Consulting Services for Environmental Flows Assessment and Water Quality Modelling within the Lesotho Lowlands Water Development Project Phase II (LLWDP II)

Final Water Resources and Water Quality Assessment Report

Ministry of Water, Lesotho

March 18th, 2022

Prepared by

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southern waters

Deltares
Enabling Delta Life

Multi - Nodal
Development Consultants

REPORT

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SUMMARY

This is the Final Water Resources and Water Quality Assessment Report of the Consulting Services for Environmental Flow Assessment (EFA) and Water Quality Modelling within the Lesotho Lowlands Water Development Project Phase II (LLWDP II).

This assignment is led by the Ministry of Water Lesotho, through the Lesotho Lowlands Water Development Phase II (LLWDP II) as Client. The study is funded by the World Bank. The LWDP II component will support the implementation of critical bulk water infrastructure in Zones 2 and 3. LLWDP II has hired Multiconsult (Norway), Southern Waters (Republic of South Africa), Deltares (the Netherlands) and Multi-Nodal Development Consultants (Lesotho) to carry out the assessment.

The main objective of the assignment is to develop an Environmental Flows (EFlows) management strategy for the Hlotse River to mitigate impacts related to the planned release of water from Katse Dam into the river and subsequent abstraction for LLWDP II in Zone 2 &3.

In this report two topics are discussed: water resources and water quality assessment.

For the **water resources assessment**, a distinction has been made between the natural water availability and the water losses. The former is derived using the wflow hydrological model with which daily discharge series were derived for the Hlotse river and its tributaries over the period 1981 – 2020, i.e. over 40 years. For the latter, an assessment is made of the evaporation and the possible water abstractions in the basin, which are considered to reach not more than 2 – 3 % of the future planned design inflow from the Adit. Climate change scenarios were also assessed and simulated with the hydrological model, based on the Lesotho's climate change scenarios report (LMS, 2018). Two future time horizons (2035 and 2050) were used with a moderate (average) and warm/dry (worst case). All these series, both for the present situation and the climate change scenarios, form input towards the eFlow analysis and the hydrodynamic modelling.

For the **water quality assessment**, first an inventory is made of the available water quality data in the basin and a description is given of the water quality sampling that was done as part of this project. A description is given of the water quality situation in the basin in terms of various water quality standards, and an overview is given of the HEC-RAS water quality simulations, including temperature.

In general, water quality in the Hlotse River is good, but it deteriorates in downstream direction, with the largest change occurring in the upper third of the river, between TS1 and CQ14, and showing a strong seasonality in the salts, with low concentrations during the summer months due to dilution and concentrations increasing during the dry winter months up to the first spring and early summer rainfalls when salts were diluted once again. Water quality in the Hlotse River is either in an Ideal or Acceptable category with respect to aquatic ecosystem requirements. In the upper reaches of the Hlotse the quality is Ideal for aquatic ecosystems, and it gradually changes to Acceptable in a downstream direction.

The quality of water that will be transferred from Katse Dam during the winter months (June to September) will be very good, the dissolved salts, nutrient concentrations and suspended sediments will be low, and dissolved oxygen concentrations high. The water temperature will be about 3-5°C warmer than the water temperatures in the upper Hlotse at the point of discharge. However, if water is transferred at the end of summer when thermal stratification is present in Katse Dam, then water with low dissolved oxygen concentrations and slightly cooler water temperatures could be discharged into the upper Hlotse River which is not desirable.

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List of Abbreviations

ASPT	Average Score per Taxon
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
DEM	Digital Elevation Model
DRIFT	Downstream Response to Imposed Flow Transformations
DRIFT DSS	Downstream Response to Imposed Flow Transformations Decision Support System
DRWS	Department of Rural Water Supply
DWA	Department of Water Affairs
EFA	Environmental Flow Assessment
EFlows	Environmental Flows
EFMP	Environmental Flow Management Plan
EFR	Environmental Flow Release
ESIA	Environmental and Social Impact Assessment
GCM	Global climate model
GIS	Geographic Information Systems
GoL	Government of Lesotho
HABFLO	Habitat Flow Simulation Model
IA	Iron Age
IUAs	Integrated Units of Analysis
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
LHDA	Lesotho Highlands Development Authority
LLWDP II	Lesotho Lowlands Water Development Project – Phase II
LLBWSS	Lesotho Lowlands Bulk Water Supply Scheme
LMS	Lesotho Meteorological Services
LSA	Last Stone Age
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
masl	Metres above sea level
MoNR	Ministry of Natural Resources
MoEMWA	Ministry of Energy, Meteorology and Water Affairs
MoW	Ministry of Water
MSA	Middle Stone Age
NGO	Non-Governmental Organisation
NNL	No-net Loss
ORASECOM	Orange-Senqu River Commission
PET	Potential evapotranspiration
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RSA	Republic of South Africa
SASS	South African Scoring System
UNDP	United Nations Development Programme
WHO	World Health Organisation

Preface

This is the Final Water Resources and Water Quality Assessment Report of the ***Consulting Services for Environmental Flow Assessment (EFA) and Water Quality Modelling within the Lesotho Lowlands Water Development Project Phase II (LLWDP II)***.

This assignment is led by the Ministry of Water Lesotho, through the Lesotho Lowlands Water Development Phase II (LLWDP II) as Client. The study is funded by the World Bank. The LWDP II component will support the implementation of critical bulk water infrastructure in Zones 2 and 3 (Hlotse and Maputsoe) accompanied by improvements to the distribution systems and implementation of low-scale sanitation and hygiene measures. LLWDP II has hired Multiconsult (Norway), Southern Waters (Republic of South Africa), Deltares (the Netherlands) and Multi-Nodal Development Consultants (Lesotho) to carry out the assessment.

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- Alison Jourbet (DRIFT DSS Manager) – Southern Waters
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[1] Our dearest team member Mantoa Moiloa sadly passed away of Covid 19 during the pandemic in 2021. She will be greatly missed by the team.

- Frederiek Sperna Weiland (Climate Change Expert) – Deltares
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1 Introduction

1.1 Project context

Lesotho is divided into four topographical regions, namely the Highlands (>2,200 m above sea level (masl)), Foothills (1,800-2,200 masl), Lowlands (1,400-1,800 masl) and the Senqu River Valley. The Lesotho Lowlands Water Development Project Phase II (LLWDP II) is a key program of the Government of Lesotho (GoL) to improve potable water supply. One aspect of LLWDP II is the Lesotho Lowlands Bulk Water Supply Scheme (LLBWSS), which aims to address the water demands in this region. Historically, the supply of water to urban areas in the Lowlands is from river abstraction and pumping from underground sources. An increase in the urban population and commercial activities in the Lowlands, and accompanying higher demand has exerted pressure on the capacity of water resources and water supply facilities. This has been noted as a major constraint to continued economic growth in the country.

LLWDP II aims to address these water-related challenges by improving water supply to the Lowlands settlements with populations exceeding 2500 for domestic, institutional and industrial purposes. The project introduces a bulk-treated water supply system and distribution networks that are technically, economically, socially, environmentally and financially viable for the Lowlands region. Figure 1-1 shows the LLWDP area and its sub-division into eight water demand zones; this study forms part of an assessment of water abstractions for Zones 2 and 3, in the north-western region of Lesotho. The LLBWSS implementation plan for Zones 2 and 3 is packaged in two phases: Phase 1 from 2018 to 2030, and Phase 2 from 2031 to 2045 (Aurecon 2018; SMEC 2017).

Water resource analyses and water demand estimates indicate that there is insufficient water in the Hlotse River[2] (mean annual runoff of 148. 55 million cubic metres) during low flow periods to supply sufficient water to meet current and future demands, as well as the environmental flow requirements to maintain ecological functioning downstream of the proposed water abstraction point. Flows during winter and droughts will therefore need to be augmented with transfers from Katse Dam (part of the Lesotho Highlands Water Project) through an existing tunnel, into the upper reaches of the Hlotse River via the Hlotse Adit. Transfers from Katse Dam have previously taken place during drought conditions (2015 and 2018).

Descriptions of the infrastructure that forms part of the bulk water supply (viz., water intake at Ha-Setene; water treatment works near Ha-Makotane; pump stations and pipelines) and a general description of the Hlotse Catchment are provided in related project reports (refer to Section 1.2).

[2] The Hlotse is a tributary of the Caledon River, which forms the north-western border between Lesotho and South Africa (SA). The Hlotse catchment drains parts of the highlands, foothills and the lowlands, and then merges with Mohokare sub-basin at the SA border.

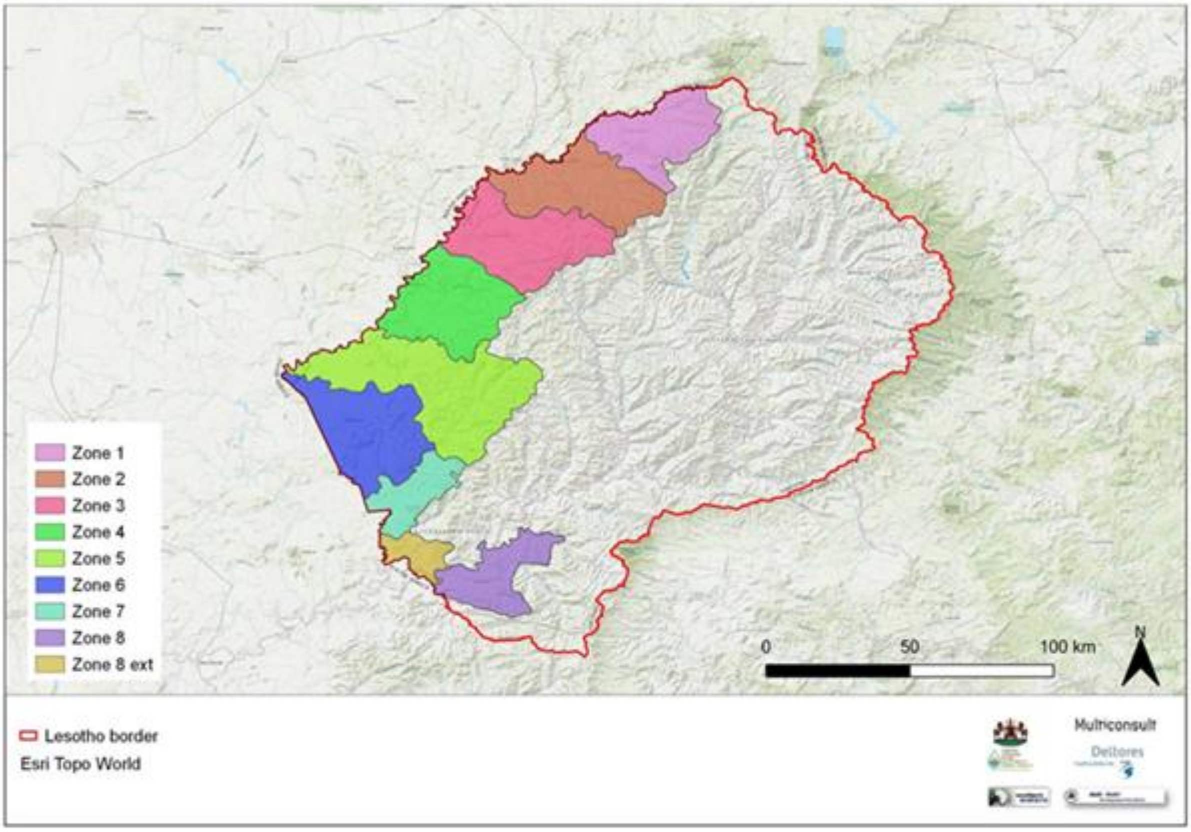


Figure 1-1: Bulk water supply zones of the Lesotho Lowlands

The GOL's LLWDP II is being supported by the World Bank and European Investment Bank/European Union to carry out the following studies for the Hlotse River:

- hydrological;
- hydraulic/hydrodynamic;
- aquatic biodiversity;
- water quality; and
- an Environmental Flow Assessment (EFA).

This report describes the Water Resources and Water Quality study component in support of the EFA.

