and groundwater is in South Africa is posing serious threats to river ecosystems and human health and if the current trend is allowed to continue regional and international conflicts may arise in future.

2.5.2 Schemes operated by other water services provider.

Irrigated agriculture and mines obtain water from other sources, including local resources. These sources will be confirmed during site visits and meetings with stakeholders.

2.6 Schematic model components

2.6.1 Procedural notes

A system schematic describes the movement of water from source to sink (and from sink to source); storage/retention and the various interconnected features. The DyWaBM network elements applied to the Ketlengrivier Local Municipality (KLM) study are shown in **Figure 2.9.** Network elements are the building blocks for a system model. They include catchments, streamflow, groundwater, overland flow, ecological infrastructure, dams, meters, gauges, water quality monitoring stations, raw water abstraction, water treatment plants, treated water, reservoirs, tanks, pump stations, water user by type, stormwater harvesting, rainwater harvesting, grey water reuse, wastewater treatment plants, treated wastewater, wastewater and connector nodes. Network elements are defined from GIS shape files.

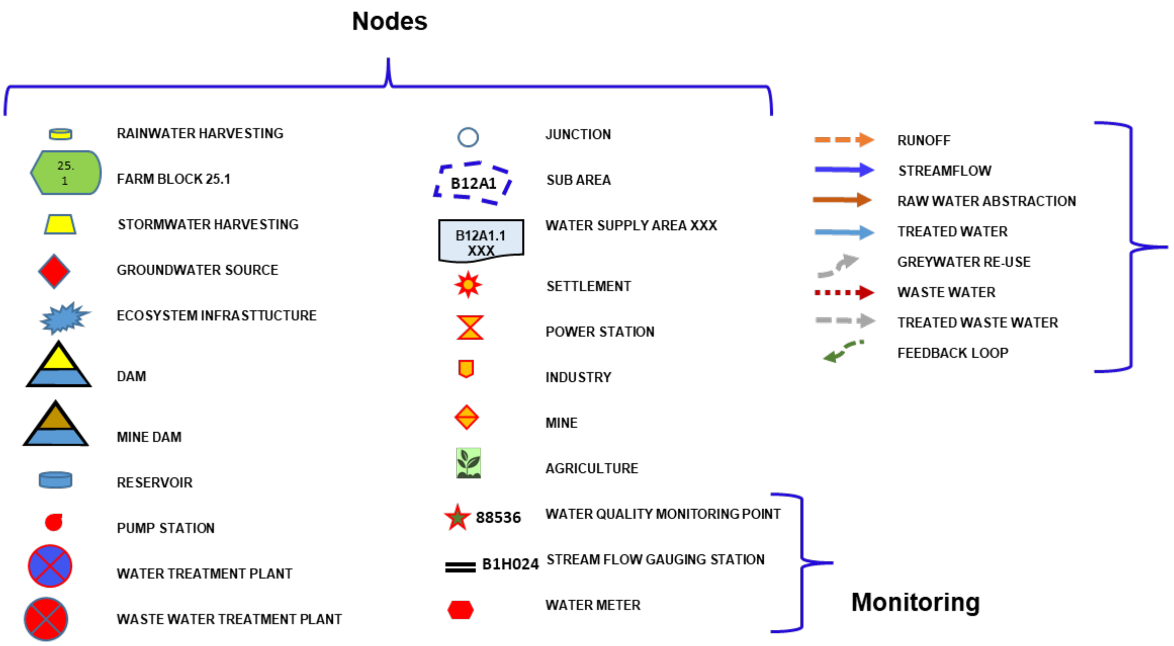


Figure 2.9: DyWaBM network elements

This set of elements was reviewed against the baseline information on Land use, Water Resources and Bulk water and wastewater infrastructure in terms of adequacy and completeness. New elements were added for mines, power stations, industry and settlements. Dams can be water supply dams or mine dams.

Most of the land use activities rely on streamflow. The data on rivers adopted for this study allows water accounting on river sections. The first step in defining the water supply area for the STLM was to determine nodes on the main stem of the Klein Olifants River as water accounting points. Altogether 23 nodes were defined and each was allocated an “M” number starting with M101. The second step was to determine nodes on tributaries as water accounting points. Altogether 17 nodes were represented, and each was allocated a “T” number starting with T101. The water accounting nodes are shown in **Figure 2.10**. These steps were implemented on Google Earth Pro. Updates were done as the study progressed.

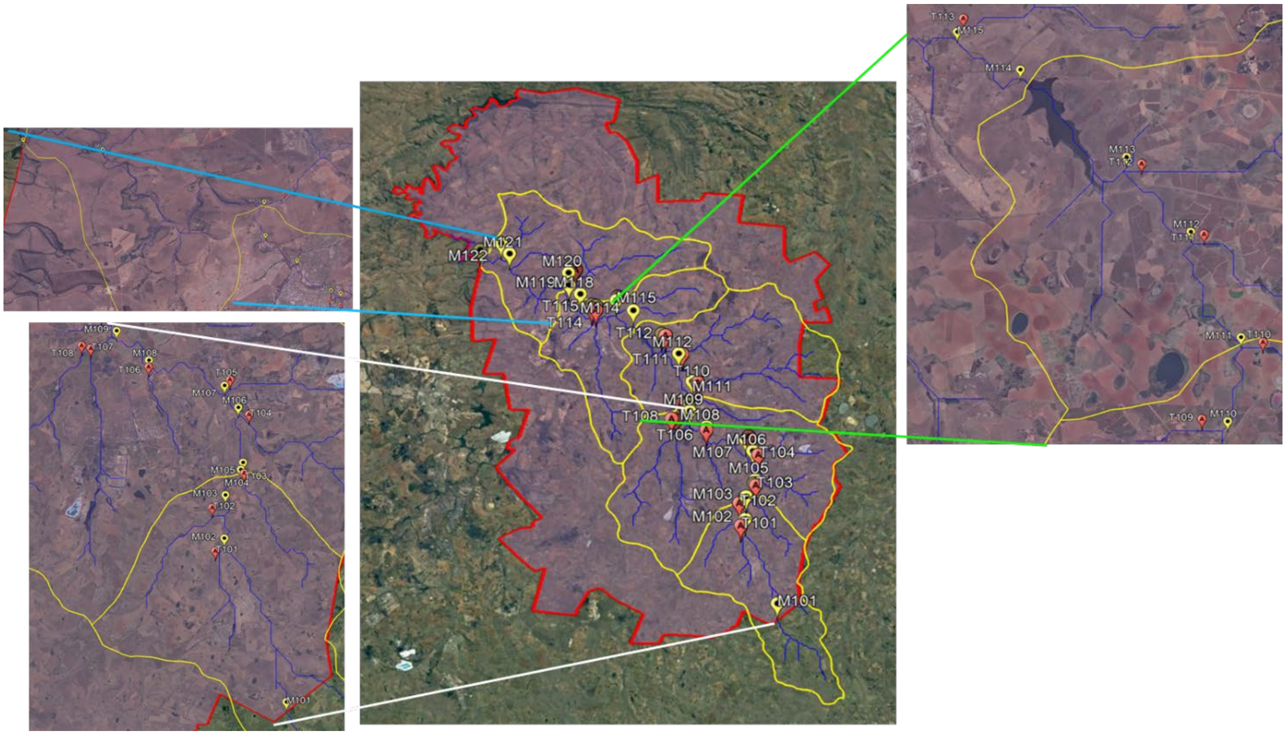


Figure 2.10: Water accounting nodes

These nodes were the basic elements to define the model schematic diagram.

2.6.2 Basic model schematic diagram

The basic model schematic diagram in **Figure 2.11** was developed. This model network diagram was updated progressively.

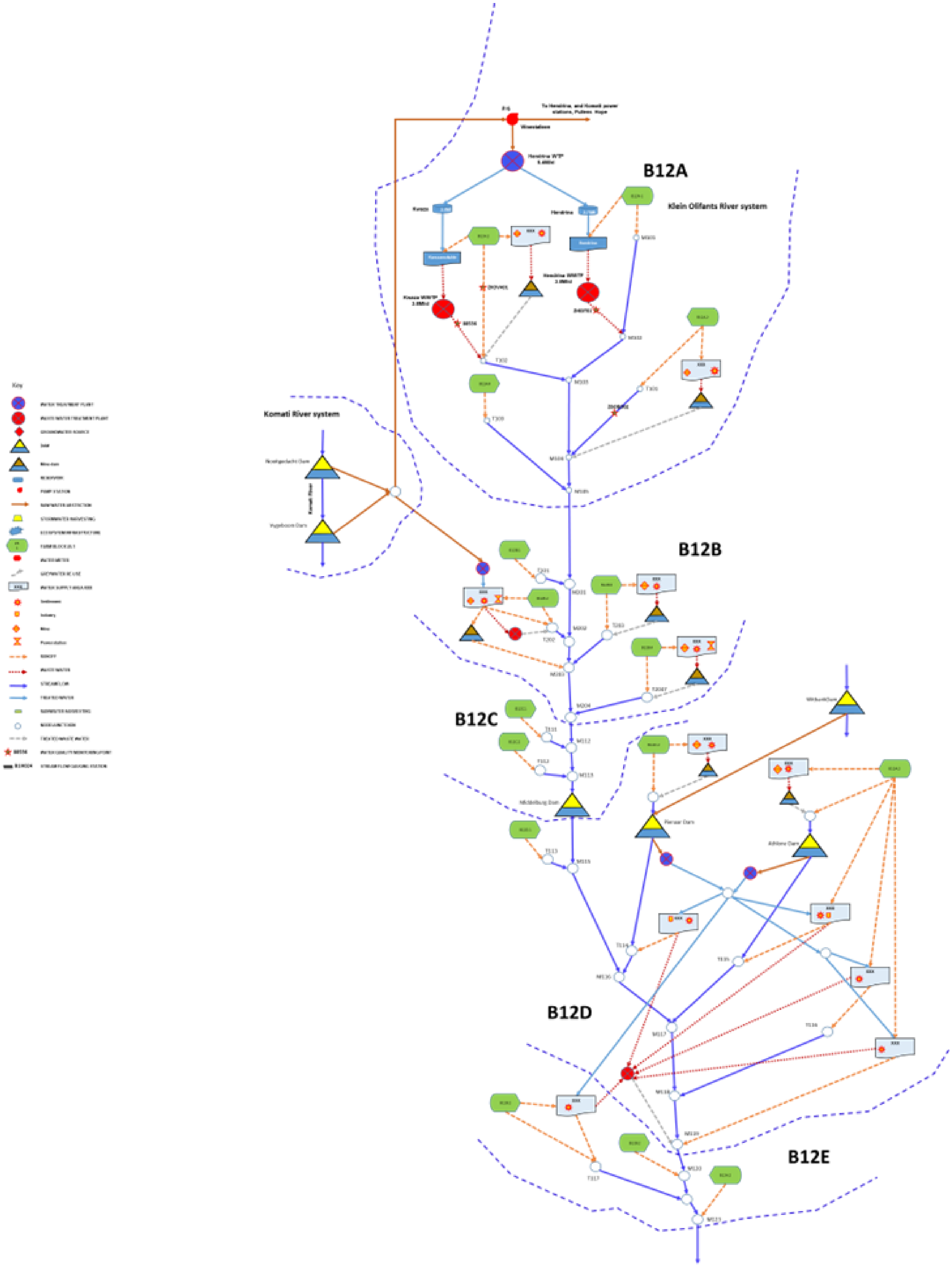


Figure 2.11: Basic model schematic diagram

CHAPTER 3: STATUS OF THE EXISTING MONITORING SYSTEMS

3.1 Introduction

For the DyWaBM to be properly tested and enhanced for practical use the following input data should be readily available. Tracking storage, movement and quality of water involved the following parameters:

1) Climatic parameters – daily rainfall totals and daily temperature (minimum and maximum) measurements
2) Flow rates – daily streamflow flow measurements and daily water meter readings
3) Water levels – daily reservoir/dam water levels and
4) Water quality – parameters of concern at daily and sub-daily time intervals

On climatic parameters the DyWaBM applies the following methodology for incorporating climate risk as described in Nyabeze and Makungo (2022):

- Seasonal climate forecast
    - Seasonal climate forecast are applied together with statistics of historical monthly data to develop basic monthly projections. The projected total annual precipitation/evaporation and 4th order regression equation are used to estimate median monthly precipitation/evaporation.
    - Southern African Regional Climate Outlook Forum (SARCOF) and South African Weather Services (SAWS) seasonal forecasts for the period October to March are applied.
- Monthly projections
    - For the selected month the representative greenhouse gas concentration pathways (RCPs) RCP4.5(lower emissions) and RCP8.5(highest emissions) scenario projections are applied to obtain change in the following parameters:
        - daily values for rainfall, evapotranspiration, maximum temperature and minimum temperature
        - total monthly rainfall
        - total monthly evapotranspiration
        - average maximum monthly temperature and
        - average minimum monthly temperature
    - For the selected month changes to the baseline (climate normal) are used to obtain the median to middle third bounds are obtained for the cumulative rainfall and evapotranspiration
    - For the selected month changes to the baseline (climate normal) are used to obtain median and middle third bounds for the average monthly minimum and maximum temperature
- Short-term weather forecasts
    - 7-14 days ahead forecast period were tested in Nyabeze and Makungo (2022) for Arnot, Hendrina Power station, Mhluzi and Middelburg CBD
- Observed data can be used to review results obtained from these methods.

Tracking flow rates and storage considers the following model elements:

- Streamflow
- Water treatment plants (inflow and outflow)
- Reservoirs (inflow, storage and outflow)
- Water supply areas (inflow)
- Water supply zones and sub-zones (inflow)
- Wastewater treatment plants (inflow and outflow)

The following observations were recorded in the baseline report (dam (Nyabeze et al., 2021):

- There are only two streamflow flow gauging stations in the study area namely B1H012 is upstream Middelburg Dam and B1H015 just downstream of the dam (Nyabeze et al., 2021).
- The Department of Water and Sanitation (DWS) monitors water levels for Middelburg. Nooitgedacht and Vygeboom dams
- 21 rainfall stations were identified from the SAWS database but only two only two of them are still open namely Middelburg Tank and Kanhym Investments
- 32 water quality sampling points were identified. However, information was required on: the status of the monitoring point (active/closed), parameters being monitored and frequency of monitoring, who conducts the monitoring (names of people and contact information) and how monitoring is actually done

Tracking water quality considers the following model elements:

- Streamflow
- Water treatment plants (inflow and outflow)
- Reservoirs (in storage)
- Water supply areas (inflow)
- Water supply zones and sub-zones (inflow)
- Wastewater treatment plants (inflow and outflow)

The enhanced DyWaBM considers a quaternary catchment as a water resource system to account for water resources, which is divided into sub-catchments. Several water supply systems can be located within a sub-catchment and a water supply system can have water supply zones and sub-zones. Model elements (see **Figure 3.1**) describe water supply network components. Water system network diagrams represent the connectivity model elements. These were developed in Deliverable 2 and further improved in Deliverables 3 (Nyabeze et al., 2022) and Deliverable 4 (Nyabeze and Makungo, 2022).

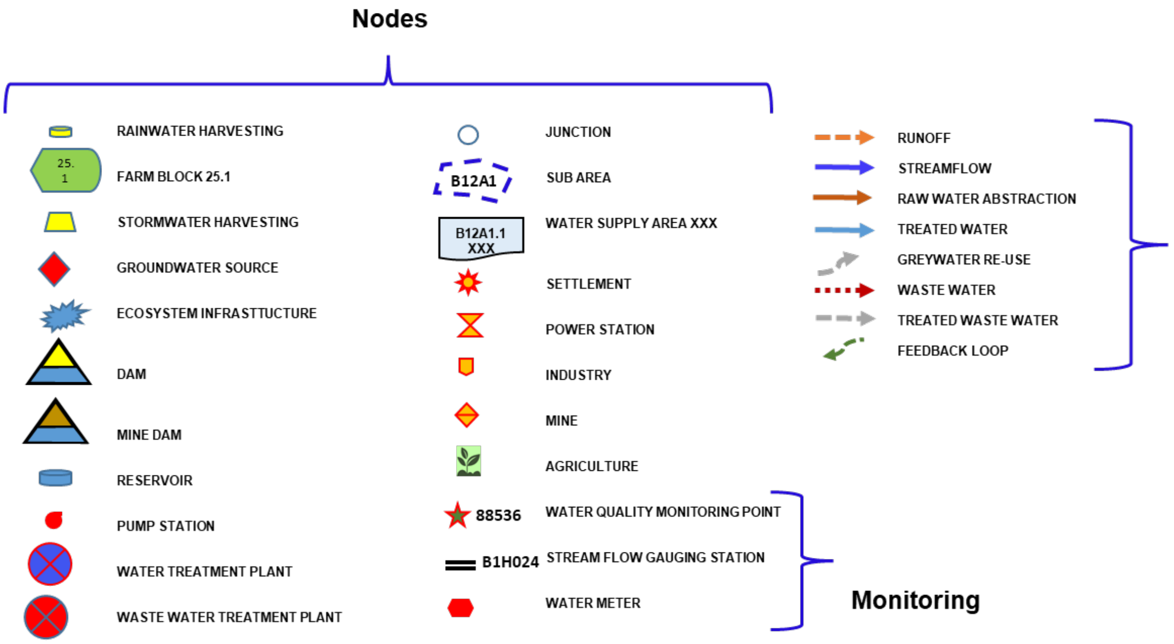


Figure 3.1: Model elements

Of the five quaternary catchments B12A, B12B, B12C, B12D and B12E, the first four were modelled as separate water resources systems while B12D and B12E were combined to form one water resource system because they are connected to the same water resource, water use and wastewater treatment elements or components.

The monitoring system for each of these water resource systems was assessed against the monitoring requirements in terms of adequacy of coverage of parameters and model elements (system components) that require monitoring and also considering reliability of monitoring systems, cost-efficiency and convenience. Available data was requested from STLM, Eskom, Mining and Industry. Through this exercise, water managers in STLM and major users were engaged in discussions on the usefulness of the datasets and the need for improved and sustainable monitoring. Results from the review of the adequacy of the existing monitoring are presented in the following section.

The purpose of chapter is to present the data requirements for the DyWaBM and evaluate the adequacy of the existing monitoring system.

3.2 B12A Water resource system

Figure 3.2 shows the connectivity of the water supply network elements and where monitoring flow, water levels, and water quality is required. The network diagram was updated to include (i) supply to Kwazamokuhle from the Hendrina reservoir and (ii) the Hendrina wastewater oxidation ponds.

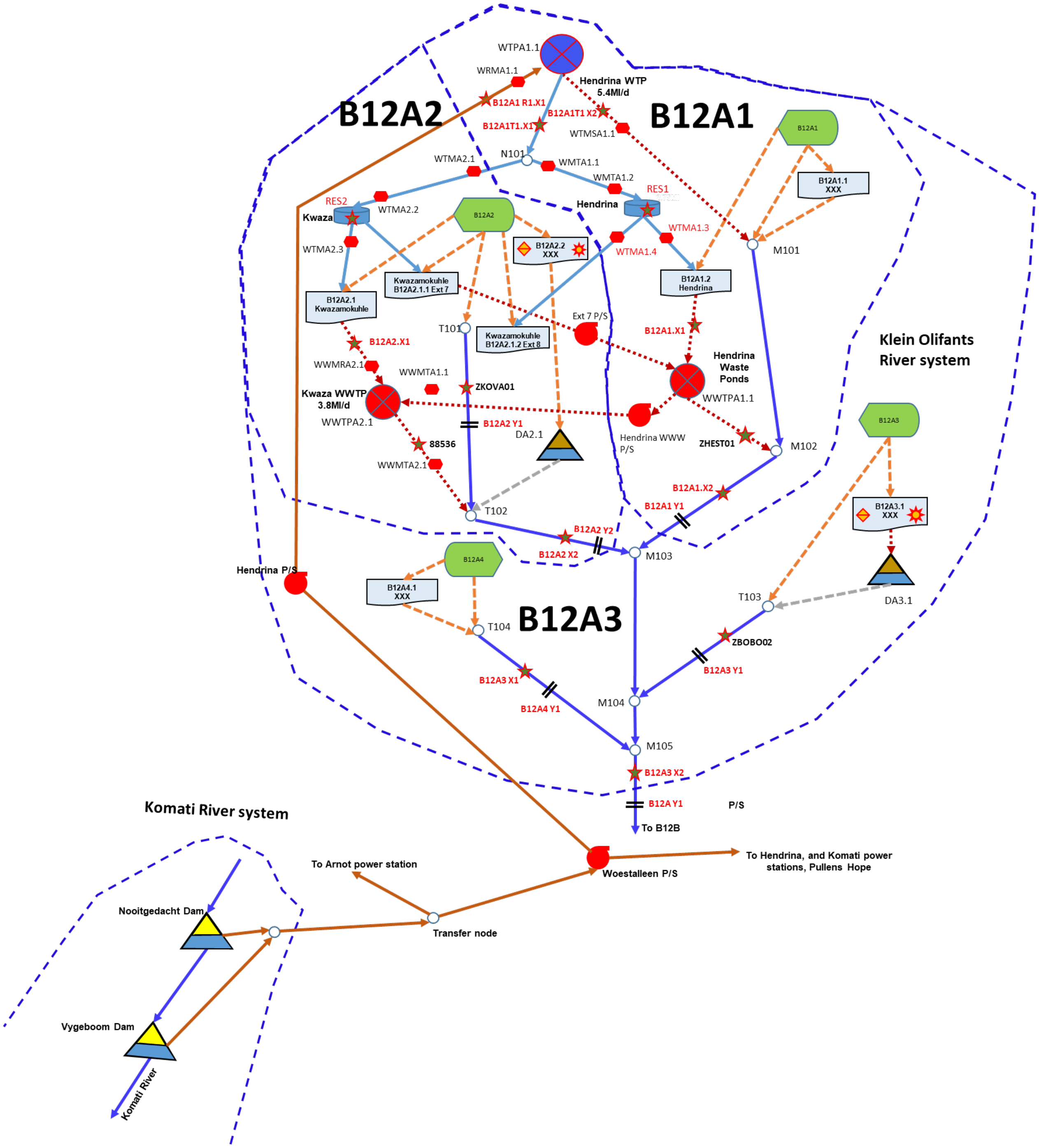


Figure 3.2: B12A-Network diagram and monitoring requirements

3.2.1 Climatic parameters

Climate data is required for Kwaza and Hendrina, but there are no equipped stations at these locations. The water and wastewater treatment plants may be the best sites for the municipality. Forecasts can be generated 14 days ahead for Arnot, Hendrina Power station. The nearest rainfall station is Kanhym Investments.

3.2.2 Flow rates

Table 3.1 lists the 6 streamflow gauges required for the model. There are no streamflow gauges in the B12A water resource system.

Table 3-1: Streamflow gauges

Station ID	Name	Upstream	Downstream	Status
B12A1 Y1	Streamflow B12A1.1	M102	M103	Does not exist
B12A2 Y1	Streamflow B12A1.2	T101	T102	Does not exist
B12A2 Y2	Streamflow B12A1.2	T102	M103	Does not exist
B12A3 Y1	Streamflow B12A1.3	T103	M104	Does not exist
B12A4 Y1	Streamflow B12A1.4	T104	M105	Does not exist

Table 3.2 lists the 12 water and wastewater flow meters required for the model. The status of monitoring is also indicated.

Table 3-2: Bulk water and wastewater infrastructure

Meter ID	Description	Upstream	Downstream	Status
WRMA1.1	Inflow Hendrina WTP	Woestalleen P/S	Hendrina WTP	Monitored daily
WMSA1.1	Sludge to stream	Inflow Hendrina WTP	M101	Does not exist
WTMA1.1	Ouflow from N101 to Hendrina Res	N101	WMTA1.1	Monitored daily
WTMA1.2	Inflow Hendrina Res	WMTA1.1	Hendrina Res	Monitored daily
WTMA1.3	Supply to Hendrina	Hendrina Res	Hendrina	Monitored daily
WTMA2.1	Outflow from Outflow from N101 to Kwaza	N101	Kwaza Res	Monitored daily
WTMA2.2	Inflow Kwaza Res	WMTA2.1	Kwaza Res	Monitored daily
WTMA2.3	Supply to Kwaza	Kwaza Res	Kwaza	Monitored daily
WWMRA1.1	Inflow Hendrina WWTP	Hendrina	Hendrina WWTP	Monitored daily
WWMTA1.1	Outflow Hendrina WWTP	Hendrina WWTP	M102	No flowmeter
WWMRA2.1	Inflow Kwaza WWTP	Kwaza	Kwaza WWTP	Monitored daily
WWMTA2.1	Outflow Kwaza WWTP	Kwaza WWTP	T102	Monitored daily

3.2.3 Water levels

Table 3.3 lists the 4 dams 2 reservoirs which should be monitored for the model. The DWS monitors water levels for Nooitgedacht and Vygeboom dams. The municipality monitors water levels for Middelburg Dam.

Table 3-3: Dams and water supply reservoirs

Reservoir ID	Description	Status
RES1	Hendrina Res	Does not exist
RES2	Kwaza Res	Does not exist
DA2.1	Small dams	Does not exist
DA3.1	Small dams	Does not exist
	Nooitgedacht Dam	Weekly monitoring
	Vygeboom Dam	Weekly monitoring

3.2.4 Water quality

Table 3.4 lists the 15 water quality sampling points required for the model. For some points, the frequency of monitoring is weekly but sometimes drops to monthly.

Table 3-4: Water quality

Sampling Point	Description	Upstream	Downstream	Status
B12A1R1.X1	Inflow Hendrina WTP			Weekly and monthly
B12A1T1.X1	Hendrina WTP to Hendrina + Kwaza		N101	Weekly and monthly
B12A1T1.X2	Hendrina WTP to streamflow		M101	Does not exist
RES1	Hendrina Reservoir			Weekly and monthly
RES2	Kwaza Reservoir			Weekly and monthly
B12A1.X1	Inflow Hendrina WWTP	Hendrina	Hendrina WWTP	Daily
ZHEST01	Outflow Hendrina WWTP	Hendrina WWTP	M102	Daily
B12A1.X2	Klein Olifants streamflow	M102	M103	Does not exist
B12A2.X1	Inflow Kwaza WWTP	Kwaza	Kwaza WWTP	Daily
88536	Outflow Kwaza WWTP	Kwaza WWTP	T102	Daily
B12A2.X2	Outflow B12A2	T102	M103	Does not exist
ZKOVA01	Streamflow B12A2	T101	T102	monthly
ZBOBO02	Streamflow B12A3	T103	M104	monthly
B12A3.X1	Streamflow B12A3	T104	M105	Does not exist
B12A3.X2	Streamflow to B12B	M105	Streamflow to B12B	Does not exist

3.3 B12B Water resource system

Figure 3.3 shows the connectivity of the water supply network elements in B12B and where monitoring flow, water levels and water quality is required.

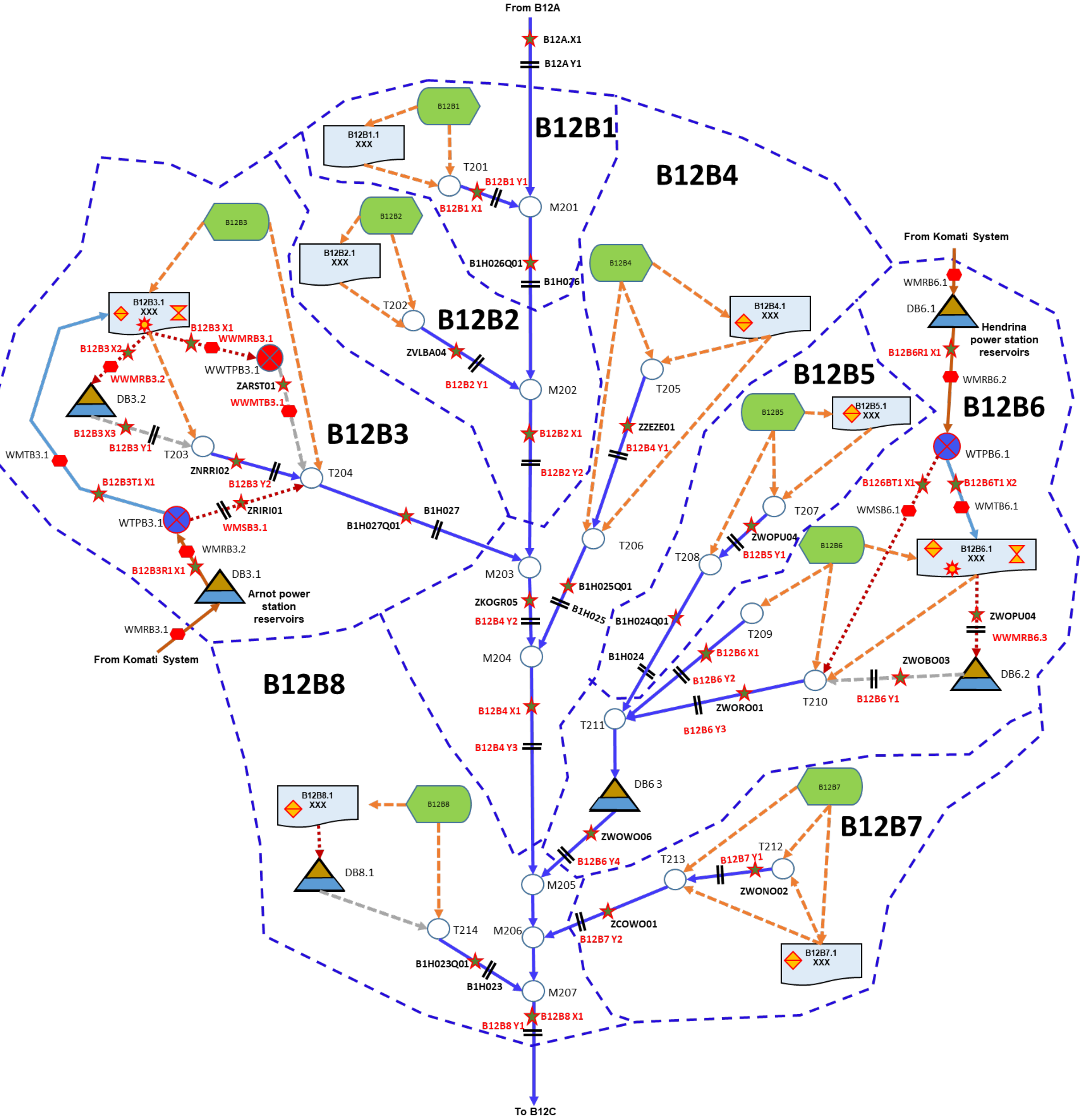


Figure 3.3: Network diagram and monitoring requirements

3.3.1 Climatic parameters

Climate data is required for Arnot and Hendrina power stations, but data from Eskom was unavailable for these locations. The water and wastewater treatment plants at these sites may be the best sites for the municipality to obtain data. From section 5.1, 7-14 days ahead, forecasts can be generated for Arnot and Hendrina Power stations. The nearest rainfall station is Kanhym Investments.

3.3.2 Flow rates

Table 3.5 lists the 22 streamflow gauges required for the model. There are no streamflow gauges in the B12B water resource system. The 5 DWS stations are closed.

Table 3-5: Streamflow gauges

Station	Description	Upstream	Downstream	Status
B12A Y1	Streamflow from B12A	B12A	M201	Does not exist
B12B1 Y1	Streamflow B12B1	T201	M201	Does not exist
B1H026	Klein Olifants streamflow	M201	M202	Closed
B12B2 Y1	Streamflow B12B2	T202	M202	Does not exist
B12B2 Y2	Streamflow B12D2	M402	M403	Does not exist
B12B3 Y1	DB3.2 outflow	DD3.2	T204	Does not exist
B12B3 Y2	Streamflow B12B3	T204	T205	Does not exist
B1H027	Streamflow B12B3	T205	M203	Closed
B12B4 Y1	Streamflow B12B4	T206	T207	Does not exist
B1H025	Streamflow B12B4	T207	M204	Closed
B12B4 Y2	Klein Olifants streamflow	M203	M204	Does not exist
B12B4 Y3	Klein Olifants streamflow	M204	M205	Does not exist
B12B5 Y1	Streamflow B12B5	T208	T209	Does not exist
B1H024	Streamflow B12B6	T209	T212	Closed
B12B6 Y1	DB6.2 outflow	DB6.2	T211	Does not exist
B12B6 Y2	Streamflow B12B6	T210	T212	Does not exist
B12B6 Y3	Streamflow B12B6	T211	T212	Does not exist
B12B6 Y4	Streamflow B12B6	DB6.3	M205	Does not exist
B12B7 Y1	Streamflow B12B7	T213	T214	Does not exist
B12B7 Y2	Streamflow B12B7	T214	M206	Does not exist
B1H023	Streamflow B12B8	T215	M207	Closed
B12B8 Y1	Outflow from B12B	M207	B12C	Does not exist

Table 3.6 lists the 12 water and wastewater flow meters required for the model. The status of monitoring is also shown.

Table 3-6: Bulk water and wastewater infrastructure

ID	Description	Upstream	Downstream	Status
WRMB3.1	Komati system to Arnot P/S Reservoir	Komati system	Arnot P/S Reservoir	Monitored daily
WRMB3.2	Arnot P/S Reservoir to Arnot WTP	Arnot P/S Reservoir	Arnot WTP	Monitored daily
WMTB3.1	Arnot WTP to B12B3.1	Arnot WTP	B12B3.1	Monitored daily
WWMRB3.1	Arnot to WWTPB3.1	Arnot	WWTPB3.1	No flowmeter
WWMRB3.2	Arnot to DB3.2	Arnot	DB3.2	No flowmeter
WWMTB3.1	WWTPB3.1 to T205	WWTPB3.1	T205	No flowmeter

ID	Description	Upstream	Downstream	Status
WMSB3.1	Arnot WTP to T205	Arnot WTP	T205	No flowmeter
WRMB6.1	Komati system to Hendrina P/S Reservoir	Komati system	Hendrina P/S Reservoir	Monitored daily
WRMB6.2	Hendrina P/S Reservoir to Hendrina WTP	Hendrina P/S Reservoir	Hendrina WTP	Monitored daily
WMSB6.1	Hendrina WTP to T211	Hendrina WTP	T211	Monitored daily
WMTB6.1	Hendrina WTP to B12B6.1	Hendrina WTP	B12B6.1	No flowmeter
WWMRB6.1	B12B6.1 to DB6.2	B12B6.1	DB6.2	No flowmeter

3.3.3 Water levels

Table 3.7 lists the 6 dams which should be monitored for the model. Water levels are not monitored for these dams.

Table 3-7: Water levels

ID	Description	Status
DB3.1	Small Dam B12B3	Does not exist
DB3.2	Small Dam B12B3	Does not exist
DB6.1	Small Dam B12B6	Does not exist
DB6.2	Small Dam B12B6	Does not exist
DB6.3	Small Dam B12B6	Does not exist
DB8.1	Small Dam B12B8	Does not exist

3.3.4 Water quality

Table 3.8 lists the 31 water quality sampling points required for the model. Of these 14 do not exist, and for the rest, sampling is done daily.

Table 3-8: Water quality

ID	Description	Upstream	Downstream	Status
B12A.X1	Inflow from B12A			Does not exist
B12B1 X1	T201 to M201	T201	M201	Does not exist
B1H026Q01	M201 to M202	M201	M202	Monitored daily
ZVLBA04	T202 to M202	T202	M202	Monitored daily
B12B2 X1	M202 to M203	M202	M203	Does not exist
B12B3R1 X1	Arnot P/S reservoir to Arnot WTP	Arnot P/S reservoir	Arnot WTP	Does not exist
B12B3T1 X1	Arnot WTP to B12B3.1	Arnot WTP	B12B3.1	Does not exist
B12B3 X1	B12B3.1 to WWTPB3.1	B12B3.1	WWTPB3.1	Does not exist
B12B3 X2	B12B3.1 to DB3.2	B12B3.1	DB3.2	Does not exist
B12B3 X3	DB3.2 to T203	DB3.2	T203	Does not exist
ZARST01	WWTPB3.1 to T204	WWTPB3.1	T204	Monitored daily
ZNRRI02	T203 to T204	T203	T204	Monitored daily

ID	Description	Upstream	Downstream	Status
B1H027Q01	T204 to M203	T204	M203	Monitored daily
ZZEZE01	T205 to T206	T205	T206	Monitored daily
B1H025Q01	T206 to M204	T206	M204	Monitored daily
ZKOGR05	M203 to M204	M203	M204	Monitored daily
B12B4 X1	M204 to M205	M204	M205	Does not exist
ZWOPU04	T207 to T208	T207	T208	Monitored daily
B1H024Q01	T208 to T110	T208	T110	Monitored daily
B12B6R1 X1	DB6.1 to Hendrina WTP	DB6.1	Hendrina WTP	Does not exist
B126BT1 X1	Hendrina WTP to T210	Hendrina WTP	T210	Does not exist
B126BT1 X2	Hendrina WTP to B12B6.1	Hendrina WTP	B12B6.1	Does not exist
ZWOPU04	B12B6.1 to DB6.2	B12B6.1	DB6.2	Monitored daily
ZWOBO03	DB6.2 to T210	DB6.2	T210	Monitored daily
ZWORO01	T210 to T211	T210	T211	Monitored daily
B12B6 X1	T209 to T211	T209	T211	Does not exist
ZWOWO06	DB6.3 to M205	DB6.3	M205	Monitored daily
ZWONO02	T212 to T213	T212	T213	Monitored daily
ZCOWO01	T212 to M206	T212	M206	Monitored daily
B1H023Q01	T214 to M207	T214	M207	Monitored daily
B12B8 X1	M207 to B12C	M207	B12C	Does not exist

3.4 B12C Water resource system

Figure 3.4 shows the connectivity of the water supply network elements in B12C and where monitoring flow, water levels and water quality is required.

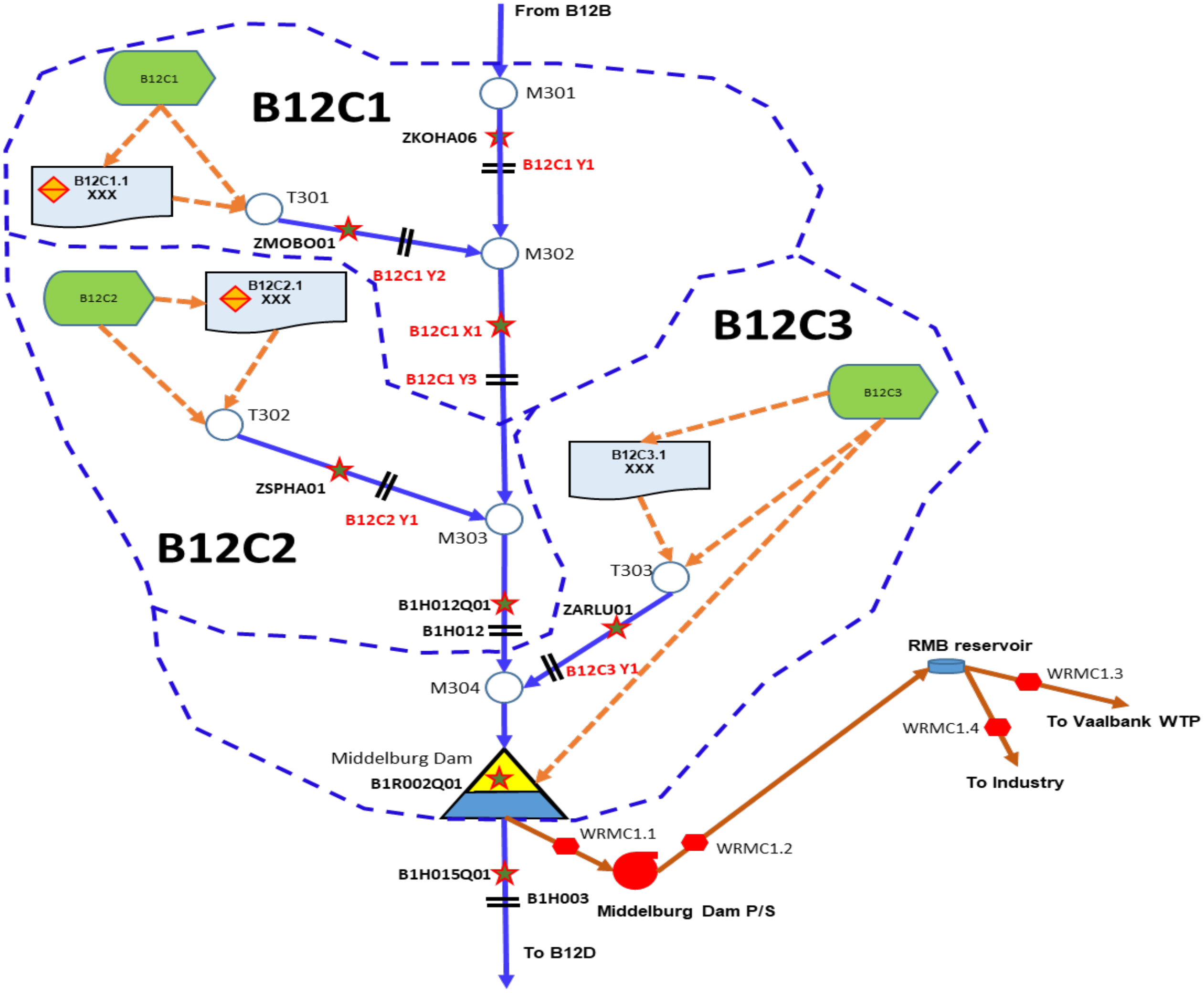


Figure 3.4: B12C-Network diagram and monitoring requirements

3.4.1 Climatic parameters

Climate data is required for Middelburg Dam, but data was unavailable for this location. Forecasts can be generated 7-14 days ahead for Middelburg CBD. The nearest rainfall station is the Middelburg Tank.

3.4.2 Flow rates

Table 3.9 lists the streamflow gauges required for the model, and of these, the DWS operates 2. The rest do not exist.

Table 3-9: Streamflow gauges

Station	Description	Upstream	Downstream	Status
B12C1 Y1	M301 to M302	M301	M302	Does not exist
B12C1 Y2	T301 to M302	T301	M302	Does not exist
B12C1 Y3	M302 to M303	M302	M303	Does not exist
B12C2 Y1	T302 to M303	T302	M303	Does not exist

Station	Description	Upstream	Downstream	Status
B1H012	M303 to M304	M303	M304	Monitored daily
B12C3 Y1	T303 to M304	T303	M304	Does not exist
B1H003	Middelburg Dam to B12 C	Middelburg Dam	B12 C	Monitored daily

Table 3.10 lists the 4 water flow meters required for the model. The status of monitoring is also shown.

Table 3-10: Bulk water and wastewater infrastructure

ID	Description	Upstream	Downstream	Status
WRMC1.1	Middelburg Dam to Middelburb P/S	Middelburg Dam	Middelburg P/S	Use pumping rates
WRMC1.2	Middelburg P/S to RMB reservoir	Middelburg P/S	RMB reservoir	Use pumping rates
WRMC1.3	RMB reservoir to Vaalbank WTP junction	RMB reservoir	Vaalbank WTP junction	Uses pumping rates
WRMC1.4	RMB reservoir to Middelburg Industry	RMB reservoir	Middelburg Industry	Monitored daily

3.4.3 Water levels

Table 3.11 lists 1 dam and 1 reservoir, which should be monitored for the model. The municipality monitors water levels for Middelburg Dam.

Table 3-11: Water levels

ID	Description	Status
Middelburg Dam	Middelburg Dam	Weekly monitoring
RES1	RMB reservoir	Not monitored

3.4.4 Water quality

Table 3.12 lists the 8 water quality sampling points required for the model. Of these only 1 does not exist and sampling is done at weekly and monthly intervals.

Table 3-12: Water quality

ID	Description	Upstream	Downstream	Status
ZKOHA06	Inflow from B12A			Monthly sampling
ZMOBO01	T201 to M201	T201	M201	Monthly sampling
B12C1 X1	M302 to M303	M302	M303	Does not exist
ZSPHA01	T302 to M303	T302	M303	Monthly sampling
B1H012Q01	M303 to M304	M303	M304	Monthly sampling
ZARLU01	T303 to M304	T303	M304	Monthly sampling
B1R002Q01	Middelburg Dam			Weekly sampling
B1H015Q01	Middelburg Dam to B12D	Middelburg Dam	B12D	Weekly sampling

3.5 B12D and B12E Water resource system

Figure 3.5 shows connectivity of the water supply network elements in B12D and B12E and where monitoring flow, water levels and quality of water is required.