1.2 This report

The reporting for the Hlotse EFlows Assessment comprises ten final milestone reports:

- Inception and Scoping Report
- Baseline Report
- Monitoring and Modelling report
- Training Manual
- Water Resources and Water Quality Assessment Report
- Hydraulics and Hydrodynamics Report
- EFlows Assessment Report
- Hlotse DRIFT Manual
- EFlows Policy and EFlows Management Plan

- Completion Report

Two supplementary (non-milestone reports) has also been elaborated. These are:

- Baseline Water Quality Monitoring Programme Design
- Baseline Water Quality Sampling Manual

This report is the 'Water Resources and Water Quality Assessment Report' and is divided into two main sections, corresponding to two subtasks, indicated in Figure 1-2 with a red shape:

- Task 3.3 – Water Resources Management
- Task 5.2 – Water Quality Assessment

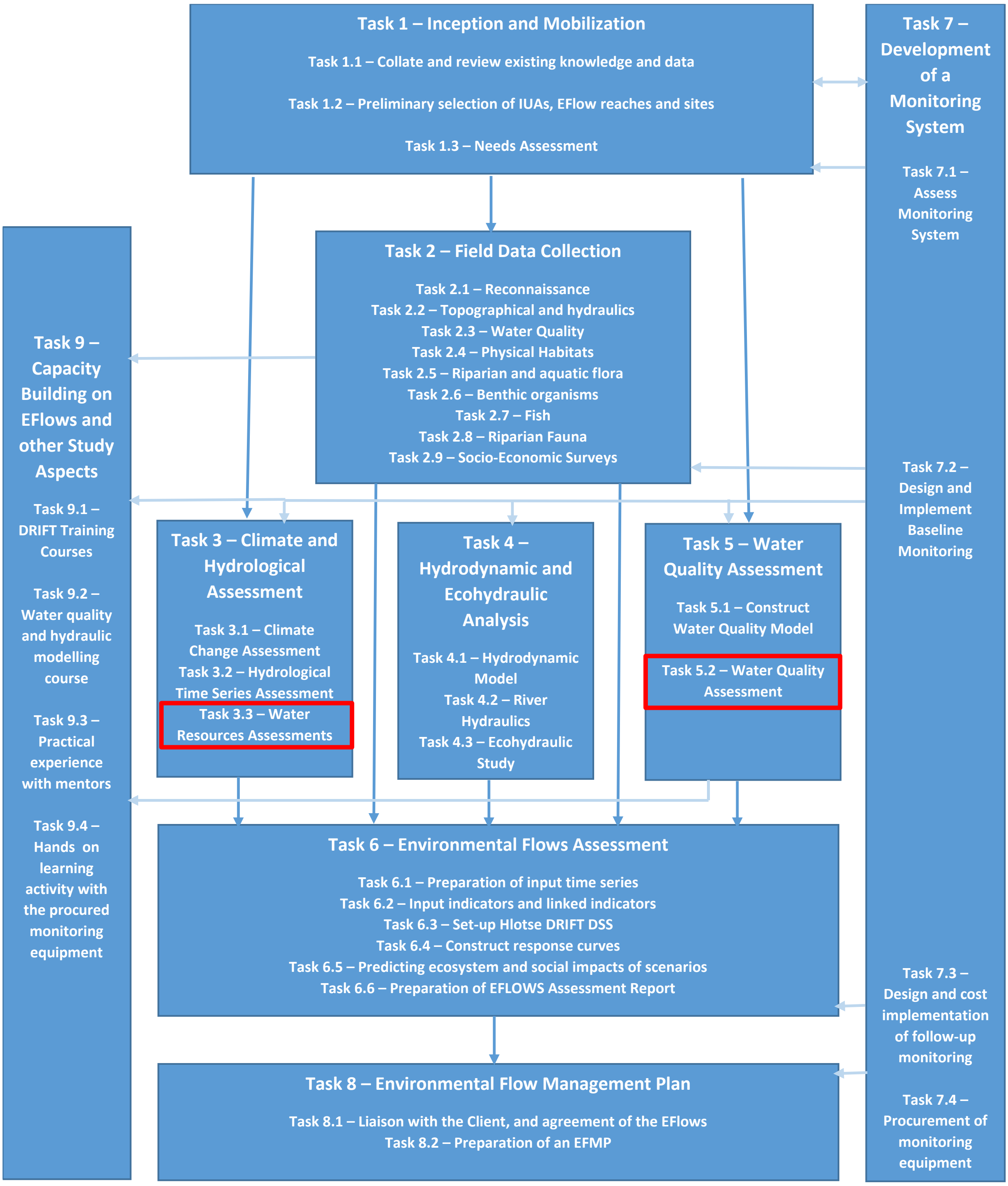


Figure 1-2: Overall sequencing and inter-relationships of the tasks with its sub-tasks in the EFlow study for Hlotse River.

1.3 Description of the Report

1.3.1 Purpose of This Report

This document serves as the "Water Resources and Water Quality Assessment Report" for the EFlows Assessment and Water Quality Modelling in the Lesotho Lowlands Water Development Project Phase II (LLWDP II). The main aims of this report are: (i) give a summary of the assessment of the water resources in the Hlotse river basin, focussing on the natural water availability and the water losses, (ii) provide an overview of the available information on water quality in the Katse Dam – Adit – Hlotse river system, (iii) give insight in the water quality situation in this system.

1.3.2 Report Structure

The Final Water Resources and Water Quality Assessment Report is structured as follows:

Chapter 1	**Introduction**: short overview of the Lesotho water-resources sector and characteristics of Hlotse Basin and outline of the present report.
Chapter 2	**Approach and Implementation:** summary of the approach for both topics that are the subject of this report
Chapter 3	**Water Resources Assessment:** description of the hydrological modelling to assess the natural water availability and the assessment of the water losses in the Hlotse basin
Chapter 4	**Water Quality Assessment:** main chapter on the water quality data availability and the analysis of these data in terms of various water quality standards
Chapter 5	**Conclusions**
Chapter 6	**Recommendations**
Chapter 7	**References**

2 Approach and Implementation

2.1 Water Resources Assessment

The water resources assessment is divided into two parts:

1. Assessment of the natural water availability by hydrological modelling
2. Assessment of the water losses in the Hlotse river system

For the assessment of the natural water availability in the Hlotse basin, hydrological simulations were made of the entire basin using the wflow rainfall-runoff model. The wflow model is an in-house development by Deltares, using existing hydrological models in a distributed way. For the present application, use was made of the SBM hydrological model, with the raster-size of about 500 x 500 m, and most of the model basic information was obtained from global data sets. For the forcing of the model, two sets of global data were initially used, ERA5[3] and CHIRPS[4]. For the validation of these datasets, and partly correcting them, measured data were used from stations in and directly outside the Hlotse basin. Finally, the CHIRPS dataset was used, with corrections, over the period 1-1-1982 till 31-12-2020. Model simulations were made for a 'natural state' of the basin, and a base case, representing the present situation. In addition, simulations were made for different levels of inflow from the Adit, and corresponding abstraction at the intake.

In addition to the simulations with the hydrological model, attention was given to the losses in the river, which can occur due to seepage, evaporation and water abstractions between the point of outflow of the Adit and the intake. The seepage was assumed to be negligible, but the evaporation should be taken into account and is actually included in the wflow hydrological model. Loss by evaporation varies over the season, and over the years, but is on average about 0.014 m^3/s, with a min. and max. value over the entire simulation period of resp. 0,0025 and 0,03 m^3/s. Losses by water abstraction are unknown, but from information over the larger region in the Northern Lowlands it can be deduced that these are negligible. In the most recent information on the design of the Adit, a loss in the river is assumed of 15% of the inflow. However, from our assessment, we assume that those losses will be much less and most likely will not surpass 2 – 3 % of the inflow (see Chapter 3.2).

2.2 Water Quality Assessment

The waters in the Hlotse River in the Lesotho Lowlands are classified as mountainous river water with no industrial pollution (SSI, 2008). During the Environmental Impact Assessment (EIA) – Northern Region (SSI, 2008) water sampling was conducted in the Hlotse River to identify water quality constituents of concern for the design of a water treatment works. The EIA also analysed data collected by the DWA between 1997 and 2003 and compared the results to the WHO Guidelines for drinking water as well as the SANS[5] drinking water quality standards. They found salinity, elevated iron, manganese, turbidity, suspended solids, microbiological, and alkalinity in the Hlotse River that would require unit treatment processes to reduce the contaminant levels to comply with SANS241:2006 drinking water standards.

The DWA operated a water quality monitoring network in the Hlotse River catchment. There are three monitoring points located at Khabo (CQ14), Setene (CQ15) and Leshoele (CQ21). Water samples have been

[3] ERA5 is the fifth generation ECMWF atmospheric reanalysis of the global climate covering the period from January 1950 to present. ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

[4] Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a 35+ year quasi-global rainfall data set. Spanning 50°S-50°N (and all longitudes) and ranging from 1981 to near-present.

[5] South African National Standard.

collected at various frequencies, varying from monthly to quarterly. Sampling started in about 1999 and stopped in 2014. Water quality data have also been collected by DWA in the Hlotse River System as part of the LLWDP II (February 2020 and still ongoing). The sampling frequency was two-weekly and the samples were analysed the constituents listed above. Samples were collected at sampling points Above Adit (TS1), Below Adit (TS3), at the abstraction point at Setene (Hlotse A), and downstream of Setene (HS2).

No formal assessment of the water quality data collected in the Hlotse River could be obtained during the Inception Phase. A water quality assessment was therefore undertaken of all the historical water quality data collected in the Hlotse River to determine spatial and temporal trends, and fitness for use characteristics in order to understand the water quality behaviour of the river under different flow conditions.

In order to assess the fitness of the Hlotse River water for aquatic ecosystems, the water quality observed during the 2021 baseline monitoring were compared to the aquatic ecosystem water quality guidelines that were developed for the Orange-Senqu River by ORASECOM (Appendix Table 5; ORASECOM 2009) and for Lesotho (Fichtner 2013).

3 Water Resources Assessment

3.1 Hydrological modelling with Wflow model

The hydrological study for the Hlotse River has the purpose of providing inflow series, historical and future, for the hydrodynamic model HEC-RAS of the Hlotse River. Although the use of measured flow series is probably the most reliable means to arrive at a daily discharge series, this is hampered by the lack of long and continuous data series, especially in case such a series should comply with the requirement here of a length of 30 years up till 2020. There is also significant uncertainty in the representation of the series for other locations to where it is transposed. The timing of the daily series may also vary significantly in case the original gauging station is far from the location of study and for those reasons, the grid-based Wflow SBM model, which is an in-house development by Deltares is used to base the inflow series for the Hlotse River on hydrological modelling.

3.1.1 Wflow Model concepts

The distributed hydrological modelling software Wflow is a free and open source distributed hydrological modelling platform developed by Deltares and targeted to perform hydrological simulations using GIS raster data, often based on global datasets (van Verseveld, 2021). The model calculates all hydrological fluxes at any given point in the model at a given time step, based on physical parameters and meteorological input data. Major hydrological processes are included such as interception, soil moisture percolation, evapotranspiration and runoff generating processes (Figure 3-1). The kinematic wave is applied for channel routing. The Wflow SBM model also includes a module that forms the basis for the sediment module.

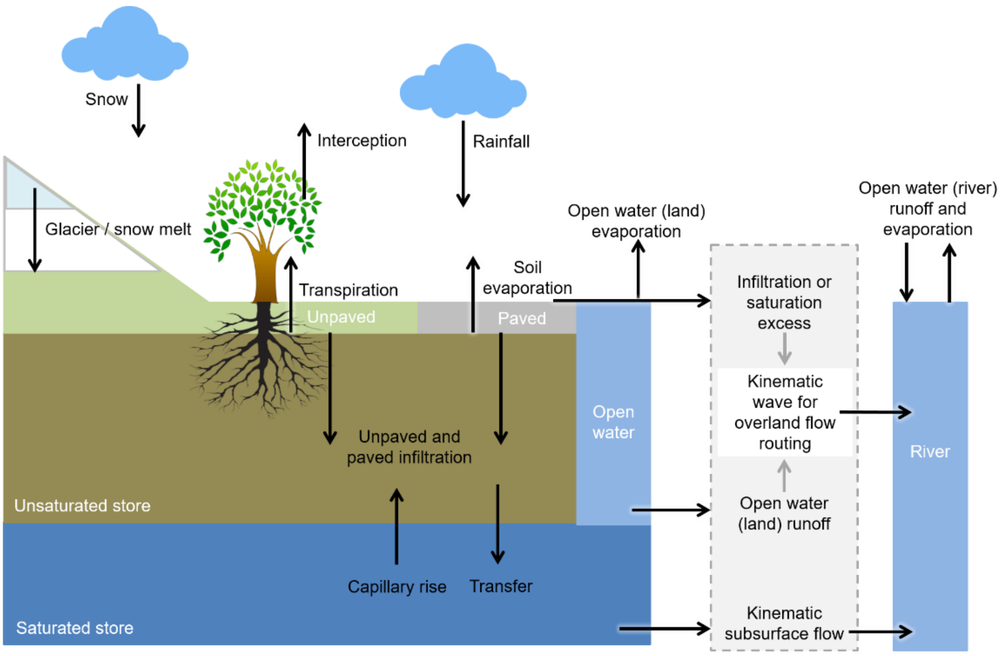


Figure 3-1: Overview of the main hydrological processes in the Wflow SBM cell

Wflow offers many advantages. It is an open source and freely available model. As it is a distributed (gridded) model, results can be obtained for any locations/cells in the studied catchment and can then easily be connected to both the water resources and the hydrodynamic model and provides information such as river or lateral inflows (Figure 3-2). This is important as it will allow to extract the discharge timeseries at various locations in the Hlotse Basin corresponding with the six zones defined for the environmental flow assessment and to easily link to the HEC-RAS model.

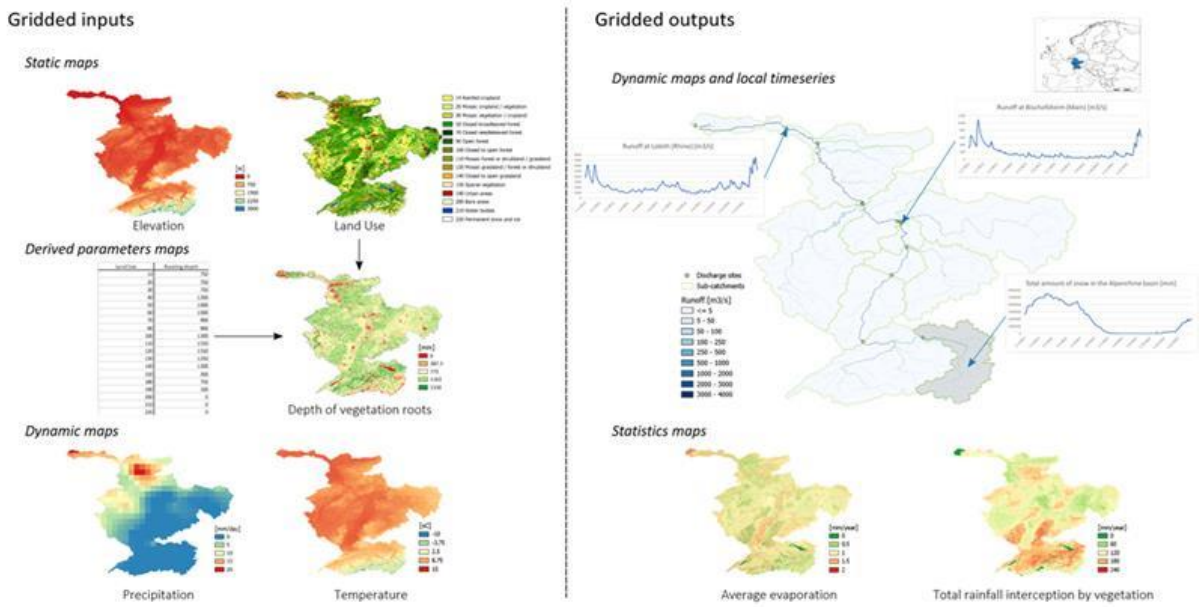


Figure 3-2: Distributed inputs and outputs of the wflow_sbm model

3.1.2 Model setup and datasets

A Wflow model (hydrology) requires three main types of inputs (Figure 3-2):

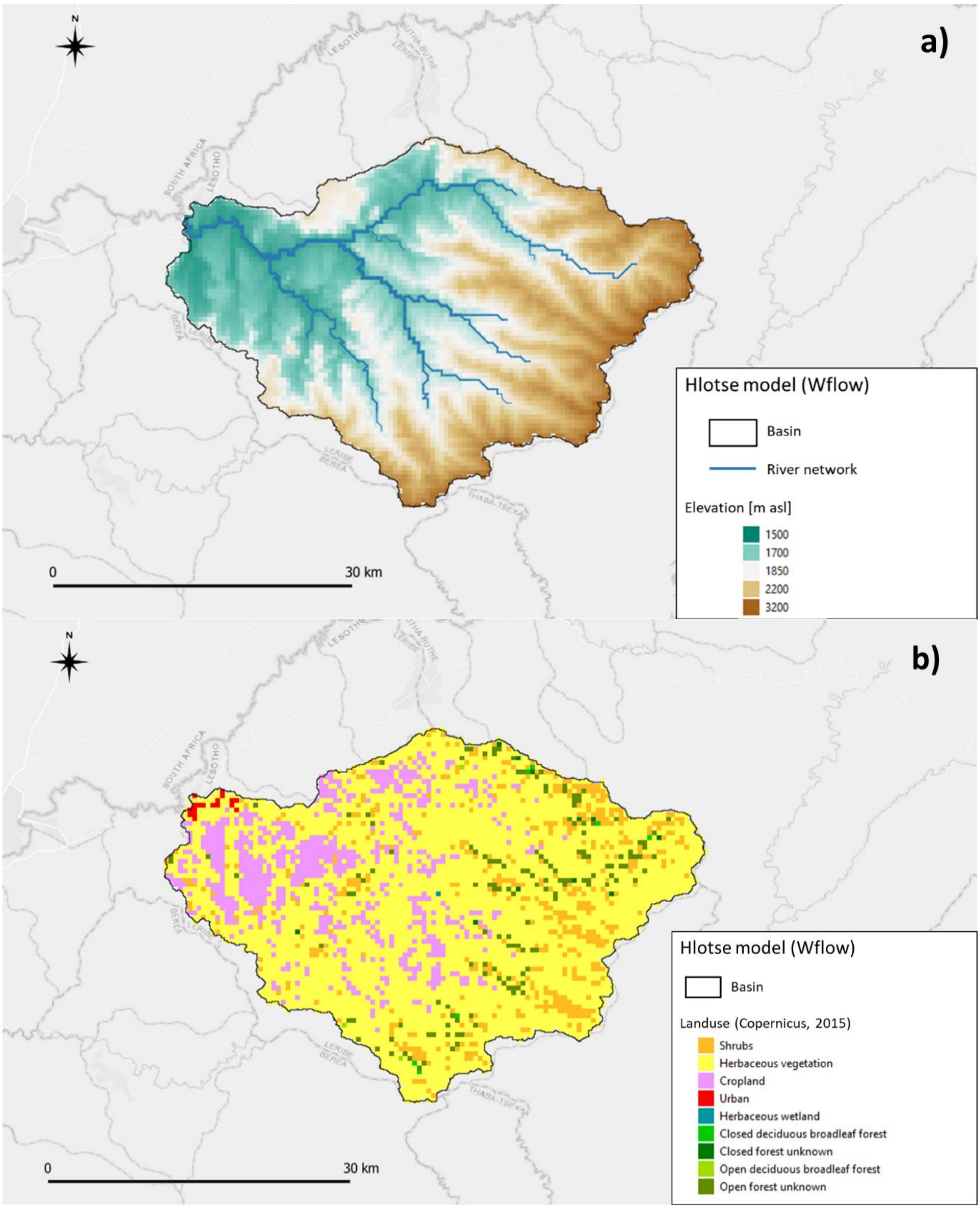
- **Model construction dataset**, such as a Digital Elevation Model (DEM), soil type, land use or stream network and the parameters derived from them (such as soil hydraulic conductivity, rooting depth or surface roughness).
- **Model forcing dataset**, such as precipitation, potential evapotranspiration or temperature.
- **Model calibration and validation dataset** such as discharge or rainfall timeseries.

A first setup of the Hlotse catchment model was prepared using open access data sources. The model catchment properties and construction datasets are:

- The global 3 arc second (~90 meters) **MERIT Hydro** Adjusted Elevations dataset (Yamazaki et al., 2019) for model elevation and associated topological information (such as catchment delineation, 1D flow direction, slope, stream network and stream characteristics).
- The global 250 meters **SoilGrids** Database (Hengl et al., 2017) for soil properties (clay, silt, and organic carbon content as well as bulk density) and derived Wflow model soil parameters (such as hydraulic conductivity, porosity, soil water content and saturation content…).
- The global 100 meters **Copernicus Global Land Service 2015** land cover map (Buchhorn et al., 2020) for land-use, land-cover classes and associated vegetation parameters (such as surface roughness, rotting depth of the vegetation, fraction of paved areas etc.).

To prepare the Wflow model maps and parameters from these datasets, we utilized Deltares in-house HydroMT model builder (Deltares, 2021), which is a Python toolbox that collects and prepares the data in a ready-to-use format. HydroMT also makes use of state-of-the-art parameter estimation techniques and (pedo)-transfer functions to limit calibration effort. These (pedo)-transfer functions are using different datasets (e.g. clay content of the soil, sand content of the soil, etc.) to combine into model parameter values based on experience from different models around the world.

The Hlotse hydrologic model was setup in LAT/LON[6] coordinates to optimally make use of available global open datasets. The model coordinates are in WGS84 (EPSG:4326) and the model resolution is 0.0041666° (approximately 500 meters). Figure 3-3 shows the Wflow model schematization and boundaries for the Hlotse basin as well as some of its main catchment characteristics.



[6] *Latitude and longitude.*

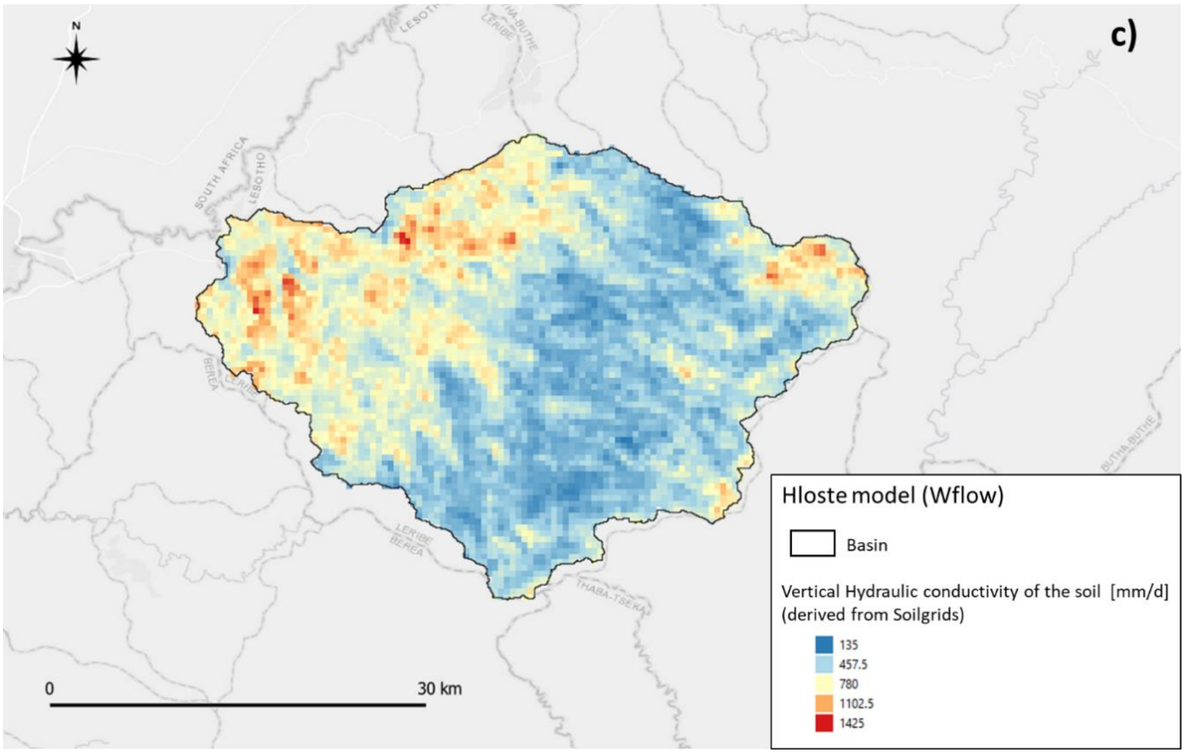


Figure 3-3: Wflow model for the Hlotse basin: (a) elevation, (b) land use and (c) soil properties

As forcing data, Wflow SBM requires three main meteorological variables, to be defined per computational grid cell per time step: total precipitation (in mm), average air temperature (in °C) and potential evapotranspiration (in mm). In this study, the meteorological data, precipitation and air temperature, were derived from the global **ERA5-Reanalysis** dataset (C3S, 2017). ERA5 provides global hourly estimates of different atmospheric, land and oceanic climate variables, from 1979 to within three months of real time, at a resolution of 0.25° (~25km). Potential evaporation is not directly available in ERA5, and was computed from air temperature, pressure, incoming shortwave radiation, and incident solar radiation, using De Bruin equation. Rainfall data quality is crucial for hydrologic modelling and therefore a second dataset was chosen: the daily **CHIRPS** dataset (Climate Hazards Group InfraRed Precipitation with Station data), available from 1979 to near present at a resolution of 0.05° (~5km) (Funk et al., 2015). Using two different datasets allows testing the sensitivity of the Wflow model to the rainfall inputs and to distinguish during the calibration phase if the potentially poor model performances originates from poor rainfall data (especially since these two datasets are synthetic and not observed) or poor model parameters values.

Furthermore, in order to validate both the rainfall grids from the global datasets and to calibrate and validate the modelled discharge values from the Wflow model, observed rainfall and discharge timeseries are crucial. Such timeseries were received from the client for different locations in the basins at either monthly or daily timesteps (Figure 3-4).

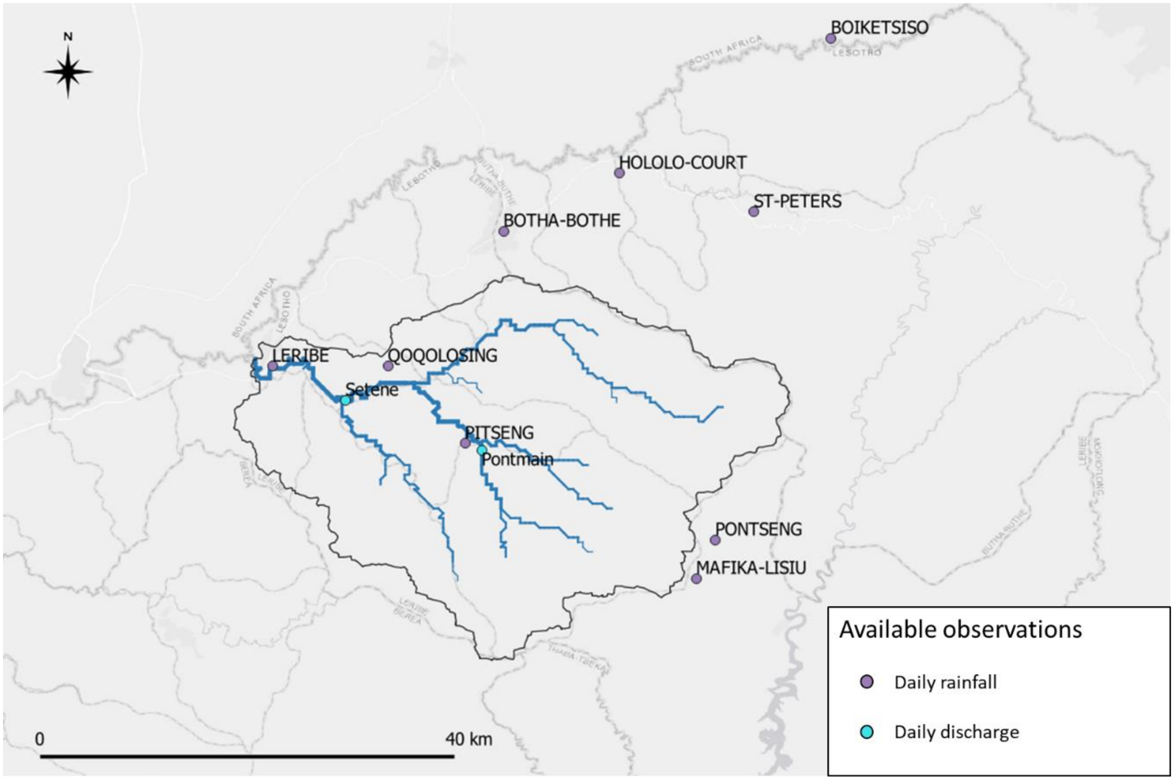


Figure 3-4: Available observed daily rainfall and discharge timeseries from calibration and validation

Table 3-1 summarizes all the different global and local datasets used to prepare the model.