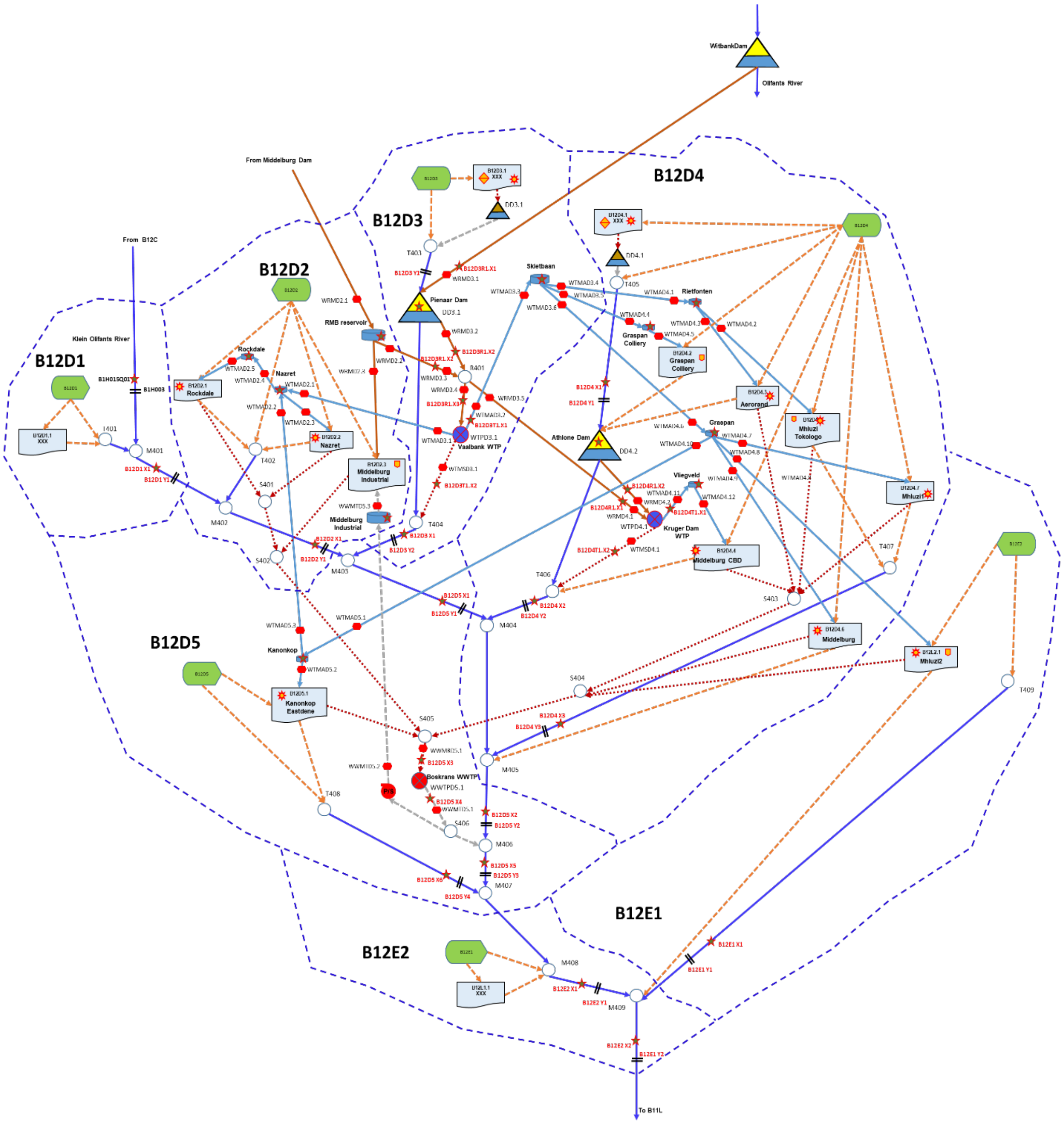


Figure 3.5: B12D and B12E-Network diagram and monitoring requirements

3.5.1 Climatic parameters

Climate data is required for Pienaar Dam, Middelburg CBD, Mhluzi and Rockdale but data was unavailable for these locations. Vaalbank, Kruger Dam, and Boskrans wastewater treatment plants may be the best sites for the municipality to install climate stations. Forecasts can be generated 7-14 days ahead for Mhluzi and Middelburg CBD. The nearest rainfall stations are Middelburg Tank and Kanhym Investments.

3.5.2 Flow rates

Table 3.13 lists the 14 streamflow gauges required for the model. Of these 13 do not exist and the DWS station is closed.

Table 3-13: Streamflow gauges

Station ID	Description	Upstream	Downstream	Status
B1H003	Streamflow from B12C	B12C	M401	Closed
B12D1 Y1	Streamflow B12D1	M401	M402	Does not exist
B12D2 Y2	Streamflow B12D2	M402	M403	Does not exist
B12D3 Y1	Streamflow Pienaar Dam	T403	DD3.1	Does not exist
B12D3 Y2	Streamflow B12D3	T404	M403	Does not exist
B12D4 Y1	Streamflow B12D4 Y1	T403	DD4.2	Does not exist
B12D4 Y2	Streamflow B12D4 Y2	T406	M404	Does not exist
B12D4 Y3	Streamflow B12D4 Y3	T407	M405	Does not exist
B12D5 Y1	Streamflow B12D5 Y1	M403	M404	Does not exist
B12D5 Y2	Streamflow B12D5 Y2	M405	M406	Does not exist
B12D5 Y3	Streamflow B12D5 Y3	M406	M407	Does not exist
B12D5 Y4	Streamflow B12D5 Y4	T408	M407	Does not exist
B12E1 Y1	Streamflow B12E1 Y1	T409	M409	Does not exist
B12E2 Y1	Streamflow B12E2 Y1	M408	M409	Does not exist

Table 3.14 lists the 36 water flow meters required for the model; only 1 does not have a flow meter.

Table 3-14: Bulk water and wastewater infrastructure

Meter ID	Description	Upstream	Downstream	Status
WRMD2.1	RMB Reservoir Inflow	Middelburg Dam P/S	RMB Reservoir	Monitored daily
WRMD2.2	RMB reservoir Outflow 1	RMB Reservoir	Vaalbank WTP junction	Monitored daily
WRMD2.3	RMB reservoir Outflow 2	RMB Reservoir	Middelburg industrial	Monitored daily
WRMD3.1	Witbank Dam transfer	Witbank Dam	Pienaar Dam	Monitored daily
WRMD3.2	Pienaar Dam supply	Pienaar Dam	Vaalbank WTP junction	Monitored daily
WRMD3.3	RMB supply	WRMD2.2	Vaalbank WTP junction	Monitored daily
WRMD3.4	Vaalbank WTP inflow	Vaalbank WTP junction	Vaalbank WTP	Monitored daily
WRMD3.5	Junction supply to Kruger WTP	Vaalbank WTP junction	WRMD4.1	Monitored daily
WRMD4.1	Kruger WTP Inflow 1	WRMD4.1	Kruger WTP	Monitored daily
WRMD4.2	Kruger WTP Inflow 2	Athlone Dam	Kruger WTP	Monitored daily

Meter ID	Description	Upstream	Downstream	Status
WTMAD3.1	Vaalbank WTP to Nasret Reservoir	Vaalbank WTP	WTMAD3.2	Monitored daily
WTMAD3.2	Vaalbank WTP to Skietbaan Reservoir	Vaalbank WTP	WTMAD3.3	Monitored daily
WTMAD3.3	Inflow Skietbaan Reservoir	WTMAD3.3	Skietbaan Reservoir	Monitored daily
WTMAD3.4	Skietbaan Reservoir to Reitfontein Reservoir	Skietbaan Reservoir	WTMAD4.1	Monitored daily
WTMAD4.1	Inflow Reitfontein Reservoir	WTMAD3.4	Reitontein Reservoir	Monitored daily
WTMAD4.2	Reitfontein Reservoir to Mhluzi and Tokologo	Reitfontein Reservoir	Mhluzi and Tokologo	Monitored daily
WTMAD4.3	Reitfontein Reservoir to Aerorand	Reitfontein Reservoir	Aerorand	Monitored daily
WTMAD3.5	Skietbaan Reservoir to Graspan Colliery Reservoir	Skietbaan Reservoir	WTMAD4.4	Monitored daily
WTMAD4.4	Inflow Graspan Colliery Reservoir	WTMAD3.5	Graspan Colliery Reservoir	Monitored daily
WTMAD4.5	Graspan Colliery Reservoir to Graspan Colliery	WTMAD4.4	Graspan Colliery	No flow meter
WTMAD3.6	Skietbaan Reservoir to Graspan Reservoir	Skietbaan Reservoir	WTMAD4.6	Monitored daily
WTMAD4.6	Inflow into Graspan Reservoir	WTMAD3.6	Graspan Reservoir	Monitored daily
WTMAD4.7	Graspan Reservoir to Mhluzi2	Graspan Reservoir	Mhluzi1	Monitored daily
WTMAD4.8	Graspan Reservoir to Mhluzi2	Graspan Reservoir	Mhluzi2	Monitored daily
WTMAD4.9	Graspan Reservoir to Middelburg	Graspan Reservoir	Middelburg	Monitored daily
WTMAD4.10	Graspan Reservoir to Kanonkop Reservoir	Graspan Reservoir	WTMAD5.1	Monitored daily
WTMAD5.1	Inflow Kanonkop Reservoir	WTMAD4.10	Kanonkop Reservoir	Monitored daily
WTMAD5.2	Kanonkop Reservoir to Kanonkop and Eastdene	Kanonkop Reservoir	Kanonkop and Eastdene	Monitored daily
WTMAD5.3	Kanonkop Reservoir to Nazret Reservoir	Kanonkop Reservoir	WTMAD2.2	Monitored daily
WTMAD2.2	Nasret Reservoir Inflow1	WTMAD5.3	Nasret Reservoir	Monitored daily
WTMAD2.1	Nasret Reservoir Inflow2	WTMAD3.1	Nasret Reservoir	Monitored daily
WTMAD2.3	Nasret Reservoir to Nasret	Nasret Reservoir	Nasret	Monitored daily
WTMAD2.4	Nasret Reservoir to Rockdale Reservoir	Rockdale Reservoir	Nasret Reservoir	Monitored daily
WTMAD2.5	Rockdale Reservoir to Rockdale	Rockdale	Rockdale Reservoir	Monitored daily
WTMAD4.11	Kruger WTP to Vliegveld Reservoir	Vliegveld Reservoir	Kruger WTP	Monitored daily
WTMAD4.12	Vliegveld Reservoir Middelburg CBD	Middelburg CBD	Vliegveld Reservoir	Monitored daily

3.5.3 Water levels

Table 3.15 lists 4 dams 9 reservoirs which should be monitored for the model. The municipality monitors water levels for the Middelburg Dam. The DWS monitors water levels for Witbank Dam. Water levels in the reservoirs are not observed.

Table 3-15: Water levels

ID	Description	Status
Middelburg Dam	Middelburg Dam	Weekly monitoring
Witbank Dam	Witbank Dam	Weekly monitoring
DD3.1	Pienaar Dam	Not monitored
DD4.2	Athlone Dam	Not monitored
RES1	RMB Reservoir	Not monitored
RES2	Skietbaan Reservoir	Not monitored
RES3	Reitfontein Reservoir	Not monitored
RES4	Graspan Colliery Reservoir	Not monitored
RES5	Graspan Reservoir	Not monitored
RES6	Kanonkop Reservoir	Not monitored
RES7	Nasret Reservoir	Not monitored
RES8	Rockdale Reservoir	Not monitored
RES9	Vliegveld Reservoir	Not monitored

3.5.4 Water quality

Table 3.16 lists the 37 water quality sampling points required for the model. Of these 22 does not exist and sampling is done at daily weekly and monthly intervals.

Table 3-16: Water quality

Sampling Point	Description	Upstream	Downstream	Status
RES1	RMB Reservoir			No sampling
B12D3R1.X2	RMB Reservoir to Junction node R401			No sampling
B12D3R1.X3	Junction node R401 to Vaalbank WTP			No sampling
DD3.1	Pienaar Dam			No sampling
B12D3R1.X1	Inflow Pienaar Dam from Witbank Dam			No sampling
B12D3R1.X3	Inflow Vaalbank WTP			Daily sampling
B12D3T1.X1	Vaalbank WTP to Skietbaan Reservoir			Daily sampling
B12D3T1.X2	Vaalbank WTP to streamflow			No sampling
RES2	Skietbaan Reservoir			Weekly sampling
RES3	Reitfontein Reservoir			Weekly sampling
RES4	Graspan Colliery Reservoir			Weekly sampling
RES5	Graspan Reservoir			Weekly sampling
RES6	Kanonkop Reservoir			Weekly sampling

Sampling Point	Description	Upstream	Downstream	Status
RES7	Nasret Reservoir			Weekly sampling
RES8	Rockdale Reservoir			Weekly sampling
RES9	Vliegveld Reservoir			Weekly sampling
DD4.2	Athlone Dam			No sampling
B12D4R1.X1	Inflow Kruger WTP from Junction node R401			No sampling
B12D4R1.X2	Inflow Kruger WTP from Athlone Dam			Daily sampling
B12D4T1.X1	Kruger WTP to Vliegveld Reservoir			Daily sampling
B12D3T1.X2	Kruger WTP to streamflow			No sampling
B1H015Q01	Streamflow Klein Olifants			Weekly sampling
B12D1 X1	Streamflow Klein Olifants B12D1	M401	M402	No sampling
B12D2 X1	Streamflow Klein Olifants B12D2	M402	M403	No sampling
B12D3 X1	Streamflow B12D3	T404	M403	No sampling
B12D4 X1	Streamflow into Pienaar Dam			No sampling
B12D4 X2	Streamflow B12D4			No sampling
B12D4 X3	Streamflow B12D4	T407	M405	No sampling
B12D5 X1	Streamflow Klein Olifants	M403	M405	No sampling
B12D5 X2	Streamflow Klein Olifants	M405	M406	No sampling
B12D5 X3	Wastewater to Boskrans WWTP	S405	Boskrans WTP	Daily sampling
B12D5 X4	Treated wastewater from Boskrans WWTP	Boskrans WTP	S406	Daily sampling
B12D5 X5	Streamflow Klein Olifants	M406	M407	No sampling
B12D5 X6	Streamflow B12D5	T408	M407	No sampling
B12E1 X1	Streamflow B12E1	T409	M409	No sampling
B12E2 X1	Streamflow Klein Olifants	M408	M409	No sampling
B12E2 X2	Streamflow Klein Olifants	M409	Outflow to B11L	No sampling

3.6 Gap filling methods

3.6.1 Climatic parameters

Regression equations can be developed to relate observed data for Middelburg Tank and Kanhym Investments with data for specific points obtained from global data sets.

3.6.2 Flow rates

The data gaps on flow rates that are missing due to the absence of flowmeters at planned localities in the network will be generated by predictive algorithms based on the inflow or outflow data at a particular locality, depending on which one of the data is available. The inflow flow rate is available at some critical points, such as the WWTP, but the outflow (effluent) data is unavailable. In such cases, scenario, predictive analytics will be used.

3.6.3 Water levels

Water levels can be estimated using mass balance equations where the inflow, outflow, and reservoirs' physical characteristics are known.

3.6.4 Water quality

The Networks has several data gaps due to the absence of monitoring localities. Gap filling of data gaps will be remediated using predictive algorithms based on the data measured at some points in the same paths with the point where data is missing.

3.7 Improving monitoring

3.7.1 Climatic parameters

This study recommends the installation of climate stations at water and wastewater treatment plants and at the Middelburg and Athlone Dam. Additional stations may be installed at strategic reservoirs.

3.7.2 Flow rates

There is a need to install flowmeters at critical points on the bulk water supply network and gauging equipment on streams. These are critical for understanding water quantity of flow. Besides being used in water biochemistry, data on flow rates in streams assists in understanding patterns of floods and droughts with climate change. Due to the improvement of instrumentation and communication, monitoring can be done remotely in real-time.

3.7.3 Water levels

The municipality should consider installing a telemetry system for water supply reservoirs. Monitoring of water levels and abstractions at Pienaar and Athlone Dams is also recommended.

3.7.4 Water quality

There are many monitoring water quality sites in the study area. Smart sensors should be installed at some of these sites to measure physical water quality parameters such as pH, TDS, and EC. Theis data can be used to predict quality of water patterns. This can reduce demand for travel and sampling time.

CHAPTER 4: WATER QUALITY METHODOLOGY

4.1 Introduction

The purpose of this chapter is to present results from (i) review of anthropogenic activities in the study areas and their potential impact on water quality, (ii) mapping of monitoring points, (iii) analysis of available data to determine relevant water quality parameters, (iv) determination of water quality computational elements, (v) updating of system network diagrams and (vi) the first iteration to develop the water quality methodology for the DyWaBM.

While undertaking these tasks the following procedures were updated:
(i) setting up new elements or features in Google Earth Pro
(ii) extracting values from Google Earth Pro for system elements
(iii) calculating attribute or system element field values to be applied in setting up network diagrams and
(iv) defining the variables to be populated with data

Water Quality compliance monitoring is governed by at least three Acts of parliaments, namely the Water Services Act [Act No. 108 of 1997, the National Water Act [Act No. 36 0f 1998], and the National Environmental Management: Waste Act [Act No. 59 of 2008]. These acts regulate the use of water resources, their equitable use, and the protection of these resources from pollution. All the water in South Africa belongs to the State, and water users at various levels are required to get a licence to have commercial access to surface and groundwater resources. A summary of these acts is presented in the next section.

4.2 Legislation relevant to water quality management

4.2.1 Water Services Act [Act No. 108 of 1997]

This Act provides for the rights of access to basic water supply and basic sanitation; the setting of national standards and of norms and standards for tariffs and the development of water services development plans. Water Service Providers' (WSP) and Water Services Authorities' (WSA) operations are governed by this Act. The WSP are responsible for abstracting, treating, and supplying bulk water to WSAs. Generally, the WSAs are either Local, District or Metropolitan municipalities. A Local Authority can act as a WSP or WSA or both. Operating licenses are issued/granted by Department of Water and Sanitation (DWS) and include conditions for monitoring water quality in the catchment and effluent released during the water treatment process. A dynamic water balance model that is able to track changes in water quality can be useful for evaluating a compliance with license conditions and predicting future compliance risks.

4.2.2 National Water Act [Act No. 36 0f 1998]

The National Water Act aims to protect, use, develop, conserve, manage and control water resources. Rivers, dams, wetlands, the surrounding land, groundwater, and human activities that influence them, are to be managed as one cycle. Anybody who wants to abstract raw water for commercial use should get a Water Use Licence (WUL). DWS is the competent authority in is WUL. Amongst the conditions included is the requirement to monitor water quality for compliance. This involves monitoring water quality upstream, downstream and within the facility where the water is used. The licensee is required to (i) monitor the quality of the wastewater generated during operations, (ii) make sure that it is stored safely to avoid contamination of downstream water resources and (iii) ensure that any effluent discharged should meet license conditions. Challenges in meeting these requirements can be better presented using a dynamic water balance model that is able to track changes in water quality.

4.2.3 National Environmental Management: Waste Act [Act No. 59 of 2008]

This Act provides for the regulation of waste management to protect health and the environment by providing reasonable measures for the prevention of pollution and ecological degradation, securing ecologically sustainable development, and providing for institutional arrangements and planning matters. For industry, mines, and municipal wastewater treatment plants to operate legally in South Africa, they should have a Waste Authorization License (WAL) where one of the conditions is the implementation of certain water quality monitoring protocols by the licensee. Water quality compliance monitoring data generated is sent to Department of Forestry, Fisheries and the Environment (DFFE), DWS, or any other designated competent authority listed in the license conditions. Measures to prevent pollution or ecological degradation can be tested using a dynamic water balance model that can track changes in water quality.

4.3 Water quality drivers in the study area

The catchment area has a lot of anthropogenic activities such as agriculture, mining, processing of minerals, other industrial activities, thermal power stations, human settlements (including unplanned settlements), and water and wastewater treatment plants. Agriculture is primarily maize and livestock farming. Coal is mined for local power station consumption, as a source of energy to steel smelters, as a supply to other local consumers outside its boundaries, and for export to regional and international markets. Extensive coal mining occurs in this catchment, contributing about 9% of South Africa’s total coal production (Maree et al., 2000). Active and closed coal mines include Arnot, Eikeboom, Woestalleen, and Optimum collieries. The mining of coal is both opencast and undergrounding, which results in environmental challenges. STLM is in the Highveld in terms of South Africa's topographic classifications. The ingress water from coal shafts and that which drains from open cast mining has near-neutral pH but high salinity due to the sulphates of group I and II elements. Export coal mined in this region is processed using the density medium separation (DMS) process aided by magnetite. Using magnetite in the process generates high dissolved iron content in the process wastewater, generally referred to as “toe-seep water”. Most of this highly contaminated mine water end-up finding its way into local water channels to the water reservoirs (dams) which are sources of raw water in the catchment and STLM as well.

In view of the discussion above, anthropogenic activities in the catchment play a significant role in influencing the water quality received at taps by residents of STLM. Hence, it is quite critical to fully understand the water pollution cycle in the catchment as this has a bearing in water quality which is conveyed in the water distribution network of STLM. It is critical to assess the various water sources and the distribution facilities in terms of the quality of water they contain or convey. Such an assessment may help identify cause and effect of the deterioration of water quality and identify critical points in the water supply chain for effective intervention to improve water quantity and quality availability to stakeholders (agriculture, industry and residents).

All the anthropogenic activities can release wastewater, which, if not managed properly, can pollute groundwater, streamflow and water impoundments in the catchment and those found downstream. The Upper Olifants catchment has major water impoundments: Witbank, Bronkhorstspruit, Middelburg, Pienaar, Athlone, Kruger and Laskop Dams. The STLM mainly get its water from the Middelburg and Athlone dams, but industrial, mining, power plants, agriculture and other activities in the catchment draw water from other sources. The Witbank Dam can augment the water supply to STLM through a pipeline linked to the Pienaar Dam. Due to the high industrial activities in the Upper Olifants Catchment area, there is a high chance that raw water sources, especially those feeding the water treatment plants operated by the STLM, may be of compromised quality.

Most large water users have a WUL and a WAL. This means that data on the quantity and quality of water abstracted/received, the water quality and the quantity of wastewater discharged should be available as required for compliance monitoring by the individual licence holders.

4.4 Assessment of water quality in STLM

Water quality monitoring of physical, chemical, and biological characteristics provides information on the quality of water resources. It provides a systematic account of water quality variations in a specified location over time (Liu et al., 2017; Allaire et al., 2018; Wu et al., 2018; Namugize and Jewitt, 2018). It is defined as an exercise of accumulating quantitative data on the physical, chemical and biological determinants of water resources over a specified space and period using samples collected from the water body that is being monitored. It is also regarded as the first step in ensuring the effective implementation of the National Water Act. The commitment to report on the water quality status creates the necessity for developing monitoring networks and programmes that are expected to continuously monitor water resources and assess their status (Bertule et al. 2018).

According to the literature, monitoring programmes work on three main levels: national, catchment (regional) and local. The purpose of the national monitoring programme is to give information on the trends and status of water quality in the country. Meanwhile, regional monitoring programmes focus on establishing information for catchment management reasons. Lastly, local monitoring programmes provide information needed by local organizations and communities (Van Niekerk et al., 2002; Van Niekerk, 2014). These monitoring programmes are usually composed of various components representing the overall structure for producing data and information (Van Niekerk et al., 2002; Van Niekerk, 2004). Different components of the monitoring programme and their interactions, are presented in **Figure 4.1**.

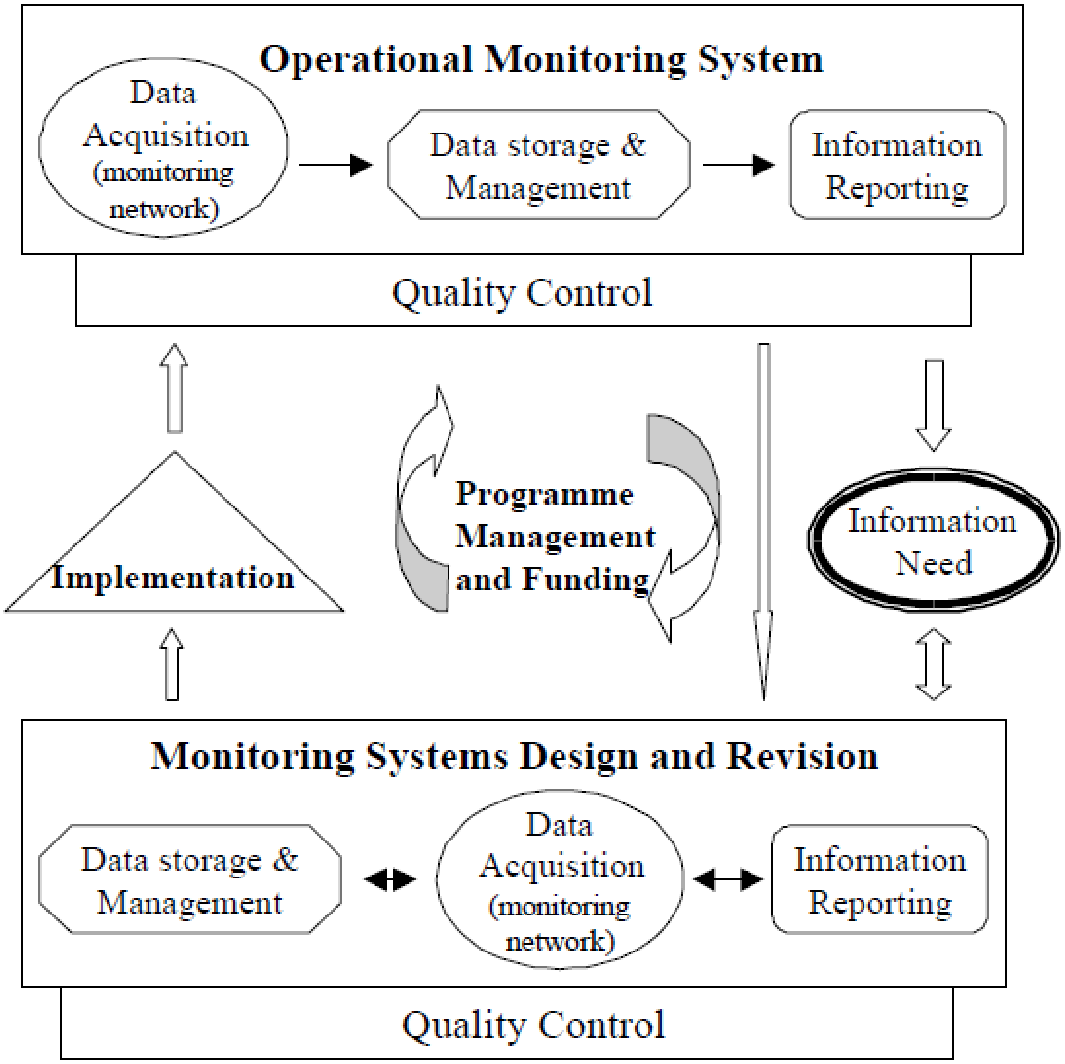


Figure 4.1: Different components in a monitoring programme (Van Niekerk et al., 2002)

4.5 National water quality monitoring programmes

The National Water Act [Act No.36 of 1998] requirements, as well as the additional increasing water quality information needs that pave the way for the Act resulted in the introduction of several national water quality compliance monitoring programmes which are expected to provide basic understanding of the status of water quality in South Africa. The main objective of establishing these monitoring programmes is to obtain data for different variables. These variables often require various monitoring sites, techniques, and skills and involve different sample shelf lives. As such, the national monitoring programmes have been designed by the South African government to monitor raw surface water quality in rivers, dams and boreholes and, produce long-term reports and provide for analysis of trends in terms of physical, chemical and biological properties and impacts on ecosystems (Mogakabe, 2017). These programmes include national eutrophication, national radioactivity, national microbial, national toxicity, and the national aquatic ecosystem health monitoring programmes (Mogakabe, 2017)). Selected monitoring programmes relevant to the current study are presented in **Table 4.1**.

Table 4-1: Selected monitoring programmes in South Africa (Mogakabe, 2017)

Monitoring programme	Objective	Parameters	Reporting
Chemical	Assessment of status and trends of water resource chemistry	Mineral and organic substances	On demand; biannually
Microbial	Assessment of status and trends of faecal pollution as well as health impacts	Bacteria, microbes	Bi-monthly, annually
Eutrophication	Assessment of trophic status, problems and trends in dams and lakes	Algae, cyanobacteria, nutrients	On demand, annually

The location of monitoring/sampling points identified in this study is shown in **Figure 4.2**. STLM water and wastewater treatment plants are also included as monitoring/sampling points.

Water quality monitoring is generally done for compliance requirements associated with discharge permits. Some of the variables of concern are Suspended Solids, COD, Nitrates, Free and Saline Ammonia, Ortho-phosphates, pH and faecal coliforms.

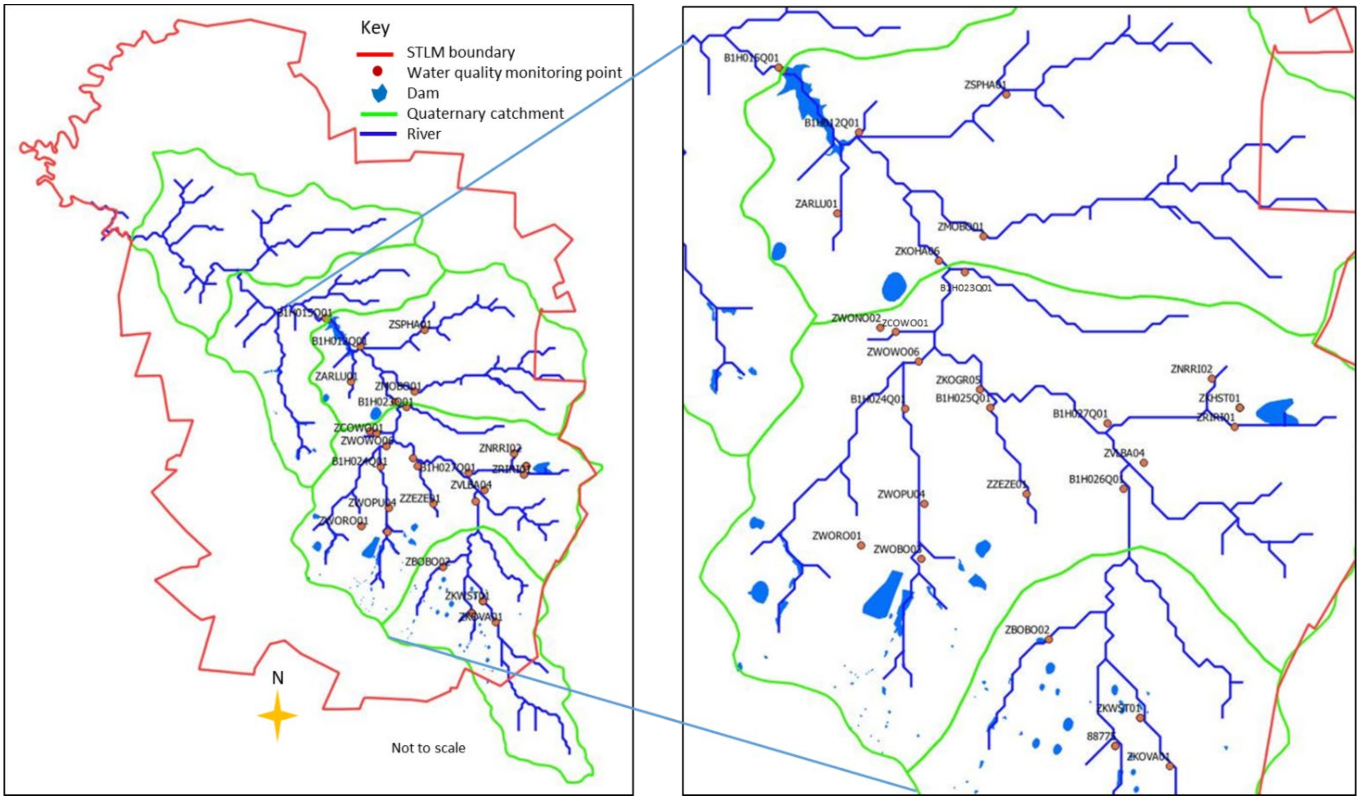


Figure 4.2: Water quality monitoring/sampling points

The monitoring/sampling points are also listed in **Table 4.2**.

Table 4-2: List of water quality monitoring/sampling points identified

STATION	QUATERNARY	DESCRIPTION	LAT.	LON.
ZKOVA01	B12A	Little Olifants River at Vaalbank 177 Js (Culvert)	-26.1469	29.753056
ZBOBO02	B12A	Bosmanspan Spruit at Boschmansfontein 182 Js	-26.0792	29.688333
88536	B12A	Kwazamokhle Sewage Treated Effluent ZKWST01	-26.1211	29.737222
ZHEST01	B12A	Hendrina Sewage Treated Effluent at Overflow 88775	-26.1361	29.723889
ZWOWO06	B12B	Eastern Woes-Alleen Mine Dam on Woestalleen 477 J	-25.9306	29.618611
ZKOGR05	B12B	Little Olifants River at De Groote Rietpan 479Js	-25.9456	29.651389
ZNRRI02	B12B	Northern Tributary of Spruit on Rietkuit 491 Js	-25.9397	29.775556
ZCOWO01	B12B	Coetzer Spruit at R65 at Woestalleen 477 Js	-25.9147	29.606389
ZRIRI01	B12B	Rietkuil Spruit D/S Arnot Power Sta on Rietkuit 4	-25.9656	29.787778
ZVLBA04	B12B	Vlakfontein Spruit at Bankvallei 160 Js (Pipe Crossing)	-25.9847	29.739167
ZWOBO03	B12B	Western Woes-Alleen Spruit at Hendrina Ash Dam On	-26.0361	29.620000
ZWONO02	B12B	Western Woes-Alleen Spruit at Noodhulp 474 Js (Bridge)	-25.9125	29.598056
ZWOPU04	B12B	Eastern Woes-Alleen Spruit at Washing Plant on Pu	-26.0067	29.621667
ZWORO01	B12B	Western Woes-Alleen Spruit at Hendrina Power Station	-26.0289	29.587778
ZZEZE01	B12B	Zevenfontein Spruit at Zevenfontein 484 Js (Weir)	-26.0014	29.676389
B1H023Q01	B12B	Bosman Spruit at Hamelfontein (Zboha01)	-25.8828	29.643333
B1H024Q01	B12B	East Woes-Alleen Spruit at Optimus/Lapa Dam	-25.9558	29.611389
B1H025Q01	B12B	Zevenfontein Spruit @ Speculati/Coastal Coal	-25.9553	29.656944
B1H026Q01	B12B	Little Olifants River at Bankvallei/Culvert	-25.9986	29.728333
B1H027Q01	B12B	Rietkuil Spruit at Kromdraai-Up/S Little Olifants	-25.9636	29.719722
ZARST01	B12B	Arnot Power Station Sewage Effluent ZKHST01, 88804	-25.9553	29.790556
ZARLU01	B12C	Zarlu01 Arendsfontein Spruit at Luipaardsfontein (Bridge)	-25.8514	29.575000
ZKOHA06	B12C	Little Olifants River at Hamelfontein 462 Js (Bridge)	-25.8767	29.629444
ZMOBO01	B12C	Mooifontein Spruit at Boschfontein 447 Js (Bridge	-25.8636	29.653333
ZSPHA01	B12C	Springbok Spruit at Hartogshof 413 Js (Bridge)	-25.7878	29.665556
B1H012Q01	B12C	Little Olifants River at Rondebosch Up/S Middelburg	-25.8081	29.586667
B1R002Q01	B12D	Middelburg Dam on Lit. Olifants River: Near Dam W	-25.775	29.545833
B1H015Q01	B12D	Middelburg Dam on Lit. Olifants River: Down Stream	-25.7733	29.543611

4.6 Water quality monitoring conducted by STLM

The STLM monitors quality of water at the following sites:

(i) raw water and treated water at water treatment plants namely Vaalbank, Presidentsrus, Kruger Dam and Hendrina

(ii) bulk water supply reservoirs namely Granspan, Nazareth, Skietbaan, Reitfontein, Kanonkop, Vliegveld, Hendrina, Kwazomukuhle and Mafube

(iii) boreholes namely: Doornkop1, Doornkop Suid, Doornkop 2, Mafube, Bankfontein and Bankfontein Ext 4

(iv) selected sites in water supply network namely: Mhluzi Ext 4,Eastdene, Groenkol, Rockdale, Rockdale 236, Dennesig, President Kruger Str/Ave and Kwaza Clinic and

(v) Boskrans wastewater treatment plant

4.7 Water quality determinants

Typical problematic water quality determinants or impacts on both land and water resources include the following:

- Bare rock and soil Sedimentation
- Cultivated (and agriculture) Nitrates
- degraded classes
- Heavy metals
- Hydrocarbons
- Man-made/synthetic organic chemicals
- Microbial contamination and pathogens
- Natural vegetation and
- Nutrients
- Organic matter
- Persistent bio-accumulative organic pollutants
- Pesticides
- Phosphates
- Plantations Sedimentation
- Salinity
- Sedimentation
- Sediments (including organic matter)
- Toxicants
- Water-bodies Sedimentation
- Wetlands Nitrates

The DWS has extensive records of flow (daily, monthly and annual) and water quality (weekly, bi-weekly to, and monthly) data at several monitoring stations nationwide. The DWS has designated monitoring sites/localities. Work is in progress to identify the organizations responsible for sampling and analysis and understand the process of making the data available to DWS. Water quality data normally supplied to DWS from the monitoring localities includes the following:

- Flow
- Major ions (Ca^{2+}, K^{+} Mg^{2+}, CO_3^{2-}, Cl^{-}, Na^{+}, SO_4^{2-})
- Nutrients (NO_3^{-}, NH_4^{+}, PO_4^{3-})
- In-situ field measurements (pH, Dissolved Oxygen, Electrical Conductivity, Temperature)

Analysis of anthropogenic activities within the localities where each sampling site is located is critical for understanding the impacts of such activities to water quality. Hence, this study seeks to analyze water quality data in terms of frequency of monitoring and statistics for the water quality parameters to understand upstream and downstream patterns and trends.

4.8 Impact of anthropogenic activities on water quality

According to previous studies, the quality of South Africa's freshwater resources is depreciating because of increased urbanization, mining, industrial discharge, improperly treated sewage, and agriculture (Du Plessis, 2017; Malaza and Mabuda, 2019; Du Plessis, 2019; Sinha and Kumar, 2019). The increasing population growth has also affected water resources through waste discharge, which increases the accumulation of pollutants and water use (Molekoa et al., 2021). Factors such as aging, inadequate capacity of infrastructure, inappropriate choice of technology, poorly constructed infrastructure, intermittent energy supply, inadequate monitoring, inadequate financial resources and lack of necessary operators' skills intensify the water quality problems (Edokpayi et al., 2020). The increasing water quality problems pose increasing threats to the ecosystem and human health. South Africa's urban areas are located on water watersheds and recent studies have revealed that rivers and dams downstream of these areas have shown increased contamination levels (Du Plessis et al., 2015; Gumbo et al., 2016). Furthermore, various rivers in the country have poor water quality and high turbidity because of clay and silt soil types (Fatoki et al., 2001). As a result of this, the state of South Africa's water resources in most catchment systems has been compromised (Namugize and Jewitt, 2018; Mudaly and der Laan, 2020), thus affecting the quality of water available for direct use by consumers and WSPs (Oberholster et al., 2010).

Several researchers have reported large quantities in rivers from improperly treated sewage (as result of damaged or inadequate capacity of sewers, damaged or improperly managed wastewater treatment plants (WWTPs)) in urban and semi-urban areas (Du Plessis, 2017, Edokpayi et al., 2017; Gemmell, and Schmidt, 2010; Atangana and Oberholster, 2021; Govender et al., 2011; Cullis et al., 2018; Namugize et al., 2018). The status of water quality South Africa not only threatens ecosystems but also affects users such as the agriculture sector (Mudaly et al., 2020). A recent study by Sigge et al. (2016) discovered that some South African rivers are contaminated by microbiological determinants, which causes great concern because they do not comply with national and international faecal requirements (Sigge et al., 2016). The high levels of microbial determinants could be attributed to the issues of inadequate sanitation facilities and poor conditions of WWTPs across the country (Sigge et al., 2016). These issues and others demonstrate a need for change in the existing methods for monitoring water quality and managing water resources. Modelling tools that allow users to pick up problems, define and test possible solutions, and support decentralized decision-making can help solve these problems.

4.9 Status of water quality in the study area and process flow diagrams

Preliminary historical data from 2015 to 2020 was obtained from various sources. STLM monitors various water quality determinants (chemical, biological and physical). The physio-chemical parameters include pH, turbidity, colour, dissolved oxygen, total dissolved solids, electrical conductivity, biochemical oxygen demand, bicarbonate, chemical oxygen demand, sodium, potassium, calcium, magnesium, chloride, phosphate, ammonia, nitrate, sulphate, iron, manganese, zinc, copper, chromium, cadmium, nickel, and lead, among others. The biological water quality parameters include total coliform counts, faecal coliform counts, and heterotrophic bacteria and plate counts (HPC). The quality of the final potable is influenced by natural and anthropogenic activities within the catchment in which it is sourced.

STLM has three main WTPs: Vaalbank, Kruger, Hendrina WTWs. The Vaalbank WTWs are the largest, with a 55 ML/day treatment capacity.

The overall water quality supplied to the residence of STLM and industry within its jurisdiction is a function of many input factors such as quality of inflow and outflow raw water from dams and residence time, the time inflow stays in the dam before it is pumped to the WTWs. **Figure 4.3** shows a simplified process diagram for raw water parameters. A situation analysis of the raw water quality parameters assessment of historical data with the aid of predictive modelling can help understand water quality scenarios for the future. Anthropogenic activities influence the quality of inflow water into the dams in the catchment. Usually, the quality of inflow, outflow and abstraction are different. Quality of water in storage may vary with depth or storage level, and for large dams, water quality at various locations may not be the same.

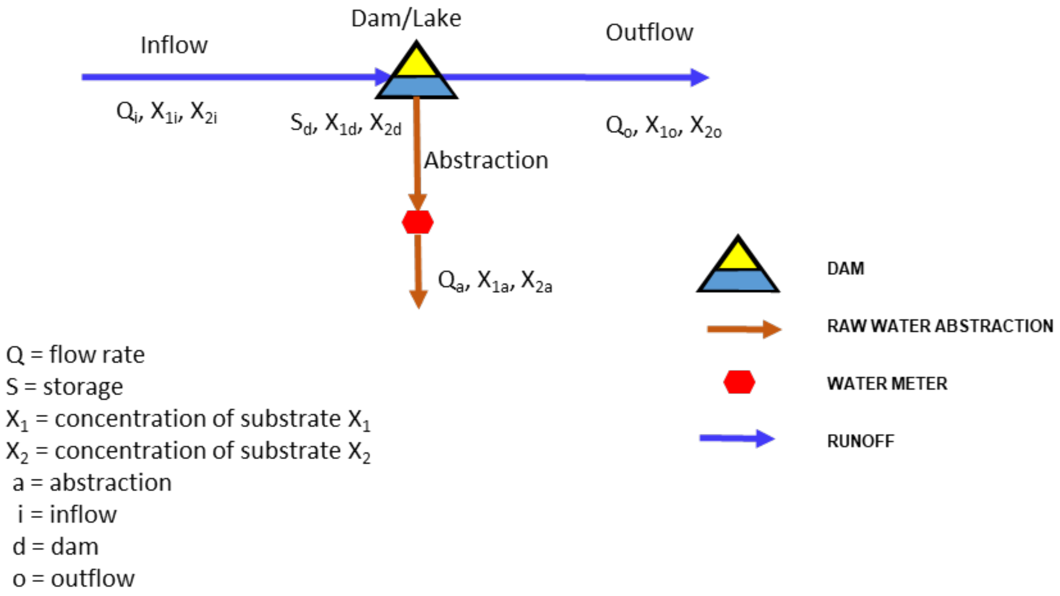


Figure 4.3: Simplified process diagram for raw water quality parameters

As shown in **Figure 4.3**, the water parameter (Q), the flow rate, is related to the water quantity and the water parameters X_1, X_2, $X_3 \ldots X_n$ is the water quality parameter. The inflow water quality parameters may differ from the outflow water quality parameters. The water quality parameters in the dam/lake are influenced by the water inflow parameters and the chemical, biological, and physical processes. Under steady-state conditions, water in the lake may be almost stationary, and the chemical, physical and biochemical processes may be approximated. Usually, for a large dam such as the Middleburg Dam abstraction works are configured to obtain water in stages and at each stage, it can be assumed that steady-state conditions prevail. Outflow parameters significantly impact the water quantity and quality of downstream users. Based on current and historical data, the water quality situation analysis for raw water reservoirs has been monitored in three zones by sampling from the upper catchment of the dams (inflow zones), sampling at points within the dams and sampling downstream (outflows). In the next paragraphs, the baseline water quality parameters data for Middelburg, Pienaars and Nooitgedacht Dams is assessed according to the three sampling zones. As discussed previously, the water quality parameters which were considered in this study are made up of the following list:

- Temperature
- Electrical conductivity

- pH
- Fluorides
- Dissolved iron
- Sulphates
- Nitrates and Nitrates
- Phosphates
- Manganese
- Total coliforms and E-coli
- Heterotrophic plate counts

4.9.1 Water treatment plants

Some of the water quality parameters from STLM's WTPs (that is, Vaalbank WTP, Presidentsrus WTP, Krugerdam WTP, etc.) are shown in **Table 4.3**, where trends show that the challenges concerning sulphates in raw water are similar to final treated water.

Table 4-3: Quality parameters deviation cause in water treatment plants

Sample	Water Sources	Pollution Sources	Parameter	2016	2017	2018	2019	2020
Vaalbank WTP raw	Middelburg, Witbank and Pienaar Dams	Coal fields upstream and farms	Turbidity (NTU)	1.59				
			Sulphates (mg/L)	392	353	348		386
			Lead (µg/L)					57
Vaalbank WTP final	Middelburg, Witbank and Pienaar Dams	Coal fields upstream and farms	Sulphates (mg/L)	407	355	338		391
			Total coliforms (MPN/100 mL)		80			
			Manganese (µg/L)					405
Presidentsrus WTP raw	Groundwater scheme		Turbidity (NTU)	5.77	10.5	2.62		3.16
			Sulphates (mg/L)	434	360	352		390
Presidentsrus WTP final	Groundwater scheme		Turbidity (NTU)	1.61	5.2	2.22		2.82
			Sulphates (mg/L)	426	371	345		393
			Aluminium (µg/L)		383			
			Manganese (µg/L)					139
Kruger Dam Raw	Athlone Dam.	Stormwater from urban areas and mines	Turbidity (NTU)	7.63		2		2.16
			Sulphates (mg/L)	393	139	246		333
Kruger Dam Final	Athlone Dam.	Stormwater from urban areas and mines	Sulphates (mg/L)	391	142	241		320
			Turbidity (NTU)					2.86
			Manganese (µg/L)					107
Hendrina Raw	Vygeboom and Nooitgedacht dams	Runoff from farms and stormwater from mines	Turbidity (NTU)					3.02
Hendrina final	Vygeboom and Nooitgedacht dams	Runoff from farms and stormwater from mines	Sulphates (mg/L)			140		343
			Turbidity (NTU)					2.47
			Total coliforms (MPN/100 mL)			43		
			Manganese (µg/L)					178

The raw data presented single values per year, an anomaly as values are expected to vary within a range. Period ranges and frequencies should be reported.

The process flow diagram for Vaalbank Water Treatment Plant (44.0 Ml/day) is shown in **Figure 4.4**.

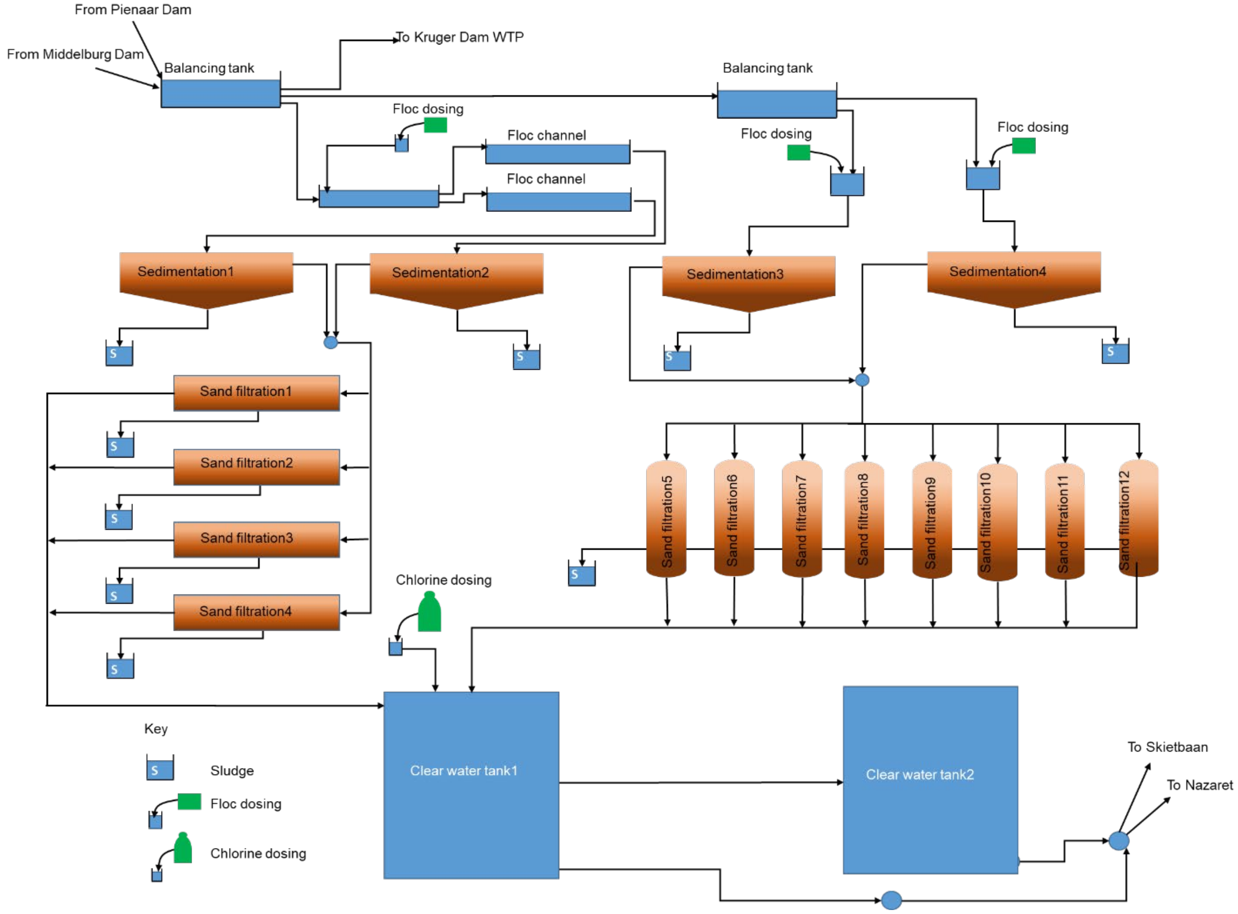


Figure 4.4: Process flow diagram for Vaalbank Water Treatment Plant

Vaalbank WTP receives water that is already contaminated by sulphates and coliforms because the raw water sources are Middelburg, Witbank, and Pienaar Dams. Middleburg Dam is MLX contaminated by discharges from Pullens Hope Colliery, Optimum Coal, Hendrina Power station and small WWTPs (Hendrina Sewage Works, Kwazomukuhle Sewage Works). Additionally, high concentrations of manganese were detected in the final treated water at Vaalbank WTP. The source of Mn is due to the addition of potassium permanganate to oxidise dissolved iron, manganese, and hydrogen sulphide into solid particles that can be eliminated by filtering out of the water. The presence Mn suggests that the chemical reaction that was supposed to convert Mn2+ to solid MnO2 was unsuccessful. In most of the WTP, turbidity was found to be above the recommended limits, likely impacting the disinfection process. This explains the presence of biological determinants in the final treated water.

Pienaar Dam receives inflow from Witbank Dam and runoff from the upstream catchment which has farmlands, Douglas Colliery tailing Dams, Douglas village Dam, and Douglas sewage works.

Witbank Dam receives water from the Olifants River catchment which has a lot of coal mining and processing operations. Major mining operations include Kleinkopje Mine. The dam also received stormwater from residential areas.

The process flow Diagram for Kruger Dam Water Treatment Plant (6.80 Ml/day) is shown in **Figure 4.5**.

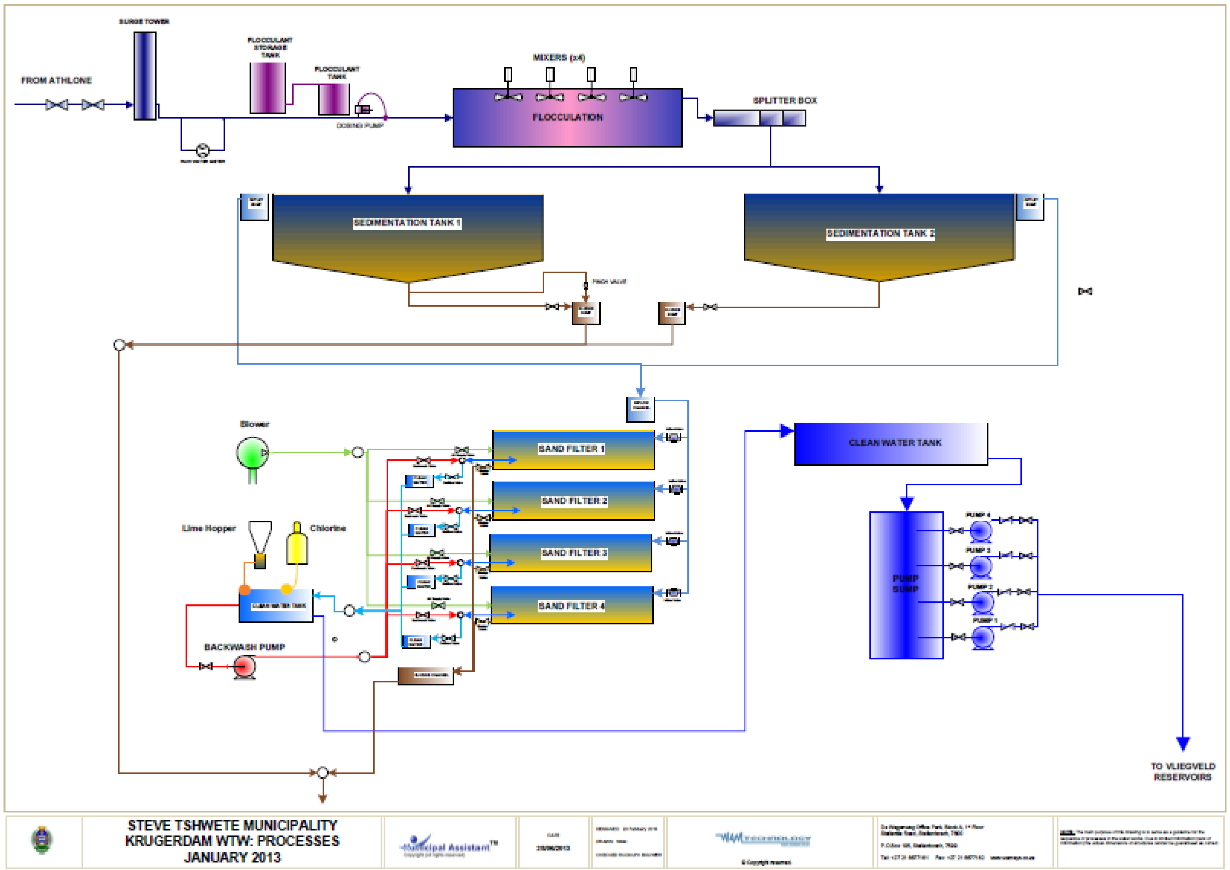


Figure 4.5: Process flow diagram for Kruger Dam Water Treatment Plant

Presidentsrus has a small water treatment plant and the process flow diagram is shown in **Figure 4.6**.

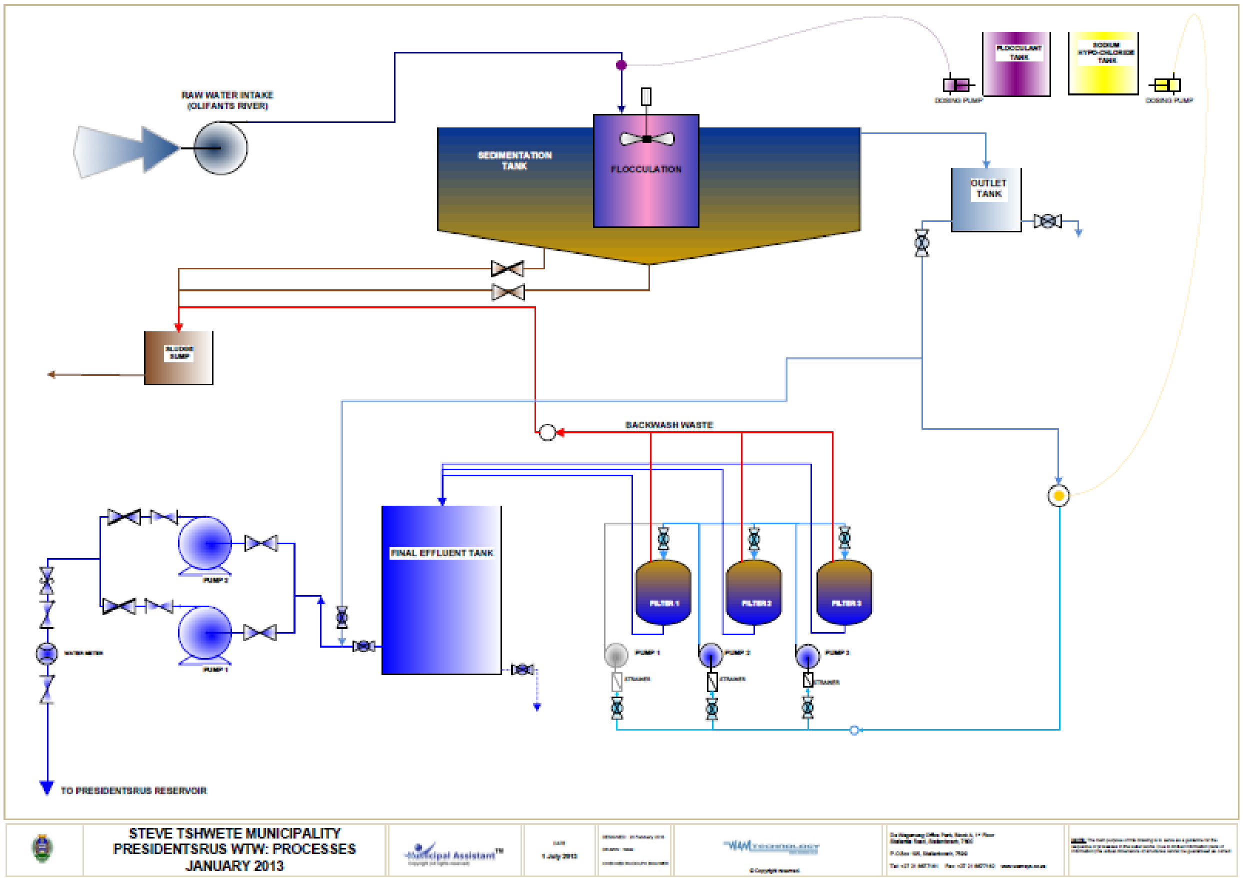


Figure 4.6: Process flow diagram for Presidentsrus Water Treatment Plant

The process flow diagram for Hendrina WTP is shown in **Figure 4.7**.

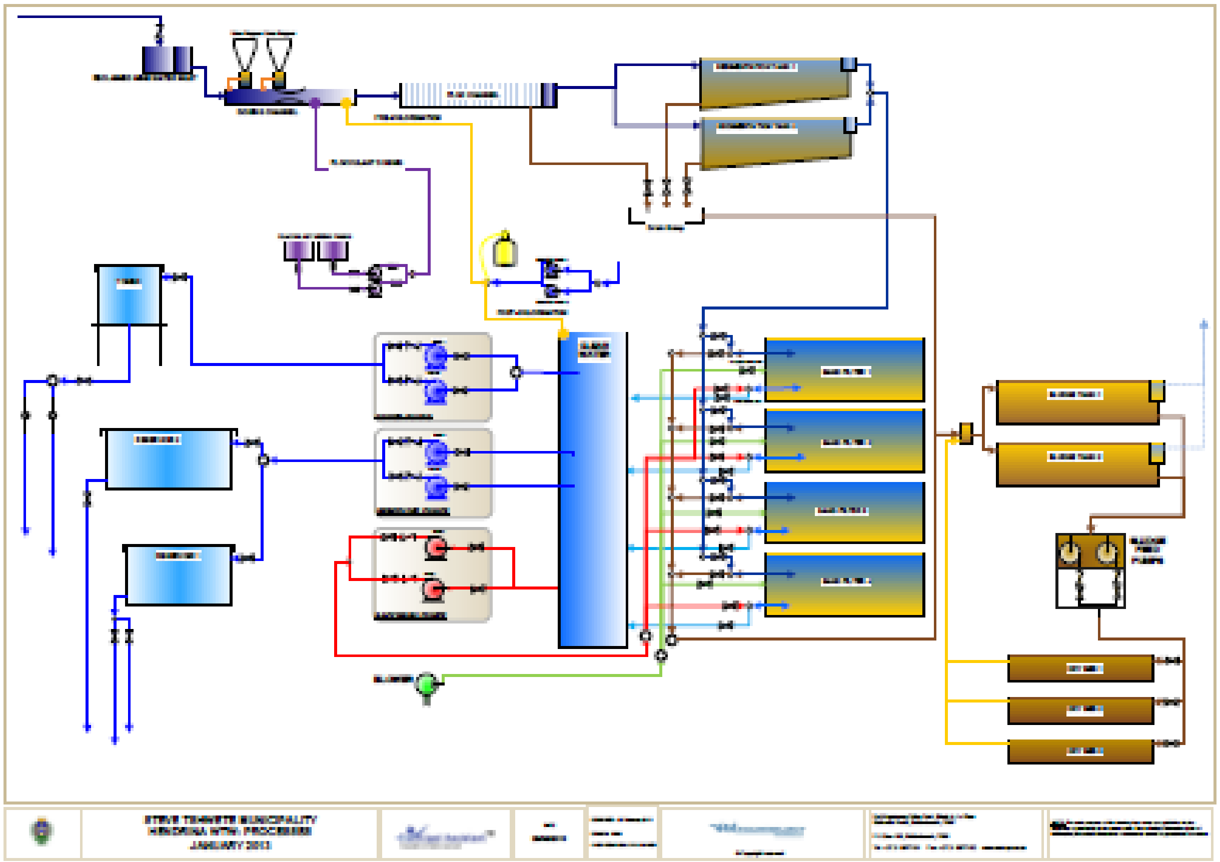


Figure 4.7: Process flow diagram for Hendrina Water Treatment Plant

4.9.2 Reservoirs

Monitoring water quality in storage systems (reservoirs) is essential to ensure safe water quality and safeguard consumer health (Semerjian et al., 2021). Herein, the water quality variation of nine sampling sites in STLM utilised as reservoirs (water storage tanks) was assessed and the results are president **Table 4.4.** The yearly water quality monitoring data shows that sulphates were mostly above the SANS recommended values. In 2017-2020, high concentrations of Mn were observed in most of the reservoirs. The microbiological parameters revealed that all investigated samples were completely free from E. Coli and total and faecal coliforms. However, the results show that reservoirs exhibited heterotrophic plate counts (up to 5550 CFU/mL) ranges. According to Sarker et al. (2019), HPC might be due to contamination due to inappropriate water treatment, poor sanitation conditions, and pipe leakage. High concentrations of Mn, sulphates, and HPC were also observed at the source, which was Vaalbank WTP final. The raw data presented single values per year, an anomaly as values are expected to vary within a range. Period ranges and frequencies should be reported.

Table 4-4: Quality parameters deviation cause in reservoirs

Item No	Sample name	Source of Water	Physico	2016	2017	2018	2019	2020
1	Granspan	VaalBank WTP	Sulphates (mg/L)	419	377	330		397
			HPC (MPN/mL)			150		
			Mn (µg/L)			220		
2	Nazareth	VaalBank WTP	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153
3	Skietbaan	VaalBank WTP	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153
4	Reitfontein	VaalBank WTP	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153
5	Kanonkop	VaalBank WTP	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153
6	Vliegveld	Kruger WTP	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153
7	Hendrina	Vygeboom and Nooitgedacht dams	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153
8	Kwazomukuhle	Vygeboom and Nooitgedacht dams	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153
9	Mafube	Mafube	Sulphates (mg/L)	421	236	324		398
			HPC (MPN/mL)					5550
			Mn (µg/L)		160			153

4.9.3 Boreholes (abstractions)

Groundwater is one of the major sources of drinking water in many countries, especially in rural areas, and it is extracted through domestic boreholes for private or public use. STLM assessed water quality determinants, including physico-chemical and biological parameters six different borehole sources. The laboratory result of physic-chemical qualities obtained revealed that when compared with the SANS recommended values, total conform in Doornkop1, Doornkop 2, Bankfontein, Ext 4 sampling sites were above the permissible limits as well as Bankfontein, and Ext 4 (**Table 4.5**). These results are evidence of microbial pollution from the farming activity and septic sources. Other parameters above the recommended values include turbidity (Mafube), sulphates, fluoride, and manganese (Bankfontein).

4.9.4 Drinking water supply – selected sites

The water quality from various water supplies such as Mhluzi, Eastdene, Groenkol, Rockdale, Rockdale 236, Dennesig, Kwaza Clinic and President Kruger Str/Ave was assessed. **Table 4.5** summarises the physicochemical and biological parameters above the permissible levels and the possible sources of pollution. As seen, Mhluzi, Eastdene, Rockdale 236 and Dennesig draw drinking water from Vaalbank WTP, which is situated near coal fields upstream and stormwater from residential areas, which might be the source of high sulphate, total coliforms and HPC. The raw data presented single values per year, an anomaly as values are expected to vary within a range. Period ranges and frequencies should be reported.

Table 4.6 lists possible causes of deviation in water quality parameters values at various water supply sites.

Table 4-5: Quality parameters deviation cause in boreholes

Item No	Pollution Sources	Comment	Sample name	Parameters	2016	2017	2018	2019	2020
1	BH in Rural/farming/ residential area	Non-severed area / Use of Septic systems	Doornkop1	Total coliforms (MPN/100 mL)			238	80	
2	BH in Rural/farming/ residential area	Non sewered area/ Use of Septic systems	Doornkop Suid						
3	BH in Rural/farming/ residential area	Non-sewered area/ Use of Septic systems	Doornkop 2	Total coliforms (MPN/100 mL)			24		
4	Monitoring locality for Mafube Colliery Tailing Dams	Plume from the tailing leachate	Mafube	Turbidity (NTU)		1.58			
5	Located at a farm school – BH is a supply source to the school	Non-sewered area, pollution from septic sources possible	Bankfontein	Total coliforms (MPN/100 mL)			1203		
				HPC (MPN/mL)			380		
				Fluoride (mg/L)	2.96	2.7		2.1	2.7
				Mn (µg/L)		110			
			Ext 4	Sulphates (mg/L)		250		434	
				Total coliforms (MPN/100 mL)				19	
				HPC (MPN/mL)				4400	

Table 4-6: Quality parameters deviation causes at various water supply sites

Sources of potable water	Location/Main raw water for WTP	Pollution Sources	Sampling site/ID	Water quality parameters	2016	2017	2018	2019	2020
Vaalbank WTP	29.545833E; -25.775000S Middelburg Dam	Coal fields upstream,	Mhluzi Ext 4	Sulphates (mg/L)	410		324		397
	29.545833E; -25.775000S Middelburg Dam	Coal fields upstream,		Total coliforms (MPN/100 mL)					15
				Turbidity (NTU)			1.36		
				HPC (MPN/mL)			2310		7380
	29.545833E; -25.775000S	Coal fields upstream,	Eastdene	Sulphates (mg/L)		264	314	435	393
				Turbidity (NTU)			3.4		
				E Coli (MPN/100 mL)				1	
				Total coliforms (MPN/100 mL)			225	19	
				HPC (MPN/mL)				1410	
	29.545833E; -25.775000S	Coal fields upstream	Groenkol	Sulphates (mg/L)	410	253	328	456	459
				Total coliforms (MPN/100 mL)				33	
				HPC (MPN/mL)				1710	
	29.545833E; -25.775000S	Coal fields upstream	Rockdale	Sulphates (mg/L)		258	341	487	375
				Turbidity (NTU)		1.25			
				Total coliforms (MPN/100 mL)			816		11
				HPC (MPN/mL)			450		7380
	29.545833E; -25.775000S	Coal fields upstream	Rockdale 236	Sulphates (mg/L)				480	396
				Total coliforms (MPN/100 mL)					17
				HPC (MPN/mL)					7380
	29.545833E; -25.775000S	Coal fields upstream	Dennesig	Sulphates (mg/L)	404	263	338	426	407
				E Coli (MPN/100 mL)				1	
				Total coliforms (MPN/100 mL)			291	99	
				HPC (MPN/mL)			230	1460	3390

Sources of potable water	Location/Main raw water for WTP	Pollution Sources	Sampling site/ID	Water quality parameters	2016	2017	2018	2019	2020
Athlone Dam		Coal fields upstream, Stormwater from residential areas feed into Athlone Dam	President Kruger Str/Ave	Sulphates (mg/L)	423	288	310		287
				HPC (MPN/mL)					7380
				Manganese (µg/L)					103
Vygeboom and Nooitgedacht dams	Hendrina	Stormwater from residential areas	Kwaza Clinic	HPC (MPN/mL)				2160	7380

4.9.5 Wastewater treatment plants

Wastewater treatment plants are indirect sources of raw water used in some industries, such as cooling tower process water in power generation, mining activities such as coal washing and raw water for potable water production. Usually, the treated wastewater (effluent) is released into the stream channels and ends in major rivers as part of recharge sources. **Figure 4.8** shows a simplified process diagram for wastewater quality parameters at a typical WWTP. The monitoring points are strategically located upstream (control site), in-process sampling points, and at the effluent sampling site.

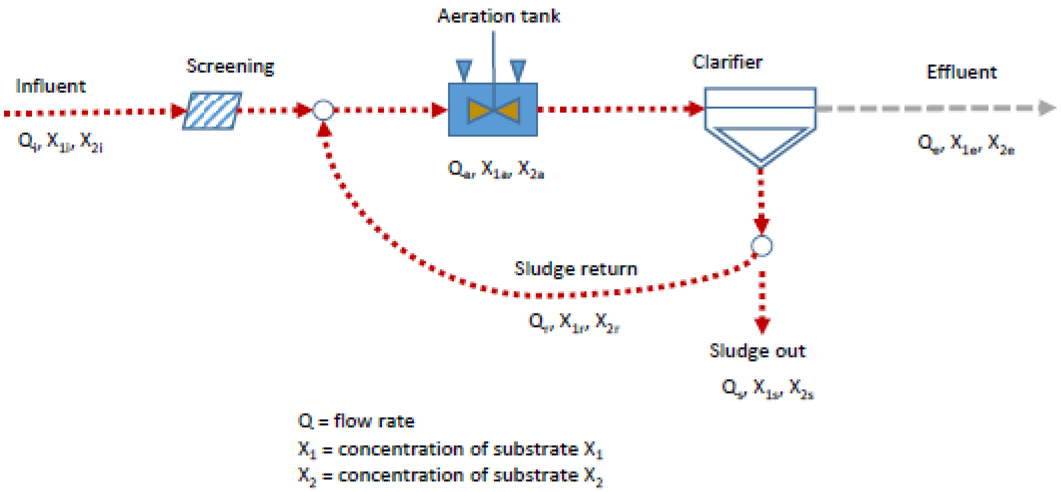


Figure 4.8: Simplified process diagram for wastewater quality parameters at a typical WWTP

Water quality sampling points are sited so that a streamflow sampling point is located upstream of the wastewater treatment plant as a control point. In the case of Boskrans WWTP, the control point is upstream of Klein River but downstream of Middelburg Dam. There are monitoring points within the WWTP. The other critical sampling point is in the Klein River, where treated effluent from Boskrans WWTP is released.

The process diagram for Boskrans WWTP is shown in **Figure 4.9**.

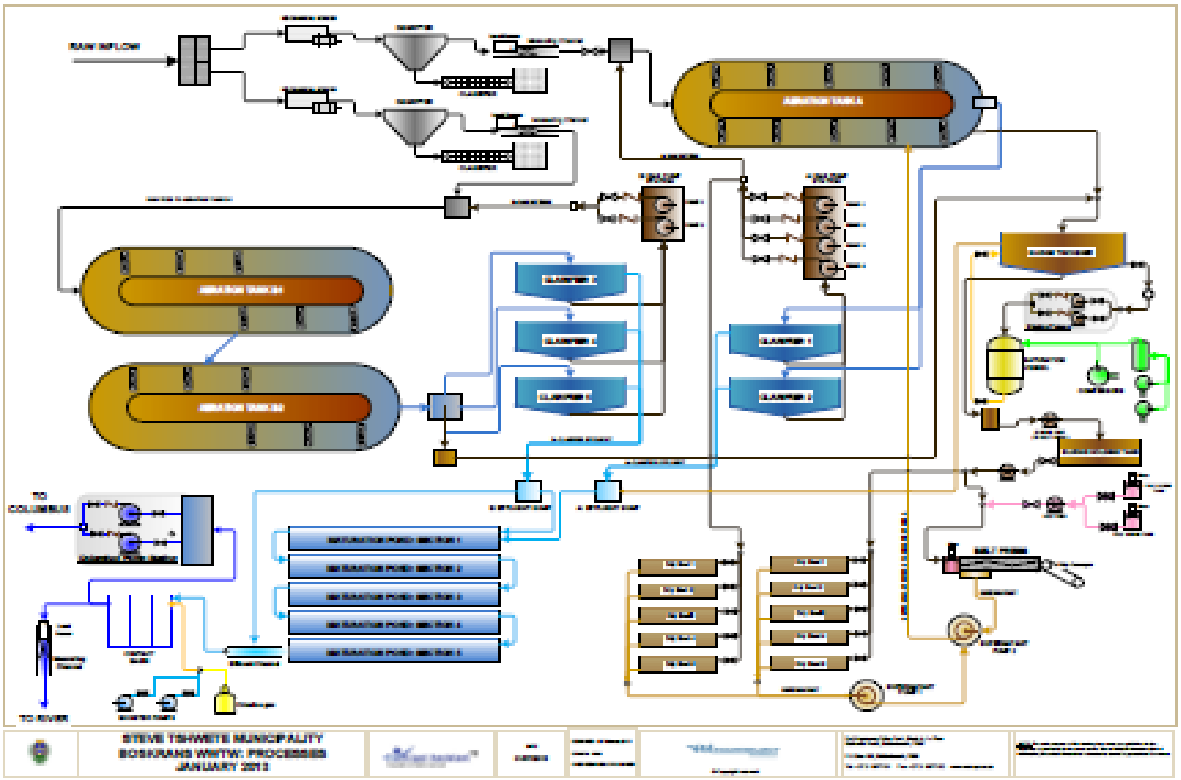


Figure 4.9: Process flow diagram for Boskrans Wastewater Treatment Plant

The process diagram for Blinkpan WWTP is shown in **Figure 4.10**.

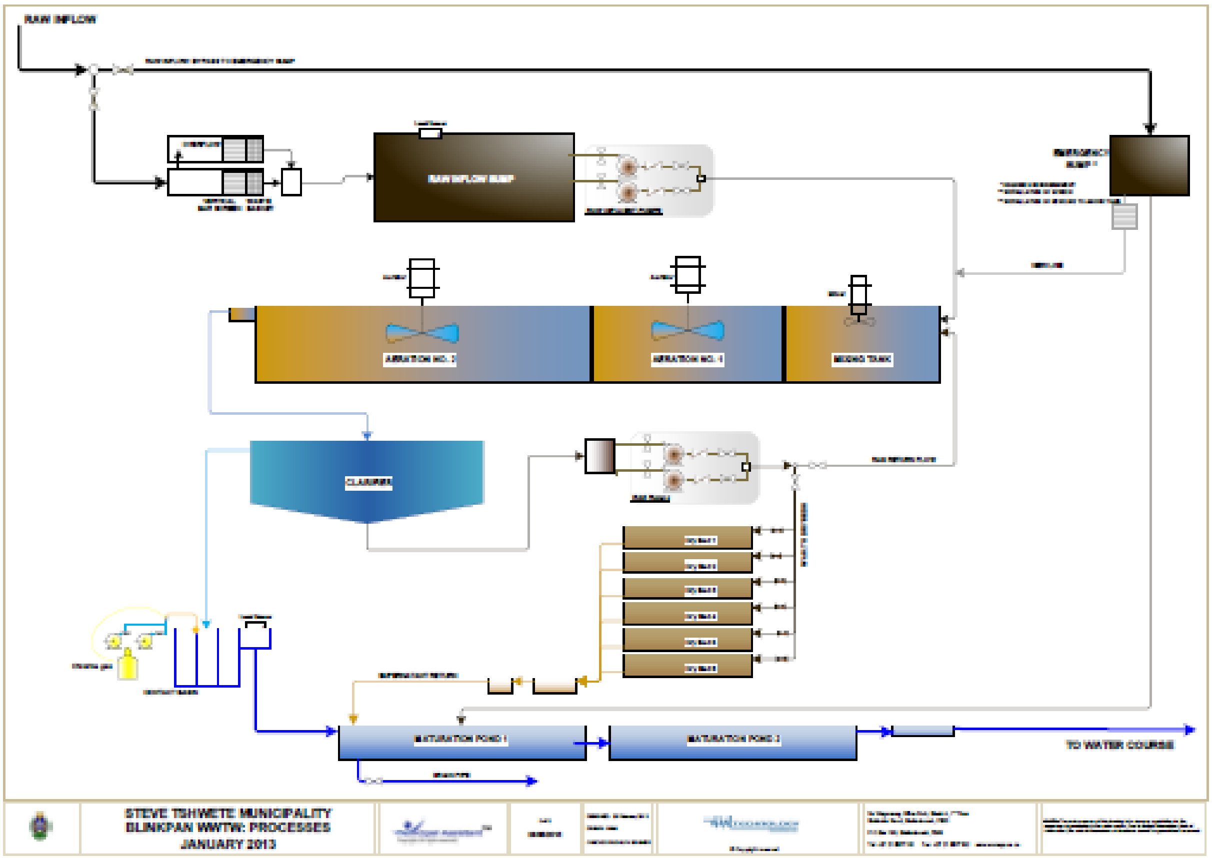


Figure 4.10: Process flow diagram for Blinkpan Wastewater Treatment Plant

The process diagrams for Kwaza WWTP is included in **Figure 4.11**.

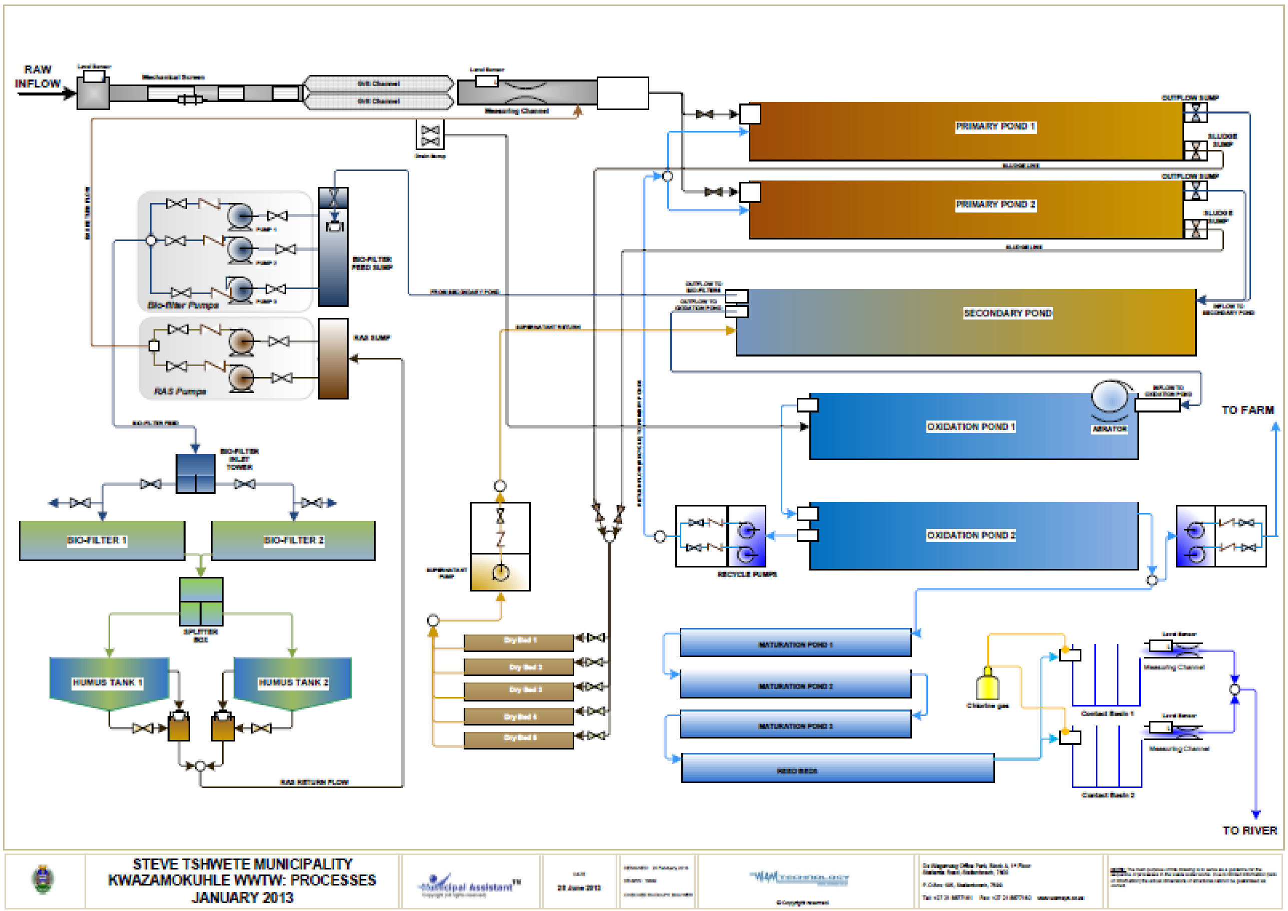


Figure 4.11: Process flow diagram for Kwazamokuhle Wastewater Treatment Plant

A situation or baseline analysis of wastewater quality parameters for the various WWTPs in the STLM was conducted. The impacts of the WWTPs as sources of pollution were evaluated by analysing historical and current data based on information from sampling points for each WWTP in STLM.

a) *Physicochemical parameters of Boskrans and Kwaza WWTPs inflow and Final wastewater*

The water quality parameters for untreated (inflow) and treated (outflow) wastewater from Boskrans and Kwaza WWTPs were used to assess their performance. The water quality parameters considered in this study are alkalinity, chemical oxygen demand (COD), pH, total dissolved solids (TDS), ammonia, ortho-phosphates, electric conductivity and *faecal coliform bacteria, (FCB)*. The monthly characteristics data of these water quality parameters for raw and treated wastewater monitored from 2019-2021 are presented in **Table 4-7.** Parameters such as pH and COD were chosen because pH can be used as an indicator for biological activities, while COD and biological oxygen demand improve nutrient removal (Nadiri et al., 2018).

b) *pH, conductivity, TDS and alkalinity*

The pH values within the monitoring period (2019-2021) for untreated and treated wastewater are **Table 4-7**. As seen the average pH values for inflow and final wastewater samples of Boskrans and Kwaza WWTPs varied between 6.89 and 7.41. The pH values recorded from 2019-2021 in these WWTPs went from slightly acidic to slightly basic. The alkalinity concentrations of the inflows ranged from 322-371 mg/L (Boskrans WWTP) and 226-306 mg/L (Kwaza WWTP). The maximum and minimum alkalinity values were observed in 2019 and 2021 for Boskrans and 2021 and 2020 for Kwaza WWTP. The variation of alkalinity data for the untreated and treated wastewater is consistent with the pH values. These results suggest that the inflow might have carbonates, meaning there is no need to add carbonates during treatment. **Table 4-7** reveals that

Boskrans WWTP recorded the highest TDS values for untreated and treated wastewater samples compared to Kwaza WWTP. High TDS values imply abundant dissolved organic matter, minerals, and inorganic salts in wastewater samples. Even though the treated water had higher TDS than untreated water in a few cases, **Table 4-7** shows that the TDS values for untreated and treated follow the same flatulating trend. Electric conductivity (EC) values, which determine the concentrations of ionized substances in wastewater, followed a similar trend as the TDS.

c) Ammonia, faecal coliform bacteria, COD and orthophosphate

Ammonia is one of the detrimental substances that WWTPs release and is known to be responsible for acute and chronic toxicities in surface water systems (Ashkanani et al., 2019). Therefore, the ammonia concentration in the treated wastewater is highly regulated, and the discharged concentration is 3 mg/L. Average ammonia concentrations in untreated wastewater for Boskrans and Kwaza WWTPs ranged from 30.5-54.7 mg/L and 17.5-52.3 mg/L. Meanwhile, the treated wastewater constantly reported lower concentrations (4.07-15.0 mg/L (Boskrans WWTP) and 1.75-26.5 mg/L (Kwaza WWTP). Generally, discharged effluents did not comply with the set limits (DWAF recommended limit of 3.0 mg/L) except in 2019-2020 for Kwaza WWTP and 2020 for Boskrans WWTP. The phosphate levels observed within 2019-2021 for both treated in both WWTPs ranged from 4.70-6.49 mg/L and 5.06-6.83 mg/L (**Table 4-7**). Meanwhile, in the effluents, the phosphate concentrations were 3.13-3.73 mg/L and 6.22-6.93 mg/L for Boskrans and Kwaza WWTPs. The concentrations in the discharged effluents were within the recommended limits of 10 mg/L. COD is the concentration of strong oxidant that is vital to degrade organic and inorganic matter. The COD profiles between 2019 and 2021 ranged from 339-829 mg/L for untreated, while the values ranged from 46.0-690 mg/L for the treated. These monitoring results show Boskrans and Kwaza WWTP did not comply with the set discharge limits of 75 mg/L except in 2019 in Kwaza WWTP. The faecal coliform bacteria concentrations in the effluent were constantly high for both WWTPs, suggesting that the discharge is likely to contaminate the nearby river system.

d) Physicochemical parameters of downstream and upstream water of Boskrans WWTP

Similarly, alkalinity, COD, pH, TDS, ammonia, ortho-phosphates, EC and faecal coliform bacteria were monitored downstream and upstream of Boskrans WWTP. Compared to the effluent discharges from the WWTPs, the waters of the river water samples are also characterized by significantly lower values of physicochemical determinants except for faecal coliform bacteria (**Table 4.7**). Regarding the faecal coliform bacteria of water quality, final effluent discharged to the nearby rivers showed no significant change. The observed deterioration in the water quality downstream is mostly affected by the effluent discharge from WWTPs, whereas the upstream might be impacted by human and agricultural activities.

Table 4-7: Physicochemical characteristics Boskrans and Kwaza WWTP

Item		Parameters							
		Alkalinity (mg/L)	COD (mg/L)	pH	TDS (mg/L)	NH3 (mg/L)	PO43- (mg/L)	EC (mS/m)	FCB (Count per 100 mL)
Boskrans WWTP									
Inflow	2019	371	829	7.12	1015	54.7	6.49	163	
	2020	340	531	7.19	888	30.57	5.14	142	
	2021	322	706	7.12	926	37	4.7	150	
Final	2019	286	170	7.3	979	15.86	3.73	149	2905
	2020	248	105	7.29	826	4.07	3.57	128	2686
	2021	329	690	7.41	874	17.2	3.13	138	1292
Downstream	2019	257	79.5	7.37	942	7.31	2.65	138	2905
	2020	162	62.7	7.18	644	2.45	1.8	101	2686
	2021	194	49	7.42	713	8.64	1.29	108	1399
Upstream	2019	136	26	7.28	707	0.82	0.19	98.2	2905
	2020	113	37.3	7.14	571	0.78	0.99	88.5	2686
	2021	119	37	7.3	632	1.37	0.28	92.3	1268
Kwaza WWTP									
Inflow	2019	306	570	7.27	581	50.3	6.83	102	
	2020	226	339	6.89	565	17.5	5.06	92.8	
	2021	290	708	7.2	536	42	5.56	99.2	
Final	2019	161	46	7.15	520	1.75	6.22	81.3	1865
	2020	204	80.9	6.92	540	2.89	6.93	88.2	2589
	2021	288	100	7.38	542	26.5	6.33	100	1431
Downstream	2019	218	96.5	7.35	554	6.34	7.58	90.8	2482
	2020	196	135	6.99	446	5.02	4.7	74.5	2312
	2021	257	78.5	7.28	484	21.4	4.83	90.1	1511
Upstream	2019	309	200	7.17	601	15.6	5.28	97.6	2497
	2020	124	63.1	7.09	373	1.49	1.62	61.1	1565
	2021	132	57.7	7.31	270	3.95	0.36	42.8	812

4.9.6 Power stations

Hendrina (1 985 MW) and Arnot (2 100 MW) power stations are supplied from Vygeboom and Nooitgedacht dams with the use of three pumping stations at Vygeboom, Bosloop and Nooitgedacht. Hendrina must obtain 79x10^{6}m^3/year, and Arnot requires about 79x10^{6}m^3/year. The dams are located on the Komati River system. Pollution risks for stream flow may arise from excessive rain, and mine decant pose, while unlined ash dams may pose risks to groundwater quality.