Table 3-1: Overview of the different datasets used by the Wflow SBM model for the Hlotse

Static data	
Digital elevation model (DEM)	• Global 3 arc second (~90 meters) MERIT Hydro Adjusted Elevations dataset (Yamazaki et al., 2019)
Land use classification	• Copernicus Global Land Service: Land Cover 100m: Collection 3: epoch 2015: Globe (Version V3.0.1) [Land Cover Classification] (Buchhorn et al., 2020)
Soil properties	• Global 250 meters SoilGrids Database (Hengl et al., 2017)
Dynamic data	
Precipitation	• Global ERA5-Reanalysis dataset (C3S, 2017) • Global CHIRPS dataset (Climate Hazard InfraRed Precipitation with Station data) (Funk et al., 2015)
Temperature	• Global ERA5-Reanalysis dataset (C3S, 2017)
Downwards and incident solar radiation	• Global ERA5-Reanalysis dataset (C3S, 2017)
Atmospheric pressure	• Global ERA5-Reanalysis dataset (C3S, 2017)
Calibration/validation data	
Rainfall timeseries	• Observations from the client
Discharge timeseries	• Observations from the client

3.1.3 Calibration and validation

3.1.3.1 Quality of the global precipitation data

The first part of the calibration/validation consist in analyzing the quality of the gridded rainfall data from CHIRPS and ERA5 compared to the observed timeseries at different locations in the basin. At the beginning of this phase, only monthly observed precipitation timeseries were available, which is not sufficient to draw a conclusion for a daily hydrological model. In order to get a first idea on the quality of the rainfall data, the Wflow model of the Hlotse was then first run with a set of default values obtained from the HydroMT Modelbuilder with both rainfall from ERA5 and CHIRPS. Figure 3-5 shows the results for several years at the Setene gauging station. The modelled discharge timeseries seems to be highly dependent on which rainfall datasets are used. With ERA5, the model seems to overestimate the baseflow and create new peaks, while with CHIRPS it seems to miss most of the observed peak flow events. The global datasets both seem to miss the major high flow events.

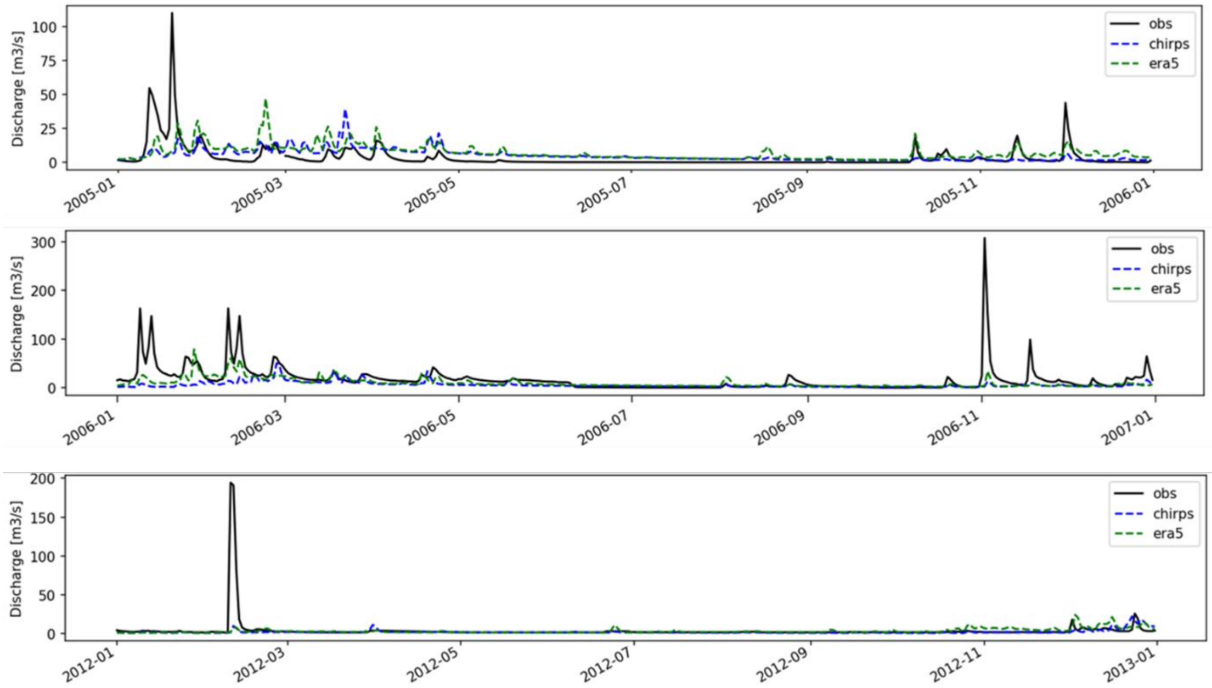


Figure 3-5: Comparison between observed **and modelled discharge at Setene using precipitation from** CHIRPS **or** ERA5

Looking at these first results, it became crucial to obtain observed daily timeseries in order to correct the global data and use them as forcing for the Wflow model. These timeseries were finally obtained and allocated to different zones of the Wflow grid as follow (Figure 3-6):

- Precipitation are local events. For this reason, the area of influence of each meteorological station was limited to a buffer of 15km.
- Most rainfall events in the basin seem to emerge from high precipitation clouds hitting the mountain valleys and plateau in the East. For this reason, precipitation data from the Mafika-Lisiu (or Pontseng when not available) were used for the Eastern cells of the grid where the elevation was more than 2200 m asl.
- To take into account elevation impact on climatology (trapping of clouds), the main tributaries of the Hlotse where then separated and rainfall was allocated from the closest station for which data is available (no missing values).

- For the rest of the model grid or when there are no data available from the station, the CHIRPS dataset was used to cover the grid.

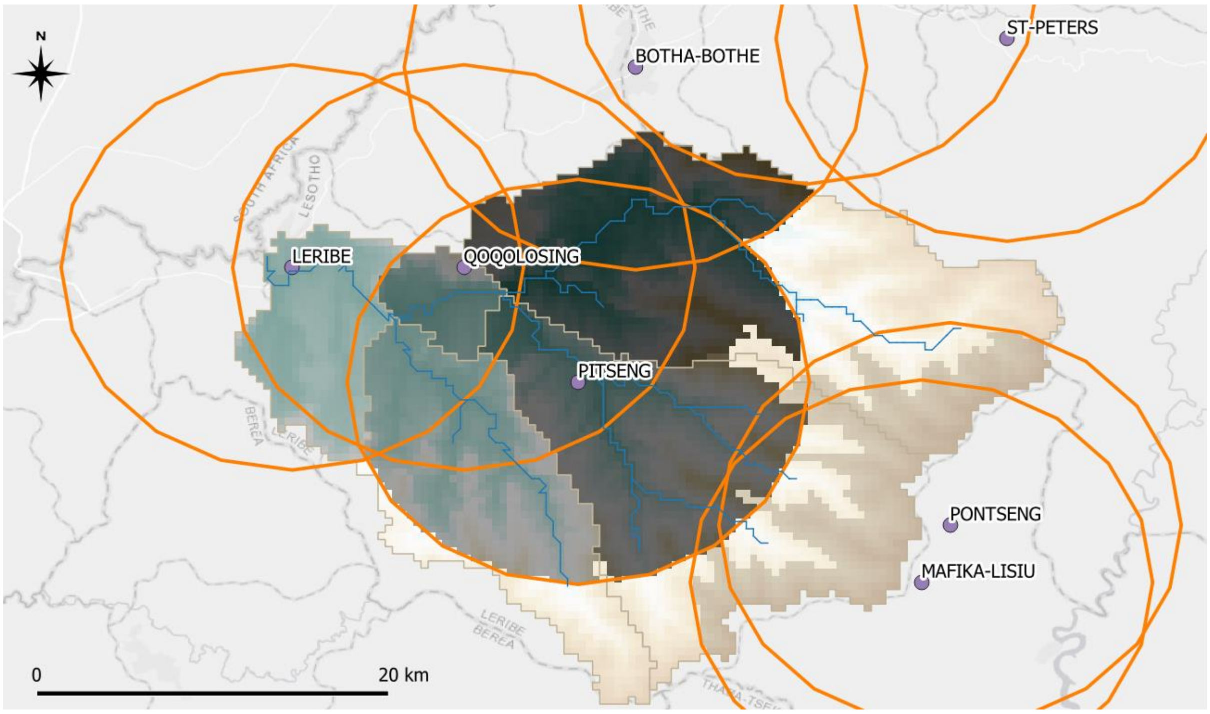


Figure 3-6: Rainfall stations and influence zones (orange circles) used to correct the CHIRPS rainfall grid (background: elevation from the Wflow model)

Figure 3-7 shows the results of the hydrological model when using the corrected rainfall grids compared to the global data. The results of the model are improved with a better estimation of peak occurrence and intensity. A few events, for example in 2006, are still overestimated (or delayed), but they correspond to very intense rain events at the Mafika-Lisiu station that were probably more local than the correction grid domain (Figure 3-8). Overall, model performance is still improved using the station data so this dataset was then used for the calibration of the model parameters.

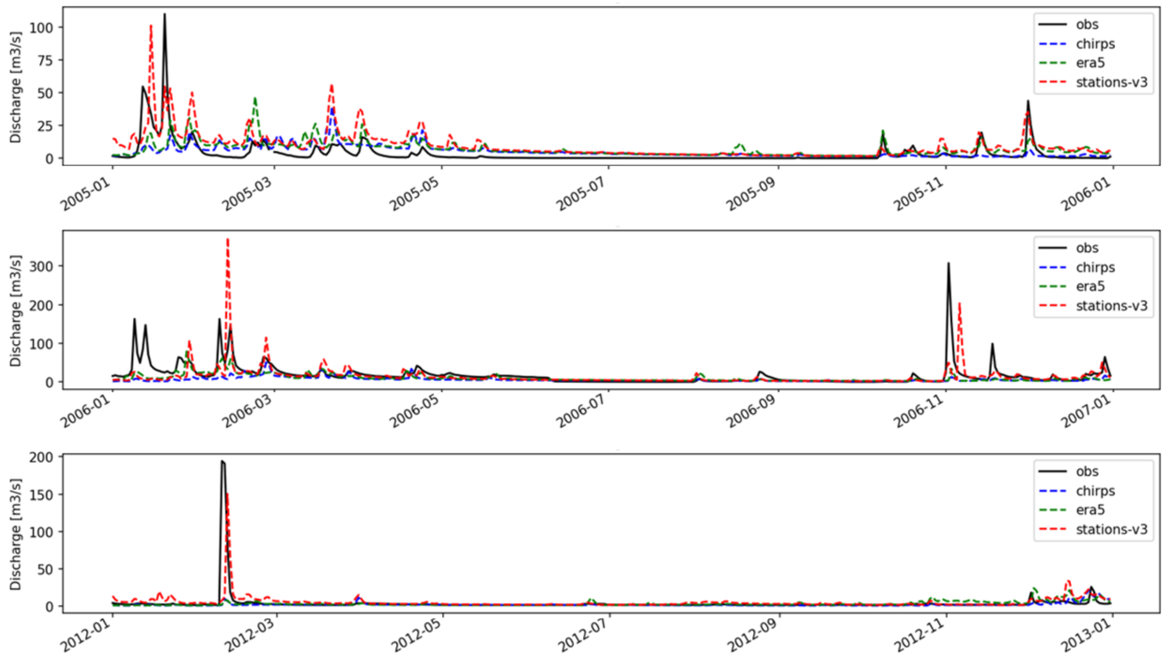


Figure 3-7 Modelled discharge at Setene using the mixed global-local rainfall datasets

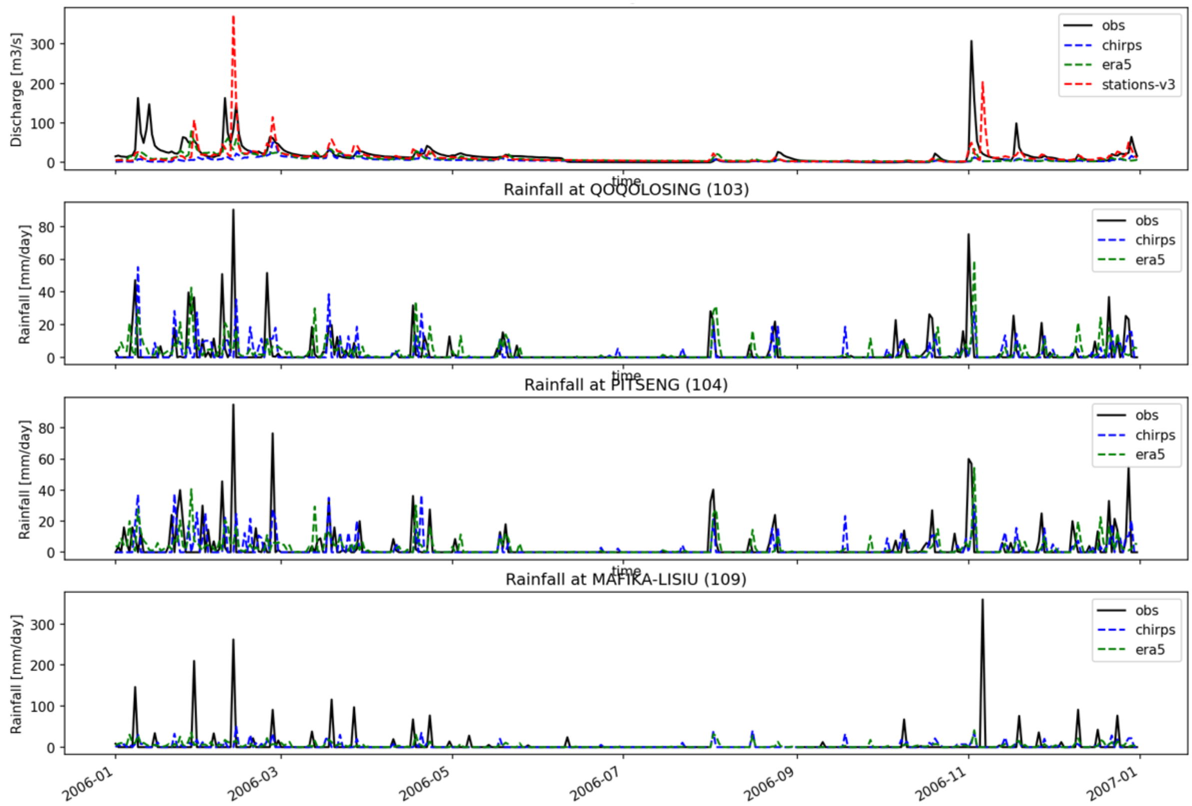


Figure 3-8: Observed and modelled discharge at Setene in 2006 and comparison with observed and global precipitation data at several upstream stations

3.1.3.2 Calibration of the hydrological model

For calibration, a few hydrological model parameters were changed one by one to perform a sensitivity analysis of the model, before being combined during calibration. The parameters that were analyzed are:

- Soil: the horizontal hydraulic conductivity at the soil surface **KsatHorFrac** (multiplier of the vertical hydraulic conductivity KsatVer)
- Soil: the scaling parameter **f** that controls the exponential decline of conductivity with soil depth
- Soil: the saturated water content (porosity) of the soil $\boldsymbol{\theta_s}$
- Vegetation/evaporation: the rooting depth of vegetation **RootingDepth**
- Snow: temperature threshold between rainfall and snowfall **TT**

The selection of the best parameter set for the Hlotse River was based on several criteria:

- Visual inspection of the hydrograph
- Best representation of the (annual) cumulative volumes
- Computation of efficiency coefficients: NSE (Nash-Sutcliffe Efficiency) and KGE (Kling-Gupta Efficiency). These coefficients vary between -∞ (very poor) and 1 (perfect). It is considered that a model starts to be acceptable at 0.4, good at 0.6 and very good from 0.8. KGE is an adapted version of NSE focusing a little less on discharge peaks and more on the water volumes (both high and low flow periods are considered).