Hendrina and Arnot power stations have wet cooling systems. The generation units convert energy from a fuel source to steam and then use the steam to drive a turbine generator. After the steam is exhausted from the turbine, it is cooled, condensed, and used again to produce steam. Heat exchange to cool the exhaust steam evaporates water. Such wet-cooled systems typically require about the 2.0litres/kWh of water (Eskom, 2022). This means the Hendrina would require 4.0 million litres an hour, while Arnot can evaporate about 4.2 million litres an hour. With evaporation losses accounting for approximately 80% of the total water requirements for a wet-cooled power plant, Hendrina and Arnot power stations would require 4.96and 4.25 2.0litres/kWh of water

Hendrina has 7 cooling towers and 10 turbine units. Each unit evaporates approximately 110 litres of water per second at full load. This loss is replaced by raw water supplied from the terminal reservoirs. Each cooling tower pond has a capacity of 8.172 million litres (Eskom, 2022). Arnot has 6 cooling towers and 6 turbine units. Each unit evaporates approximately 194 litres of water per second at full load. Hendrina power station supplies about 70 Ml per day of raw water from the Vygeboom and Nooitgedacht dams via the Arnot power station. On average, about 62 Ml per day goes to cooling water and about 8 Ml/day goes to a water treatment plant. About half the water is treated for domestic use, and the other half is used for boiler feed-water, depending on demand (Eskom, 2022). A typical simplified process flow diagram for a
wet-cooled thermal power station is shown in **Figure 4.12.**

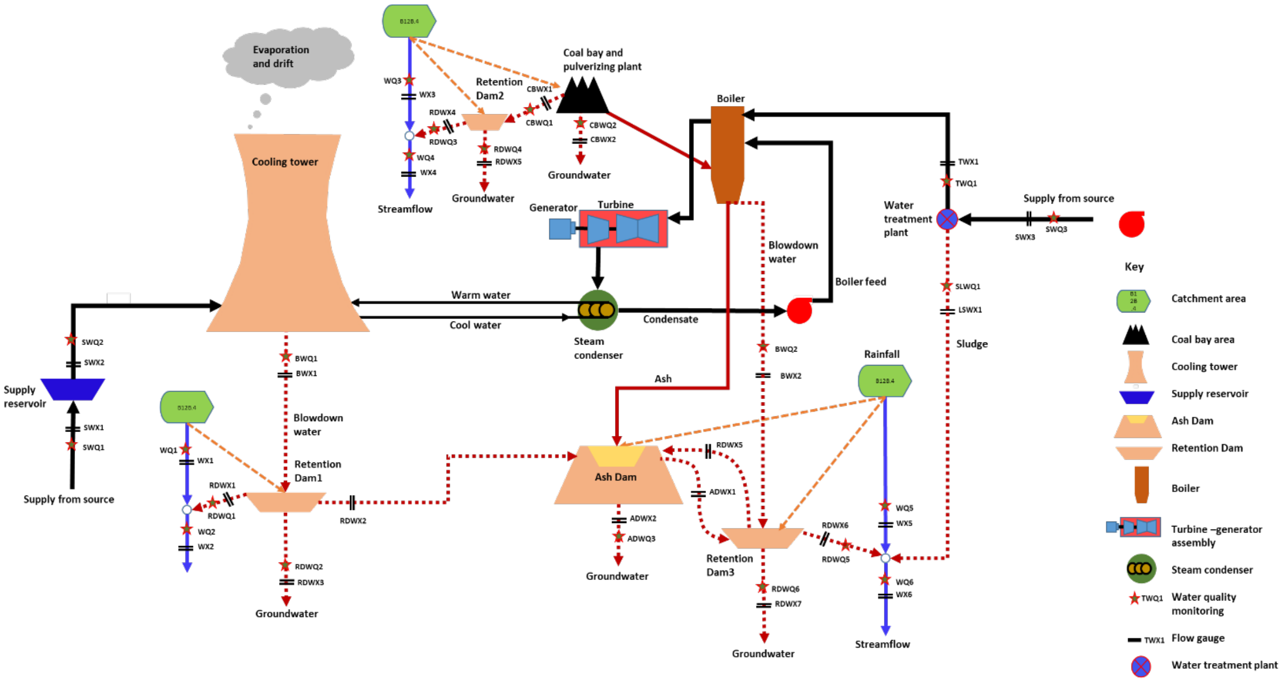


Figure 4.12: Process flow diagram for a wet-cooled thermal power station

The fly ash and slurry from thermal power plants is stored in dams or ponds. These dams should be designed, constructed and operated to avoid polluting the air, groundwater and streamflow. Eskom tries to contain the 1:50 year rainfall on-site.

4.9.7 Collieries

Hendrina power station coal is obtained for the Optimum Colliery, about 30 km southeast of Middelburg and about 20 km northwest of Hendrina. The mine is located in the Middelburg Dam catchment. Arnot coal mine directly feeds the Arnot power station, and supplies come from Mafube Colliery. Other large collieries in the study area include Graspan, Black Wattle, Woestalleen, Klipfontein, Hakhano, Polmaise and Wildfontein. These are open pit mines with relatively shallow or very large low-grade deposits. Mining techniques typically involve blasting, excavating, loading, and hauling of waste rock and ore. Mines can have permanent waste rock storage facilities and temporary ore stockpiles. An open pit is formed by successive rock removal from benches as the mine deepens. Such mines have high potential for acid rock drainage (ARD), which alters surface water and groundwater conditions. Fractures opened during blasting and excavation are pathways for water. Diversion of surface water or dewatering activities to lower the groundwater table may be required to access the ore body. Dewatering and blasting may expose rocks to atmospheric oxygen, initiating oxidation and acid generation (INAP, 2014). A typical simplified process flow diagram for an open-pit colliery is shown in **Figure 4.13**.

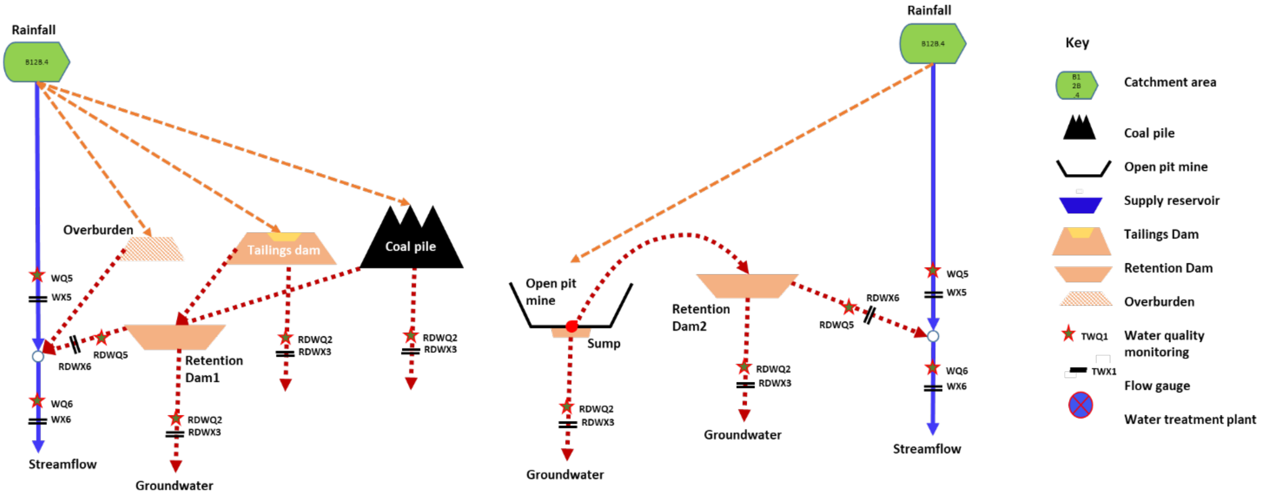


Figure 4.13: Process flow diagram for open-pit collieries

4.9.8 Industry

South Africa's and Africa's only producer of stainless steel flat products, Columbus Stainless, is located in the Middelburg industrial area. Water is used to cleanse coke-oven gases, quench coke and slag, descale steel, as boiler feed water and for cooling (to protect equipment and to improve the working conditions of the employees and for sanitary and service water (Van der Merwe-Botha et al., 2017). A simplified process flow diagram for the Columbus Stainless plant is shown in **Figure 4.14**.

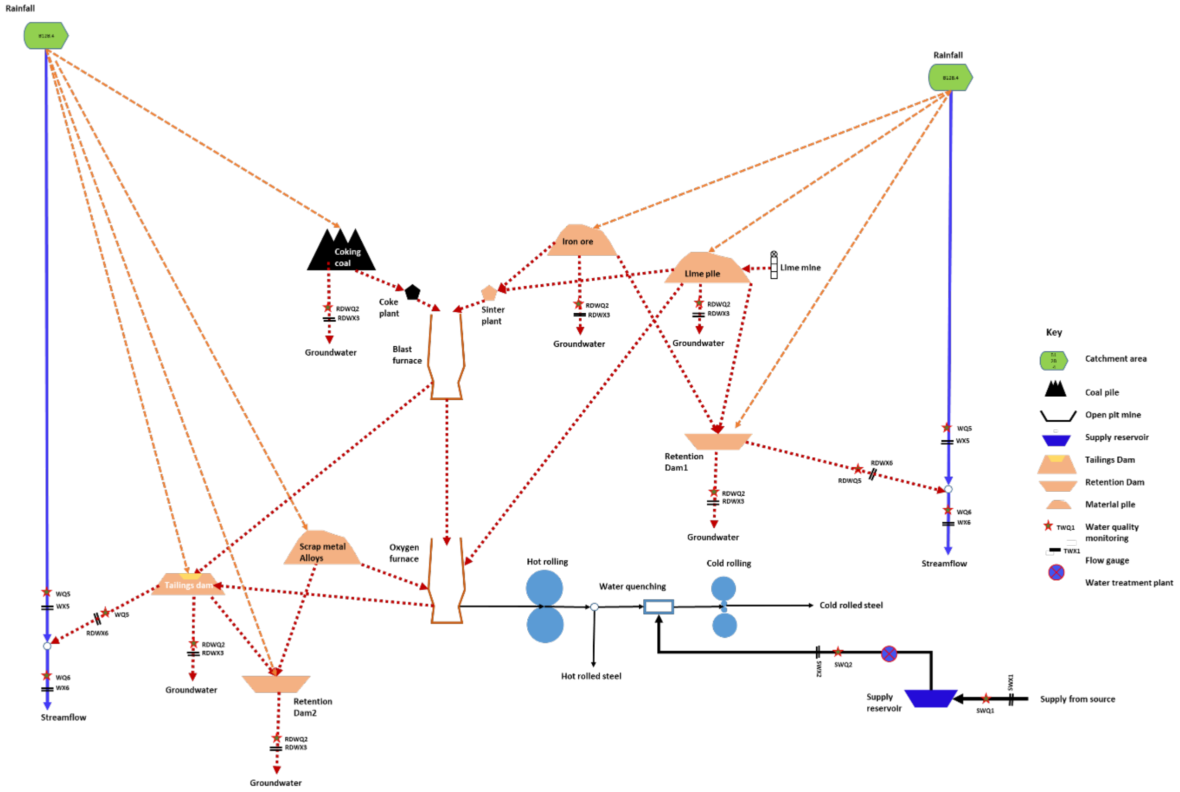


Figure 4.14: Process flow diagram steel making plant – Columbus Steel

4.10 Status of water quality in the study area

Stream Water Quality calculations can be carried out using procedures that include classical and pragmatic conceptual approaches; the conceptual approaches use simulation models. A typical example of such calculations can be performed of physical water quality parameters such as observed Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD) and Electrical Conductivity (EC).

4.11 Point source dilution calculations

Point sources of pollution such as mining activities, wastewater effluent discharge, and other industrial wastewater discharges influence the water quality of streams, rivers, or dams. The physical water quality parameters are usually monitored at designated upstream and downstream sites. The overall dilution or concentration of these water quality parameters will depend on several parameters and can be calculated using the following equation:

$$C_d = \frac{Q_u C_U + Q_e C_E}{Q_u + Q_E}$$

Where:

C_d = completely mixed constituent concentration of the effluent, mg/L

Q_u = Stream flow upstream of the effluent, cubic metres per second, cms (m^3/s)

C_U = constituent concentration of upstream flow, mg/L

Q_E = flow of the effluent, cms (m^3/s)

C_E = constituent concentration of the effluent, mg/L

4.12 Discharge measurement

Many variables, including flow and river depth, influence the water quality in a stream at a particular time. Hence, it is critical to measure discharge flow rates to get the basic data required for a river or stream water quality. A river with a low discharge rate will behave as a stagnant water source with minimal dilution of the source.

The discharge in a river cross-section can be measured from a subsection by the following equation:

$$Q = Sum\ (mean\ depth\ x\ width\ x\ mean\ velocity)$$

$$Q = \sum_{k=0}^{n} {}^{1}\!/_{2}\,(h_n + h_{n-1})(w_n - w_{n-1})x\,{}^{1}\!/_{2}\,(v_n + v_{n-1})$$

In the case where the width (w) is the same for various segments, the equation will then reduce to:

$$Q = \sum_{k=0}^{n} \frac{w}{4}(h_n + h_{n-1})(v_n + v_{n-1})$$

Where:

Q = discharge, cms (m^3/s)
$\mathrm{w_n}$ = nth distance from initial point 0, metres (m)
$\mathrm{h_n}$= nth water depth in metres (m)
$\mathrm{v_n}$ = nth velocity, m/s

A velocity meter is used to measure the velocity discharge in the river.

4.13 Time of travel of water between up- and downstream points

The velocity at which water flows downstream is influenced by several factors, such as the width, riverbed, gradient and depth of the river section. Hence, the characteristics of the river geometry can be calculated using a volume displacement/ dynamic model. The travel time can be determined by using fluorescent tracers or dyes.

The time of travel is determined at any specific reach as the channel volume of the reach divided by the flow as follows:

$$t = \frac{V}{Q} \times \frac{1}{86400}$$

Where,

t = time of travel at a stream reach, days
V = stream reach volume, m^3
Q = average stream flow in the reach, m^3/s
86400 = a factor, s/d

4.14 Influence of water temperature on dissolved oxygen (DO)

Most portable equipment probes for measuring DO simultaneously measure the temperature of the water as DO of a particular water is temperature dependent among other water impurities. **Figure 4.15** illustrates the interlinkages of factors which affect DO concentration in water.

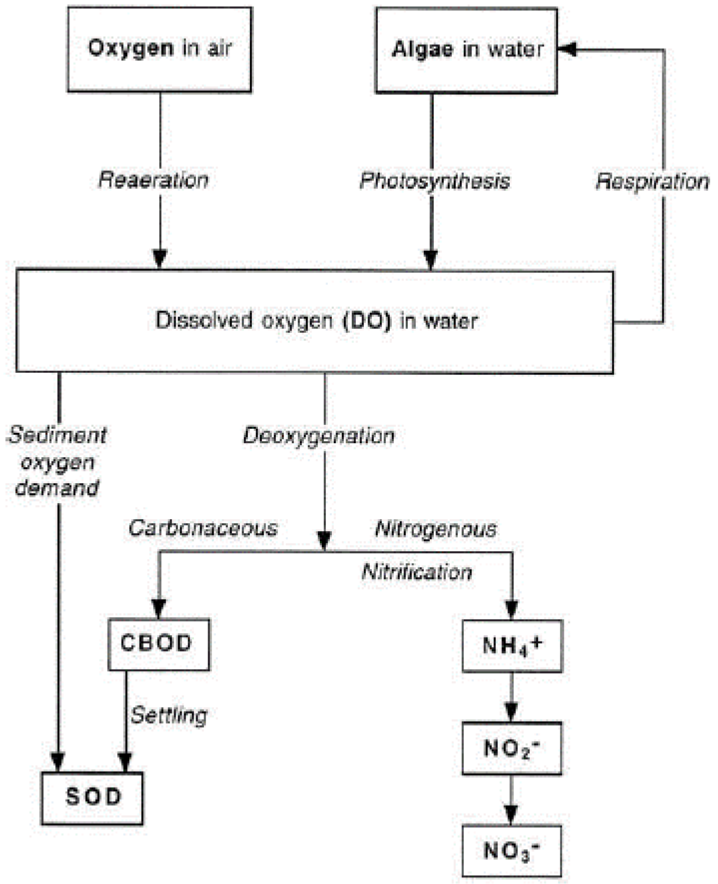


Figure 4.15: Factors affecting DO concentration in water (Lin, 2007)

The dissolved oxygen (DO) can be calculated by the following equation (ASCECSER, 1960):

$$DO_{sat} = 14.652 - 0.41022T - 0.0079910T^2 - 0.000077774T^3$$

Where, DO_{sat} *= dissolved oxygen saturation concentration, mg/L*
T *= water temperature, °C*

Dissolved oxygen is influenced by water impurities, which can either increase the saturation level (β). The saturation values for distilled water, β =1, at sea level pressure; when impurities increase saturation, β > 1.0; when impurities lower saturation, β < 1.0 mg/L.

The above equation for DO will be adopted to test the dynamic models in the next sections of this study.

4.15 Analysis of biochemical oxygen demand

Organic matter in water and wastewater significantly influences the overall biochemical oxygen demand. The presence and levels of organic matter in water can be determined indirectly by measuring BOD, chemical oxygen demand (COD), total organic carbon (TOC) and total oxygen demand (TOD). The BOD test is based on the use of microbes, the COD is based on using an oxidation reagent, common a dichromate and the TOC and TOD tests are accomplished by instrumental analysis.

The following equations for calculation of BOD for seeded and non-seeded samples are based on the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF, 2017):

When dilution water is not seeded:

$$BOD, mg/L = \frac{D_1 - D_2}{P}$$

When dilution water is seeded:

$$BOD, mg/L = \frac{(D_i - D_e) - (B_i - B_e)f}{P}$$

Where:

$\mathrm{D_1}$, $\mathrm{D_i}$ = DO of diluted sample immediately after preparation, mg/L
$\mathrm{D_2}$, $\mathrm{D_e}$ = DO of diluted sample after incubation at 20°C, mg/L
$\mathrm{B_i}$= DO of seed control before incubation, mg/L
$\mathrm{B_e}$ = DO of seed control after incubation, mg/L
f = ratio of seed in diluted sample to seed in seed control
P = percent seed in diluted sample/percent seed in seed control in above equation.

If seed material is added directly to the sample and to control bottles:

f = volume of seed in diluted sample/volume of seed in seed control

4.16 Oxygen sag formula: Streeter-Phelps equation

The Streeter-Phelps equation calculates oxygen resources in rivers and streams that are receivers of effluent discharges. The Streeter-Phelps equation can be written as follows:

$$D_t = \frac{K_1 L_a}{K_2 - K_1}[e^{-K_1 t} - e^{-K_2 t}] + D_a e^{-K_2 t}$$

or:

$$D_t = \frac{k_2 L_a}{k_2 - k_1}[10^{-k_1 t} - 10^{-k_2 t}] + D_a 10^{-k_2 t}$$

In the second equation, natural logarithms are replaced by logs to base 10.
Where

$\mathrm{D_t}$= DO saturation deficit downstream, mg/L ($\mathrm{DO_{sat}} - \mathrm{DO_a}$) at time, t.
t = time of travel from upstream to downstream, days
$\mathrm{D_a}$ = initial DO saturation deficit of upstream water, mg/L
$\mathrm{L_a}$ = upstream BOD, mg/L
e = base of natural logarithm, 2.7183
$\mathrm{K_1}$= deoxygenation coefficient to the base e, per day
$\mathrm{K_2}$= reoxygenation coefficient to the base e, per day
$\mathrm{k_1}$ = deoxygenation coefficient to the base 10, per day
$\mathrm{k_2}$ = reoxygenation coefficient to the base 10, per day

The derivatives of the preceding equations represent the net rate of change in the DO deficit or the absolute change of DO deficit (D) over and incremental of time dt due to stream waste assimilative capacity affected by deoxygenation coefficient K_1

The Streeter Phelps equation is based on the assumption that the deoxygenation rate is directly proportional to the amount of oxidisable organic matter from the discharge and the reoxygenation rate is directly proportional to the DO deficit respectively represented as follows:

$$\frac{dD}{dt} = K_1(L_a - L_t)$$
$$\frac{dD}{dt} = K_2 D$$

Where:

$\frac{\mathrm{dD}}{\mathrm{d}}$ = the net rate of change in the DO deficit, or the absolute change of DO deficit (D) over an increment of time dt due to stream waste assimilative capacity affected by deoxygenation coefficient K_1 and due to an atmospheric exchange of oxygen at the air/water interface affected by the reaeration coefficient K_2

L_a= ultimate upstream BOD, mg/L

L_t= ultimate downstream BOD at any time t, mg/L.

BOD increase or decrease follows first-order kinetics like my biochemical processes. Hence, the above two equations can be integrated, and the integral equation will be used to determine/model the upstream and downstream BOD, respectively, for future levels of BOD. Assuming that the rate of biochemical oxidation of organic matter follows the first-order kinetics, Phelps's law can then be expressed as follows for a unimolecular chemical reaction:

$$-\frac{dL_t}{dt} = K_1 L_t$$
$$\frac{dL_t}{dt} = -K_1 L_t$$

By integration

$$\int_{L_a}^{L_t} \frac{dL_t}{L_t} = -K_1 \int_0^t dt_1$$
$$\ln\frac{L_t}{L_a} = -K_1 t$$
$$\frac{L_t}{L_a} = e^{-K_1 t}$$
$$L_t = L_a e^{-K_1 t}$$

Where

L_t = BOD remaining after time days, mg/L

L_a = first stage BOD, mg/L

K_1 = deoxygenation rate based on e, K_1 = 2.303 k_1, per day (base 10)

4.16.1 Effects of Temperature on the rate of deoxygenation coefficient

Temperature influences the BOD, and, subsequently, the deoxygenation coefficient (rate). Temperature is related to the deoxygenation coefficient by the following equation:

$$\frac{K_{1a}}{K_{1b}} = \theta^{(T_a - T_b)}$$

Where, K_{1a} = reaction rate at temperature T_a per day

K_{1b}= reaction rate at temperature T_b per day

θ = temperature coefficient

Based on several experimental results over the usual range of river temperature, θ is accepted as 1.047 and any working temperature deviated from 20°C. Hence, the variation deviation of the deoxygenation rate with a temperature from 20°C is illustrated by the equation below:

$$K_{1(T)} = K_{1(20\,^{o}C} \times 1.047^{(T-20)}$$

The re-oxygenation rate can also be shown as:

$$k_{1(T)} = k_{1(20\,^{o}C} \times 1.047^{(T-20)}$$

or:

$$L_{a(T)} = L_{a(20^{0}C)(0.6+0.2T)}$$

Many researchers have reported second-order kinetics for BOD, and they were of the preposition that BOD fits very well in a second-order reaction.

$$\frac{dC}{dt} = KC^2$$

Where:

K is the constant
C is the initial substate concertation C=(L_a-y)
at any time, t.

4.17 Determination of water quality index

The well-documented water sources include lakes, rivers, streams and dams. These water sources are used as portable water supply in several sectors such as agriculture, transportation, sanitation, generation of hydropower, sand mining, recreation and industrialization (Barakat et al., 2016; Mustapha et al., 2013; Mohamed et al., 2015). Information about water quality is crucial for better managing these water sources (Mohamed et al., 2015; Barakat et al., 2016; Mustapha et al., 2013). Water quality management is even more vital in developing countries like South Africa because many water sources are converted to surface waters due to climate change, rapid population growth and environmental water pollution. Literature studies have reported that the quality of surface waters from lakes, rivers, streams and dams is mostly affected by anthropogenic activities such as agricultural runoffs, mining drainages, and industrial and domestic wastewater discharges (Mgbenu and Egbueri, 2019; Kawo and Karuppannan, 2018, Wu et al., 2018). The diminishing of water quality presents far-reaching consequences on the livelihood of aquatic life, humans, vegetation and animals (Barakat et al., 2016; Mustapha et al., 2013; Mohamed et al., 2015). Therefore, frequent evaluation and monitoring of surface water quality are required for the integrated management of lakes, rivers, streams and dams (Wu et al., 2018; Mena-Rivera et al., 2017; Mgbenu and Egbueri, 2019; Ustaoğlu et al., 2020, Xiao et al., 2019). Without water quality monitoring, it is impossible to present the best allocation option for water sources (Zeinalzadeh and Rezaei, 2017). Water quality monitoring programs are important tools that can be used to prevent possible river water pollution, and they can be incorporated into remedial policies (Zeinalzadeh and Rezaei, 2017). In addition, from economic, social and environmental points of view, identifying contamination contributors that affect the quality of surface water from lakes, rivers, streams, and dams is crucial (Barakat et al., 2016).

The water quality index (WQI) is a mathematical expression widely used for the evaluation of the portability of water (Mester et al., 2020; Varol, 2020; Ustaoğlu et al., 2020). According to previous studies, WQI assists in informing the public and government administrators about the state of the water quality in their area and enables the communication to be of worldwide water quality status (Guettaf et al., 2017). The WQI approach has been used in many countries around the world to classify water according to its degree of purity or pollution as well as to assess the quality of water (Mgbenu and Egbueri, 2019; Aguilar et al., 2019; Zotou et al., 2018). These countries include Germany (Nguyen and Bui, 2020), Nigeria (Mgbenu and Egbueri, 2019), China (Wu et al., 2018, Tian et al., 2019, Liu and Mao, 2020), South Africa (Marara and Palamuleni, 2020, Banda and Kumarasamy, 2020), Spain (Aguilar et al., 2019), India (Lkr et al., 2020), Algeria (Guettaf et al., 2017), Greece (Zotou et al., 2018), USA (Alnahit et al., 2020), Turkey (Varol, 2020, Ustaoğlu et al., 2020), Brazil (Teixeira de Souza et al., 2021), Mexico (La Mora-Orozco et al., 2017), among others.

The WQI calculation method allows researchers to use the values of various physicochemical parameters specific to the water. The values of physico-chemical parameters, WHO or SANS 241 water standards, weight and relative weights are used to estimate the water quality index (WQI) values. The assignment of weights to calculate the WQI values for physicochemical parameters is widely reported in the literature (Dhayachandhran and Jothilakshmi, 2020). The equations 1-4 are used to calculate relative weights and WQI values.

The relative weight (RWi) is calculated with the following equation:

$$\mathrm{RWi} = \mathrm{AWi} / \sum \mathrm{AWi}$$

Where,

RWi = Relative weight and
AWi = Assigned weight

The quality rating scale for each parameter is conveyed with the following equation:

$$\mathrm{qi} = (\mathrm{ci}/\mathrm{si}) * 100$$

Where,

i = i^{th} parameter
qi = Quality rating, for i^{th} parameter
si = permissible standard for i^{th} parameter set by the SANS 241 or WHO guidelines
ci = Concentration of i^{th} chemical parameter of water sample (mg L^{-1})

Sub index (SIi) for each parameter is calculated by equation:

$$\mathrm{SIi} = \mathrm{RWi} * \mathrm{qi}$$

Where,

i = i^{th} parameter
SIi = sub index of i^{th} parameter and
qi = rating based on concentration of i^{th} parameter

WQI is calculated using the following equation:

$$\mathrm{WQI} = \sum \mathrm{SIi}$$

A widely applied methodology for conveying the different physicochemical parameters in one single expression is the calculation of a Water Quality Index (WQI), which is a number, a scale, a word, a symbol, or a colour that expresses the water quality of an aquatic system at a specific area in a specific period (Trikoilidou et al., 2017).

The water quality index is defined by the following equation:

$$WQI = \frac{\sum_{i=1}^{n}[(average(q_i * RW_i + \sum_{i=1}^{n}(R_i e * Average(q_i, e * RW_i)]}{\sum_{i=1}^{n} RW_i}$$

where:

q_i = Sub-index of sample for i parameter;
$q_{i,e}$ = Sub-index of sample for i parameter exceeding permitted value;
RW_i = relative weight of i parameter;
$R_{i,e}$ = The ratio of samples exceeding permitted value of parameter i to total number of samples of parameter *I; n* = number of control parameters (Charoula et al., 2020).

The sub-index q_i is calculated from the equation:

$$q_i A = \frac{100 * |C_i - V_{io}|}{|S_i - V_{io}|}$$

where:

C_i = measured value of the *i-water* quality parameter;
S_i = limit i water quality parameter value obtained from regulatory authority;
V_{io} = the ideal value of i water quality parameter according to water quality objectives.

CHAPTER 5: CLIMATE CHANGE METHODOLOGY

The DyWaBM considers three climatic parameters, namely rainfall, temperature and evaporation. These parameters are relevant for estimating water available from rainfall and stormwater harvesting, analysing water quality, and assessing storage conditions and pollution risks. Operators and managers of dynamic water supply system systems may want to obtain answers to the following questions related to climate change risks:

(i) How will climate change affect the availability of water, quality, and demand for water at selected points in the water supply system?
(ii) What interventions can be implemented to mitigate these impacts?

This report presents (i) climate patterns obtained from analysis of historical trends and (ii) the proposed methodology for incorporating climate risk in the DyWaBM to be tested in this study.

5.1 Historical Climate Data

Historical rainfall, temperature and evaporation data are required to calibrate DyWaBM functions and initialise model runs. Historical data is also used to determine patterns for the "baseline scenario", verify forecasts' accuracy, and update projections.

The following integrated databases obtained from surface observations data have been applied to the Upper Zambezi River Basin (Nyabeze, 2020a), Limpopo River Basin (Nyabeze, 2020b), Middle Zambezi River Basin (Nyabeze, 2020c), Buzi, Pungwe and Save River Basins (Nyabeze, 2020d) in Southern Africa:

(i) Global Precipitation Climatology Centre (GPCC) full data, 0.25°x0.25° version 2022 gridded precipitation dataset produced by the German Weather Service, Deutscher Wetterdienst GPCC (DWD, 2022). It covers January 1891 to December 2020 as single 10 years monthly NETCDF data files, each file size about 2.9 GB.
(ii) University of East Anglia Climate Research Unit (CRU) Time-series (TS) data version 4.06, 0.5°x0.5° gridded precipitation, maximum temperature, minimum temperature, and potential evapotranspiration datasets (Harris et al., 2020; CRU, 2022). It covers January 1901 to December 2021 as one monthly NETCDF data file size of about 2.9 GB.

These studies also reviewed the following merged satellite and gauge measurements:

(i) Global Precipitation Climatology Project (GPCP) Version 1.3, 0.25°x 0.25° gridded precipitation dataset (NOAA, 2019b; University of Maryland, 2022; Adler et al., 2003). It covers October 1996 to July 2022 as a single month daily NETCDF data files.
(ii) Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS) on 0.05°x 0.05° grid spanning 50°S-50°N. It covers the period 1981 to 2020. (Funck et al., 2015; CHIRPS, 2020).

The following factors are the main determinants of the choice of data set:

(i) accuracy (comparison with observed data),
(ii) ease of handling (file size, number of files),
(iii) length of data set (30 years minimum)
(iv) time step (monthly time step for long-term statistical parameter values, patterns and trends and daily time step for short-term statistical parameter values, patterns and trends) and
(v) after considering (i) to (iv) grid resolution (the finer the resolution the better,

The GPCC data set was selected for long-term precipitation analysis. The CRU TS data set was selected for long term maximum temperature, minimum temperature, and potential evapotranspiration analysis. The CHIRPS data set was selected for short-term precipitation analysis for the most recent climate. This study is concerned with incorporating climate change into the DyWaBM. The WMO (2017) endorses using the most recent 30-year period, finishing in a year and ending with 0, for estimating climatological standard averages. This study is concerned with climate change, which requires analysis of period changes and trends. The consecutive 30 years periods with available data would be January 1931 to December 1960, January 1961 to December 1990, and January 1991 to December 2020. With the wet season starting in October, the hydrological periods of interest are October 1931 to September 1960, October 1960 to September 1990 and October 1990 to September 2020.

5.2 Long term climate projections

Two representative greenhouse gas concentration pathways (referred to as representative concentration pathways (RCPs)) adopted by the Intergovernmental Panel on Climate Change (IPCC) were selected for application in this study, namely RCP4.5 and RCP8.5. The RCP4.5 emissions peak around 2040, then decline. The IPCC considers this to be the most probable basis for future scenarios. The RCP8.5 emissions continue to rise throughout the 21st century and is thought to be very unlikely. It is taken as the basis for worst-case climate change scenarios. The IPCC representative concentration pathways are illustrated in **Figure 5.1**.

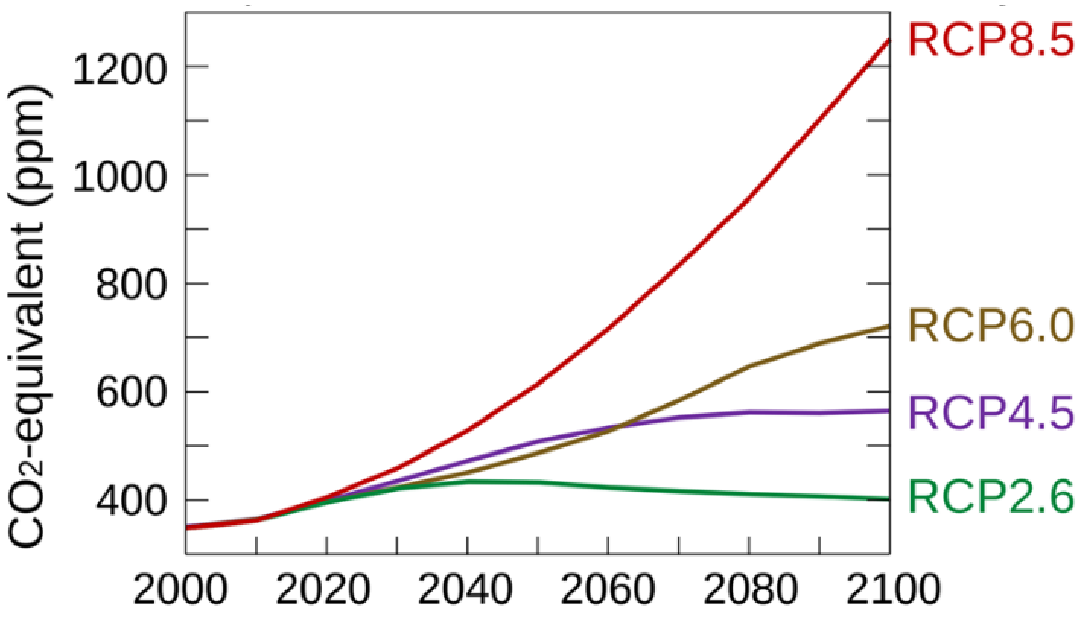


Figure 5.1: IPCC representative concentration pathways (IPCC, 2014)

CORDEX RCP4.5 (lower emissions) and RCP8.5 (highest emissions) climate model scenarios were applied on this study. CORDEX data was generated for the study area with 0.22 x 0.22 degrees grid resolution.

5.3 Seasonal climate forecasts

Towards the end of August each year the Southern African Regional Climate Outlook Forum (SARCOF) process provides seasonal forecasts or predictions of precipitation for the period October to March as average totals for overlapping three-month periods, namely October-November-December (OND); November-December-January (NDJ); December-January-February (DJF); and January-February-March (JFM). Forecasts are assigned probabilities relative to average totals for the most recent 30 year period (a 30-years period is also referred to as a “normal”) with data. **Table 5.1** shows how the SARCOF climate outlook categories are defined, with the middle third being the “normal” period centred on the median of the 30 year period (SADC, 2022). The forecasts are presented as coarse maps.

Table 5-1: SARCOF Seasonal Outlook Categories

Category/Colour Code	% Probability/chance of occurring		
	Above normal	**Normal**	**Below Normal**
Above Normal	40%	35%	25%
Normal to Above Normal	35%	40%	25%
Normal to Below Normal	25%	40%	35%
Below Normal	25%	35%	40%

Soon after publishing the SARCOF statement, the National Climate Outlook Fora (NACOF) produced national outlooks. The South African Weather Services issues its outlook for the season in the form of probabilistic maps for average total rainfall and average temperature (minimum and maximum) for October-November-December (OND); November-December-January (NDJ), and December-January-February (DJF). The maps use a qualitative sliding scale to indicate the probability of Above-Normal, Normal-Above Normal, Near-Normal and Below-Normal (SAWS, 2022).

The SARCOF and SAWS also explain the challenges in obtaining precise seasonal climate forecasts and the limitations of using them for operational decisions. They recommend complimenting them with shorter horizon forecasts, which fits in well with the purpose of DyWaBM.

5.4 Short-term weather forecasts

The effects of climate change are felt in changes in weather patterns, particularly extreme weather events. Extreme events can be picked up in weather observations and forecasts. Short team weather forecast data can be used to simulate future conditions and inform operational and management decisions. Meteorological conditions are non-linear and heterogeneous and predictions are not entirely accurate. With longer periods, forecasts become less accurate. A forecast period 7-14 days ahead can be reasonably accurate. Improvements can be expected with advances in scientific knowledge. Sources of “promising” forecast rainfall data listed in **Table 5.2** were selected from a study conducted for the Global Water Partnership Southern Africa (GWPSA) (Nyabeze, 2022). From this list Rainboo, the Weather Network, Yr, and Freemeteo, are easier to navigate and extract data.

Table 5-2: List of other freeware real-time forecast rainfall data

Data set	Web link	Comment
SAT24	https://en.sat24.com/en/forecastimages/afrika/forecastprecip	Web page has 3hr, 5 day forecasts on a map with mm/hour legend.
Rainboo	https://www.rainboo.co.za/	Forecasts for selected points, 5 day Hourly and 14 day daily forecasts.
The Weather Network	https://www.theweathernetwork.com/za	Forecasts for selected places, 7 day 24 hour rainfall expressed as a range
Weather2	http://www.myweather2.com/	3hr, 7 day forecasts for selected locations. Free Forecast Weather API available for non-commercial use
Yr	https://www.yr.no/?spr=eng	Forecasts for selected points, Hourly for 48 hours and 6 Hourly for 9 days. The forecasts are based on data from the Norwegian Meteorological Institute and several international meteorological organisations (ECMWF, EUMETSAT, etc.).
Freemeteo	https://freemeteo.co.za/	Forecasts for selected points, 7 day 3 Hourly forecasts. The source of data is not disclosed.

Data set	Web link	Comment
		Also has historical day, 7 days from current day. Maximum and Minimum Temperature and Rainfall
Besttimetovisit	https://www.besttimetovisit.com.au/	Forecasts for selected points, 14 day Daily forecasts. The source of data is not disclosed.

Table 5.3 provides an example of forecast data available from Rainboo. Values of minimum and maximum temperatures for Arnot and Hendrina are the same.

Table 5-3: Example of forecast data from Rainboo

Location	Day No (Day 1 is 27/10/22)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Rainfall (mm)														
Arnot	7	10	2.1	0	42.2	19	2.3	35.4	8.9	6.2	8	9.3	8.6	9
Hendrina PS	9.5	15.1	0.9	2.1	37.6	14.9	5.7	30.4	7.3	6.1	7.2	9	7.1	8.8
Mhluzi	10.2	17.4	2.2	0	29.8	28.6	1.1	24.1	9.4	5.1	5.5	10	7	7.7
Middelburg CBD	12	16.6	0.3	0	32	17.1	4.3	15.9	7.3	6.1	7.2	9	7.1	8.8
Minimum Temperature °C														
Arnot	13	11	9	10	12	10	11	13	12	13	13	12	12	13
Hendrina PS	13	11	9	10	12	10	12	13	13	13	13	12	12	13
Mhluzi	15	14	12	12	14	13	13	15	15	15	15	14	14	15
Middelburg CBD	15	14	12	12	16	13	14	14	15	15	15	14	14	15
Maximum Temperature °C														
Arnot	20	22	22	27	20	17	22	21	22	23	22	20	22	22
Hendrina PS	20	22	22	27	20	18	22	21	22	23	22	20	22	23
Mhluzi	20	24	24	28	21	19	24	23	24	24	23	22	24	24
Middelburg CBD	22	24	23	27	22	18	22	23	23	24	22	21	23	23

Table 5.4 provides an example of forecast data available from Yr. The minimum and maximum temperatures for Middelburg CBD and Mhuzi are the same. Yr forecasts much lower rainfall than Rainboo over similar periods, suggesting the need to use multiple sources of forecast data and evaluate them against observed values.

Table 5-4: Example of forecast data from Yr

Location	Day No (Day 1 is 27/10/22)								
	1	2	3	4	5	6	7	8	9
Rainfall (mm)									
Hendrina	8.7	3.5	0.5	0	26	15	2.2	3.8	3.5
Arnot	2.3	2.5	0.1	0	12	14	0.9	0.9	1.4
Middelburg CBD	2.8	1.2	0.7	0	26	32	10	5.1	2.8
Mhluzi	2.8	1.2	0.7	0	26	32	10	5.1	2.8
Minimum Temperature °C									
Hendrina	13	12	11	11	12	11	10	10	13
Arnot	15	14	12	12	14	12	12	12	12
Middelburg CBD	13	13	12	11	13	12	11	11	14
Mhluzi	13	13	12	11	13	12	11	11	14

Location	Day No (Day 1 is 27/10/22)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Maximum Temperature °C									
Hendrina	20	24	23	25	22	16	17	20	22
Arnot	20	26	22	27	27	20	19	19	22
Middelburg CBD	20	25	24	26	24	18	19	20	22
Mhluzi	20	25	24	26	24	18	19	20	22

5.5 Pre-processing of climate data

Climate data sets typically come in large file sizes. They are stored in the network common data form (NetCDF) as single or multiple files. The Framework Open Source Software to Analyze Large Gridded Data (FOSS-LGD) developed by Nyabeze (2020d) in Python can extract NetCDF gridded data. It is also accompanied by spreadsheets to obtain statistical parameter values and conduct pattern and trend analysis.

The FOSS-LGD was used to extract, process and analyse the following data sets:

- GPCC version 2022, 0.25°x0.25° gridded monthly precipitation data set
- CRU version 4.06, 0.5°x0.5°gridded monthly temperature and evaporation data sets
- CRU version 4.06, 0.5°x0.5°gridded daily rainfall, temperature and evaporation data sets.
- CORDEX RCP4.5 and RCP8.5, 0.22°x0.22°0 gridded monthly rainfall, temperature and evaporation for the period 1971 to 2000 as hindcast and 1921 to 2050 as projections
- CORDEX RCP4.5 and RCP8.5, 0.22°x0.22°0 gridded daily rainfall, temperature and evaporation for the period 1971 to 2000 as hindcast and 1921 to 2050 as projections

5.6 Climate statistics, patterns and trends

Operators and managers of dynamic water systems may want to understand how precipitation, evaporation and temperature affect the water availability, water quality, water demand, and the movement and storage of water in the water supply system. The purpose of this chapter is to provide a view of the study area's climate statistics, patterns and trends. Knowledge of spatial and temporal climate patterns with and without climate change impacts can enable them to make optimal decisions.

5.7 Historical climate

Historical climate statistics and patterns were analysed for monthly and annual time scales, while trends were only for the yearly time scale.

5.7.1 Rainfall

With GPCC DWD data, mean annual precipitation (MAP) for the period **1909-2020** was in the range of 550 mm/year to 700 mm/year, with parts of B12A, B12C and B12D being relatively drier than parts of B12B, B12C, B12D and most of B12D. The coefficient of variation (CV) shows that annual precipitation is more variable in the study area's central and upstream parts. This spatial distribution of MAP and CV is shown **in Figure 5.2**.

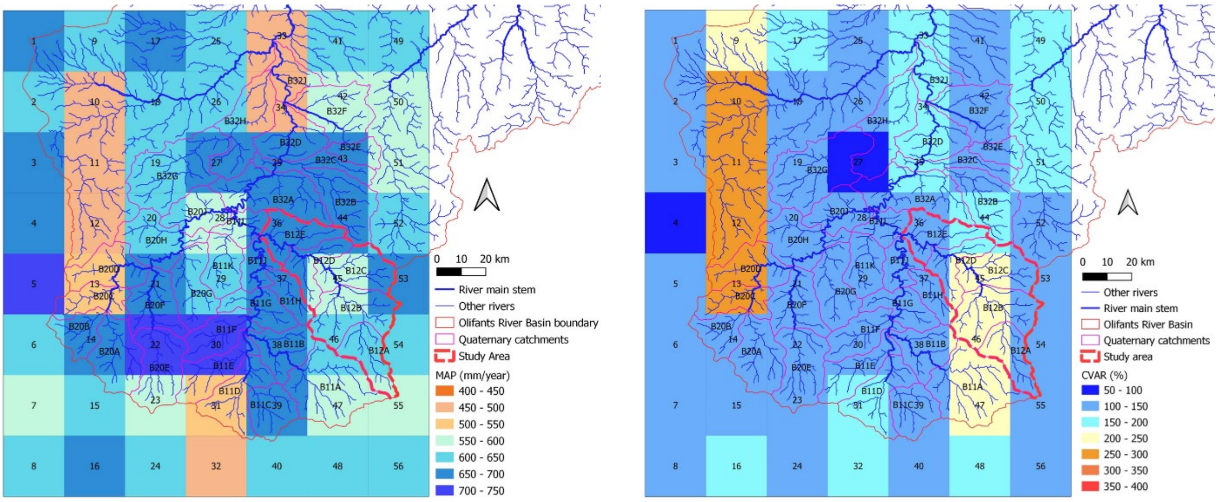


Figure 5.2: Mean annual precipitation and coefficient of variation (1909-2020)

Table 5.5 shows that MAP for 1909-2020 and for the 30 years climate periods of 1931-1960, 1951-1980 and 1981-2010 for each secondary catchment and the incremental change. The 1931-2060 climate was drier than the 1961-1990 and 1991-2020 climates. Generally, MAP for the sub-catchments decreased by about -29 mm between the 1931-1960 and 1961-1990 climates; however, MAP for B12A and B12D increased. Generally, MAP decreased by about -21 mm between the 1961-1990 and 1991-2020 climates; however, MAP in B12D and B12E increased. This suggests that the change in precipitation is not monotonic.

Table 5-5: Catchment average precipitation

Sub Catchment	MAP in period (mm/year)				Change(mm)	
	1909-2020	1931-1960	1961-1990	1991-2020	1931-1960 vs 1961-1990	1961-1990 vs 1991-2020
B12A	693	724	703	663	21	-40
B12B	1037	1002	1080	1008	-78	-72
B12C	987	880	1046	973	-166	-73
B12D	773	750	751	782	-1	31
B12E	814	879	735	831	144	96
Average	887	867	896	875	-29	-21

Table 5.6 shows that except for B12A, the CV decreased for the 1961-1990 climate compared to the 1931-1960 climate, with B12C sub-catchment having the biggest reduction. It increased marginally for B12A to B12D for the 1961-1990 climate compared to the 1991-2020 climate.

Table 5-6: Coefficient of variation about MAP

Sub Catchment	Coefficient of Variation (%)				Change (%)	
	1909-2020	1931-1960	1961-1990	1991-2020	1931-1960 vs 1961-1990	1961-1990 vs 1991-2020
B12A	16%	18%	14%	16%	4%	2%
B12B	17%	16%	17%	18%	-1%	1%
B12C	21%	17%	21%	23%	**-4%**	2%
B12D	19%	18%	19%	20%	-1%	1%
B12E	17%	15%	16%	16%	-1%	0%
Average	**18%**	**17%**	**17%**	**19%**	**-1%**	**1%**

The climate changes (MAP and CV) are not uniform across the sub-catchments. This suggests that a differentiated approach to the operational management of water resources for the sub-catchments may be important. The ratio of average daily precipitation for each month to average daily rainfall for the year obtained with the GPCC DWD data shows that with the 1931-1960, 1961-1990 and 1991-2020 climates, most precipitation was received during October and March as illustrated in **Figure 5.3**. This pattern was repeated for all of the five sub-catchments.

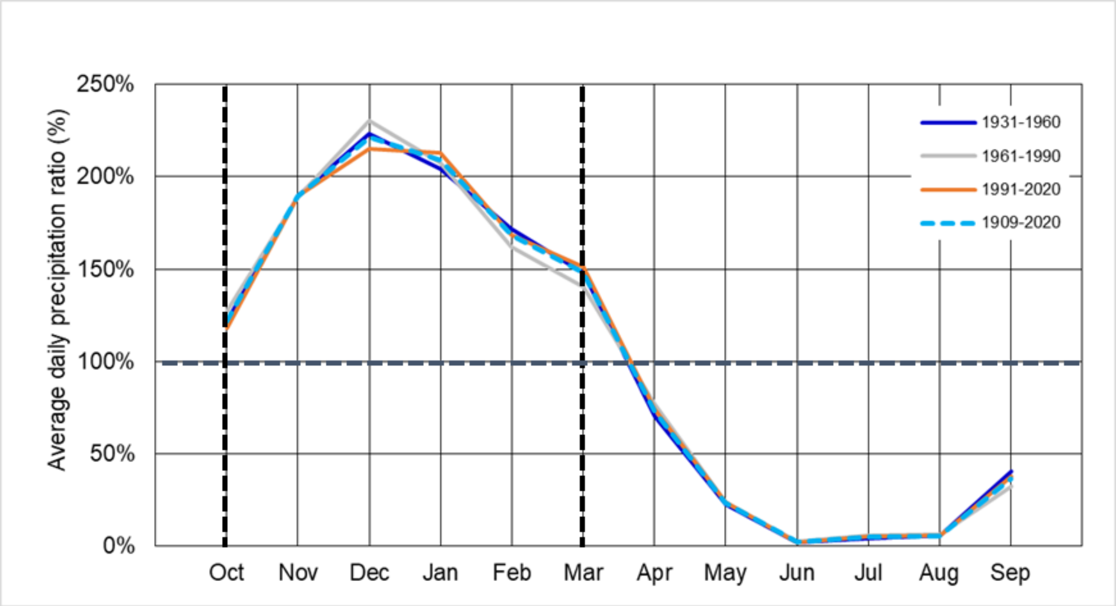


Figure 5.3: Mean daily precipitation ratio

The total rainfall for overlapping three-month periods OND; NDJ; DJF, and JFM can be calculated and shows results for sub-catchment B12E. In this example, the wettest season was for the 1931-1960 period, followed by 1991-2020, which agrees with the results in **Table 5.7**.

Table 5-7: Cumulative average monthly precipitation for B12E

30-years period	Period Total (mm)			
	OND	NDJ	DJF	JFM
1931-1960	394	456	436	380
1961-1990	337	387	365	309
1991-2020	364	431	410	365
1909-2020	365	426	405	354.

Figure 5.4 shows how the average rainfall season developed for sub-catchment B12E, and the cumulative monthly ratios are shown in **Table 5.7**.

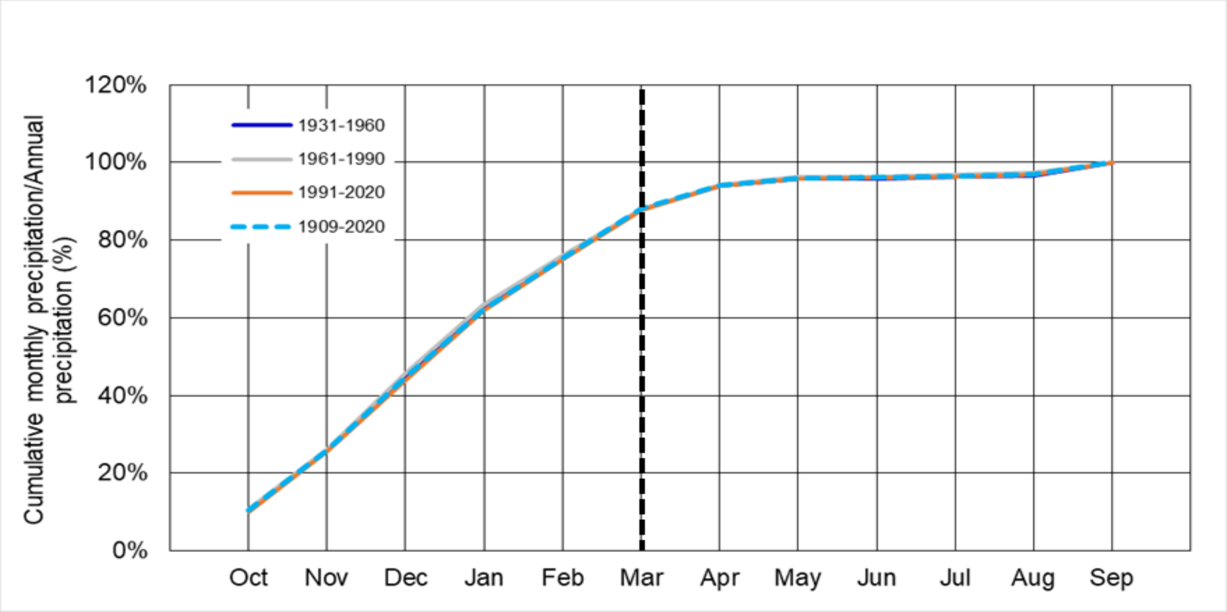


Figure 5.4: Cumulative average monthly precipitation for B12E

Cumulative precipitation to month i (P_i) can be estimated using the following 4th order regression equation:

$$P_i = 0.0003x^4 - 0.0069x^3 + 0.0423x^2 + 0.0809x - 0.0193$$

The curve fit is illustrated in **Figure 5.5**.

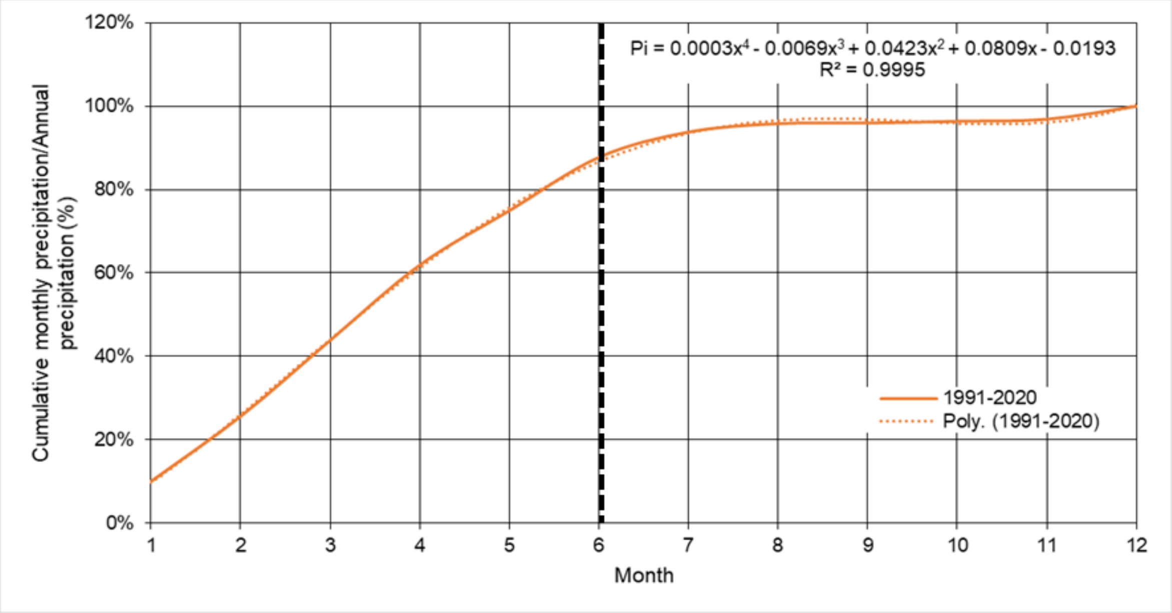


Figure 5.5: Cumulative average monthly precipitation to month i

A view of how the wet season (October to March) may develop and progress can be useful, as evidenced by the SARCOF and NACOF seasonal climate forecasts. The DyWaBM only considers one-month ahead, which requires a monthly outlook. **Figure 5.6** shows median and middle third extents for B12E with the 1991-2020 climate. The diagrams show that the climate outlook can change drastically due to transformations during the wet season (October to March).

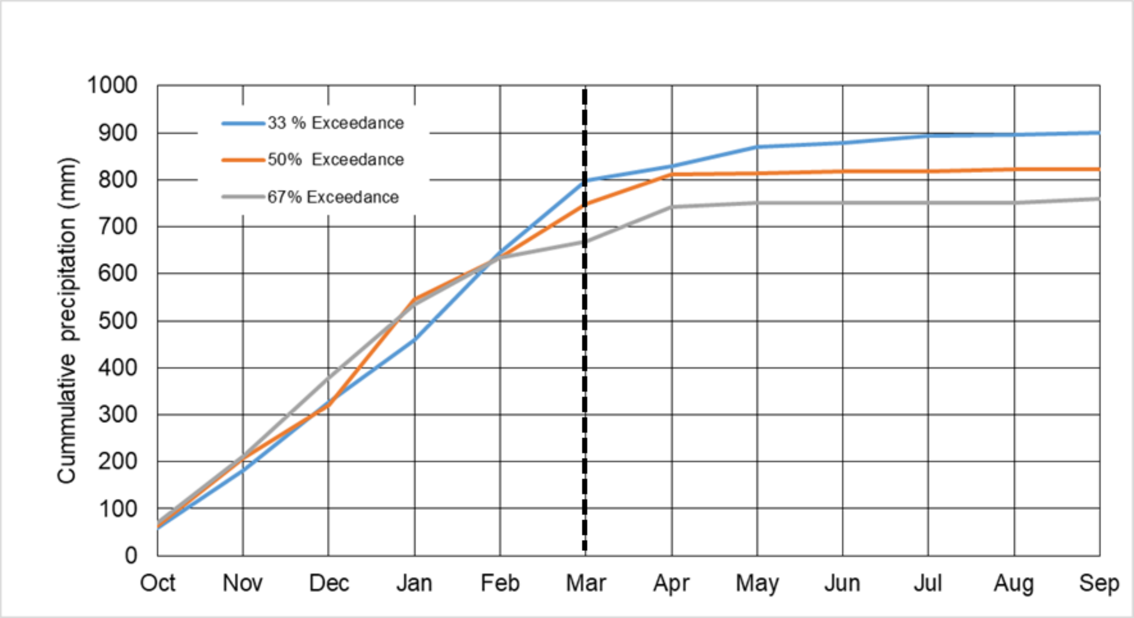


Figure 5.6: Median and middle third extents for B12E with the 1991-2020 climate

Figure 5.7 shows an example of median and middle third extents for cumulative daily precipitation using December for B12C with the 1971-2000 CORDEX hind cast climate. Analysis of daily values showed that this outlook can change drastically because of short-duration high-intensity rainfall events or dry spells.

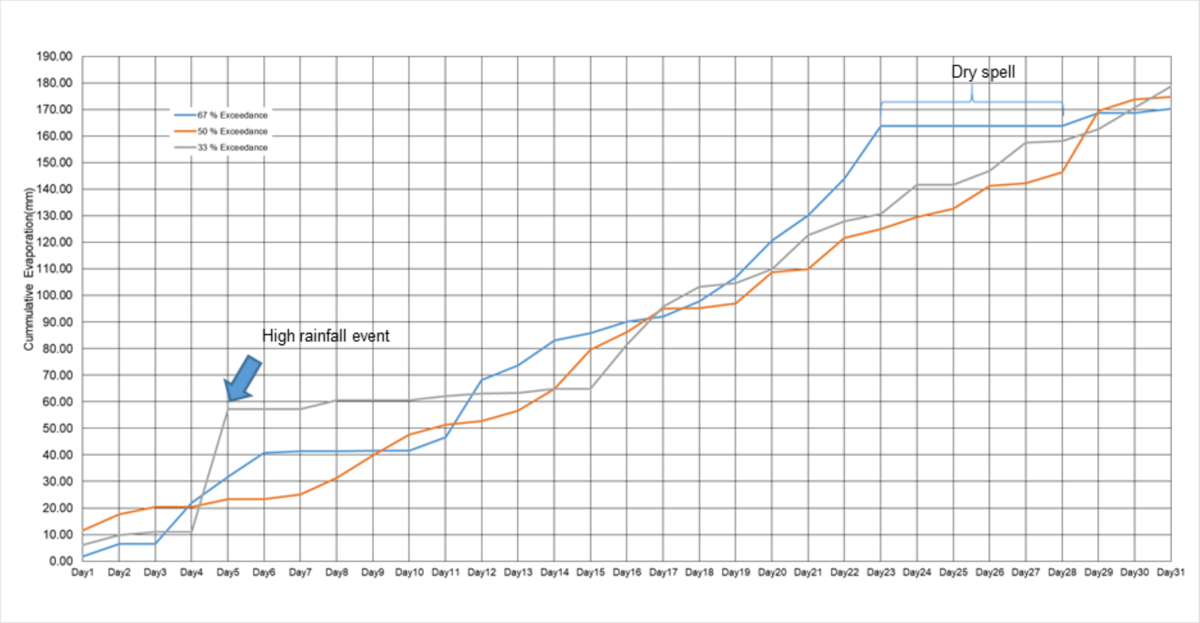
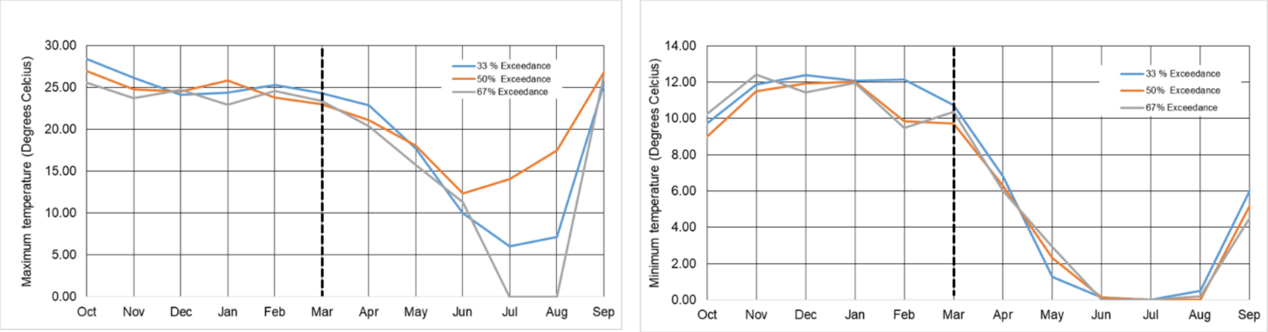


Figure 5.7: Cumulative daily precipitation extents for B12B with the 1971-2000 climate

5.7.2 Temperature

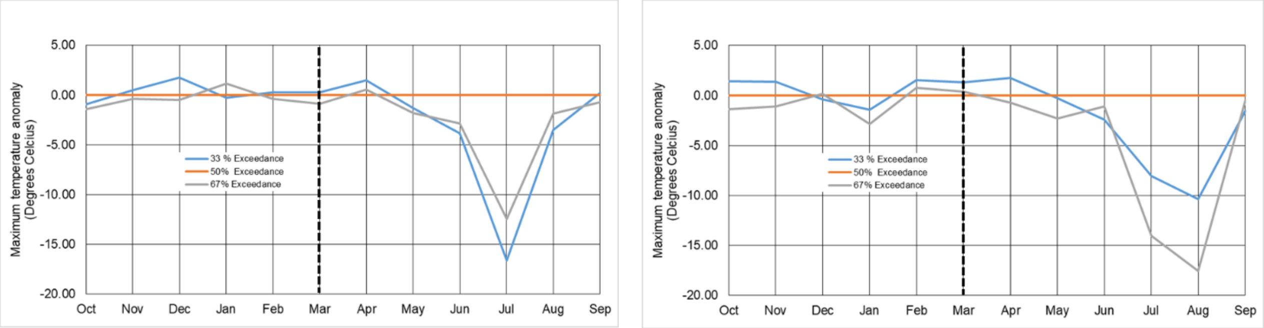
For all sub-catchments with the CORDEX hind-cast period 1971 to 2000, maximum temperature was generally highest in October and lowest in June to August while minimum temperature was lowest in June to August as illustrated in **Figure 5.8** using B12C as an example.



B12C B12C

Figure 5.8: Maximum and minimum temperature with the 1971-2000 climate

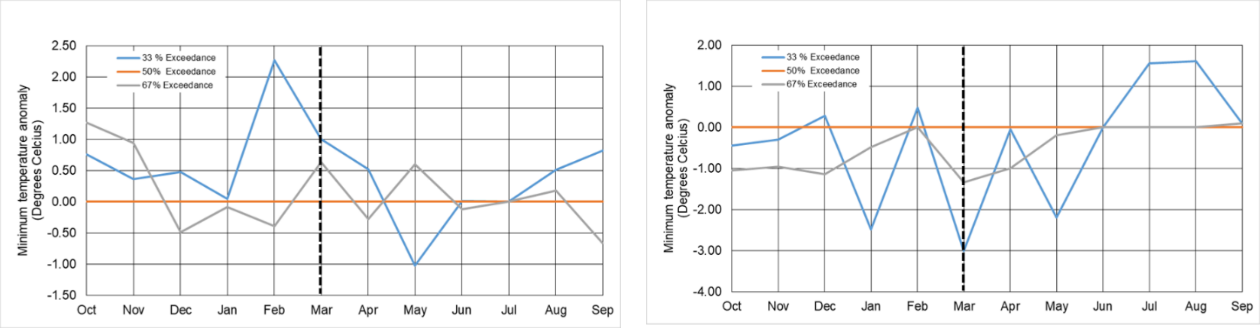
Figure 5.9 shows anomalies for maximum temperature for the CORDEX hind-cast period 1971 to 2000 using B12C and B12D as examples. Generally, monthly deviations from "normal" for the two sub-catchments follow different patterns.



B12C B12D

Figure 5.9: Maximum temperature anomalies for B12C and B12D

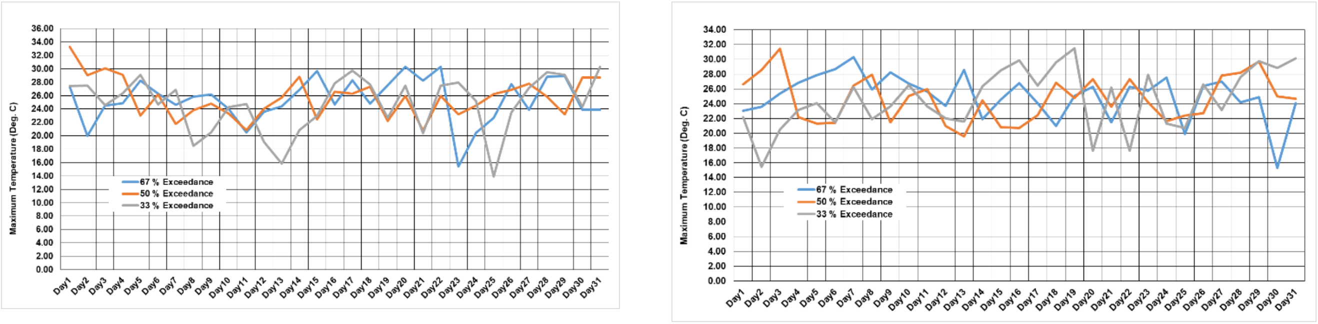
Figure 5.10 shows anomalies for minimum temperature for the CORDEX hind-cast period 1971 till 2000 with B12C and B12D as examples. Generally, monthly deviations from "normal" for the two sub-catchments follow different patterns.



B12C B12D

Figure 5.10: Minimum temperature anomalies for B12C and B12D

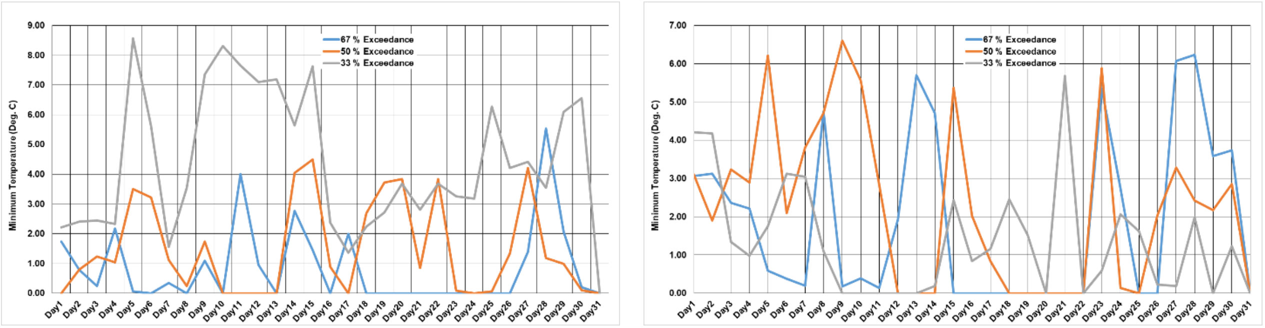
Figure 5.11 illustrates the variability in maximum daily temperature for December for the CORDEX hind-cast period 1971 to 2000 using B12C and B12D as examples. Generally, the maximum temperature for the two sub-catchments follows different patterns.



B12C B12D

Figure 5.11: Maximum daily temperature for B12C and B12D

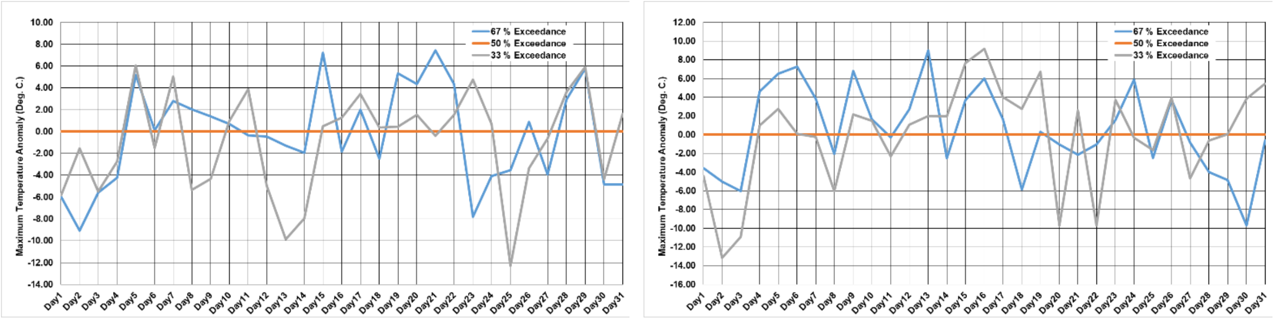
Figure 5.12 illustrates the variability in minimum daily temperature for June for the CORDEX hind-cast period 1971 to 2000 using B12C and B12D as examples. Generally, the minimum daily temperature for the two sub-catchments follows different patterns.



B12C B12D

Figure 5.12: Minimum daily temperature for B12C and B12D

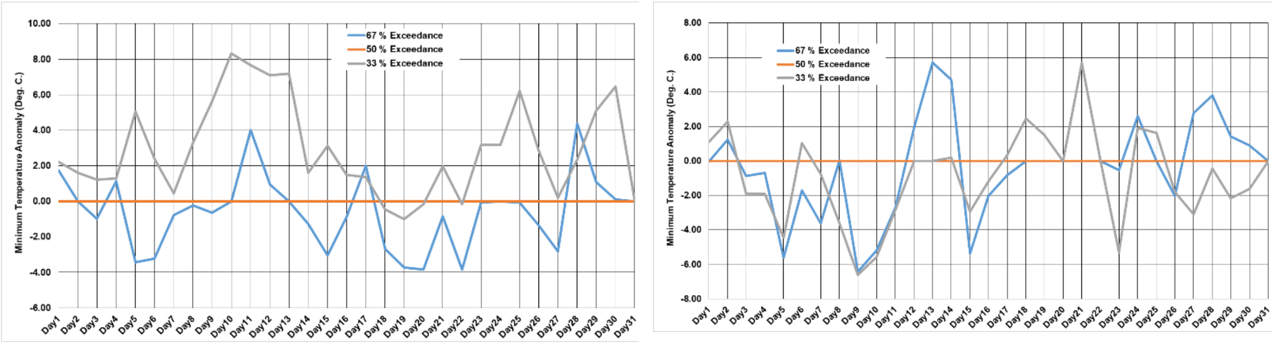
Figure 5.13 shows anomalies for maximum daily temperature for December for the CORDEX hind-cast period 1971 to 2000 using B12C and B12D as examples. Generally, daily deviations from “normal” for the two sub-catchments follow different patterns.



B12C B12D

Figure 5.13: Maximum daily temperature anomalies for B12C and B12D

Figure 5.14 shows anomalies for minimum daily temperature for June for the CORDEX hind-cast period 1971 to 2000 using B12C and B12D as examples. Generally, daily deviations from “normal” for the two sub-catchments follow different patterns.



B12C B12D

Figure 5.14: Minimum daily temperature anomalies for B12C and B12D

5.7.3 Evaporation

Cumulative evapotranspiration to month *i* (P_i) can be estimated using the following 4th order regression equation:

$$E_i = 0.0001x^4 - 0.0029x^3 + 0.0131x^2 + 0.1448x - 0.1092$$

The curve fit is illustrated in **Figure 5.15**.

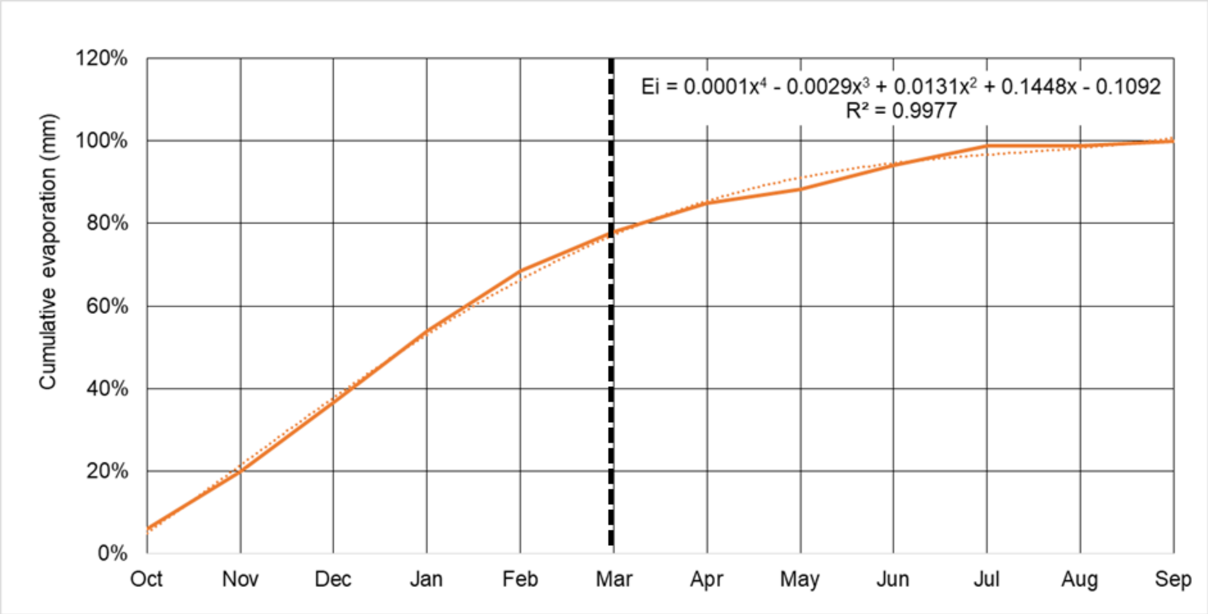


Figure 5.15: Cumulative average monthly evapo-transpiration to month i

Figure 5.16 shows median and middle third extents for evapotranspiration for B12E with the 1971-2000 CORDEX hindcast climate. The diagram indicates that the outlook can change drastically due to transformations which are not limited to the wet season (October to March).

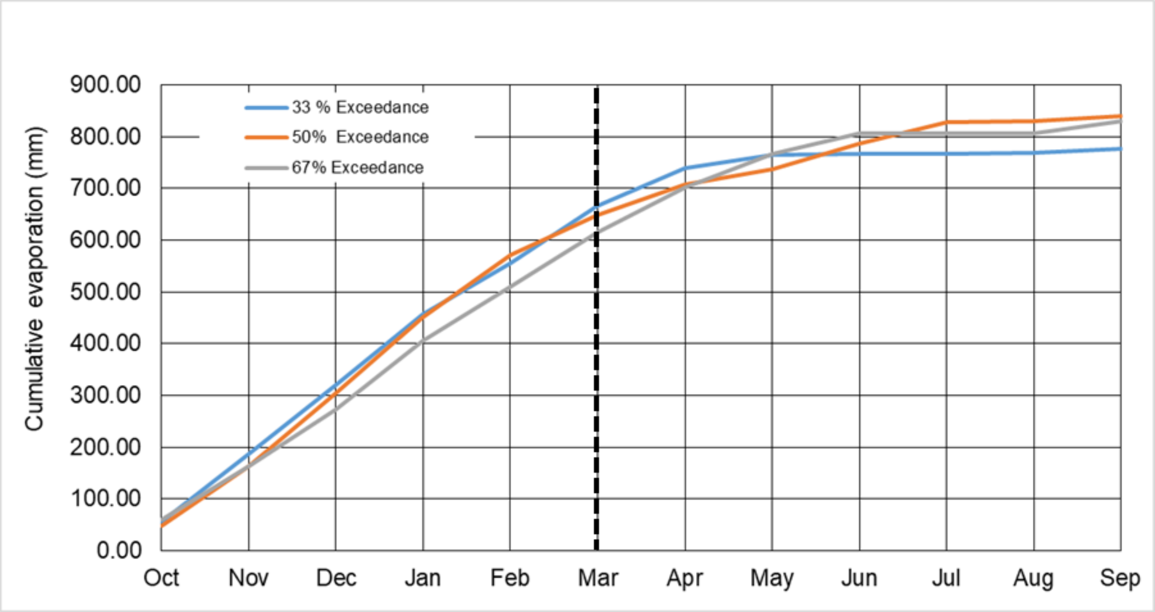


Figure 5.16: Median and middle third extents for B12E with the 1971-2000 climate

Figure 5.17 shows an example of median and middle third extents for cumulative daily evaporation using October for B12B with the 1971-2000 CORDEX hind cast climate. The outlook can change drastically due to transformations not limited to the wet season (October till March).

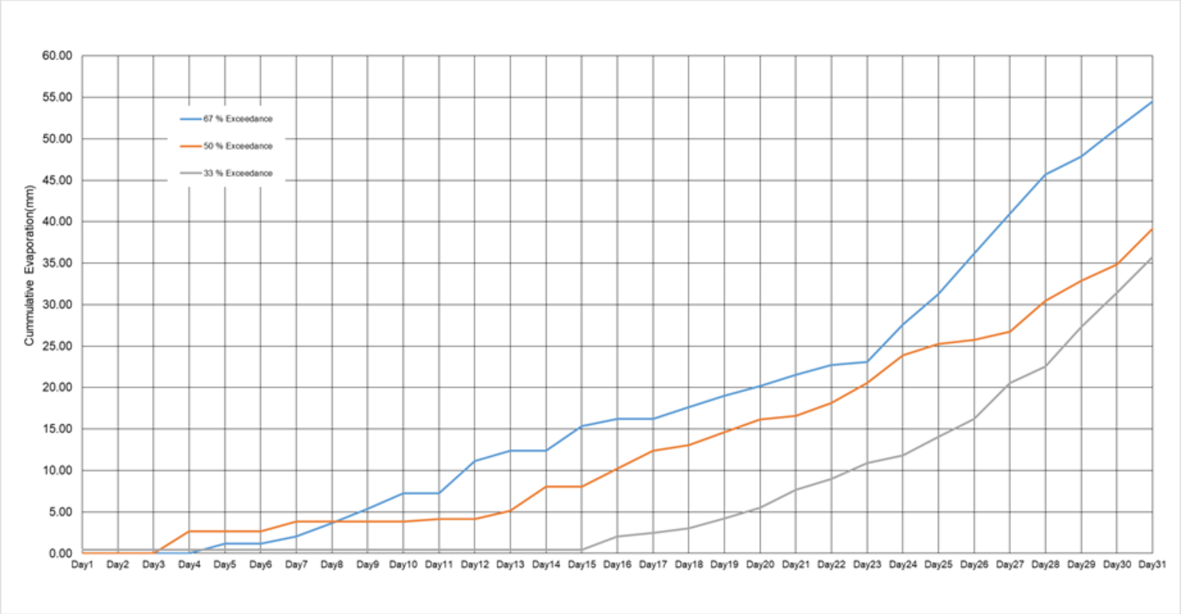


Figure 5.17: Cumulative daily evaporation extents for B12B with the 1971-2000 climate

5.8 Trend analysis

Analysis of trends was performed using the slope of the regression line or regression coefficient of total annual precipitation (GPCC data), total annual evaporation (CRU TS data), average annual maximum and minimum temperature (CRU TS data) over a period as a predictor of the average change in annual values.

Figure 5.18 shows the typical precipitation graph with a simple linear regression line of the form:

$$y_i = mx_i + c$$

where

y_i is the dependent variable at time i,
x_i is the independent variable at time i,
m is the slope of the line or regression coefficient and
c is the value of y_i when x_i is zero or the intercept.

The slope of the m is estimate as follows:

$$m = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sum_{i=1}^{n}(x_i - \overline{x})^2}$$

where

$\overline{x}$ is average of the x_i values
$\overline{y}$ is average of the y_i values

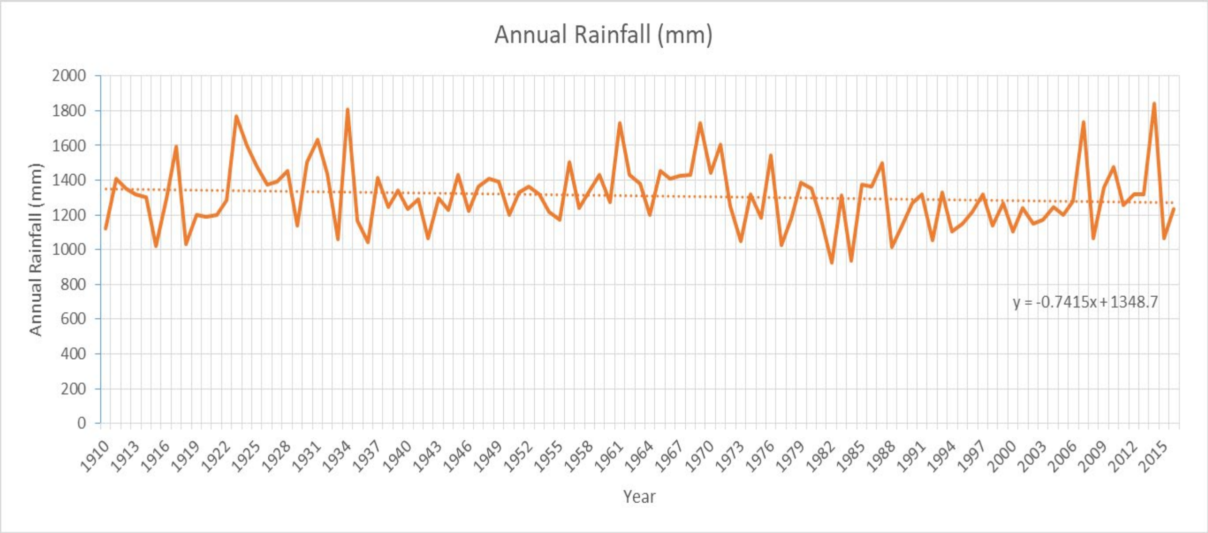


Figure 5.18: Linear regression example

Trend tests were performed using the Mann-Kendall non-parametric monotonic trend test (Kendall, 1975). Mann-Kendall statistic S (M-K S) was calculated using the following formula for each grid cell for the periods 1909 to 2020, 1931 to 1960, 1961 to 1990 and 1991 to 2020:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k)$$

where:

$$sign(x_j - x_k) \quad \begin{aligned} &= 1 \; if \; x_j - x_k > 0 \\ &= 0 \; if \; x_j - x_k = 0 \\ &= -1 \; if \; x_j - x_k < 0 \end{aligned}$$

A negative value of S suggests a decreasing trend, while a positive value suggests an increasing trend.

The Kendall normal approximation test (Kendall, 1975), first calculates the variance of S using the following formula:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5n) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)\right]$$

where:

n = the number of data points
g = the number of tied groups in the data set
t_p = the number of data points in the p^{th} tied group

Correction for ties becomes important when there are many repeated values in a data set.
The normalized test statistic Z is then calculated as follows:

$$Z = \frac{S-1}{[VAR(S)]^{1/2}}\ if\ S > 0$$

$$Z = 0\ if\ S = 0$$

$$Z = \frac{S+1}{[VAR(S)]^{1/2}}\ if\ S < 0$$

And finally the probability associated with the Z statistic is calculated as follows:

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}$$

For consistent interpretation of significance or confidence levels and transparency levels, the probability ranges were assigned qualitative interpretations, as shown in **Table 5.8.** These were adopted from Mastrandrea et al. (2011) in the guidance notes for working groups of the IPCC Fifth Assessment Report.

Table 5-8: Summary – results from trend tests

Probability Range	Qualitative interpretation
≥ 99%	virtually certain
≥ 90%<99%	very likely
≥ 66%<90%	likely
≥ 33% <66%	about as likely as not
≥ 10% <33%	unlikely
≥1 % <10%	very unlikely
<1%	exceptionally unlikely

5.8.1 Rainfall

Historical data shows changes in precipitation of about -5.8 mm/10 years, -12 mm/10 years and 40.8 mm/10 years for 1931-1960, 1961-1990 and 1991-2020 respectively, as listed in **Table 5.9**. The period 1909-2020 shows a decrease in annual catchment precipitation of about 0.9 mm/10 years. These observations suggest that the change in precipitation is not monotonic.

Table 5-9: Sub catchments – regression slopes

Sub Catchment	Average slope for period (Deg./10 years)			
	1901-2020	1931-1960	1961-1990	1991-2020
B12A	-2.9	-5.9	32.7	-11.8
B12B	-1.3	-33.5	22.6	56.7
B12C	4.2	-28.3	10.6	90.8
B12D	-0.8	15.6	-3.8	47.5
B12E	-4.9	45.5	-8.4	-0.2
Average	-0.9	-5.8	12.0	40.8

The results from trend tests are presented in **Table 5.10**. The highlighted numbers show where the confidence level for the precipitation trend detected for a sub-catchment can be stated as likely, very likely or virtually certain by applying the qualitative interpretations in **Table 5.8**.

The results suggest the following:

- For the period 1909-2020, a decreasing precipitation trend was sustained at a very high level of confidence for sub-catchments B12A.
- For 1931-1960, an increasing precipitation trend was sustained at a high confidence level for B12A and B12B sub-catchments.
- For the period 1961-1990, an increasing precipitation trend was sustained at a high confidence level for B12D sub-catchment; during the same period, a decreasing precipitation trend was certain for B12A and B12C sub-catchments.
- For the period 1991-1920, an increasing precipitation trend was sustained at a high level of confidence for B12B and B12D sub-catchments and during the same period a decreasing precipitation trend was sustained at a high level of confidence for B1C and B21E sub-catchments.

The results show that trends are not one way.

Table 5-10: Summary – confidence levels for detected trends

Sub Catchment	1909-2020		1931-1960		1961-1990		1991-2020	
	MKS	Probability	MKS	Probability	MKS	Probability	MKS	Probability
B12A	-558	84%	91	89%	-175	100%	96	63%
B12B	-133	26%	69	77%	1	0%	361	96%
B12C	37	7%	35	46%	141	99%	-157	100%
B12D	-131	26%	11	14%	73	80%	49	66%
B12E	-165	32%	51	63%	-53	65%	-54	100%
Average	-173	33%	53	60%	3	63%	79	88%

5.8.2 Temperature

Historical data shows changes in average maximum temperature of about 0.3°C /10 years, -0.2°C /10 years and 0.5°C /10 years for 1931-1960, 1961-1990 and 1991-2020, respectively as shown in **Table 5.11**. The period 1909-2020 shows an increase in average annual maximum temperature of about -0.9°C /10 years period. These observations suggest that the change in maximum temperature is not monotonic.

Table 5-11: Sub catchments – regression slopes

Sub Catchment	Average slope for period (mm/10 years)			
	1909-2020	1931-1960	191-1990	1991-2020
B12A	0.3	-0.1	0.6	1.1
B12B	0.3	-0.3	0.6	1.2
B12C	0.4	-0.3	0.7	1.3
B12D	0.3	-0.3	0.4	1.0
B12E	0.2	-0.2	0.3	0.8
Average	0.3	-0.2	0.5	1.1

The results from trend tests are presented in **Table 5.12**. The highlighted numbers show where the confidence level for the average maximum temperature trend detected for a sub-catchment can be stated as likely, very likely or virtually certain. The results suggest the following:

- For the periods 1909-2020 and1991-2020, an increasing trend for maximum temperature was certain for all sub-catchments
- For 1931-1960, a decreasing maximum temperature trend was sustained at a likely confidence level for B12C, B12D and B12E sub-catchments.
- For the periods 1961-1990, an increasing trend for maximum temperature could not be sustained for all sub-catchments

The results show that trends are not one way.

Table 5-12: Summary – confidence levels for detected trends

Sub Catchment	1909-2020		1931-1960		1961-1990		1991-2020	
	MKS	Probability	MKS	Probability	MKS	Probability	MKS	Probability
B12A	2119	100%	-24	35%	128	98%	259	100%
B12B	2046	100%	-43	59%	135	98%	257	100%
B12C	1924	100%	-67	81%	125	97%	259	100%
B12D	1939	100%	-63	78%	129	98%	251	100%
B12E	1920	100%	-79	88%	113	95%	237	100%
Average	1992	100%	-55	68%	127	97%	253	100%

Historical data shows changes in average minimum temperature of about 0.2°C /10 years, 0.3°C /10 years and 0.1°C /10 years for 1931-1960, 1961-1990 and 1991-2020, respectively, as shown in **Table 5.13**. The period 1909-2020 shows an average annual minimum temperature increase of about 0.1^{o}C/10-year period. These observations suggest that the change in minimum temperature is not monotonic.