Figure 3-9 shows an example of the sensitivity analysis of Wflow parameters at Setene in 2006. From the analysis, KsatHorFrac and f seem to have the most influence and RootingDepth and TT the least. For most years though, a change in model parameter seemed to have too low an impact compared to getting the right precipitation. For this reason, in the refinement phase, only the KsatHorFrac parameter was updated, as this is the only one that does not have a default physics-based value from the HydroMT model builder. KsatHorFrac was then reduced in order to increase the peak flows and decrease the low flow. The final parameter value retained for KsatHorFrac was 50 [-].

From this combination (Figure 3-10), the baseflow are lowered and more peaks are better estimated. However, the events linked to an overestimation (or area of influence) when using the Mafika-Lisiu station are amplified (for example in 2006 at Setene).

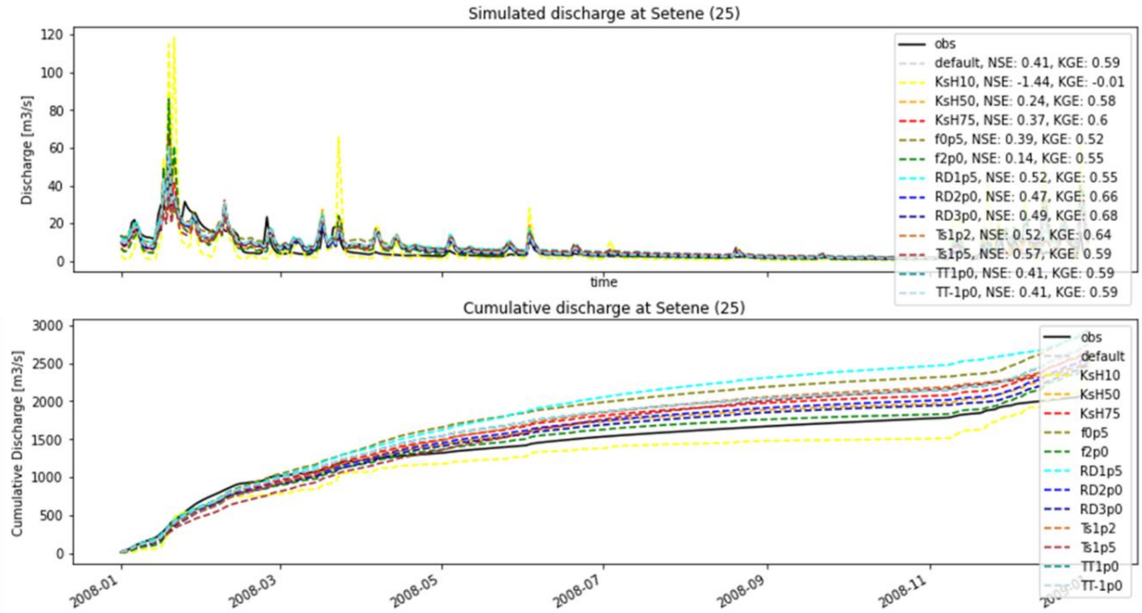


Figure 3-9: Sensitivity analysis of the Wflow model parameters

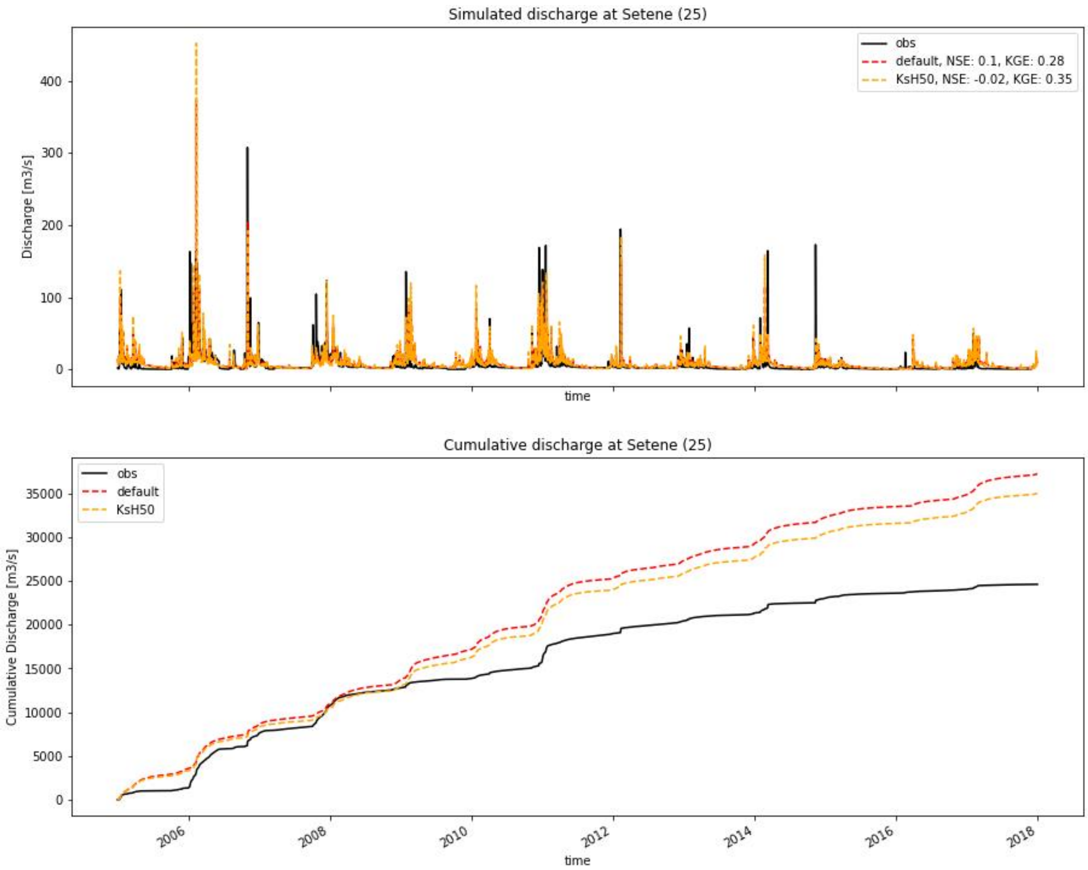


Figure 3-10: Observed **and modelled discharge with the** default **and** calibrated **value of KsatHorFrac at Setene**

3.1.4 Results and scenarios

The Wflow model of the Hlotse River is used to provide 40 years of river discharge timeseries at several locations for the different models (Figure 3-11):

- EFlow sites for DRIFT
- Main tributaries for HEC-RAS as well as lateral inflows in between the different Eflow sites

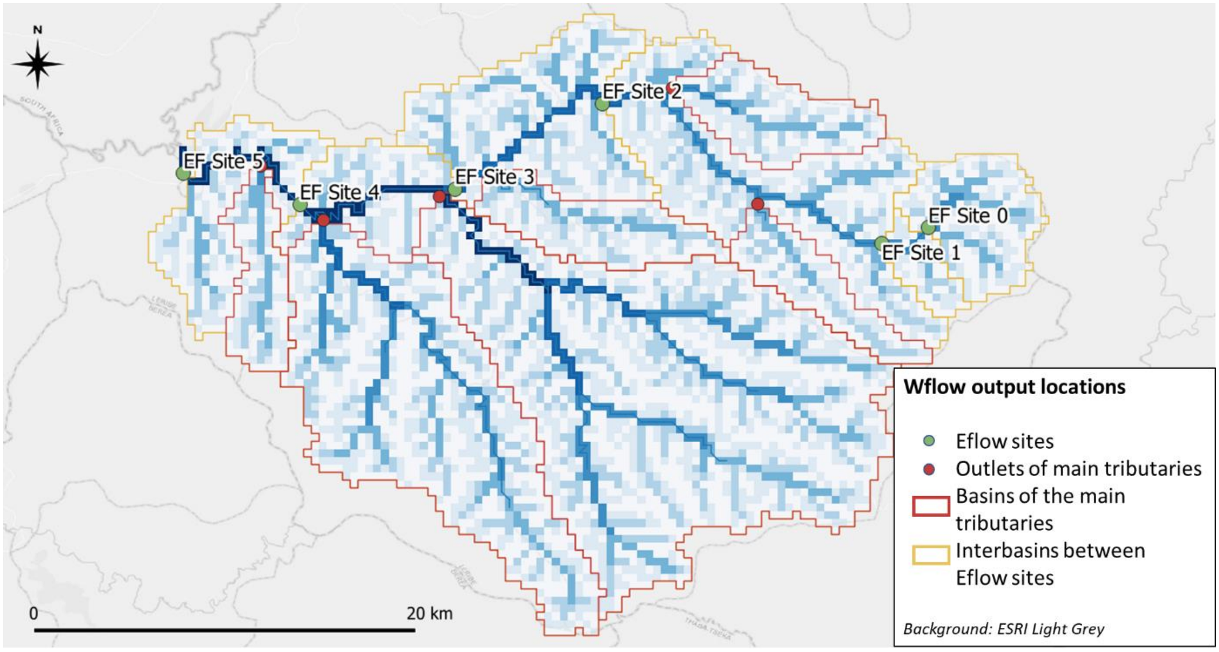


Figure 3-11: Locations of Wflow outputs for DRIFT (EFlow sites) and HEC-RAS (main tributaries)

In addition, the model was also used to provide several scenarios:

- Baseline or current flow scenario
- Natural flow scenario (historical or with pristine vegetation)
- Release and abstractions linked to the Adit developments
- Climate change scenarios (see paragraph 3.3)

To produce the natural flow scenario, the land use map of the model was modified in order to reflect a more pristine vegetation. Existing croplands were changed into grasslands (herbaceous vegetation) and the model parameters of the pristine grassland were updated to reflect a denser mix of red grass and shrubs that is not impacted by grazing from cattle (Figure 3-12). Those parameters are the Manning surface roughness N to reflect a denser vegetation, and the rooting depth of the mixed grassland/shrubs to reflect the mixed vegetation and the older grassland/less compacted soil due to grazing. The natural flow scenario compared to the baseline reflect a difference in peak flow intensity (Figure 3-13).

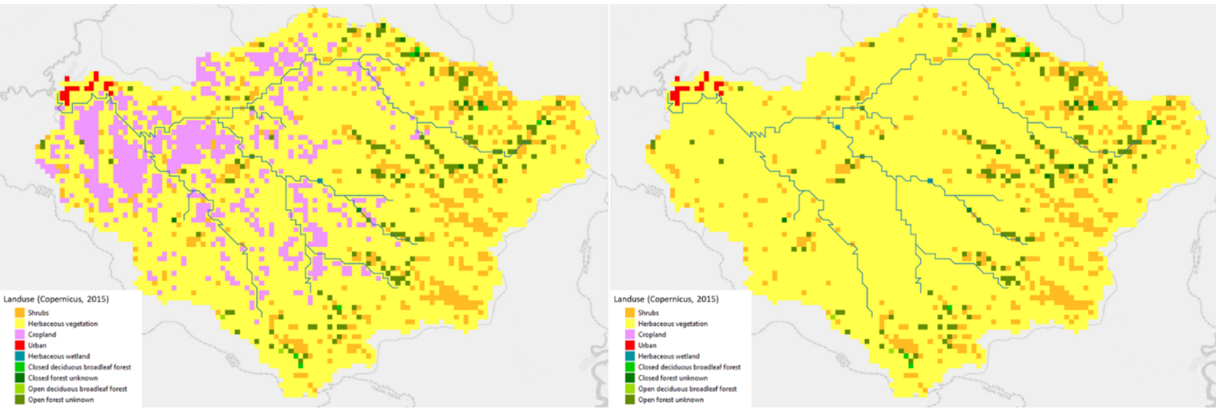


Figure 3-12: Land-use map corresponding to the baseline (left) and natural (right) scenarios