Table 5-13: Sub catchments – regression slopes

Sub Catchment	Average slope for period (mm/10 years)			
	1909-2020	1931-1960	1961-1990	1991-2020
B12A	0.2	0.2	0.2	0.1
B12B	0.2	0.2	0.3	0.1
B12C	0.2	0.2	0.3	0.1
B12D	0.2	0.1	0.3	0.1
B12E	0.2	0.1	0.3	0.1
Average	0.2	0.2	0.3	0.1

The results from trend tests are presented in **Table 5.14**. The highlighted numbers show where the confidence level for the average maximum temperature trend detected for a sub-catchment can be stated as likely, very likely or virtually certain. The results suggest the following:

- For the periods 1909-2020 and 1961-1990, an increasing trend for minimum temperature was certain for all sub-catchments
- For the period 1931-1960, an increasing minimum temperature trend was certain for B12A, B12B and B12C and very likely level of confidence for B12D and B12E sub-catchments.
- For the period 1991-2020, an increasing trend for minimum temperature was sustained at a very likely level of confidence for all sub-catchments

The results show that trends are not one way.

Table 5-14: Summary – confidence levels for detected trends

Sub Catchment	1909-2020		1931-1960		1961-1990		1991-2020	
	MKS	Probability	MKS	Probability	MKS	Probability	MKS	Probability
B12A	3092	100%	169	100%	141	99%	45	57%
B12B	2929	100%	148	100%	159	100%	54	66%
B12C	2816	100%	126	99%	175	100%	44	56%
B12D	2848	100%	112	97%	179	100%	30	40%
B12E	2876	100%	105	96%	181	100%	22	29%
Average	2910	100%	133	99%	167	100%	41	52%

5.8.3 Evaporation

Historical data shows changes in evaporation of about 15.0 mm/10 years, -9.9 mm/10 years and 33.2 mm/10 years for 1931-1960, 1961-1990 and 1991-2020, respectively, as listed in **Table 5.15**. The period 1909-2020 shows a decrease in annual catchment evaporation of about 7.8 mm/10-years period. These observations suggest that change in precipitation is not monotonic.

Table 5-15: Sub catchments – regression slopes – evaporation

Sub Catchment	**Average slope for period (mm/10 years)**			
	1909-2020	**1931-1960**	**1961-1990**	**1991-2020**
B12A	9.7	21.3	-10.2	47.4
B12B	8.9	19.1	-10.4	36.3
B12C	8.2	17.2	-10.6	26.8
B12D	6.5	10.1	-9.5	27.4
B12E	5.0	4.1	-8.6	27.8
Average	7.8	15.0	-9.9	33.2

The results from trend tests are presented in **Table 5.16**. The highlighted numbers show where the confidence level for the evaporation trend detected for a sub-catchment can be stated as likely, very likely or virtually certain. The results suggest the following:

- For 1909-2020, 1961-1990, and 1991-1920, an increasing evaporation trend was observed in certain sub-catchments B12A, B12B, and B12C.
- For 1931-1960, an increasing evaporation trend was sustained at a high level of confidence for B12A and B12B sub-catchments.
- For the period 1961-1990, an increasing evaporation trend was certain for B12D sub-catchment and very likely for B12E sub-catchment
- For 1991-2020, an increasing evaporation trend was certain for B12D sub-catchments and very likely for B12E.
- For 1909-2020 an increasing evaporation trend was certain for B12D sub-catchments.

The results show that trends are not one way.

Table 5-16: Summary – confidence levels for detected trends – evaporation

Sub Catchment	**1909-2020**		**1931-1960**		**1961-1990**		**1991-2020**	
	MKS	**Probability**	**MKS**	**Probability**	**MKS**	**Probability**	**MKS**	**Probability**
B12A	1147	100%	-69	78%	174	100%	240	100%
B12B	1095	100%	-104	93%	191	100%	216	100%
B12C	1007	100%	-139	99%	160	100%	190	100%
B12D	933	99%	-179	100%	153	99%	202	100%
B12E	-225	43%	-255	100%	115	96%	-98	92%
Average	819.1	89%	-144.7	94%	162	99%	154.9	99%

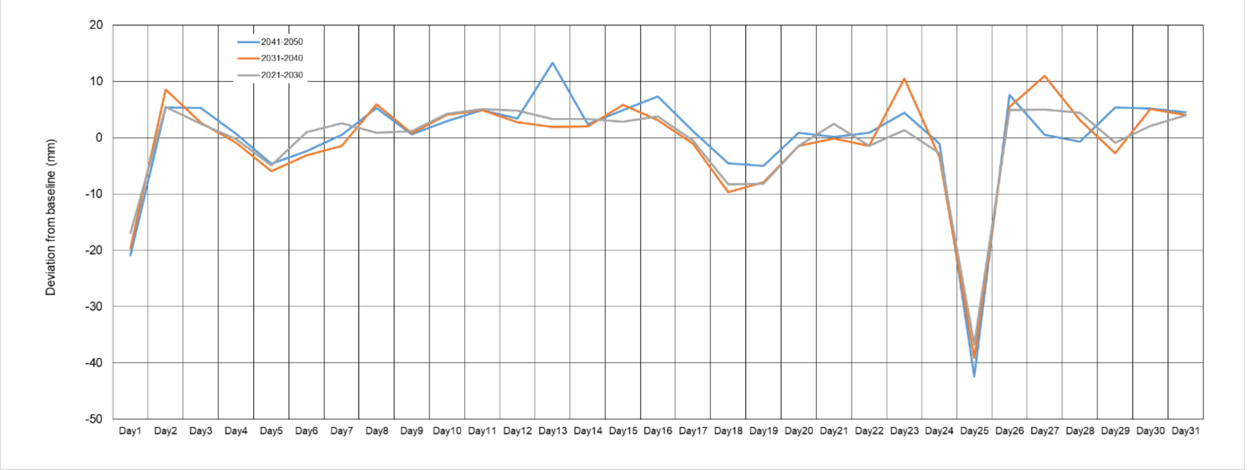
5.9 Climate change projections

The current practice in water resources management is to select plausible climate scenarios and determine parameter values with the future climate. These future values are compared with values for the selected baseline to evaluate the impact of climate change.

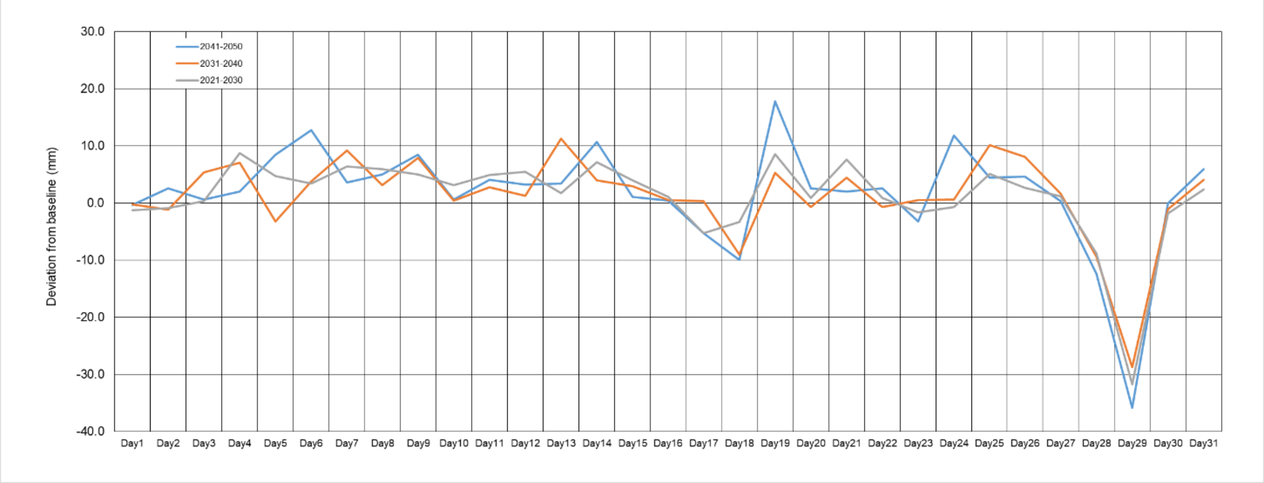
In daily management of water resources the observed parameter values already reflect changed climate and so do weather and seasonal climate forecasting parameters. Beyond these time scales climate scenarios are used to obtain projected parameter values. CORDEX RCP4.5 and RCP8.5 climate model scenarios were selected for this study. In Section 4.6, a procedure to determine median and middle third extents for cumulative daily data was developed. With the projection period of 2021 to 2050 average conditions for periods of ten years 2021-2030, 2031-2040 and 2041-2050 time horizons can be informative.

5.9.1 Rainfall

With a baseline of 2021, the change in daily precipitation for January for the period 2021-2030 as an example is shown in **Figure 5.19**. With both scenarios, projected daily climate precipitation was generally lower than the baseline; however, a very high rainfall event in the baseline climate is not present in the projection period.



RCP4.5



RCP8.5

Figure 5.19: Change in precipitation 2021-2030 relative to 2021 baseline B12C

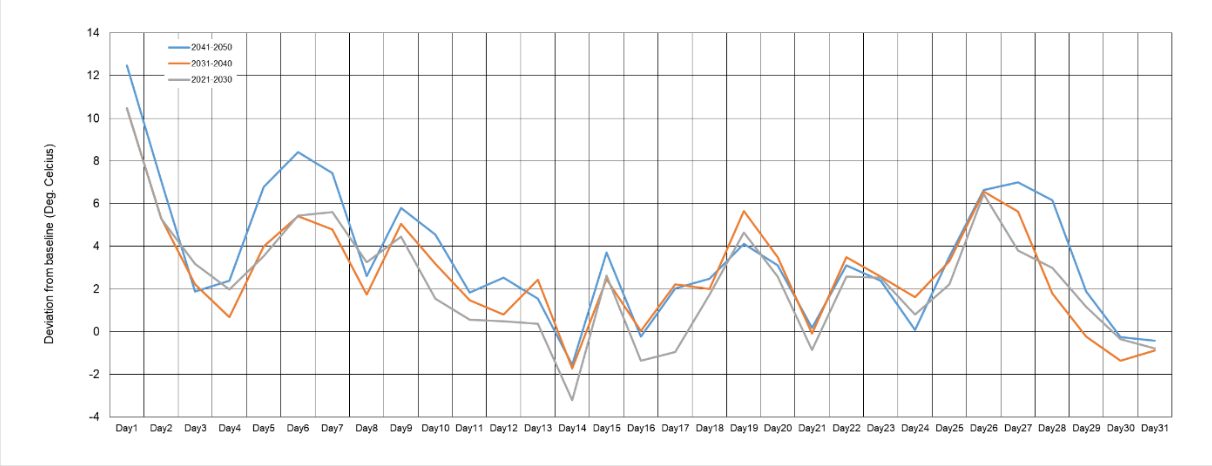
Generally, the RCP4.5 sub-catchments B12A and B12B have reduced total precipitation for January across all periods, as shown in **Table 5.17.** The RCP8.5 projections show increased rainfall for all sub-catchments across all periods.

Table 5-17: Change in sub catchments precipitation

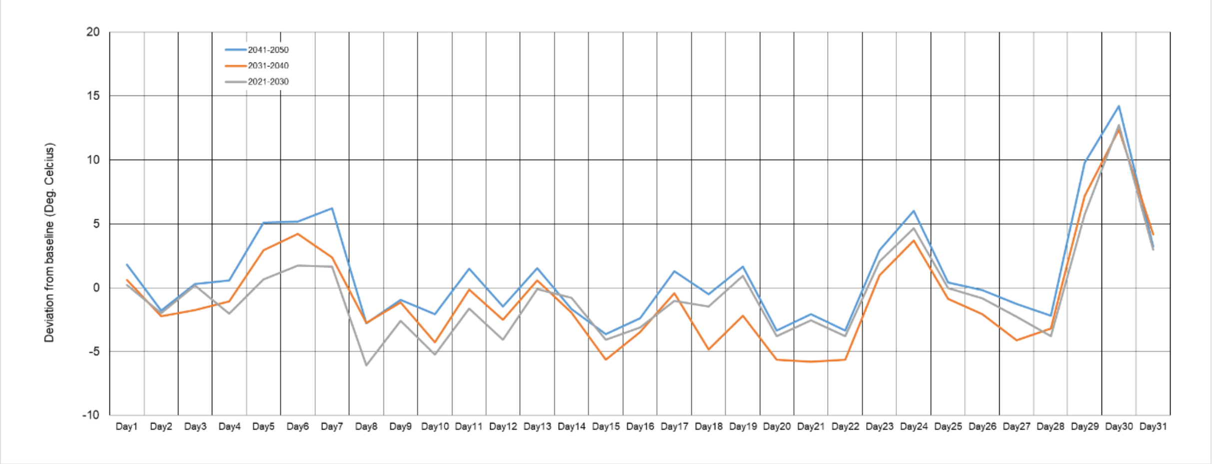
Sub catchment	RCP4.5			RCP8.5		
	2021-2030	2031-2040	2041-2050	2021-2030	2031-2040	2041-2050
B12A	-32%	-37%	-30%	75%	101%	103%
B12B	-24%	-27%	-18%	50%	59%	70%
B12C	-11%	-10%	3%	26%	29%	38%
B12D	-2%	1%	16%	17%	13%	30%
B12E	-6%	-2%	7%	33%	21%	36%

5.9.2 Temperature

With a baseline of 2021, the change in maximum daily temperature for January for 2021-2030 is shown in **Figure 5.20** for sub-catchment B12C as an example. The RCP4.5 projected climate is generally warmer than the baseline while the RCP8.5 climate is generally cooler.



RCP4.5



RCP8.5

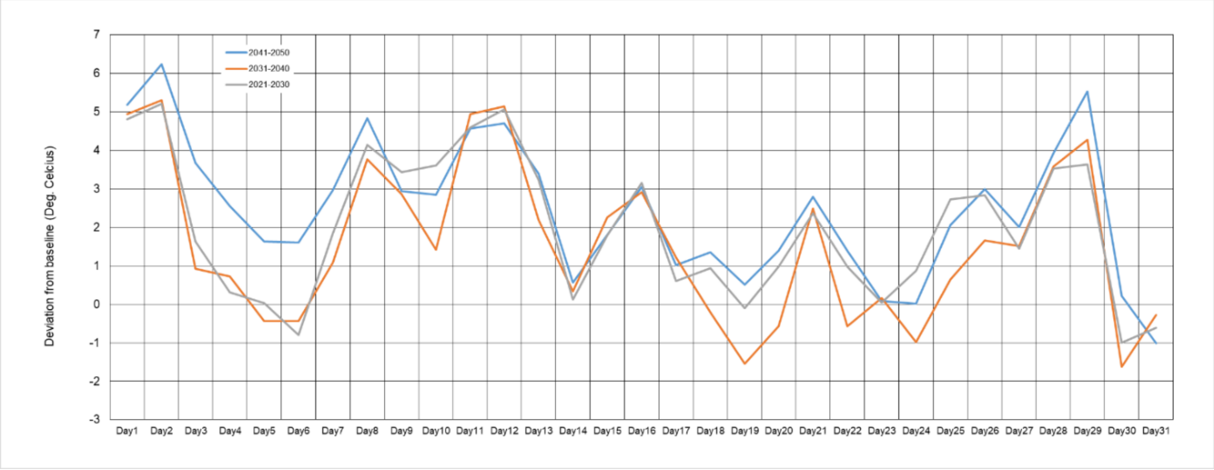
Figure 5.20: Change in maximum temperature 2021-2030 relative to 2021 baseline B12C

On average, with the RCP4.5 scenario, all sub-catchments have higher maximum monthly temperatures for January across all periods, as shown in **Table 5.18**. With the RCP8.5 scenario, the 2021-2030 and 2031-2040 maximum monthly temperature is lower than the baseline, but for the 2041-2050 period, it is higher than the baseline. The RCP4.5 gives higher maximum monthly temperatures than the RCP8.5 which contradicts intuitive thinking.

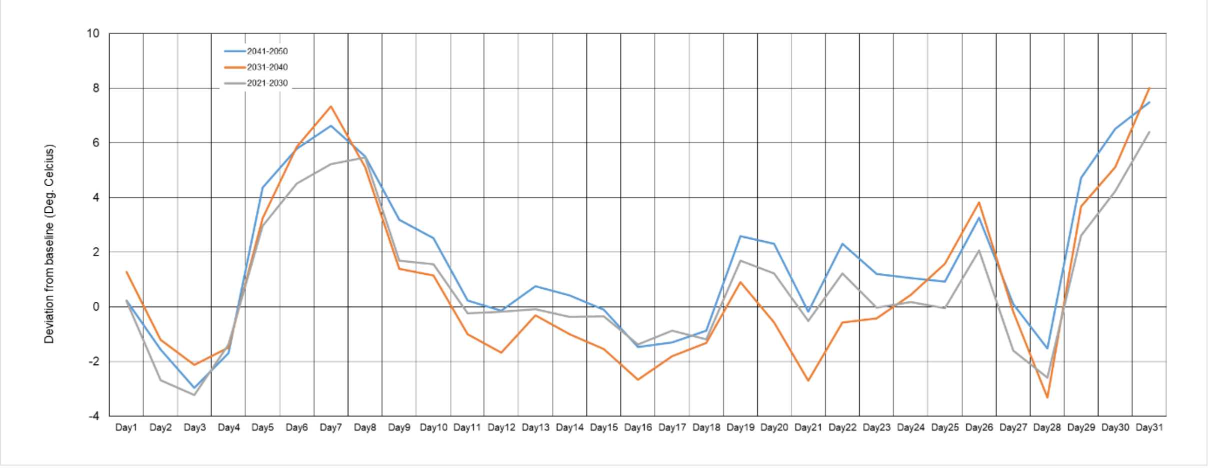
Table 5-18: Change in maximum temperature for sub catchments

Sub catchment	RCP4.5			RCP8.5		
	2021-2030	2031-2040	2041-2050	2021-2030	2031-2040	2041-2050
B12A	11%	13%	16%	-3%	-3%	3%
B12B	10%	13%	15%	-3%	-3%	3%
B12C	9%	11%	14%	-2%	-3%	4%
B12D	9%	11%	14%	-2%	-3%	3%
B12E	9%	10%	14%	-2%	-3%	3%

The minimum daily temperature for sub-catchment B12C in January for the period 2021-2030, as an example, is generally higher than the baseline as shown in **Figure 5.21**. The minimum daily temperature with RCP4.5 scenario for January is higher than with the RCP8.5 scenario.



RCP4.5



RCP8.5

Figure 5.21: Change in minimum temperature 2021-2030 relative to 2021 baseline B12C

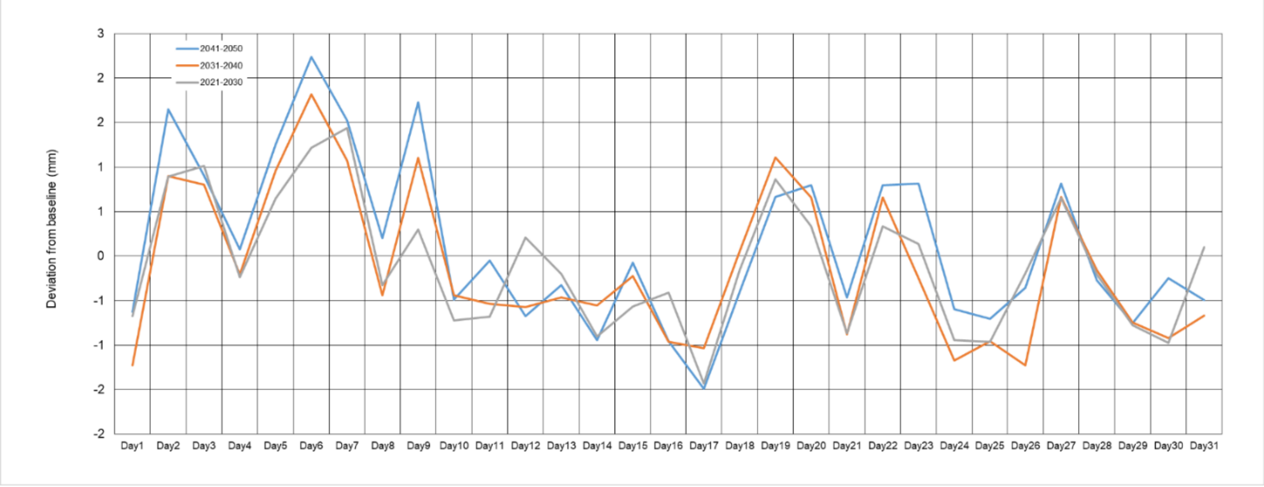
On average, all sub-catchments have higher minimum monthly temperatures for January for all climate scenarios, as shown in **Table 5.19**. Generally, the change in minimum temperature for the RCP4.5 scenario is higher than with the RCP8.5 scenario.

Table 5-19: Change in minimum temperature for sub-catchments

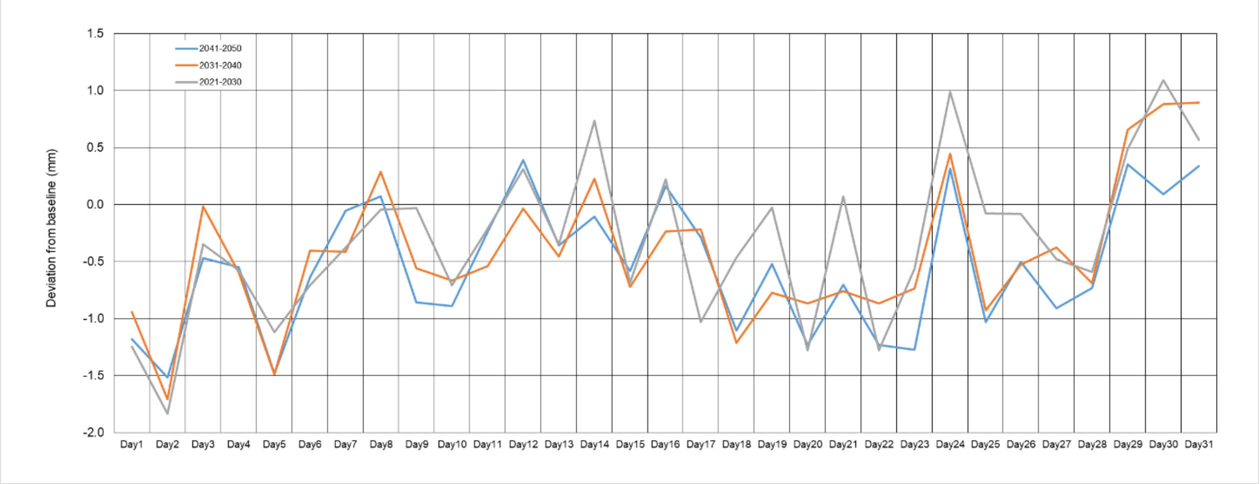
Sub catchment	RCP4.5			RCP8.5		
	2021-2030	2031-2040	2041-2050	2021-2030	2031-2040	2041-2050
B12A	14%	11%	18%	8%	8%	14%
B12B	15%	11%	18%	7%	7%	13%
B12C	16%	13%	20%	6%	6%	12%
B12D	16%	12%	20%	5%	5%	11%
B12E	15%	11%	20%	3%	4%	9%

5.9.3 Evaporation

With a baseline of 2021, the change in daily evapotranspiration for January 2021-2030 is shown in **Figure 5.22** for sub-catchment B12C as an example. On average, for the RCP8.5 projection, daily evapotranspiration for January is higher than the baseline, while the RCP4.5 direction of change is unclear.



RCP4.5



RCP8.5

Figure 5.22: Change in evapotranspiration 2021-2030 relative to 2021 baseline B12C

On average, with the RCP4.5 scenario all sub-catchments for January evapotranspiration is lower than the baseline for the 2031-2040 period and higher for the 2041-2050 period as shown in **Table 5.20**. The RCP8.5 scenario for monthly evapotranspiration is generally lower than the baseline for all periods.

Table 5-20: Change in sub-catchments evapotranspiration

Sub catchment	RCP4.5			RCP8.5		
	2021-2030	2031-2040	2041-2050	2021-2030	2031-2040	2041-2050
B12A	-4%	-3%	2%	-3%	-7%	-7%
B12B	-3%	-2%	2%	-5%	-8%	-9%
B12C	-2%	-3%	3%	-6%	-8%	-11%
B12D	0%	-2%	5%	-7%	-9%	-10%
B12E	2%	-1%	3%	-6%	-10%	-9%

5.10 Summary of the results and discussions

Precipitation, evaporation and temperature affect availability and demand for water. They may also affect water quality at water treatment plants, reservoirs, boreholes, wastewater treatment plants, power stations, selected drinking water supply systems, collieries, and industrial sites. In Chapter 2 sources of readily available data were identified and the pre-processing procedure was explained. This data can be grouped into historical forecasts and projections.

The classification of seasonal climate forecast as Above Normal, Normal to Above Normal, Normal to Below Normal, or Below Normal relative to the middle third of the most recent climate (30 years period) informed the application of the middle third to characterise the climate in the sub-catchments using historical data with the 33% and 67% exceedance values as extents for the middle third. Seasonal climate forecasts combined with the statistics of historical monthly data can provide one basic scenario for the DyWaBM with a longer but perhaps less accurate forecast of the season. While seasonal forecasting models would already include changes in future climate compared to the baseline for a past climate. The latest climate normal should be 1991 to 2020.

Analysis of historical rainfall patterns shows that change between climate normals is not monotonic in time and across the sub-catchments in the study area. This points to presence of climate cycles which should be investigated in future studies . This phenomenon was identified in other catchment studies in Southern Africa, namely the Upper Zambezi River Basin (Nyabeze, 2020a), Limpopo River Basin (Nyabeze, 2020b), Middle Zambezi River Basin (Nyabeze, 2020c), Buzi, Pungwe and Save River Basins (Nyabeze, 2020d).

Results from analysis also show the sub-catchments are characterised by high rainfall variability with CV values range from 14-23%. Gyamfi et al. (2013) reported that rainfall in the Olifants River basin exhibits spatio-temporal variation with CV value of 24%. Inter-annual and seasonal variability was also dominant in the records examined in the study by Gyamfi et al. (2013). The results of this study show that with the 1931-1960, 1961-1990, and 1991-2020 climates, most precipitation was received during the period October and March for all the sub-catchments. Several studies (for example Fauchereau et al., 2003; Preece, 2008; Daron, 2014; Dedekind et al., 2016) have established that rainfall variability in South Africa is associated with atmospheric circulation patterns, including El Niño Southern Oscillation (ENSO), regional sea surface temperatures (SSTs) and Intertropical Convergence Zone (ITCZ). Throughout the year, the timing and magnitude of the summer rains is largely dictated by the seasonal migration of ITCZ (Daron, 2014).

While the climate outlook can change drastically during the wet season (October to March) and the bounds for the middle third can change, a regression curve can be fitted on cumulative average monthly rainfall and evapotranspiration. Generally, maximum temperature is highest in October, while minimum temperature is lowest from June to August.

The results from trend tests can be summarised as follows:

(a) precipitation
  - For the period 1909-2020, a decreasing precipitation trend at a very high level of confidence for sub-catchments B12A.
  - For 1931-1960, an increasing precipitation trend at a high confidence level for B12A and B12B sub-catchments.
  - For the period 1961-1990, an increasing precipitation trend at a high level of confidence for B12D sub-catchment and during the same period a decreasing precipitation trend was certain for B12A and B12C sub-catchments.
  - For the period 1991-1920, an increasing precipitation trend at a high level of confidence for B12B and B12D sub-catchments and during the same period a decreasing precipitation trend at a high level of confidence for B1C and B21E sub-catchments.

(b) Maximum temperature
  - For 1909-2020 and 1991-2020, an increasing trend for maximum temperature was certain for all sub-catchments
  - For 1931-1960 a decreasing maximum temperature trend was at likely confidence level for B12C, B12D and B12E sub catchments.
  - For 1961-1990 an increasing trend for maximum temperature could not be sustained for all sub-catchments

(c) Minimum temperature
  - For the periods 1909-2020 and 1961-1990 an increasing trend for minimum temperature was certain for all sub-catchments
  - For 1931-1960, an increasing minimum temperature trend was certain for B12A, B12B, and B12C, and there was a very likely confidence level for B12D and B12E sub-catchments.
  - For the period 1991-2020 an increasing trend for minimum temperature was the very likely level of confidence for all sub-catchments

(d) Evapotranspiration
  - For 1909-2020, 1961-1990 and 1991-1920, an increasing evapotranspiration trend was certain sub-catchments B12A, B12B and B12C.
  - For 1931-1960, an increasing evapotranspiration trend was sustained at a high confidence level for B12A and B12B sub-catchments.
  - For 1961-1990, an increasing evapotranspiration trend was certain for B12D sub-catchment and very likely for B12E sub catchment.
  - For 1991-2020, an increasing evapotranspiration trend was certain for B12D sub-catchments and very likely for B12E.
  - For 1909-2020, an increasing evapotranspiration trend was certain for B12D sub-catchments.

A methodology to extract daily values of rainfall, evaporation and temperature, (i) compute period averages for one month (January) and compare with a selected baseline and (ii) compute period averages and compare with a selected baseline climate was developed and tested. Results were obtained using B12C as the test sub-catchment and 2021 as the baseline.

Results obtained can be summarised as follows:

- With RCP4.5 and RCP8.5 scenarios, the projected climate for daily rainfall for January for sub-catchment B12C was generally lower than the baseline for all periods.
- Generally, with the RCP4.5 sub-catchments B12A and B12B total rainfall for January was lower than the baseline across all periods The RCP8.5 projections showed an increase in total rainfall for January for all sub-catchments.
- The maximum daily temperature for with the RCP4.5 for January for sub-catchment B12C was generally higher than the baseline while the RCP8.5 climate is generally lower than the baseline.

- Generally, with the RCP4.5 scenario all sub catchments have higher maximum monthly temperature than the baseline for January across all periods. With the RCP8.5 scenario the 2021-2030 and 2031-2040 maximum monthly temperature was lower than the baseline, but for the 2041-2050 period, it was higher than the baseline.
- The minimum daily temperature for sub-catchment B12C in January 2021-2030 was generally higher than the baseline. The minimum daily temperature in the RCP4.5 scenario was higher than in the RCP8.5 scenario.
- Generally, all sub-catchments have higher minimum monthly temperature for January for all climate scenarios across all periods**.** Generally, the change in minimum monthly temperature for the RCP4.5 scenario is higher than with the RCP8.5 scenario.
- Generally, daily evapotranspiration for January for the period 2021-2030 for sub catchment B12C with the RCP8.5 projection is higher than the baseline while with the RCP4.5 direction of change is not clear.
- Generally, with the RCP4.5 scenario all sub-catchments for January monthly evapotranspiration is lower than the baseline for the 2031-2040 period and higher for the 2041-2050 period. With the RCP8.5 scenario, monthly evapotranspiration was generally lower that the baseline for all periods.

5.11 Selected methodology

The DyWaBM supports operational and management decisions one week, one-month and possibly three months ahead. The following methodology is proposed for the DyWABM based on these requirements and the results presented in this document:

(a) Basic Scenario: Projection for the season
  - Obtain seasonal climate forecast.
  - Use this together with statistics of historical monthly data to develop basic monthly projections.
  - Use projected total annual precipitation and 4th order regression equation to estimate median monthly precipitation.
  - Use projected total annual evapotranspiration and 4th order regression equation to estimate median monthly evapotranspiration:

(b) Monthly Scenarios: Monthly projections
  - Select the applicable month from the baseline and apply RCP4.5 and RCP8.5 scenario projections to obtain the change in the following parameters:
    - daily values for rainfall, evapotranspiration, maximum temperature and minimum temperature
    - total monthly rainfall
    - total monthly evapotranspiration
    - average maximum monthly temperature and
    - average minimum monthly temperature
  - For rainfall and evapotranspiration, select the applicable month from the baseline (climate normal) apply the changes and obtain median to middle-third bounds for the cumulative values
  - For minimum and maximum temperature, select applicable month from the baseline (climate normal) apply the changes to obtain median and middle third bounds for the average monthly values

(c) Short-term weather forecast Scenarios
  - Set-up each weather forecast data-set as a separate Scenario

CHAPTER 6: MODELLING TEST RESULTS

6.1 Model set up

The enhanced DyWaBM considers a quaternary catchment as a water resource system to account for water resources, which is divided into sub-catchments. Several water supply systems can be located within a sub-catchment and a water supply system can have water supply zones and sub-zones. The 21 nodes and 8 connectors which describe a water supply network and its connectivity are shown in **Figure 6.1**.

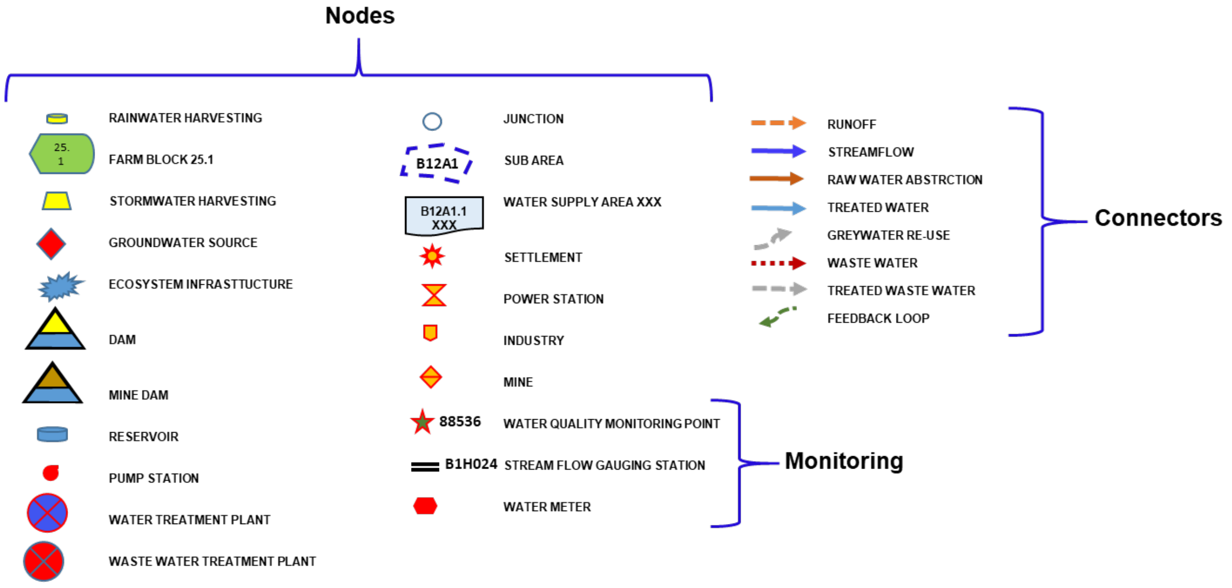


Figure 6.1: Model elements

The DyWaBM model applies loss, infrastructure condition and resource utilisation in feedback loops as factors affecting inflow, stock of water and outflow. Water quality will be included through a water condition factor. The determination and application of these factors is iterative and is illustrated in **Figure 6.2.** This component of the model is still under development.

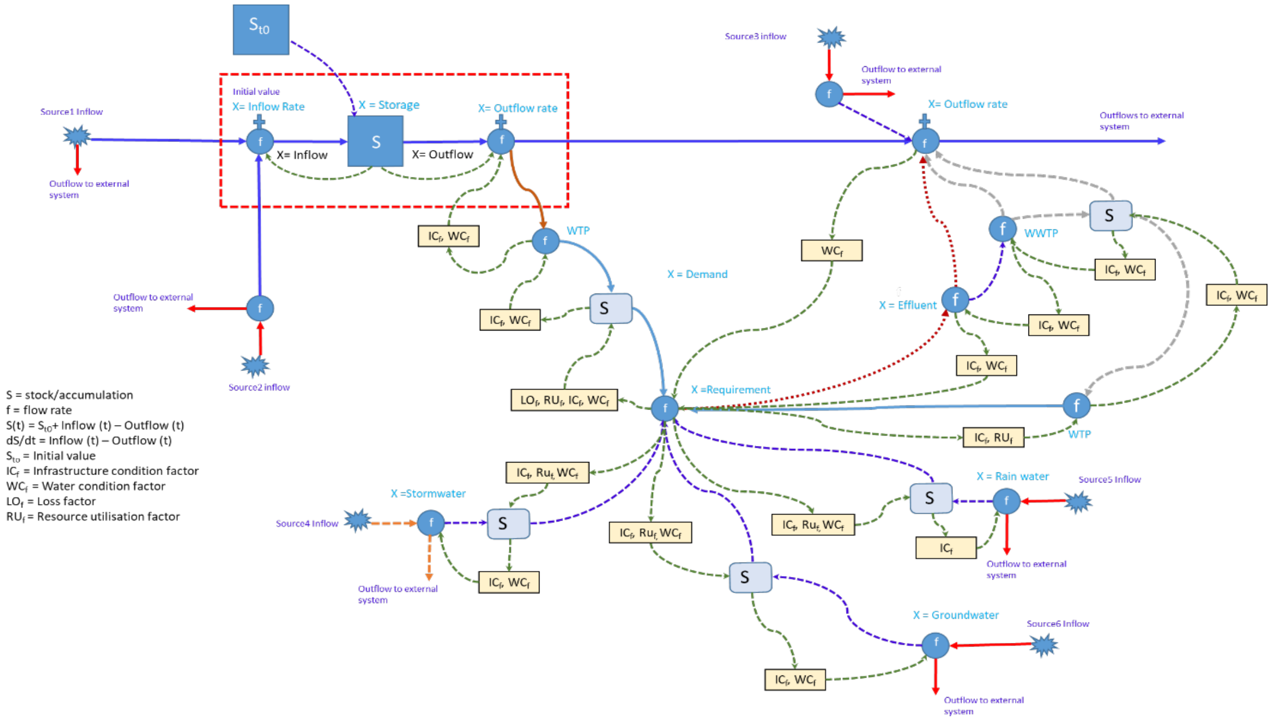


Figure 6.2: Illustration of feedback loops at the water supply system level

The DyWaBM was set up as water resource systems for quaternary catchments B12A, B12B, B12C, B12D, and B12E. B12D and B12E were combined to form one water resource system because they are connected to the same water resource, water use and wastewater treatment elements or components.

The model was tested with a control data set for October 2021 to September 2022, and results are presented per water resource system. The model distribution of outflow from junction nodes applies proportions of subsystem water demands as initial values. The proportions can be adjusted with changes in demand. The results presented in this report version are only illustrative of the functioning of the connectivity of model components.

6.2 B12A Water resource system tests

Figure 6.3 shows the connectivity of the water supply network elements for the B12A water resource system. Kwaza and Hendrina settlements are supplied through a transfer from the Komati system. The main components of the water resource system shown in the diagram include catchment runoff, stormwater, streamflow and dams. The test model was set up to connect water supply elements in B12A1 and B12A2 subsystems. The water quality component of the model is being set up, and it will include the river system.

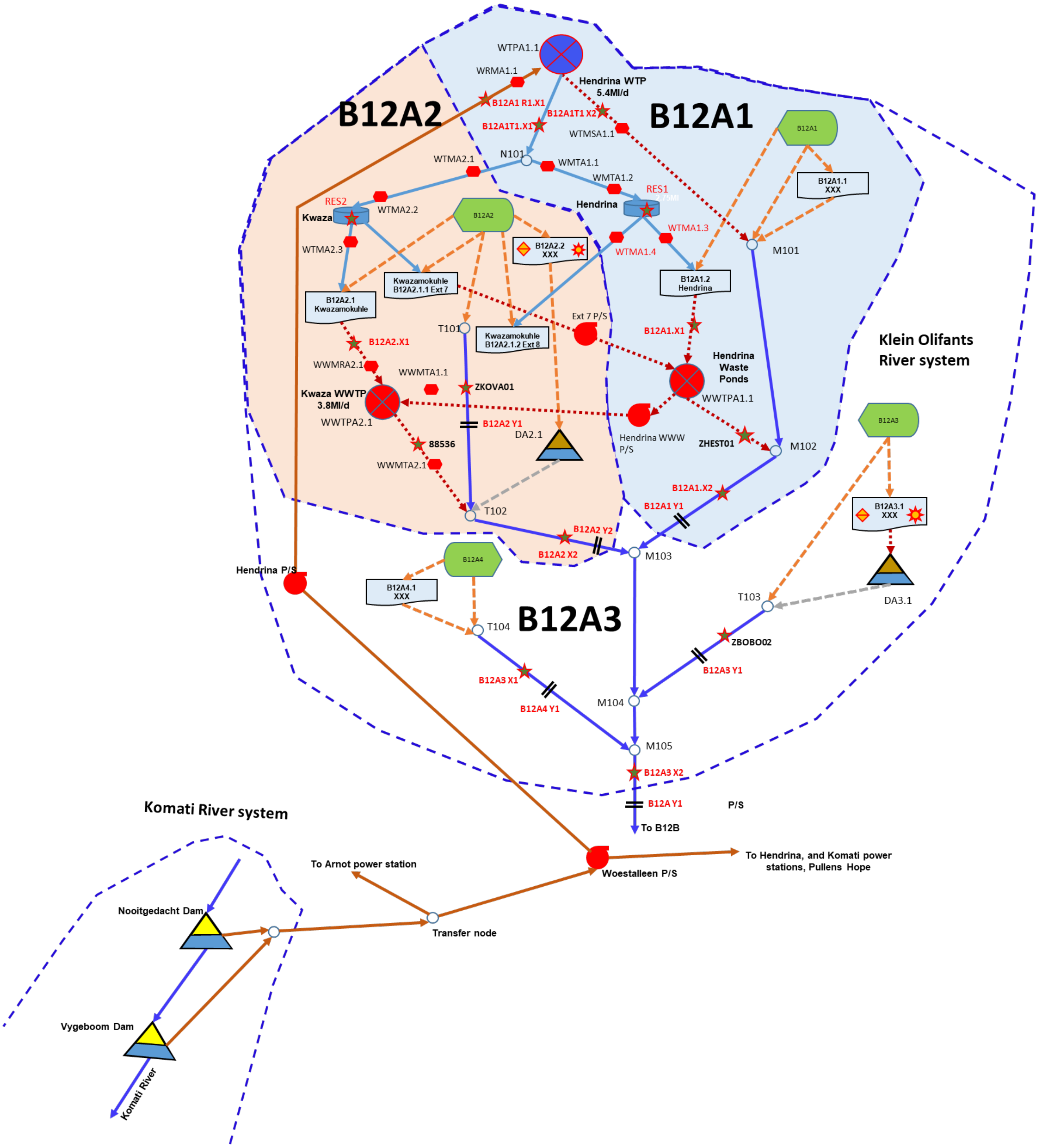


Figure 6.3: B12A-Network diagram and monitoring requirements

6.2.1 Adequacy of water resources

Figure 6.4 shows percentage of the demand supplied from the available water resource fof B12A for the period October 2022 to September 2023. Water demand is far more than the resource available. When this is compared with actual experience water supply areas the need for urgent attention can be confirmed and interventions can be tested before they are implemented.

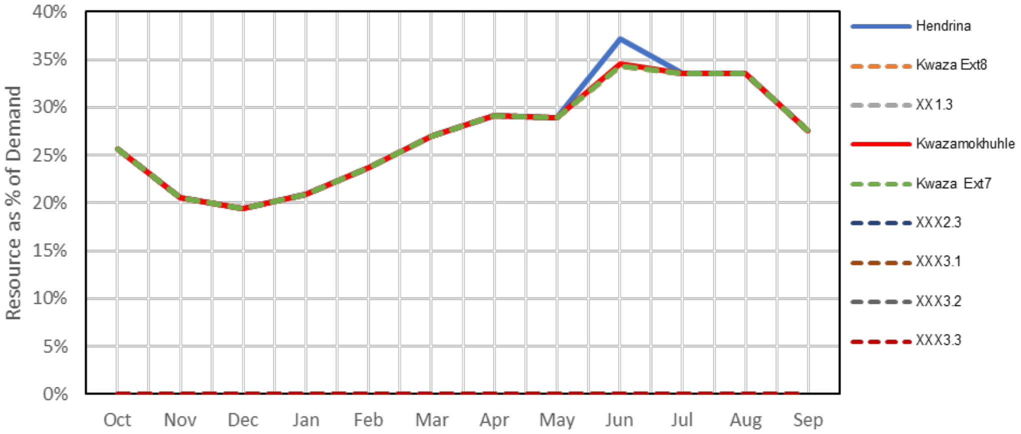


Figure 6.4: Adequacy of water resource

6.2.2 Application of equity principles on access to water

Figure 6.5 illustrates that Kwazamokuhle which has the largest population has a very low supply/demand index.

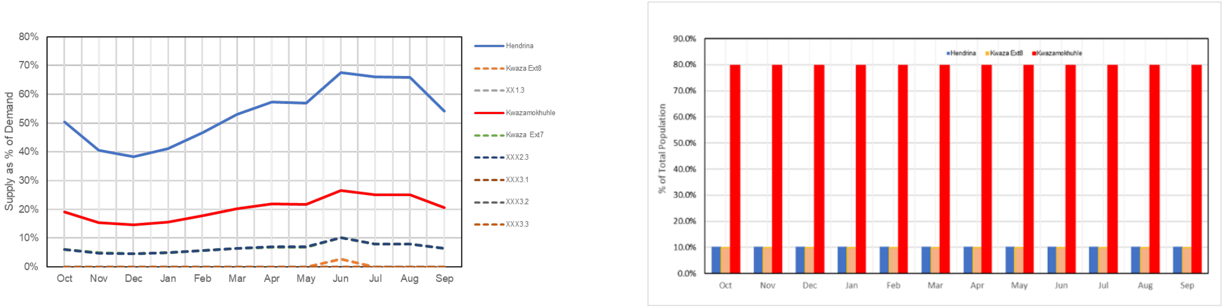


Figure 6.5: Unequal access to water – average monthly supply vs demand

Figure 6.6 illustrates that Hendrina which has about 10% of the total population in B12A, for some months the maximum supply level exceeded the water demand.

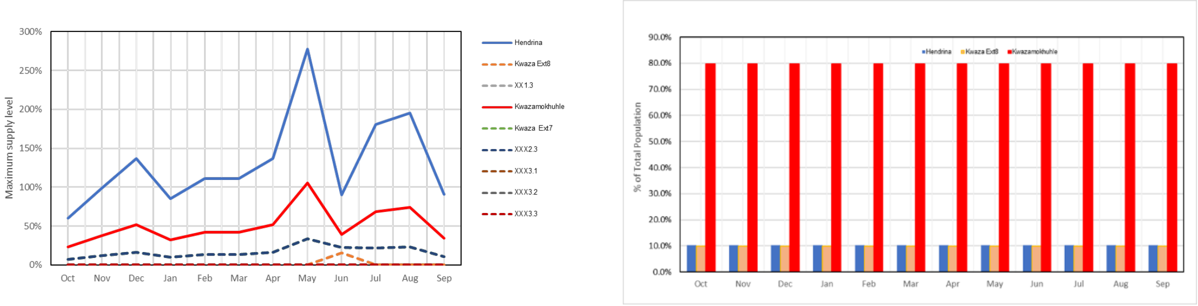


Figure 6.6: Unequal access to water – maximum daily supply

Figure 6.7 illustrates that for days at maximum supply level are nearly the same as for all areas but in June 2023 Kwaza Extension 8 the number of days were very low.

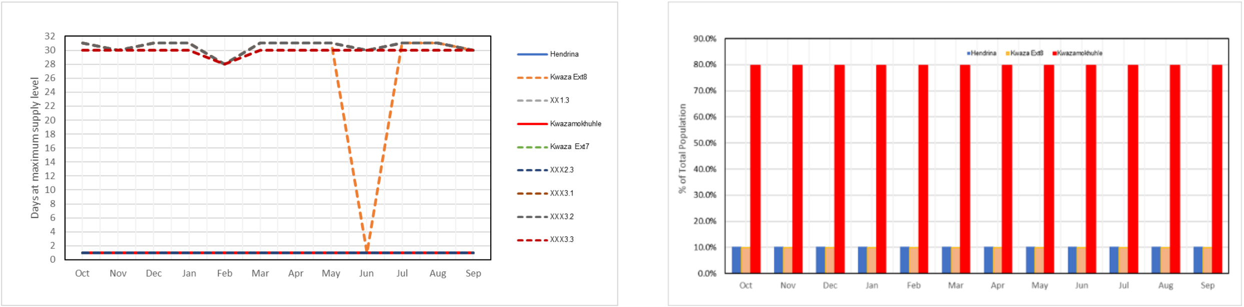


Figure 6.7: Unequal access to water – days at maximum supply

Figure 6.8 illustrates that high variability on minimum supply as percentage of water demand. For Hendrina, which has a lower population the minimum supply level was higher and more variable than Kwazamokuhle.

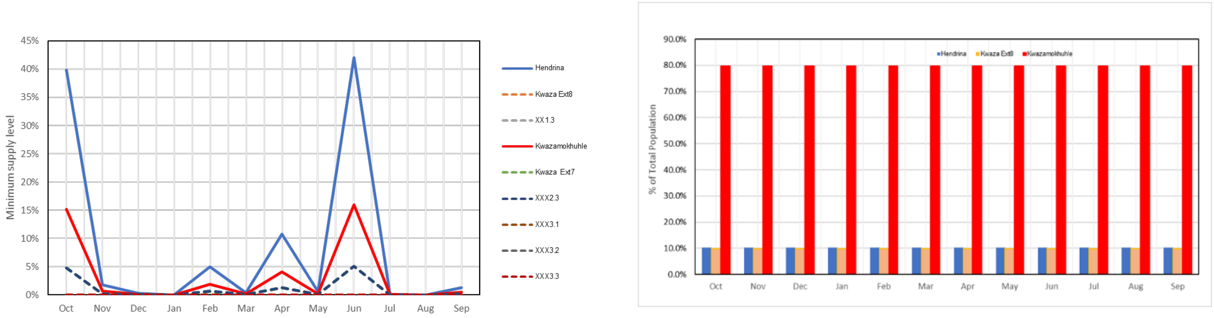


Figure 6.8: Unequal access to water – minimum supply

Figure 6.9 illustrates that except for Kwaza Extension 8 days at minimum supply level were generally low.

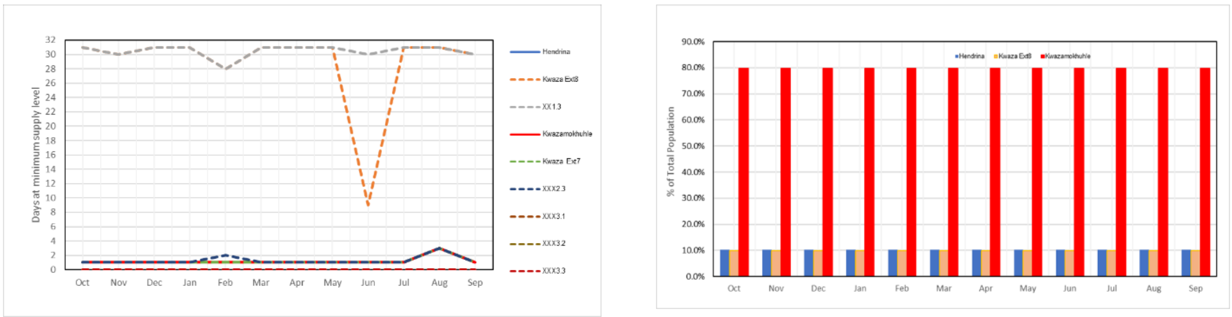
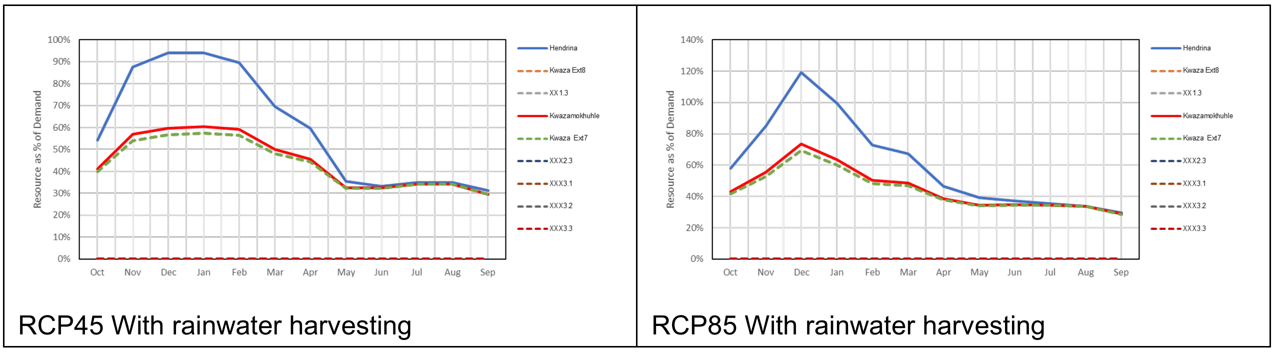


Figure 6.9: RCP45 Unequal access to water – days at minimum supply

6.2.3 Water security with climate change risks and mitigation measures

Rainfall data from seasonal climate forecasts, monthly projections, and short-term weather forecasts already incorporate the impacts of climate change. Rainfall and stormwater harvesting are tested as climate change mitigation measures, taking October to March as the wet season.

Figure 6.10 illustrates that the RCP8.5 (most unlikely) scenario presents a higher opportunity for rainwater harvesting to add to the available water resource than the RCP4.5 (likely) scenario using the resource as a percentage of demand as the indicator.

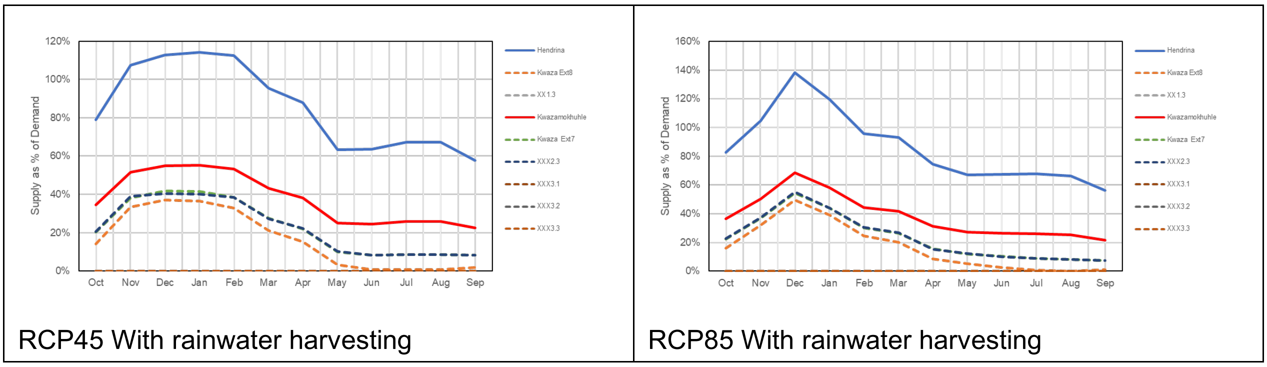


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.10: Adequacy of water resources with rainwater harvesting

Figure 6.11 illustrates that the RCP8.5 (most unlikely) scenario presents a **lower** opportunity for rainwater harvesting to improve water supply levels than the RCP4.5 (likely) scenario using supply as a percentage of demand as an indicator.

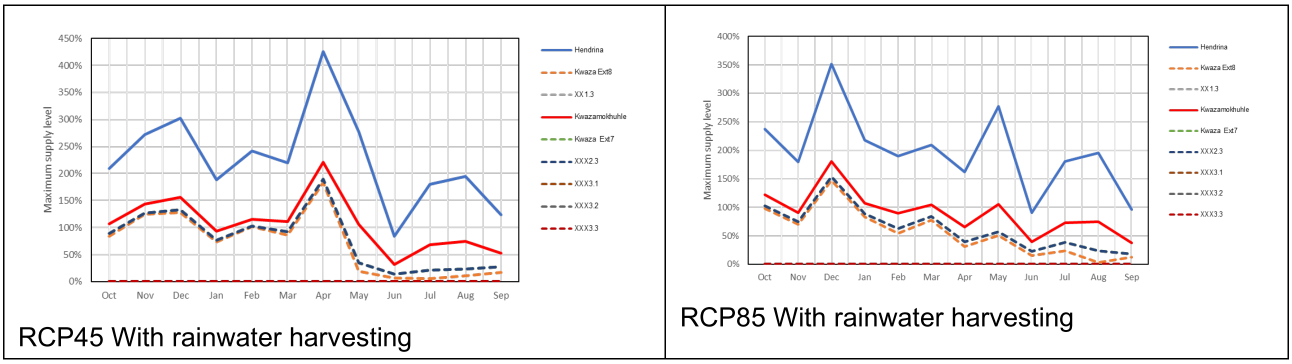


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.11: Supply versus demand with rainwater harvesting

Figure 6.12 illustrates that the RCP8.5 (most unlikely) scenario presents a **lower** opportunity for rainwater harvesting to improve water supply levels than the RCP4.5 (likely) scenario using maximum water supply level as an indicator.

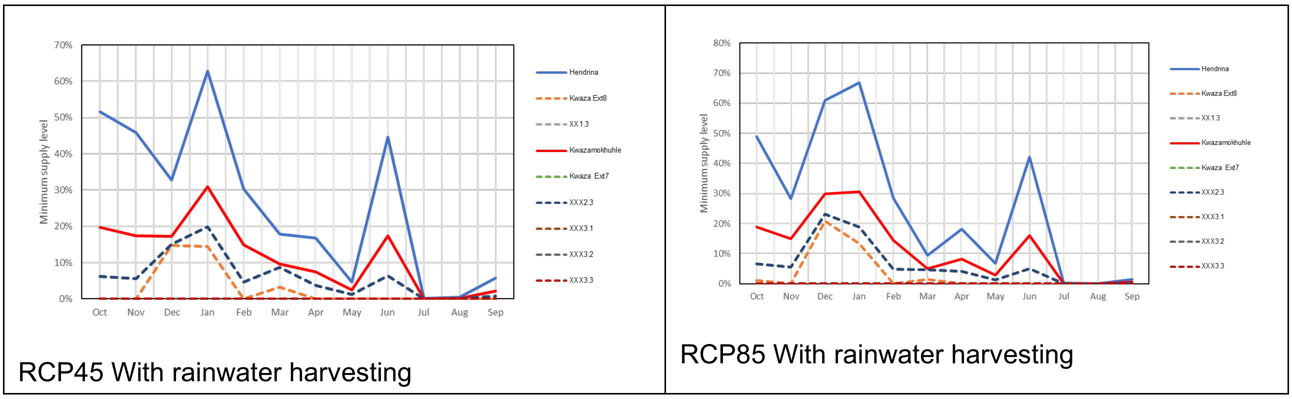


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.12: Maximum water supply level with rainwater harvesting

Figure 6.13 illustrates that the RCP8.5 (most unlikely) scenario presents a **lower** opportunity for rainwater harvesting to improve water supply levels than the RCP4.5 (likely) scenario using minimum water supply level as an indicator.



RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.13: Minimum water supply level with rainwater harvesting

6.2.4 Impact of water quality on water security

The raw water quality supplied to Hendrina WTP is was of poor quality in the winter months of May, June up to July as shown in **Figure 6.14**. These are the months of low rainfall and temperature. Poor dilution of water by clean natural rain water could be the factor responsible.

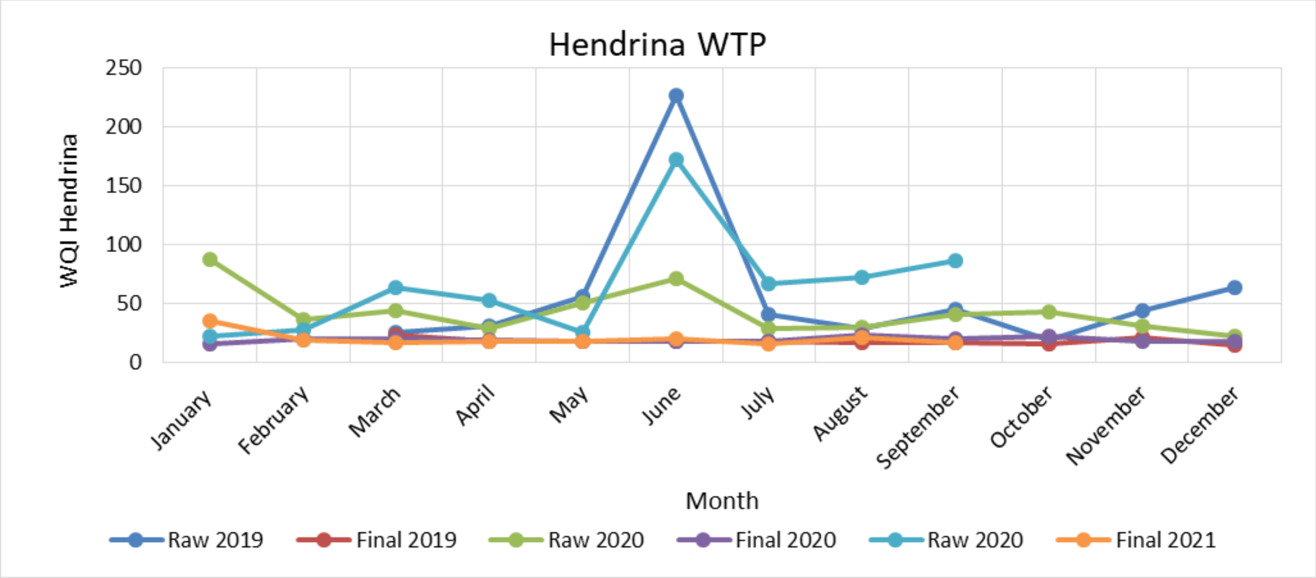


Figure 6.14: Hendrina WTP – Water quality index

6.3 B12B Water resource system tests

Figure 6.15 shows the connectivity of the water supply network elements in B12B and where flow monitoring, water levels and water quality is required. The main components of the water resource system shown in the diagram include catchment runoff, stormwater, streamflow and dams. The water quality component of the model is being set up and will include the river system. The model was set up to test the connectivity of the 28 water supply areas in the 6 water resource sub-systems B12B1 to B12B8. Arnot and Hendrina power stations located in B12B3 and B12B6 provide good test cases for the model if the data required can be obtained from Eskom. The power stations are supplied through a transfer from the Komati system. Results obtained with the test case are presented in this report.

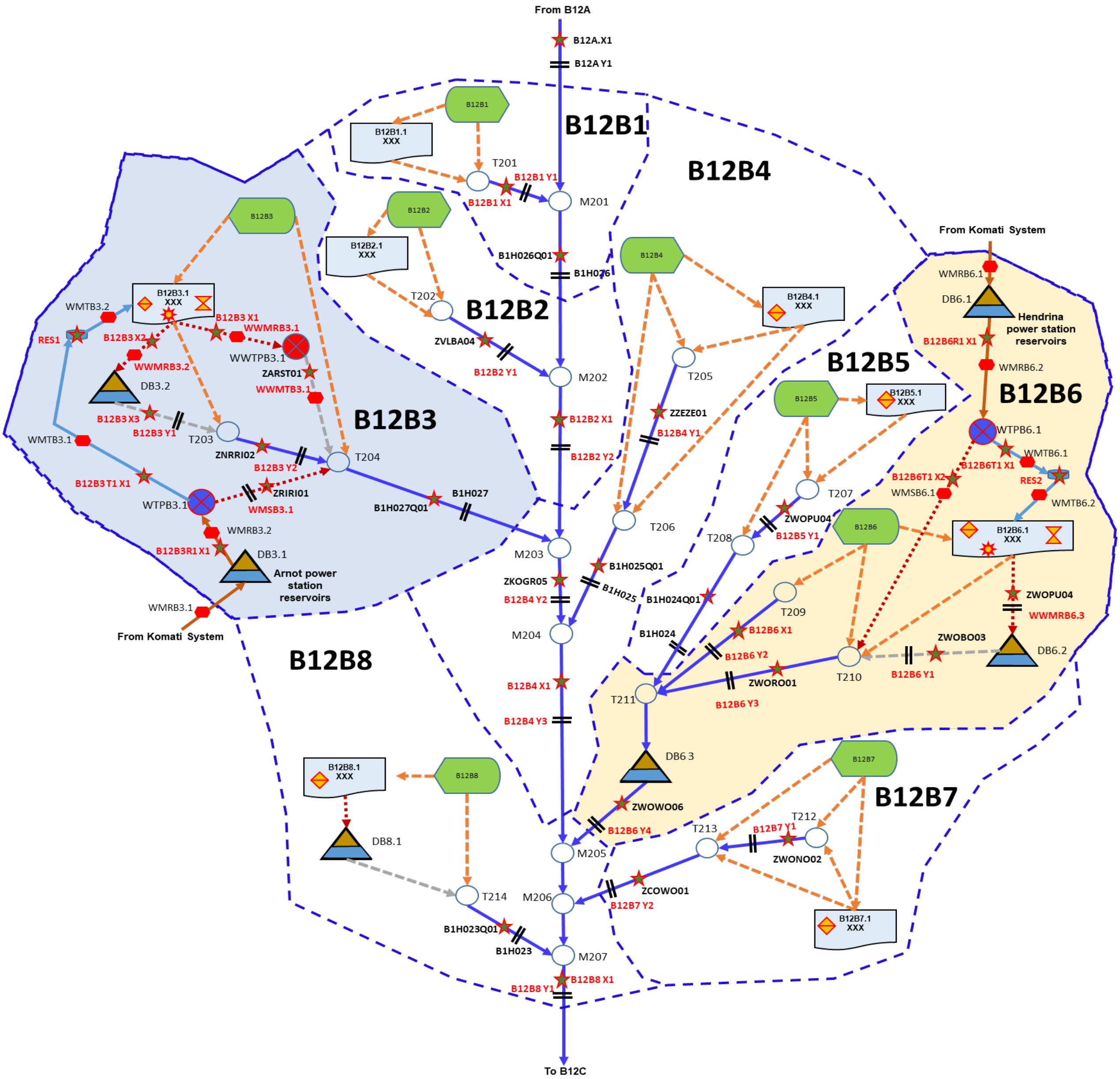


Figure 6.15: B12B-Network diagram and monitoring requirements

6.3.1 Adequacy of water resources

Figures 6.16 suggests that the resource available can supply a high percentage of the demand.

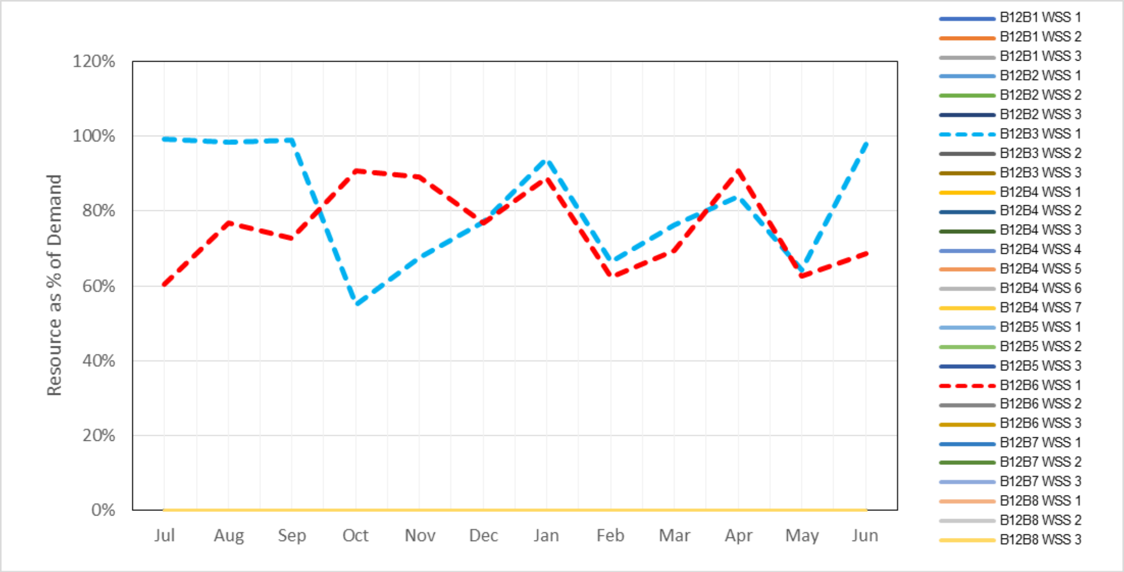


Figure 6.16: Adequacy of water resource

6.3.2 Application of equity principles on access to water

Figure 6.17 illustrates that a high percentage of the demand can be supplied. This indicator would capture impact of infrastructure condition, water condition and water losses when these factors are included in the model.

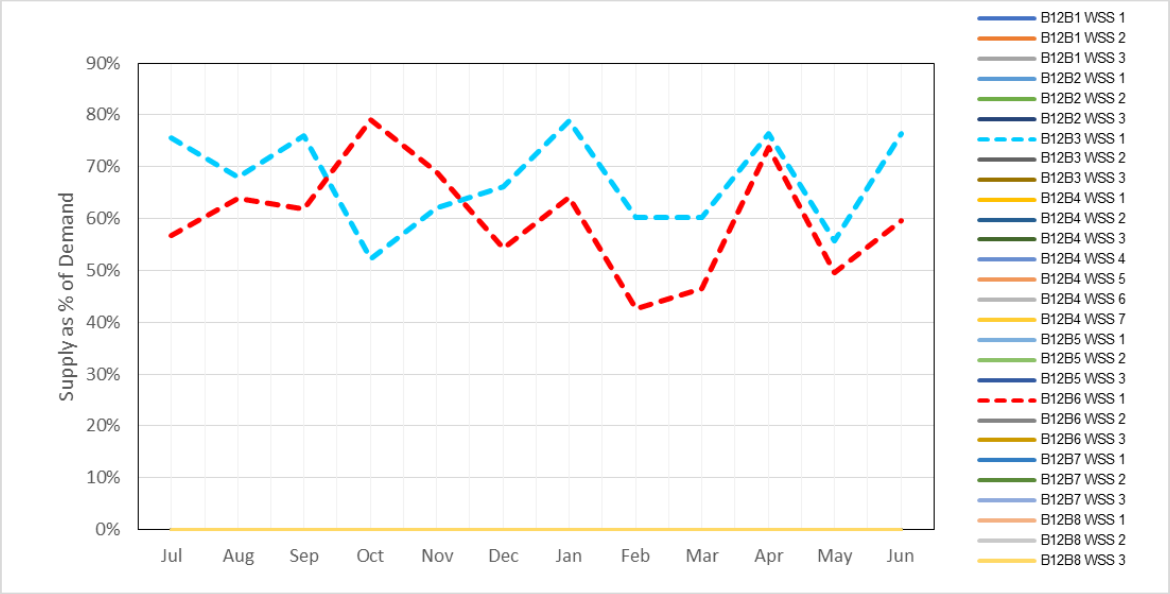
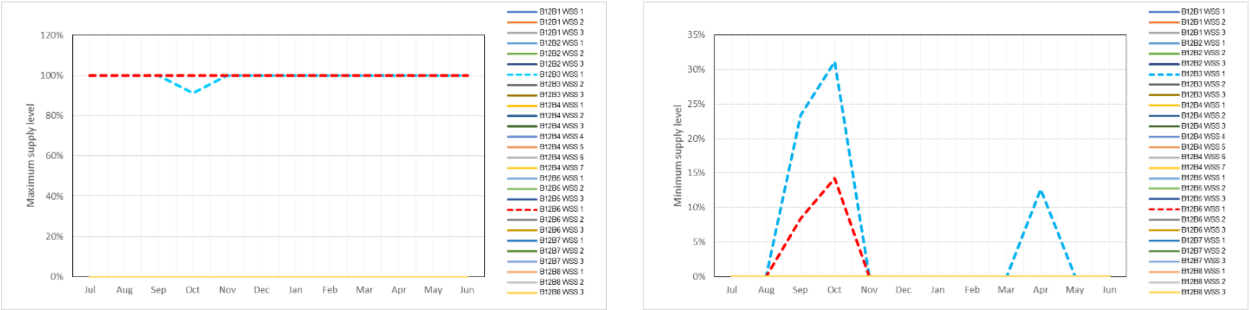


Figure 6.17: Unequal access to water – average monthly supply vs demand

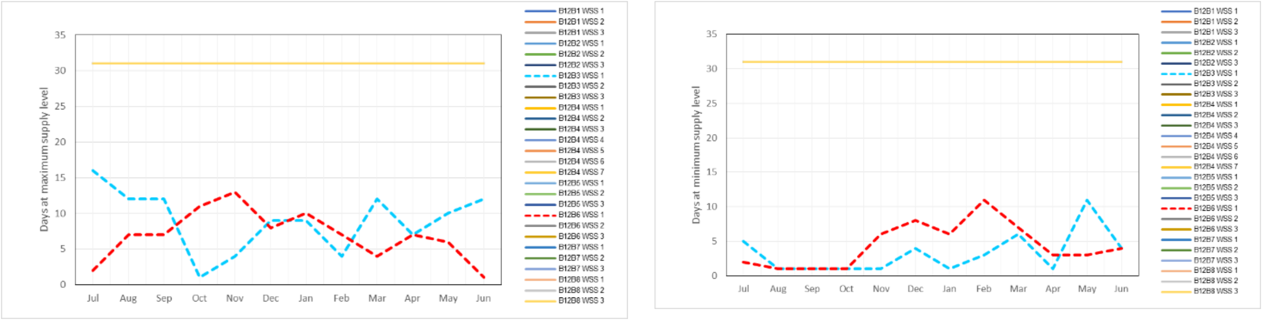
Figures 2.18 shows the percentage of the demand supplied at maximum and minimum supply levels and which months this occurs. Thus, the patterns and extent of augmentation can be identified, and interventions can be tested.



Maximum supply level Minimum supply level

Figure 6.18: Unequal access to water – maximum and minimum daily supply levels

Figures 2.19 shows a number of days at maximum and minimum supply levels for each month. Periods which require urgent attention can be estimated as months and days. This communicates the severity of the supply condition when applied with results in Figure 6.16 and the urgency of interventions.

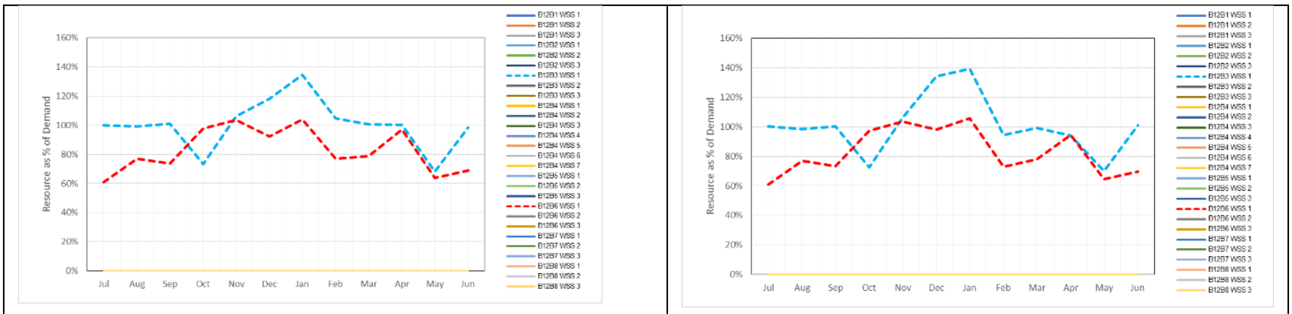


Days at maximum supply level Days at minimum supply level

Figure 6.19: Unequal access to water – days at maximum and minimum supply

6.3.3 Water security with climate change risks and mitigation measures

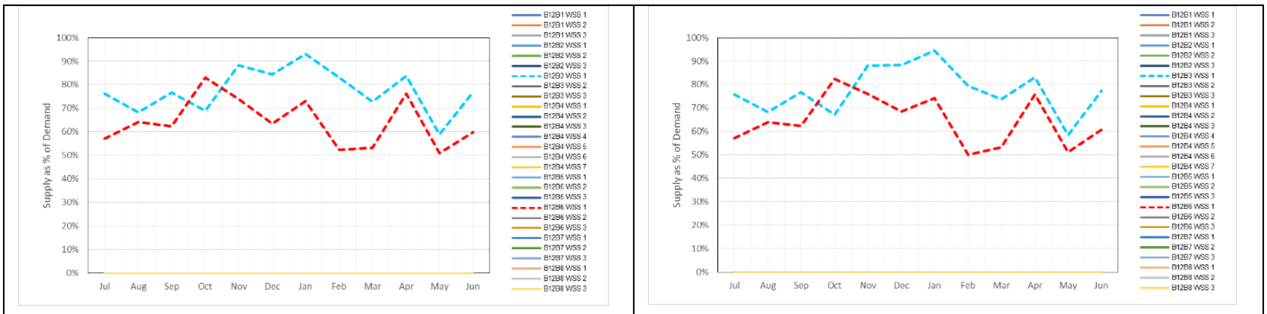
Figure 6.20 illustrates that the RCP8.5 (most unlikely) scenario presents a higher opportunity for rainwater harvesting to add to the available water resource than the RCP4.5 (likely) scenario using resource as a percentage of demand as the indicator.



RCP45 With rainwater harvesting RCP85 With rainwater harvesting

Figure 6.20: Adequacy of water resource with rainwater harvesting

Figure 6.21 illustrates that the RCP8.5 (most unlikely) and the RCP4.5 (likely) scenarios present more or less the same opportunity for rainwater harvesting using supply as percentage of demand as an indicator.

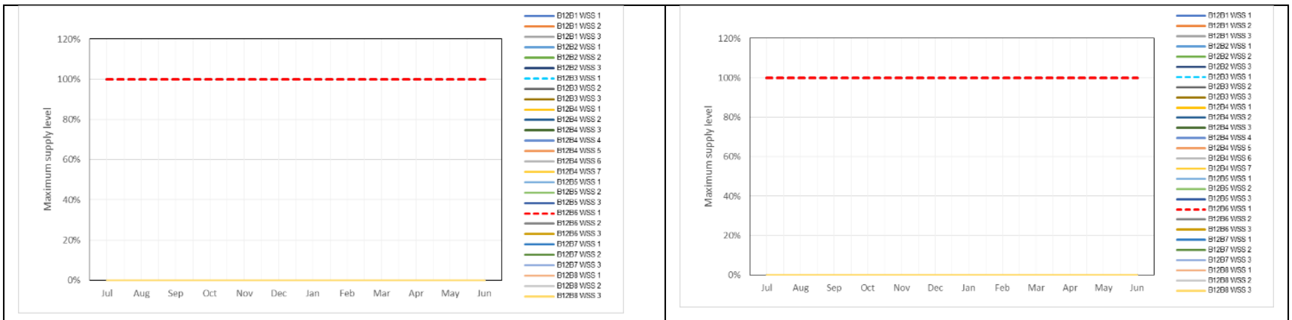


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.21: Supply versus demand with rainwater harvesting

Figure 6.21 illustrates that the RCP8.5 (most unlikely) and the RCP4.5 (likely) scenarios present more or less the same opportunity for rainwater harvesting using maximum water supply level as an indicator.

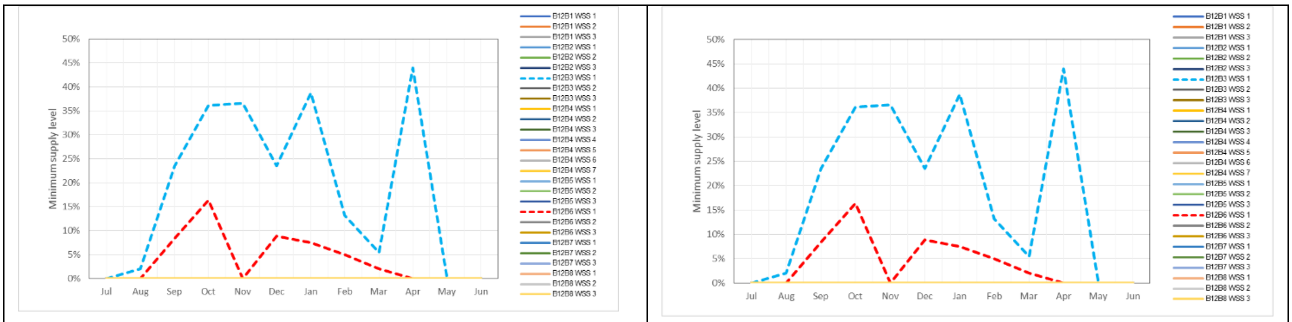


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.22: Maximum water supply level with rainwater harvesting

Figure 6.22 illustrates that the RCP8.5 (most unlikely) and the RCP4.5 (likely) scenarios present more or less the same opportunity for rainwater harvesting using minimum water supply level as an indicator.



RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.23: Minimum water supply level with rainwater harvesting

6.3.4 Impact of water quality on water security

Monitoring is taking place at Arnot and Hendrina power stations which have major water infrastructures. The variation of water quality parameters in the form Water Quality Index (WQI) will be determined.

6.4 B12C Water resource system tests

Figure 6.23 shows connectivity of the water supply network elements in B12C and where monitoring flow, water levels and quality of water is required.

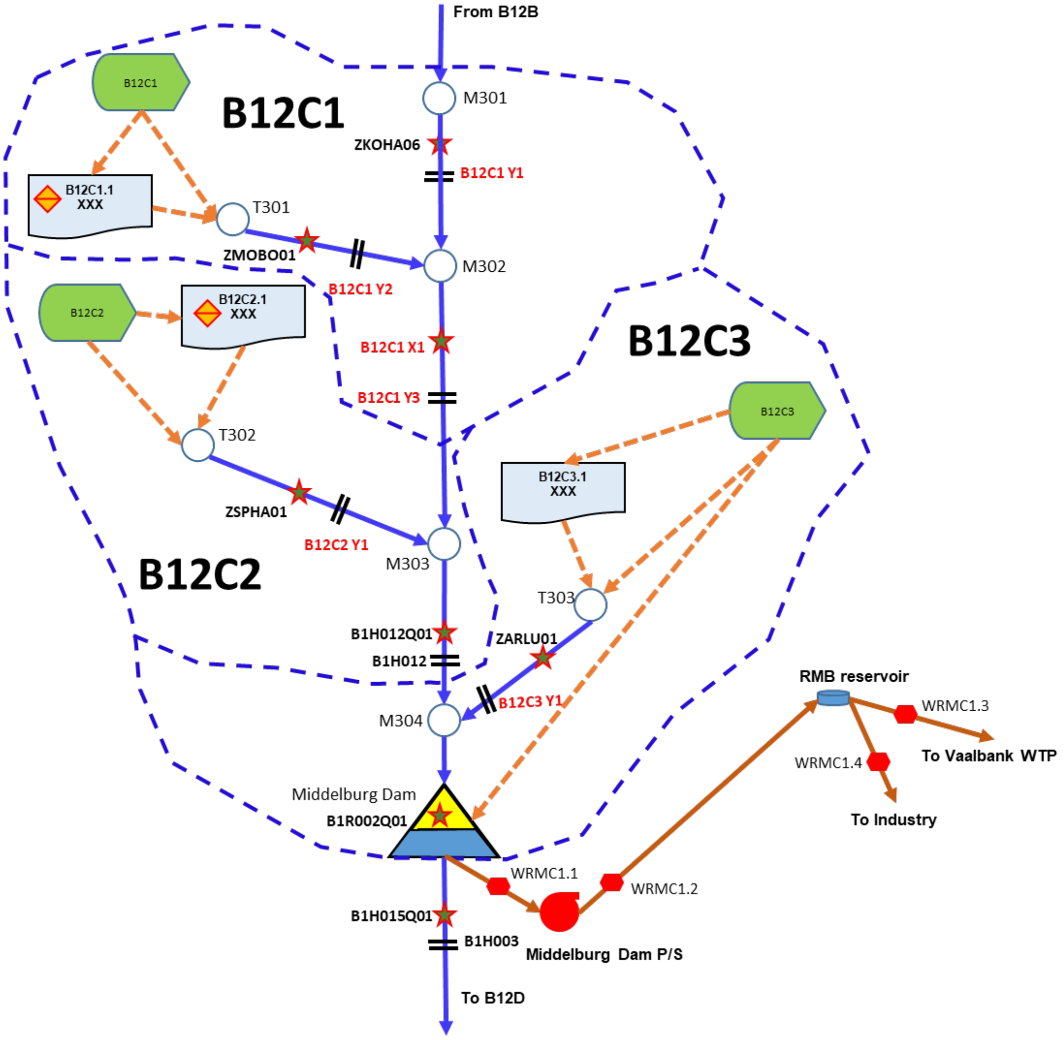


Figure 6.24: B12C-Network diagram and monitoring requirements

Middelburg Dam is the major water infrastructure where monitoring is taking place. The variation of water quality parameters in the form of the Water Quality Index (WQI) will be determined.

6.5 B12D and B12E Water resource system tests

Figure 6.25 shows the connectivity of the water supply network elements in B12D and B12E and where monitoring flow, water levels and water quality is required.

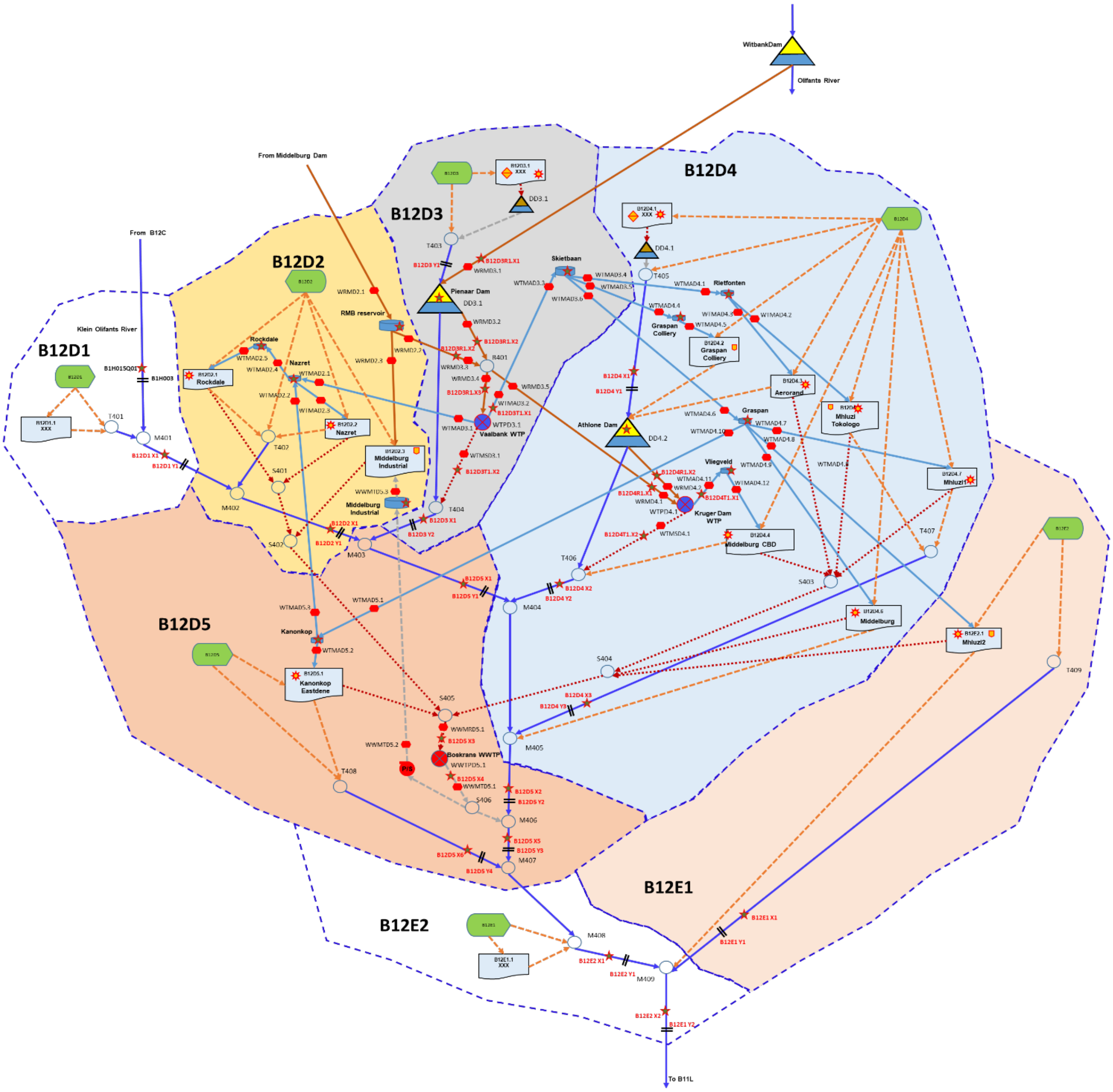


Figure 6.25: B12D and B12E-Network diagram and monitoring requirements

6.5.1 Adequacy of water resources

Figures 6.26 suggests that for some of the water supply systems, for some months, the resource available is relatively high compared to the demand but for others the resource available is very low compared to the demand.