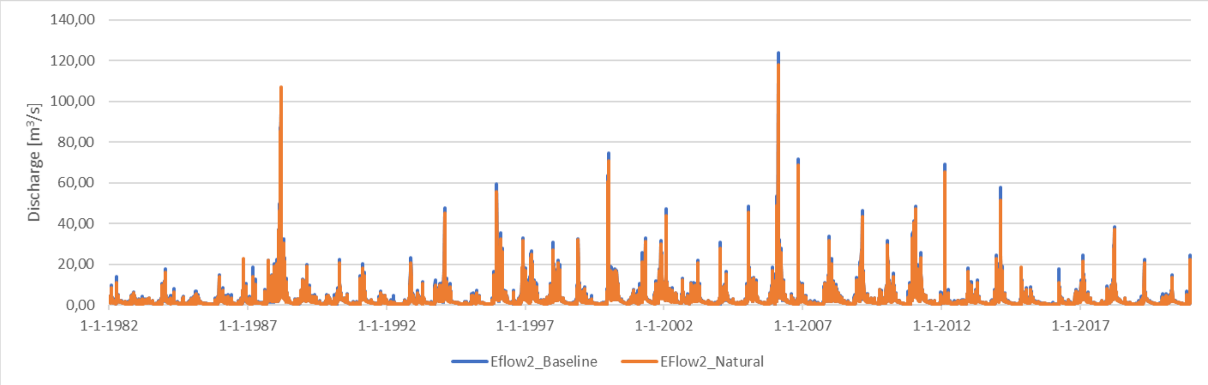


Figure 3-13: Difference in discharge at EFlow site 2 between the baseline and natural scenario

Finally, the Wflow model was also used to produce long discharge timeseries for a future scenario in which additional water is released via the Hlotse Adit infrastructure in the basin (between EFlow sites 0 and 1), and later removed at the abstraction point (between EFlow sites 3 and 4) to satisfy future water demands (Figure 3-14). The studied scenarios are:

1. Daily addition of **0.4 m^3/s** at the Adit site and removal of 0.4 m^3/s at the Abstraction point between **June and September** every year (4 months)
2. Daily addition of **0.6 m^3/s** at the Adit site and removal of 0.6 m^3/s at the Abstraction point between **June and September** every year (4 months)
3. Daily addition of **0.8 m^3/s** at the Adit site and removal of 0.8 m^3/s at the Abstraction point between **June and September** every year (4 months)
4. Daily addition of **1.0 m^3/s** at the Adit site and removal of 1.0 m^3/s at the Abstraction point between **June and September** every year (4 months)
5. Daily addition of **1.2 m^3/s** at the Adit site and removal of 1.2 m^3/s at the Abstraction point between **June and September** every year (4 months)

Between the addition and abstraction point, water is routed in Wflow using the kinematic wave equation and accounting for open water evaporation of the river based on daily potential evapotranspiration values. Figure 3-15 shows the difference between the baseline and scenario 3 (+/- 0.8m^3/s) at EFlow site 3.

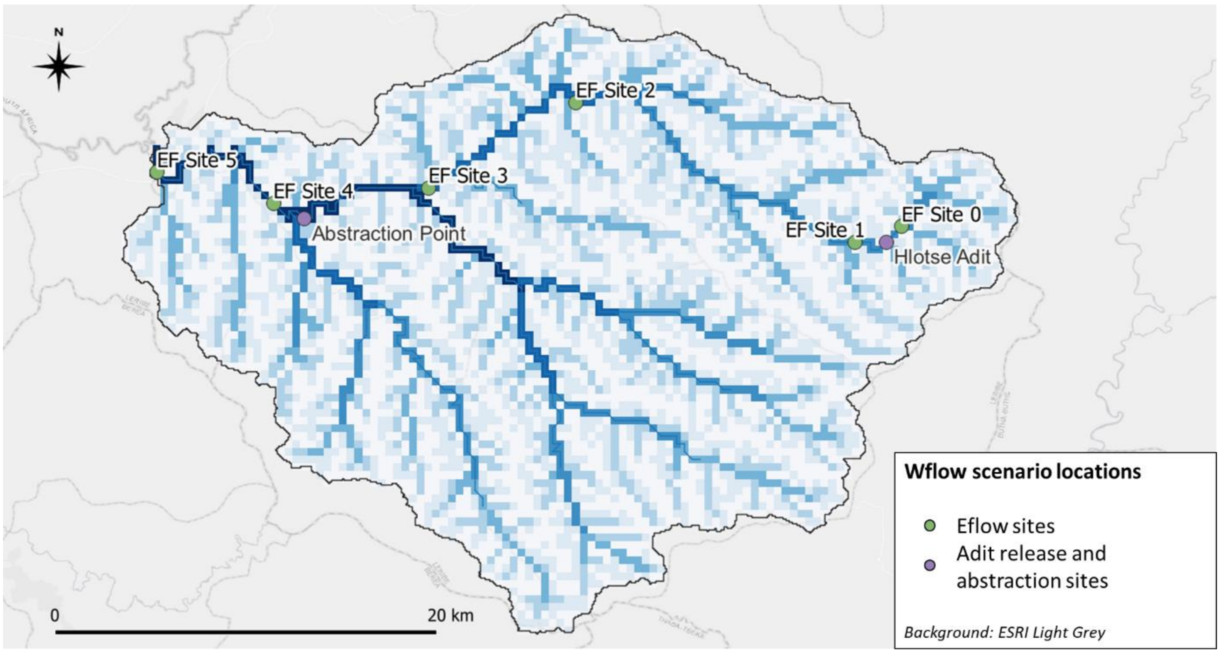


Figure 3-14: Hlotse Adit Release and Abstraction site locations

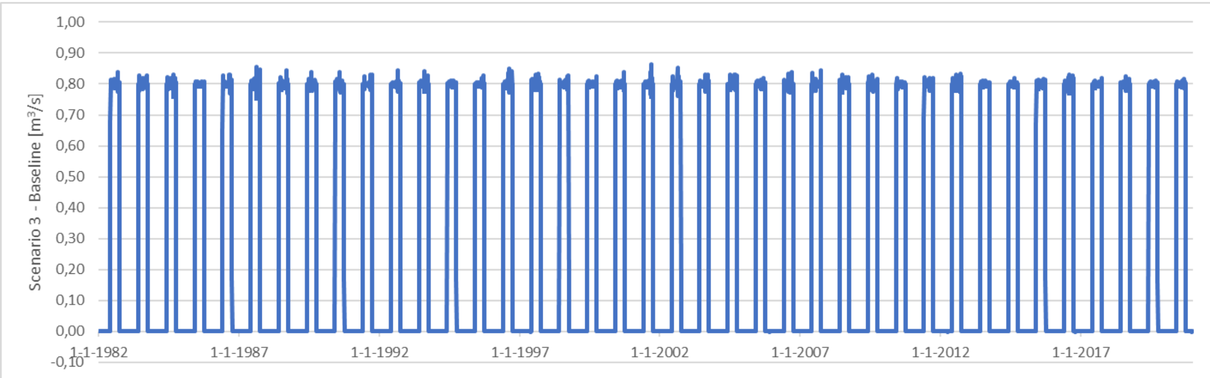


Figure 3-15: Difference in discharge between the baseline and Adit 3 scenario (+/- 0.8m^3/s) at EFlow Site 3

3.2 Losses along the Hlotse river

In the design study for the Hlotse Adit, assumptions are made on the losses that will occur along the stretch of the river from the Adit till the point of intake, which has a length of about 49 km. The losses were estimated at 15% of the inflow from the Adit as a fixed value, which according to the information provided should be seen as a worst-case estimate. These losses represent all possible losses along the stretch, i.e. evaporation, seepage and water abstractions. In Table 3-2 the characteristics of the present and future Adit arrangement are given, both in m^3/d and m^3/s. As can be seen, the losses (“Outflow 01”) are assumed to amount to 15% of the inflow through the Adit (“Outflow_01B”).

Table 3-2: Design data for the present and future arrangement of the Hlotse Adit

	In m3/d			*In m3/s*			
Description	Minimum	Maximum	Design	Minimum	Maximum	Design	% of Design
Inflow_01A - Present arrangment (DN150)	18.268	31.469		0,211	0,364	0,000	
Inflow_01B - Future arrangment (DN800)	93.228	283.774	132.145	1,079	3,284	1,529	
Inflow_02 - Release used backwash water from WTW	2.147	6.536	3.044	0,025	0,076	0,035	
Outflow 01 - Losses in the river	13.984	42.566	19.822	0,162	0,493	0,229	15,0%
Outflow 02 - Water Supply to WTW	42.945	130.717	60.871	0,497	1,513	0,705	46,1%
Outflow 03 - EFR	36.300	110.491	51.452	0,420	1,279	0,596	38,9%

Of the three sources of losses, in the hydrological model wflow only the evaporation is included. It is assumed that no seepage will occur, and if so, this amount will be very small. The evaporation is simulated as part of the modelling and the results show that the evaporation over the entire stretch of about 49 km varies over the year with the season, with min. and max. values between about 0,0025 and 0,03 m^3/s, and an average value of 0,014 m^3/s. For the present capacity of the Adit (max. about 0,4 m^3/s), this amounts to about 3,9% of the inflow, while for the future arrangement, with 1,529 m^3/s, the evaporation losses are estimated at about 0,9%. At the highest level of evaporation, the percentage would be 2,1%. In Table 3-3 the loss by evaporation is expressed as percentage of the flow for the present and future arrangement of the Hlotse Adit, for the average, max. en min. value of evaporation, and the min., max. and design values of the flow from the Adit.

Table 3-3: Evaporation losses as percentage of the present and future flow from the Hlotse Adit

Evapor.		% of Present Adit		% of Future Adit		
	m3/s	Min	Max	Min	Max	Design
Average	0,014	6,7%	3,9%	1,3%	0,4%	**0,9%**
Max	0,032	14,9%	8,7%	2,9%	1,0%	**2,1%**
Min	0,002	1,2%	0,7%	0,2%	0,1%	**0,2%**

The values of the evaporation will change under climate change scenarios, due to their dependency on temperature, but this will not have a major impact on the percentages.

For this study, information was gathered on the abstractions in the region, but there are no records of abstractions on the Hlotse river itself. As the total amount of the abstractions in the whole region around the Hlotse basin are in the order of 0,025 m^3/s, it is likely that the abstractions from the Hlotse river itself are far less, and probably only due to irregular intakes for small irrigated plots. For this reason, it is assumed that the abstractions can be ignored in this study, particularly in comparison with possible errors in the hydrological modelling.

In conclusion we can state that the losses that are now used in the design of the Adit, 15% as a continuous value of the Adit inflow, are far higher than might be expected from the combination of evaporation and the abstractions, and most likely will not exceed 2 – 3 % of the inflow.

3.3 Climate change model scenarios

3.3.1 Climate change scenarios for the Hlotse river basin

Following the feedback of the client during the Inception Phase the climate change analysis is fully based on Lesotho's Climate change Scenarios Report (LMS, 2018). This report summarizes the national climate change scenarios that were constructed as input for the Third National Communication on Climate Change for the United Nations. The scenarios are based on simulations of the international Coupled Model Inter-comparison Project Phase 5 (CMIP5; Taylor et al., 2011). Global climate model (GCM) simulations from the basis of this report. For this study use was made of the higher resolution down-scaled climate simulations from Regional Climate Models (RCMs) that are developed as part of the Coordinated Regional climate Downscaling Experiment (CORDEX; Filippo, 2009). The RCMs use the GCM data as boundary conditions and down-scale those to a higher resolution of approximately 10 – 15 kilometers.

The report provides projections for the future periods 2011-2040 and 2041-2070 for the four seasons September-October-November (SON), December-January-February (DJF), March-April-May (MAM) and June-July-August (JJA). Those are used in our study as the time horizons for the resp. 2035 and 2050. For temperature only changes for minimum and maximum temperature are provided. For mean temperature the average of both changes was used.

The climate change analysis in this report will focus on RCP4.5 that projects a moderate increase in greenhouse gasses and RCP8.5, the scenario that projects the largest increases in greenhouse gasses. In this study we work with (1) a moderate (average) and (2) a warm / dry scenario (worst case).

The report (NCCSDTT, 2018) provides boxplots of projected change in temperature (degrees) and precipitation (mm per season). In Figure 3-16 an example for projected precipitation change for the winter (JJA). Projections are differentiated into 4 zones. The Hlotse is located in the Foothills (FH) and Lowlands (LL).

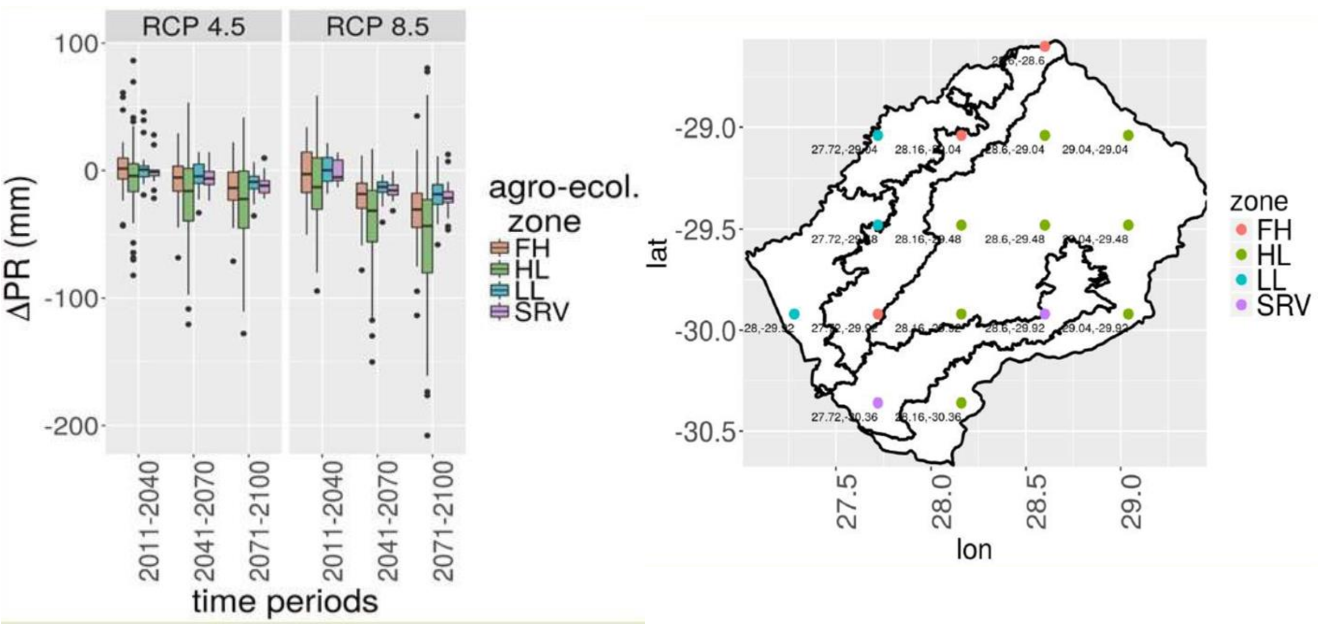


Figure 3-16: Summary of projected change in winter (JJA) precipitation in mm relative to the baseline period (1971-2000)

For the dry scenario we use the boundaries of the lower boundary of the RCP8.5 boxes, e.g. the 25% values and for the median precipitation scenario the median of the RCP4.5 boxplot.

For temperature there is a clear difference between the temperature projections for the two RCPs we will work with median of the projections of RCP4.5 for the median scenario and with the median of the projections for RCP8.5 for the worst-case scenario. The highest temperatures will lead to less snow accumulations and increases in evaporation and are therefore very relevant.

Figure 3-17 presents the derived projected temperature changes according to the moderate scenario. For the short term that is approximately an increase of 1 degree, for the long-term 2 degrees. There is little difference in change projected for the Foot Hills and Low Lands except for the winter season where the projected increase is lower for the Foot Hills. For the warm scenario, especially towards the second half of the century, the temperature increases are larger.

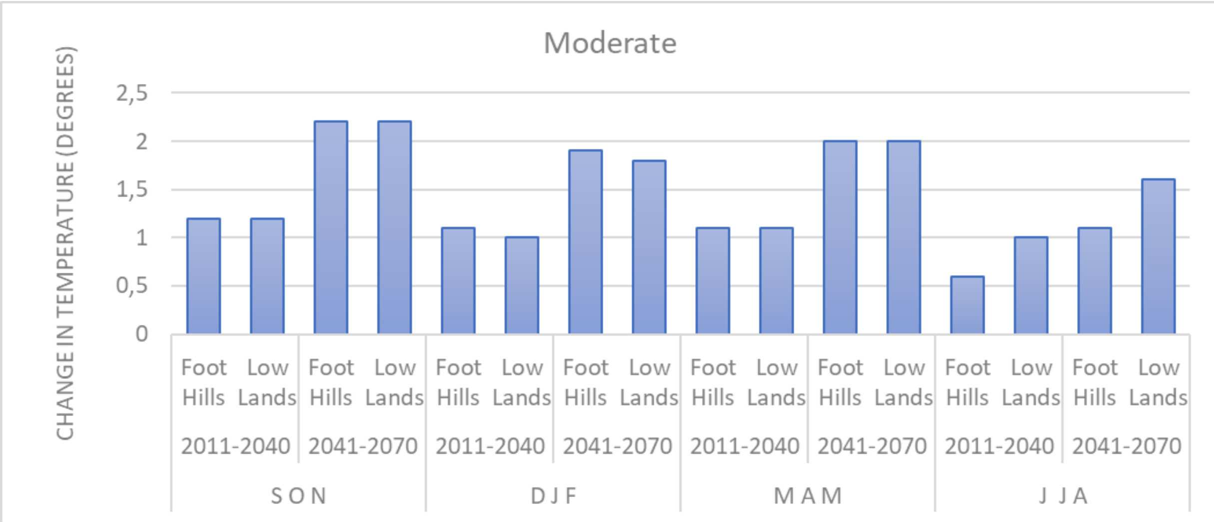


Figure 3-17: Projected change in temperature (degrees) for the four seasons, for the Foot Hills and Low Lands and for the two future time periods (2011-2040 and 2041-2070) for the average scenario.

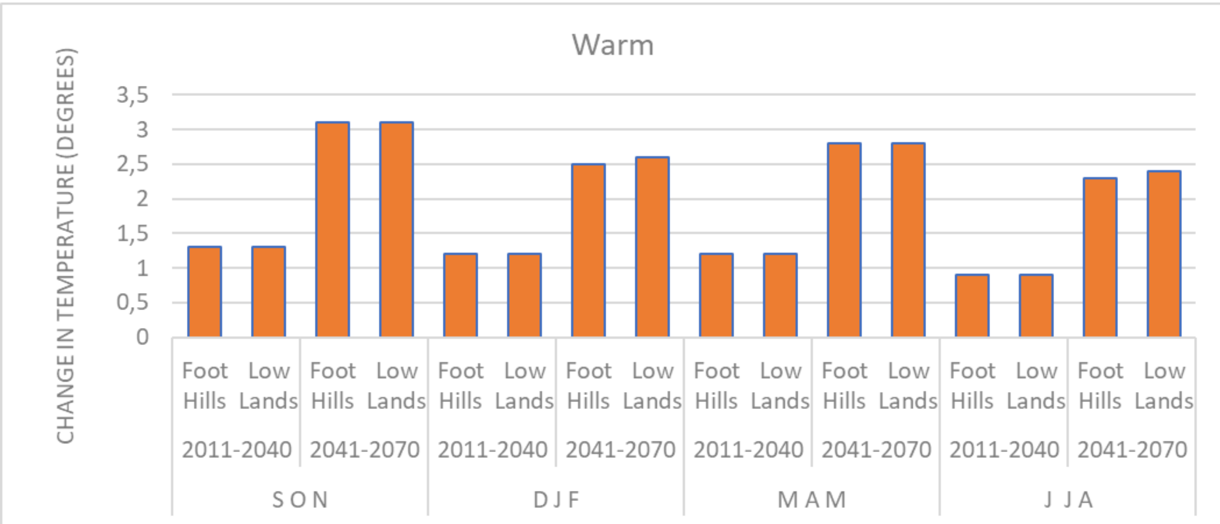


Figure 3-18: Projected change in temperature (degrees) for the four seasons, for the Foot Hills and Low Lands and for the two future time periods (2011-2040 and 2041-2070) for the worst case scenario.

Figure 3-19 and Figure 3-20 present the precipitation projections according to the moderate and dry scenario. The scenarios mainly project precipitation decreases that may increase the pressure on the system, except the moderate scenario for the DJF season.

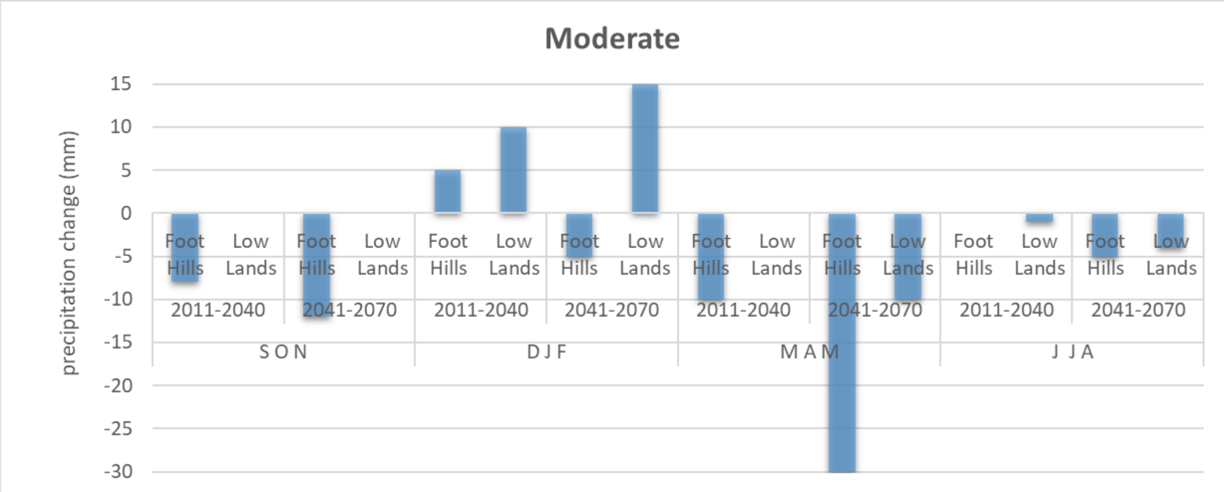


Figure 3-19: Projected change in precipitation (mm) for the four seasons, for the Foot Hills and Low Lands and for the two future time periods (2011-2040 and 2041-2070) for the average scenario.

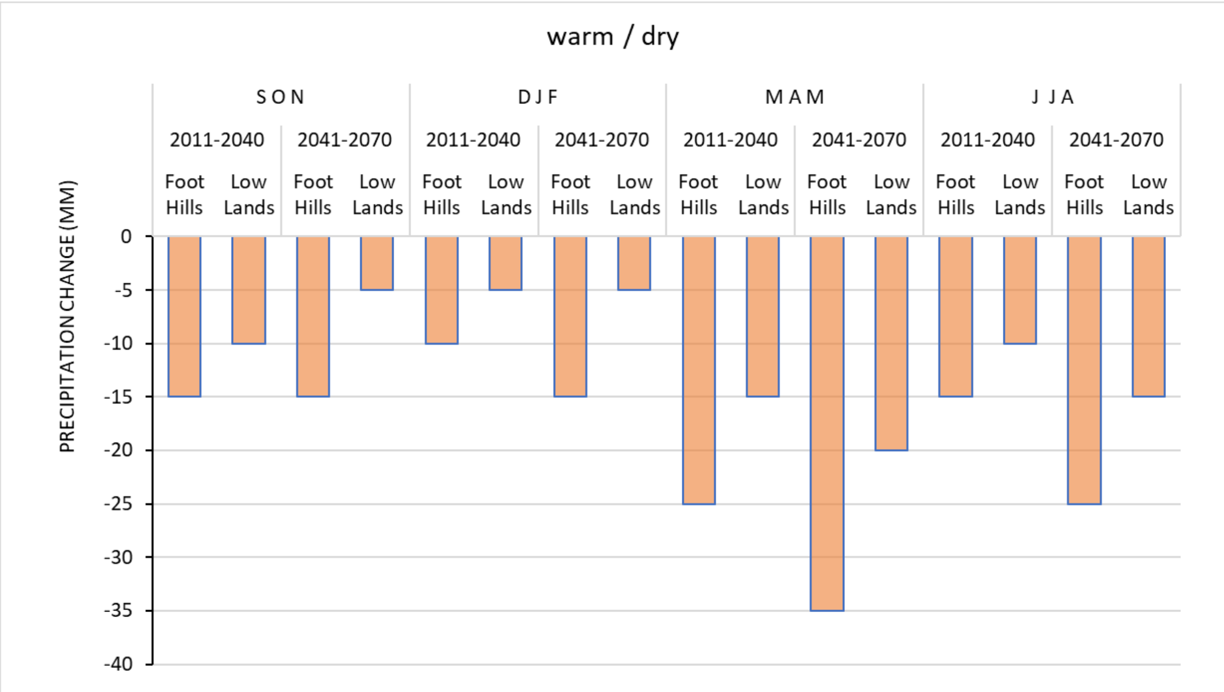


Figure 3-20: Projected change in precipitation (mm) for the four seasons, for the Foot Hills and Low Lands and for the two future time periods (2011-2040 and 2041-2070) for the worst case scenario.

3.3.2 Inclusion of the climate scenarios in the hydrological model

In order to include the climate scenarios into the wflow model of the Hlotse river, the basin was split into two regions for the Foot Hills and Low Lands according to Figure 3-21.

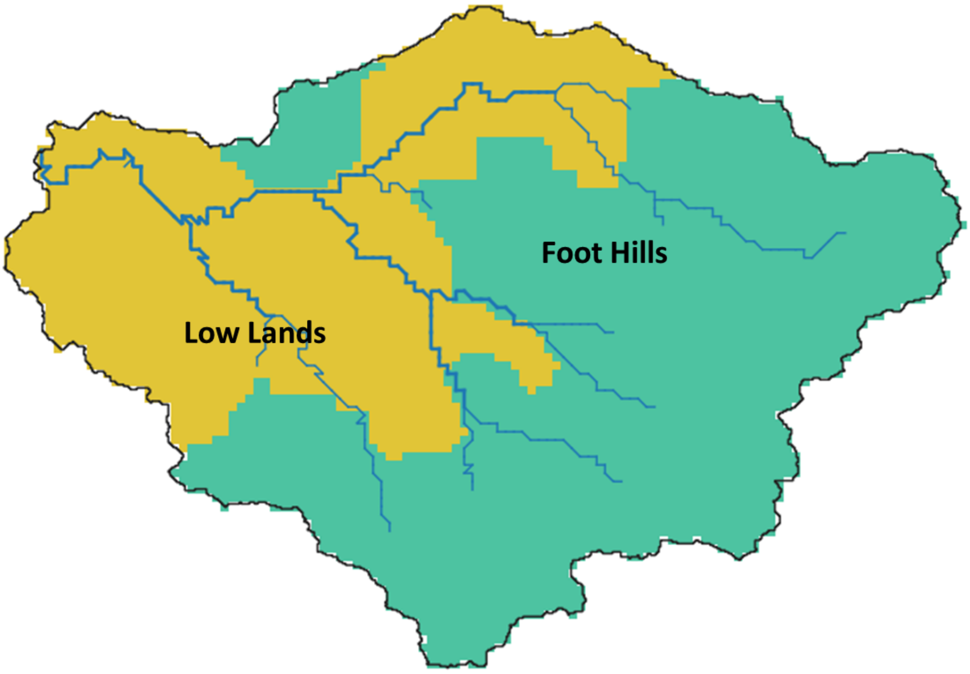


Figure 3-21: Foot Hills and Low Lands climate zones in the Hlotse basin.

For precipitation, the projections in absolute mm/season were converted into fractions (percent decrease or increase in precipitation compared to historic values) in order to avoid removing too much water during dry month. In order to derive these coefficients, the seasonal precipitation amounts on the two climate regions of the Hlotse were computed from the historic precipitation grids and averaged over the whole period (1981-2020). The decrease percentage was then computed by comparing the precipitation projections amounts to the historic seasonal precipitations. This leads to the fraction coefficients presented in Figure 3-22 for the average scenario and Figure 3-23 for the warm/dry (worst case) scenario.