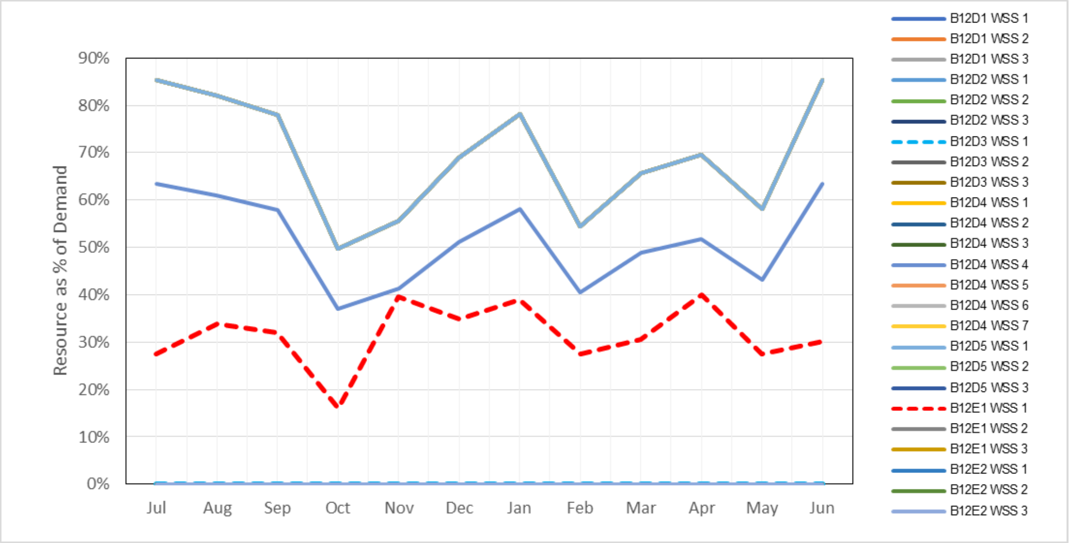


Figure 6.26: Adequacy of water resource

The results plotted in **Figure 6.26** are rare and also shown in **Table 6.1.**

Table 6-1: B12D and B12E – available water resource as percentage of water demand

Month	B12D2 WSS 1	B12D2 WSS 2	B12D4 WSS 1	B12D4 WSS 2	B12D4 WSS 3	B12D4 WSS 4	B12D4 WSS 5	B12D4 WSS 6	B12D4 WSS 7	B12E1 WSS 1
Jul	85%	85%	85%	85%	85%	63%	85%	85%	85%	28%
Aug	82%	82%	82%	82%	82%	61%	82%	82%	82%	34%
Sep	78%	78%	78%	78%	78%	58%	78%	78%	78%	32%
Oct	50%	50%	50%	50%	50%	37%	50%	50%	50%	16%
Nov	56%	56%	56%	56%	56%	41%	56%	56%	56%	40%
Dec	69%	69%	69%	69%	69%	51%	69%	69%	69%	35%
Jan	78%	78%	78%	78%	78%	58%	78%	78%	78%	39%
Feb	54%	54%	54%	54%	54%	40%	54%	54%	54%	27%
Mar	66%	66%	66%	66%	66%	49%	66%	66%	66%	31%
Apr	70%	70%	70%	70%	70%	52%	70%	70%	70%	40%
May	58%	58%	58%	58%	58%	43%	58%	58%	58%	27%
Jun	85%	85%	85%	85%	85%	63%	85%	85%	85%	30%

6.5.2 Application of equity principles on access to water

Figure 6.27 illustrates that a low percentage of the demand can be supplied for all water supply systems. This indicator would capture impact of infrastructure condition, water condition and water losses when these factors are included in the model.

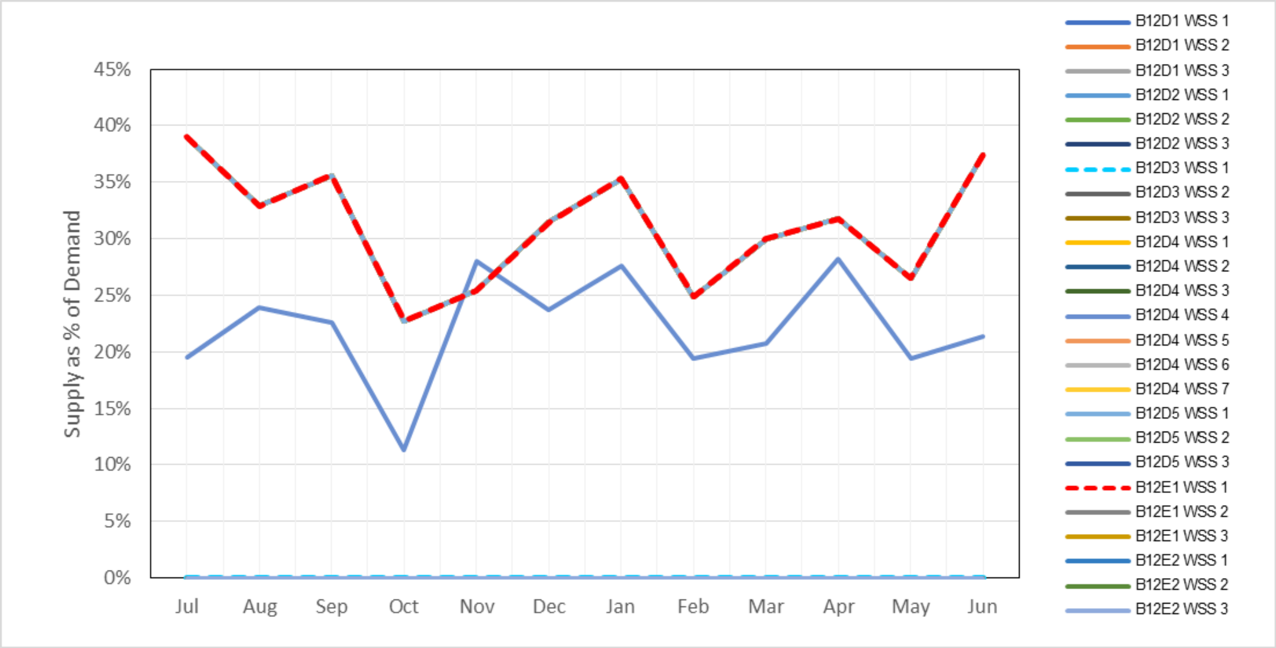
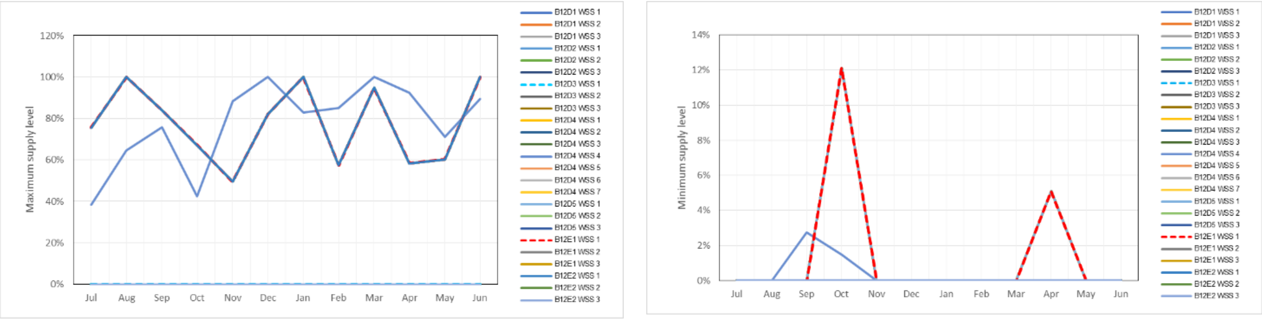


Figure 6.27: Unequal access to water – average monthly supply vs demand

Figures 6.28 shows the percentage of the demand supplied at maximum and minimum supply levels and in which months this occurs. These periods (months or days) require urgent attention, and the extent of augmentation can be identified, and interventions can be tested.

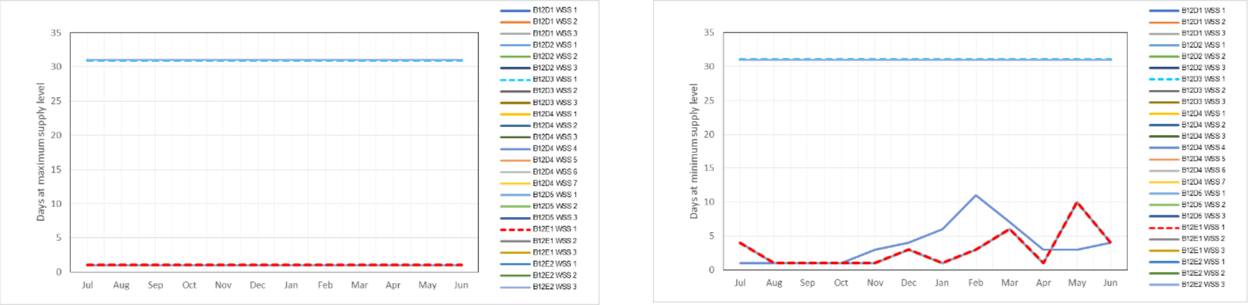


Maximum supply level

Minimum supply level

Figure 6.28: Unequal access to water – maximum and minimum daily supply levels

Figures 6.29 shows number of days at maximum and minimum supply levels for each month. This communicates the severity of the supply condition when applied with results in **Figure 6.28** and emphasise the urgency of interventions.



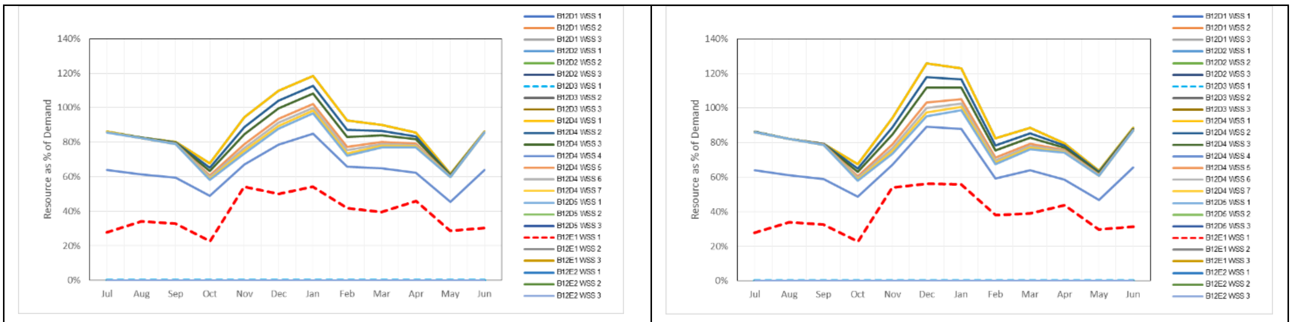
Days at maximum supply level

Days at minimum supply level

Figure 6.29: Unequal access to water – days at maximum and minimum supply

6.5.3 Water security with climate change risks and mitigation measures

Figure 6.30 illustrates that the RCP8.5 (most unlikely) scenario presents a **higher** opportunity for rainwater harvesting to add to the available water resource than the RCP4.5 (likely) scenario using resource as percentage of demand as the indicator.

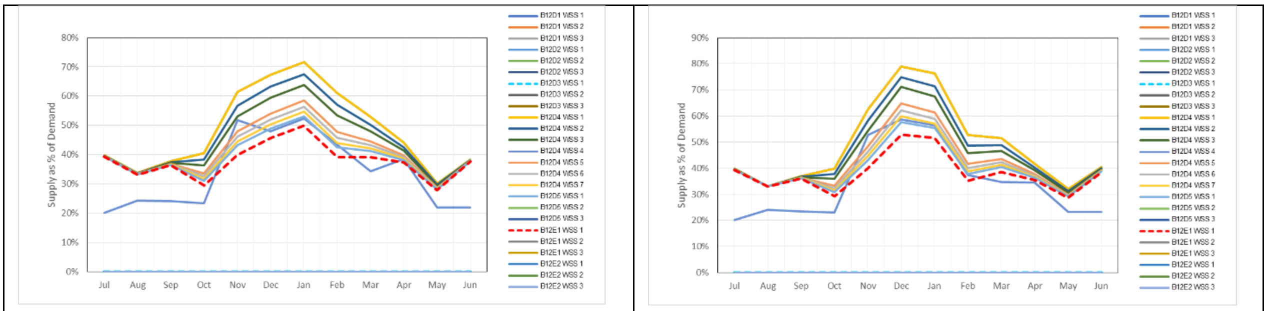


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.30: Adequacy of water resource with rainwater harvesting

Figure 6.31 illustrates that the RCP8.5 (most unlikely) scenario presents a **higher** opportunity for rainwater harvesting to add to the available water resource than the RCP4.5 (likely) scenario using supply as a percentage of demand as an indicator.

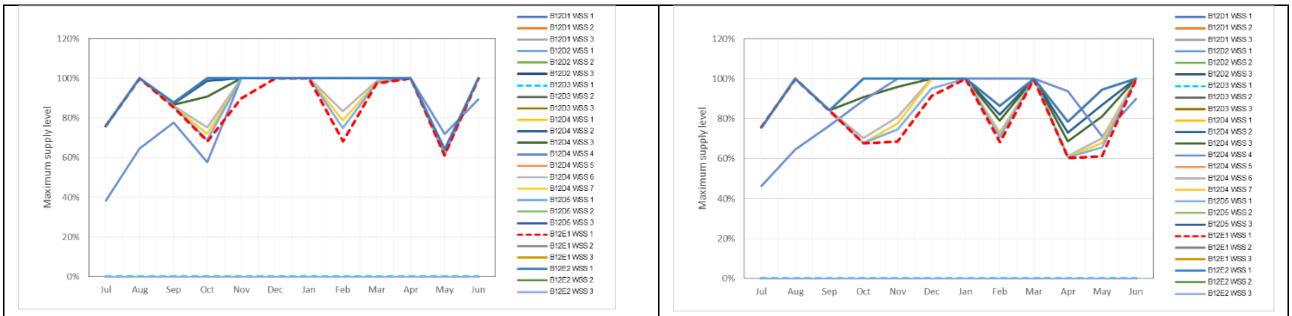


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.31: Supply versus demand with rainwater harvesting

Figure 6.32 illustrates that the RCP8.5 (most unlikely) scenario presents a **higher** opportunity for rainwater harvesting to add to the available water resource than the RCP4.5 (likely) scenario using the maximum water supply level as an indicator.

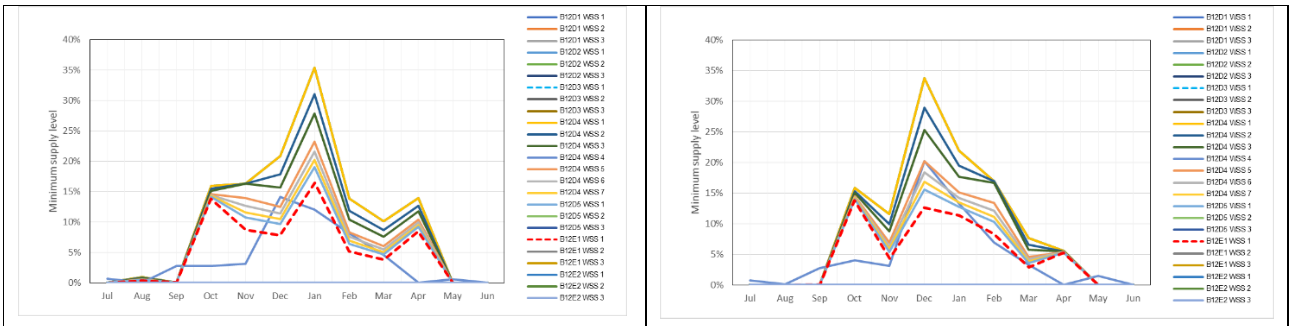


RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.32: Maximum water supply level with rainwater harvesting

Figure 6.33 illustrates that the RCP8.5 (most unlikely) scenario presents a **lower** opportunity for rainwater harvesting to add to the available water resource than the RCP4.5 (likely) scenario using minimum water supply level as an indicator.



RCP45 With rainwater harvesting

RCP85 With rainwater harvesting

Figure 6.33: Minimum water supply level with rainwater harvesting

6.5.4 Impact of water quality on water security

The water quality in the Nazareth Reservoir in **Figure 6.34** shows the influence of climatic conditions. The WQI is high in during the onset of rainy season meaning better water quality. Hence, the dilution of the source water improves the water quality. Hence, the water sources are susceptible to climatic conditions.

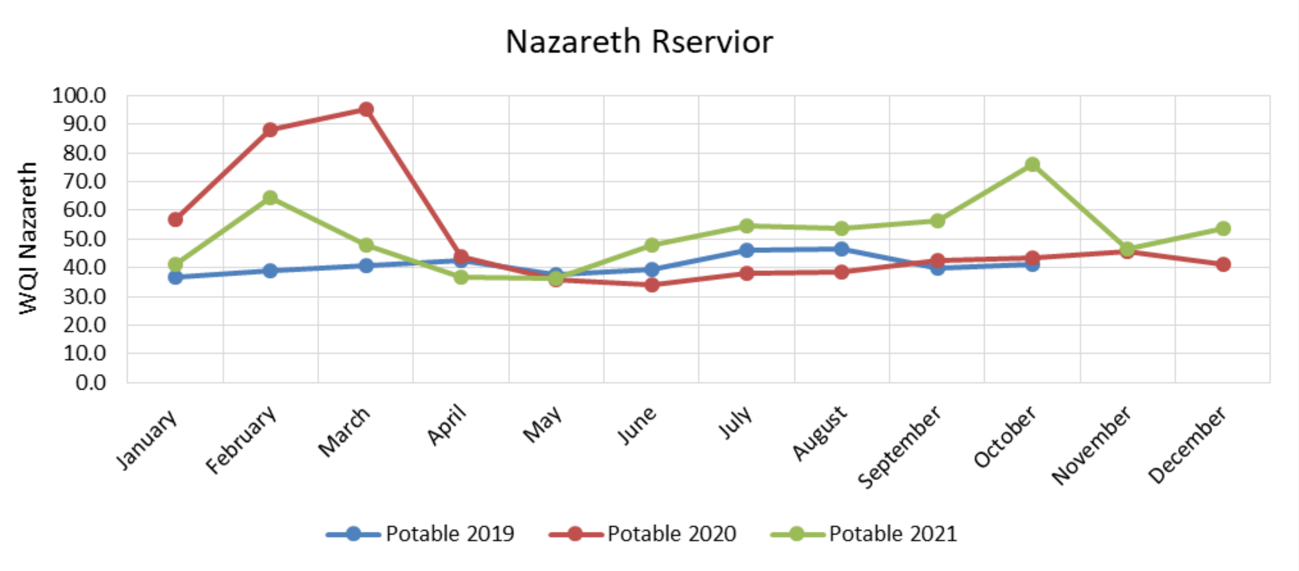


Figure 6.34: Nazreth Reservoir – Water quality index

Figure 6.35 shows that the water quality both raw and treated (final) at Kruger WTP is influenced by several factors such as temperature and rainfall.

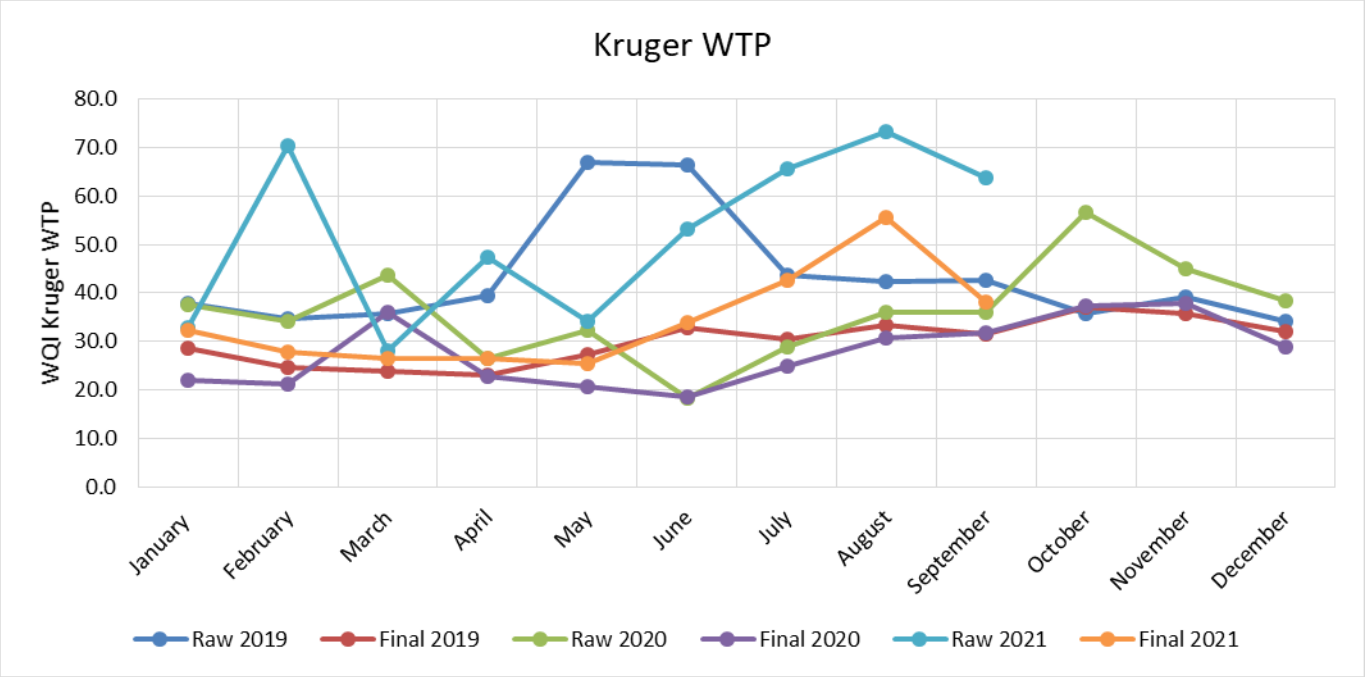


Figure 6.35: Kruger WTP – Water quality index

Figure 6.36 shows that Doornkop 1 reservoir has WQI between 10 and 20 for the period January 2019 to December 2021, which follows a similar pattern with minimal influence from the climatic conditions such as temperature and seasonal rainfall patterns.

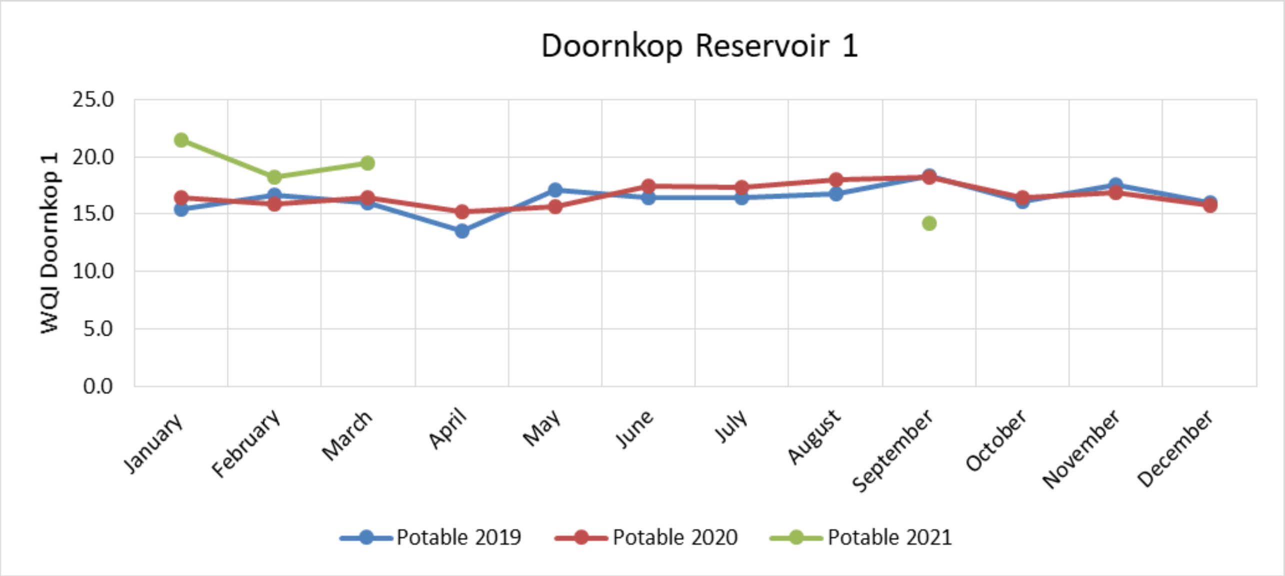


Figure 6.36: Doornkop Reservoir1 – Water quality index

Figure 6.37 shows that the water quality in the Doornkop 2 Reservoir is influenced by seasonal variations such as rainfall, which is high from January to March and is relatively high for the three years under consideration.

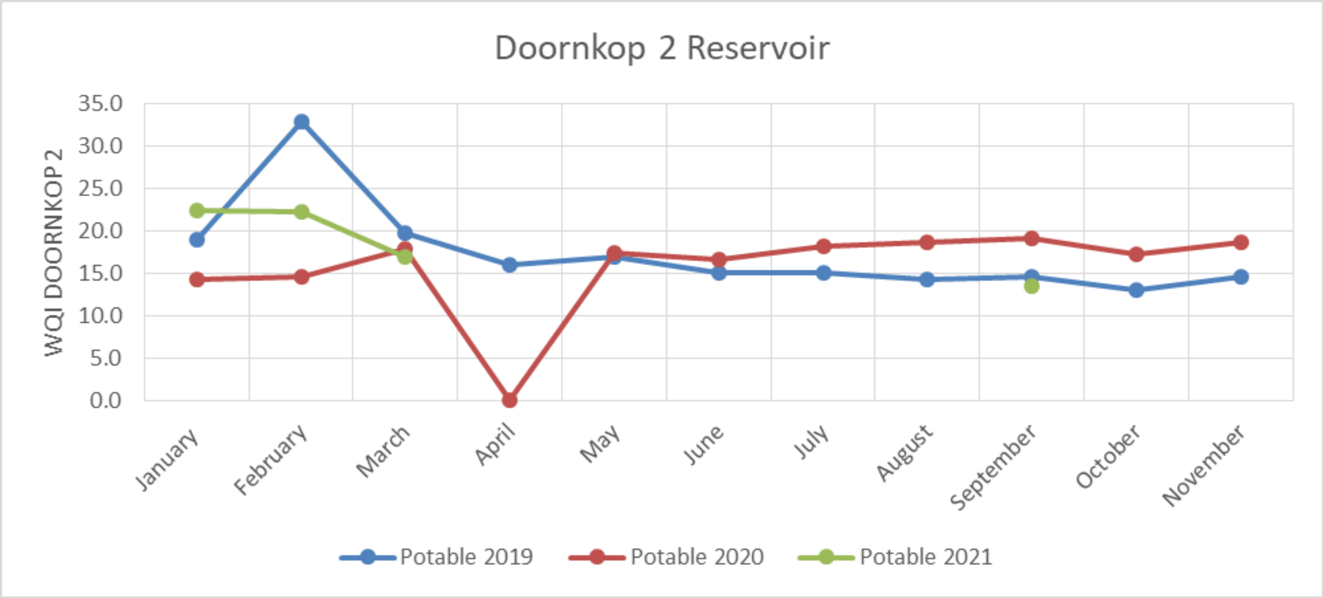


Figure 6.37: Doornkop Reservoir2 – Water quality index

CHAPTER 7: UPDATED DYWABM PROCEDURE

7.1 Overview

The updated DyWaBM spreadsheet model has 11 worksheets as illustrated in **Figure 7.1**.

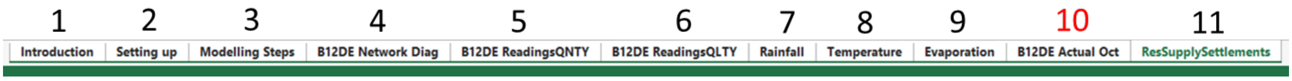


Figure 7.1: Tabs for spreadsheet model

Worksheet 1 provides background to the model, Worksheet 2 describes how to set up the model for a water resource system, and Worksheet 3 describes each of the modelling steps. Worksheet 4 captures the lists the Water Resource Systems to be included in the model. The model elements from the network diagram are then captured in the following order:

- Administration
- Land use
- Water resources
- Bulk water infrastructure

Worksheet 5 has flow gauge/meter data, Worksheet 6 has data for the selected water quality parameters and worksheets 7, 8 and 9 have Rainfall, Temperature and Evaporation data. Computations are performed in Worksheet 10. This worksheet is replicated for subsequent months and modified as necessary for the model runs. Worksheet 11 presents results from the model runs.

7.2 Computations – Worksheet 10

The following can be changed in each worksheet:

1) Start date (beginning 1st day of selected month)
2) Sources of water and available yield
3) Water supply constraints
4) Connectivity for flow routing
5) Switch for Rainwater harvesting, Stormwater harvesting and Water re-use
6) Initial values:
    - Starting values for water meters
    - Water demand at WTPs, Reservoirs, Junctions, and Water transfer routes,
    - Percentage of demand that is active
    - Water loss factor
    - Reservoirs access
    - Water requirements
    - Rainwater harvesting, stormwater and re-use parameters
    - Percentage of water used from Rainwater harvesting, Stormwater harvesting and Water re-use.

7.2.1 Typical results from computational worksheet

A typical computation worksheet provides results as tables and data. Daily data can be plotted as graphs, and selected monthly statistics, namely average, maximum, minimum and total values, are captured in a table. An example of a water balance is shown in **Figure 7.2** where S is the percentage of water demand supplied.

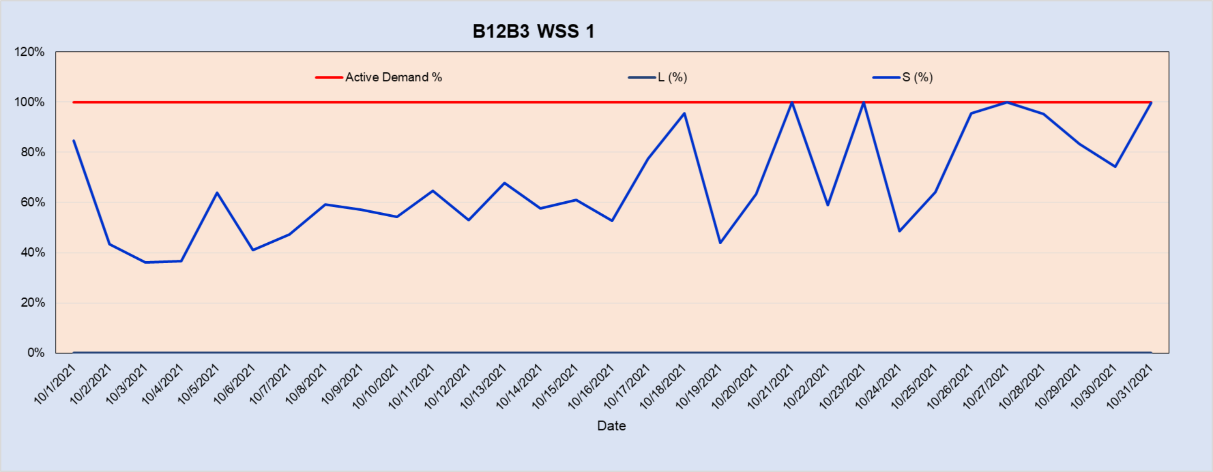
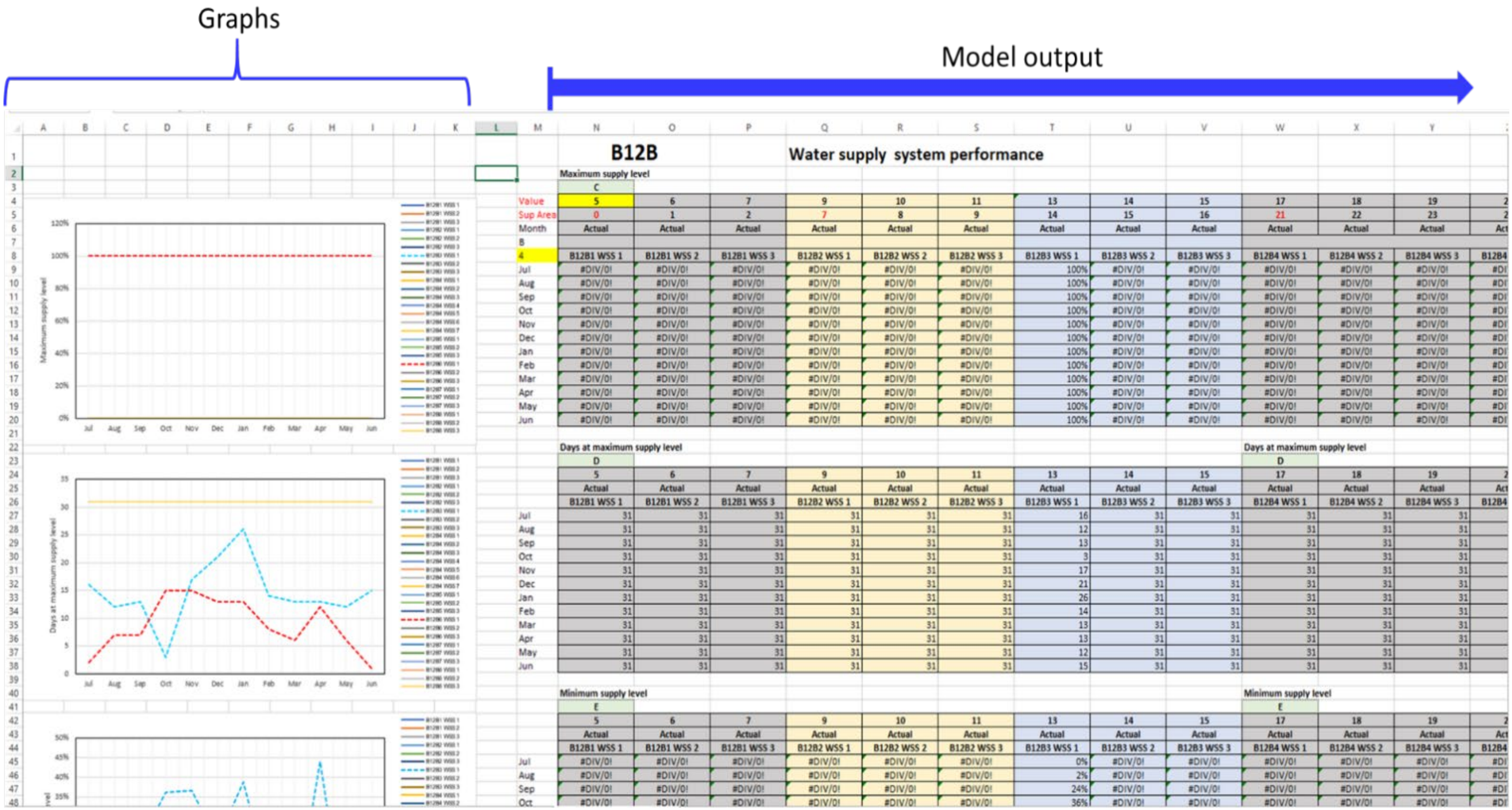


Figure 7.2: Example of Water Supply versus Water Demand graph

7.2.2 Model Results – Worksheet 11

The results panel (**Figure 7.3**) is located right below the Water Supply Area Schematic. It will demonstrate the overall water availability viz requirements when the spreadsheet model has been fully set up.



B12B Water supply system performance

Maximum supply level

	C											
Value	5	6	7	9	10	11	13	14	15	17	18	19
Sup Area	0	1	2	7	8	9	14	15	16	21	22	23
Month	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual
B												
4	B12B1 WSS 1	B12B1 WSS 2	B12B1 WSS 3	B12B2 WSS 1	B12B2 WSS 2	B12B2 WSS 3	B12B3 WSS 1	B12B3 WSS 2	B12B3 WSS 3	B12B4 WSS 1	B12B4 WSS 2	B12B4 WSS 3
Jul	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Aug	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Sep	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Oct	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Nov	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Dec	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Jan	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Feb	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Mar	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Apr	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
May	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Jun	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	100%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Days at maximum supply level

	D									D		
	5	6	7	9	10	11	13	14	15	17	18	19
	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual
	B12B1 WSS 1	B12B1 WSS 2	B12B1 WSS 3	B12B2 WSS 1	B12B2 WSS 2	B12B2 WSS 3	B12B3 WSS 1	B12B3 WSS 2	B12B3 WSS 3	B12B4 WSS 1	B12B4 WSS 2	B12B4 WSS 3
Jul	31	31	31	31	31	31	16	31	31	31	31	31
Aug	31	31	31	31	31	31	12	31	31	31	31	31
Sep	31	31	31	31	31	31	13	31	31	31	31	31
Oct	31	31	31	31	31	31	3	31	31	31	31	31
Nov	31	31	31	31	31	31	17	31	31	31	31	31
Dec	31	31	31	31	31	31	21	31	31	31	31	31
Jan	31	31	31	31	31	31	26	31	31	31	31	31
Feb	31	31	31	31	31	31	14	31	31	31	31	31
Mar	31	31	31	31	31	31	13	31	31	31	31	31
Apr	31	31	31	31	31	31	13	31	31	31	31	31
May	31	31	31	31	31	31	12	31	31	31	31	31
Jun	31	31	31	31	31	31	15	31	31	31	31	31

Minimum supply level

	E									E		
	5	6	7	9	10	11	13	14	15	17	18	19
	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual	Actual
	B12B1 WSS 1	B12B1 WSS 2	B12B1 WSS 3	B12B2 WSS 1	B12B2 WSS 2	B12B2 WSS 3	B12B3 WSS 1	B12B3 WSS 2	B12B3 WSS 3	B12B4 WSS 1	B12B4 WSS 2	B12B4 WSS 3
Jul	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Aug	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	2%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Sep	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	24%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Oct	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	36%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Figure 7.3: Model results

CHAPTER 8: REPORT ON CAPACITY BUILDING

Meetings were held with scientists (including STLM water managers) to discuss methods, data requirements and obtain team involvement. Three workshops were held with STLM water managers. The first was the Inception Workshop. The second workshop discussed data requirements and the status of monitoring. The third workshop discussed results from the analysis of available water quality data. Updated network diagrams were shared with participants.

The project team tried to engage with Eskom to obtain data for the power stations as dynamic water supply systems. After four meetings, it became clear that Eskom was unwilling to cooperate. Useful insights were obtained during the meetings on the system configuration water management procedures at power stations but these were not specific to Arnot and Hendrina power stations.

The research team targeted the Waternet annual symposium, the Water Institute of Southern Africa (WISA) and the Institute of Municipal Engineering of Southern Africa (IMESA) annual conferences for the presentation of papers. One seminar was held at the University of Johannesburg to present model results and obtain feedback.

The study started with two students. Unfortunately, they both had to halt their studies due to Covid-19 restrictions. The study engaged an intern, Mr Ndivheni Ravhura, a post-graduate student from the University of Venda to assist with data collation, populating water supply system models and conducting tests to support software development. One of the students, Mr April Ntuli, was engaged in the study activities but could not re-register with the University of Johannesburg due to work pressures. A female student Ms Nicollete Mahlare was engaged on water quality investigations. The study is at an advanced stage and engage an intern who will be involved on software programming.

Mr Ndivheni Ravhura made a presentation at the University of Johannesburg seminar and at the 2023 WSA Water Reuse Symposium.

CHAPTER 9: RECOMMENDATIONS AND FEEDBACK FROM WATER MANAGERS

Water Managers in STLM have been involved in this project since its inception through site visits and project meetings. They provided feedback on the results obtained, including the status of the monitoring system. Their insights were taken into consideration in formulating recommendations.

The constraints in monitoring the rivers and dams for system performance assessment was noted. The municipality wants to obtain support in implementing technologies to assist in the collecting related data. This may include electronic inline monitoring systems, to measure certain critical parameters.

Availability of data would make it possible for the municipality to be pro-active on water and wastewater treatment. For example they could identify and by implementing pre-treatment where necessary. The municipality also wants to improve supply of water to communities in terms of quality and quantity, reduce periods of low/no supply and avoid under and over-supply.

The development of a software application that can provide information of resource availability and quality status of a water source, would be of great assistance.

CHAPTER 10: SUMMARY OF ACHIEVEMENTS AND FUTURE RESEARCH WORK

This section summarises the achievements of this project against its aims and outcomes and provides an indication of further research work required.

10.1 Project aims

This project investigated how to set up the dynamic water balance model on a complex system. The achievements can be summarised as follows:

No	Aim	ACHIEVEMENTS AND FUTURE RESEARCH WORK
1	To enhance the GIS and Schematisation components of the DyWABM by delineating the STLM into supply area into water supply zones define the water supply system network components, connectivity and constraints	GIS shape files and Google Earth KML were assembled for the STLM system included new features such as mines, power stations and colliery, wastewater and raw water treatment plants. New schematic model elements were identified for the new features. The *Feedback loops can be further refined for linking upstream actions with and downstream impacts to identify positive and negative functions.*
2	To enhance the DyWaBM to track quality of water and evaluate its impact on different users including the ecology	Process diagrams were developed for the new elements. Work commenced on extending the model to track historical, current and simulated trends of water quality, however further refinement is required. *Future developments include links to enhanced network and process flow diagrams. End users should be able to capture current water quality data, obtain information on compliance status and simulate interventions and evaluate impacts*
3	To enhance the DyWaBM to incorporate climate change scenarios and evaluate risks to quantity and quality of water	RCP4.5 and RCP8.5 climate projections for precipitation, temperature and evaporation were adopted as climate change scenarios. Model was enhanced to include impact on rainwater harvesting potential. *Future enhancements may include modelling of impact of climate change on quality of water and stormwater harvesting potential.*
4	To evaluate the adequacy of the existing monitoring system for application of the DyWaBM	Adequacy of monitoring system was reviewed and gaps were identified. *The municipality wants assistance in improving monitoring of the water resource system. Recommendations were made on critical monitoring points. Future work includes installing of monitoring equipment and critical points and linking the data collection system to the model.*
5	To develop the DyWaBM for the STLM water supply system and make recommendations on to improve water security	The excel model was developed for the water supply system and results obtained were shared with system operators and managers. *The municipality wants to have a software application with the DyWaBM capabilities. Further work to get software coded in Python with GIS and database capabilities could not proceed because of inadequate budget. The costs were estimated at about R3 000 000.*

10.2 Project outcomes

10.2.1 Outcome 1

This outcome is concerned with an enhanced innovative DyWaBM model which makes it possible to obtain continuous water balance information at finer spatial and temporal scales than the existing tools. Comments on the identified impacts and recommendation are provided in the following table:

IMPACT	**ACHIEVEMENTS AND FUTURE RESEARCH WORK**
1) The availability of a set of indices for evaluating quality and water service conditions at zone or sub-zone level on a monthly basis will enable water managers to develop and test practical integrated conjunctive use strategies which consider augmentation from local sources of water and redistribution water resources in the water system.	Indices for major pollution water quality parameters were calculated and applied to describe the quality of water. *Further simulation and tests should be done with water managers.*
2) Results from the model can be used by decision makers to select investments that maximize water security within a supply zone. This may lead to reduced system losses, improved pollution control and improved water security for water users and ecosystems.	Data obtained was useful to decision makers, plant operators and water quality compliance monitors in STLM. While investments were identified actual implementation was not realised. *This can be improved by deployment of a software application and engagement with system managers and decision makers on results and impact of interventions.*
3) Evidence on inequities in water quality and water services will be supported by evidence enabling decision makers and more advantaged users to find solutions for redistributing water.	Inequity in access to water resources, level of water supply and continuity of water supply were demonstrated. Tests with potential interventions showed enhanced system performance.
4) The ability to track sources of pollution will enable decision makers and water managers to enforce by-laws on pollution control while water users will be able to self-regulate. Water Services Authority can develop bylaws to encourage and regulate efficient and sustainable use of water resources.	Linking pollution sources and receptors such as raw water reservoirs was theoretically discussed and as there was inadequate data perform tests. Pollution sources include settlements, collieries, power stations and industry and the affected receptors include Middelburg Dam and the Klein Olifants River. *Development of these links is recommended as future work.*
5) Problems of water quality and in adequate water resources are experienced in South Africa and beyond. The transition from a linear to a circular water economy has been identified as one of the promising solutions but uptake has been very slow. This model can become a catalyst in by identifying the pressures and opportunities in areas where water constraints are acutely felt. Through observing, changing and evaluating the behaviour of all actors in the water system can be changed	Manpower challenges negatively affect monitoring and performance of water system for points. *The opportunity for job creation is huge but innovative ways of mobilisation of funds, enabling regulations and a system of financial accountability and obtaining value for money are required*

10.2.2 Outcome 2

The second outcome is a data set describing the water supply system components including sources of water, sources of pollution, water supply zones/sub-zones, water quality and quantity, climatic data and scenarios. Comments on the identified impacts and recommendation are provided in the following table:

IMPACT	ACHIEVEMENTS AND FUTURE RESEARCH WORK
1) Through assembling data, setting up and testing the DyWaBM water managers who will come mainly from historically disadvantaged groups to appreciate the need to collect data	Municipalities experience high staff turnover with new managers coming from come mainly from historically disadvantaged groups. Inadequate monitoring systems, lack of historical and current monitoring data and lack of tools to analyse this data makes it difficult for them to make informed decisions they make. *Feedback from STLM staff has amplified the need to further develop the DyWaBM software and database.*
2) By appreciating the usefulness of the datasets water managers will motivate for improved metering and testing water quality	Feedback from the municipality presented in Chapter 10 shows appreciation for the need for improved monitoring flows and testing quality of water. *The municipality needs assistance in improving its monitoring system*
3) Increased use of climate change scenarios at operational levels which may lead to better management of water security risks	Climate change scenarios were included in the enhanced DyWaBM and tested for impact on rainwater harvesting potential. *Future investigations include tests on impact on water quality and other interventions.*

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