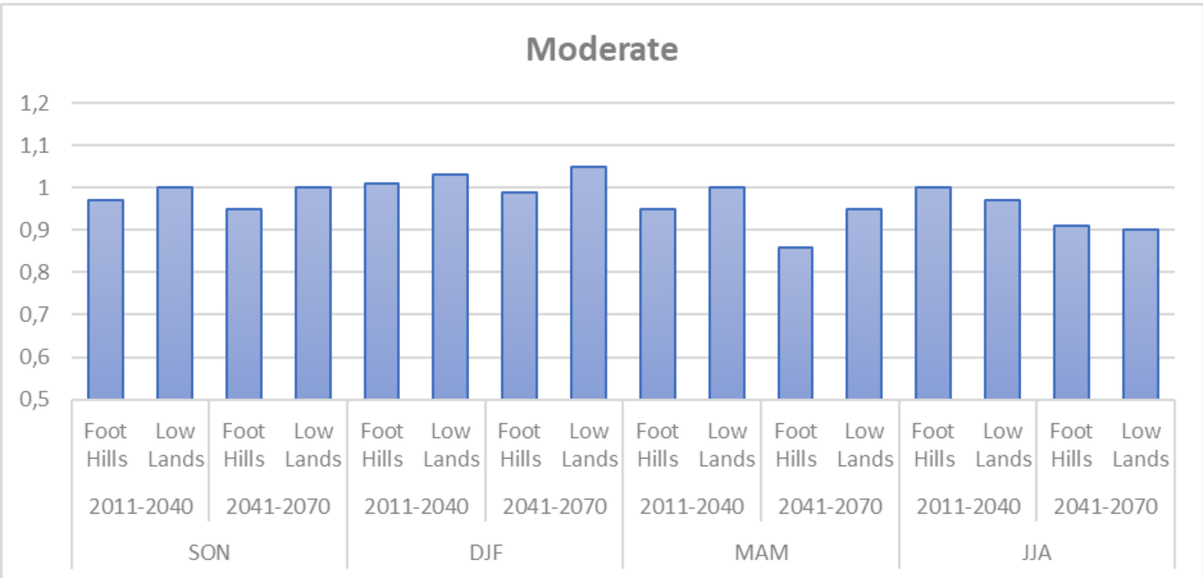


Figure 3-22: Projected change in precipitation (-) for the four seasons, for the Foot Hills and Low Lands and for the two future time periods (2011-2040 and 2041-2070) for the average scenario.

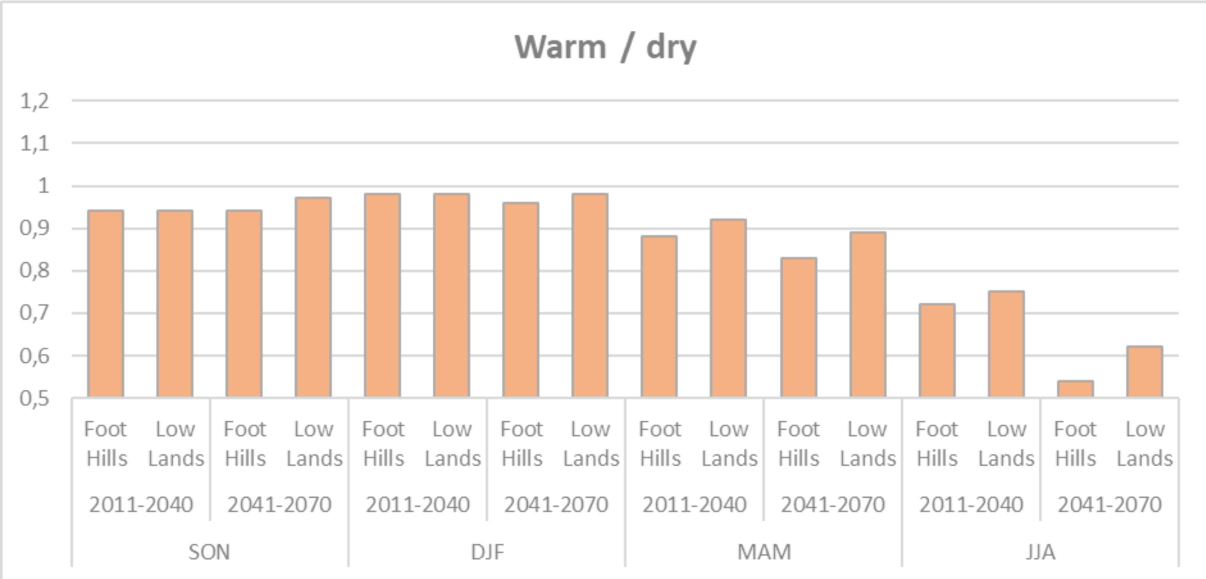


Figure 3-23: Projected change in precipitation (-) for the four seasons, for the Foot Hills and Low Lands and for the two future time periods (2011-2040 and 2041-2070) for the worst case scenario.

Finally, the forty years historic meteorological data was adjusted according to the coefficients from the Lesotho's Climate change scenarios report:

- Precipitation: CHIRPS and rain gauges combined precipitation grids were multiplied by the precipitation fraction coefficients depending on the season.
- Temperature: the temperature projections in degrees were added to the ERA5 grids depending on the season.
- Potential evapotranspiration: PET was recomputed using De Bruin equation in which the increased temperatures grids were used (radiation and pressure were not changed).

The different climate scenarios were run in combination with the baseline (actual) scenario as well as with the addition/abstraction scenario of the Adit of 1.5m^3/s. The resulting timeseries were then used in the hydraulic and EFlows models, so there are four climate change scenarios: 2035 (average and worst case), and 2050 (average and worst case).

4 Water Quality Assessment

4.1 Introduction

No previous assessment of water quality in the Hlotse River could be located during the project inception phase. The consultant therefore undertook to conduct a water quality assessment as part of this study. A water quality model was also developed for the river based on the HEC-RAS model that was set up for the hydraulics of the river. This chapter briefly describes the water quality monitoring programmes active in the study area as well as baseline monitoring programme that was designed and implemented as part of the project. There is also a description of spatial and temporal changes in the Hlotse River by analysing the historical and baseline water quality. The quality of water that will be transferred into the Hlotse River at the Adit is also reviewed based on physico-chemical data provided by LHDA. The fitness of the water in the river for aquatic ecosystems is also reviewed. Lastly, implementation of the water quality model of HEC-RAS is described.

4.2 Assessment of water quality monitoring programmes

4.2.1 Baseline Water Quality Monitoring Programme

A baseline water quality monitoring programme was designed for the project, "*Consulting Services for Environmental Flow Assessment (EFA) and Water Quality Modelling within the Lesotho Lowlands Water Development Project Phase II (LLWDP II)*" (Multiconsult, 2021). The objectives of the baseline water quality monitoring programme are to (1) establish what the current water quality status is of the Hlotse River up to the confluence with the Mohokare / Caledon River, prior to the start of any construction activities related to water abstraction works, and any further water transfers from Katse Dam via the Hlotse Adit; (2) to determine what the temporal and spatial water quality patterns are in the study area; and (3) to establish a baseline water quality data set against which future water quality impacts can be assessed.

The monitoring points that were identified for the baseline water quality monitoring programme are presented in Table 4-1 and Figure 4-1.

Note, in August 2021 the locations of three sampling points were updated during a site visit by the biomonitoring and hydraulics team. These were Eflows2, Eflows3 and Eflows4.

Table 4-1: Water quality monitoring points - arranged from upstream to downstream

Code	Latitude	Longitude	Description
0/TS1	-28.920321	28.433852	EFlows 0, Hlotse River upstream of the Hlotse Adit in the Tsehlanyane National Park, just upstream of EFlows 0 site, existing site for LLWP II sampling programme (TS1). Located at the road culvert.
EFlows 1	-28.928603	28.411950	EFlows 1, Hlotse River at EFlows 1 site
Eflows 2	*-28.850111*	*28.260444*	*New location for Eflows 2 site – not used for water quality sampling, 2/CQ14 retained to remain compatible with the DWA sampling network.*
2/CQ14	-28.848094	28.246977	EFlows 2, Hlotse River near EFlows 2 site, existing DWA monitoring point – CQ14 - Hlotse@Ha Khabo. Located at the B27 road bridge over Hlotse River.
EFlows 3	*-28.893012*	*28.183066*	*EFlows 3, Hlotse River at EFlows 3 site. Sampling point relocated to Eflows 3_1 (August 2021)*

Code	Latitude	Longitude	Description
Eflows 3_1	-28.897806	28.182556	New location of Eflows 3 site, about 600m downstream of original site. Water quality sampling relocated to this site (August 2021).
3-4/CQ15	-28.911358	28.109572	Hlotse abstraction point at existing DWA sampling site – CQ15 - Hlotse@Ha Setene. Not associated with a specific Eflows site, Between Eflows3 and Eflows4. Located some 450m downstream of the A25 road bridge over Hlotse River.
Eflows 4_1	-28.907833	28.096889	New location for Eflows 4 site, about 2km upstream of original site. Water quality sampling was relocated to this site (form August 2021).
EFlows 4	*-28.894880*	*28.085910*	*EFlows 4, Hlotse River at EFlows 4 site. Sampling point was relocated to Eflows 4_1 (up to August 2021) due to sand mining operations at this site.*
5/CQ21	-28.891490	28.034000	EFlows 5, Hlotse River at EFlows 5 site, existing DWA monitoring point – CQ21 - Hlotse@Ha Leshoele. Located about 400m downstream of the A1 road bridge over Hlotse River.

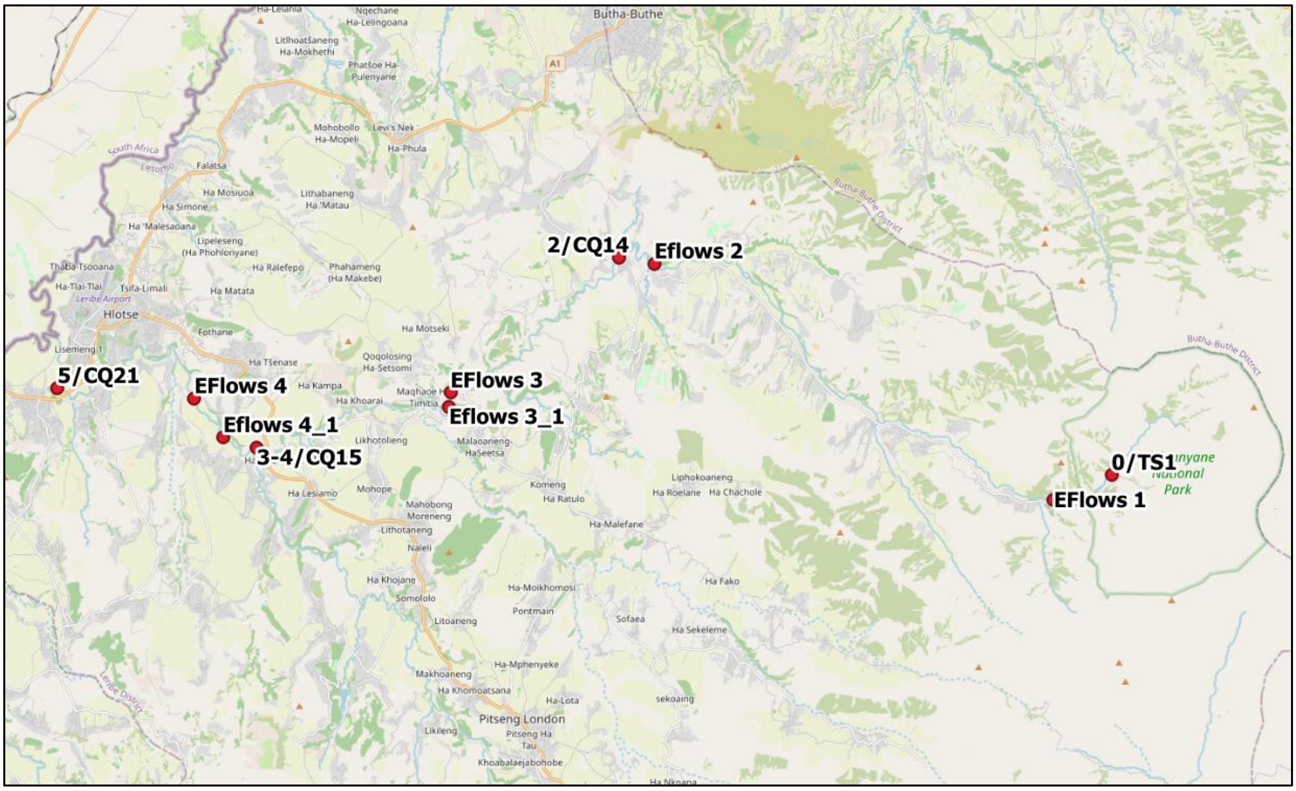


Figure 4-1: Location of the water quality sampling points for the Baseline Water Quality Monitoring Programme. In August 2021, sampling sites Eflows 4 was relocated to Eflows 4_1 and Eflows 3 was relocated to Eflows 3_1

At each sampling point, in-river measurements were made, and visual observations were recorded about the state of the river at the time of sampling. In-river measurements included water temperature, electrical conductivity, total dissolved solids, dissolved oxygen concentration, dissolved oxygen saturation, oxygen reduction potential, pH and turbidity. A measurement of water clarity was also made using a turbidity tube.

Water samples were collected for chemical and microbiological analyses. Chemical analyses were undertaken at BEMLAB, the accredited water testing laboratory of the Pathcare Group. The water quality samples were tested for pH, Electrical Conductivity, Total Dissolved Salts, Turbidity, Total Suspended Sediment, Chemical Oxygen Demand, Total Hardness ($CaCO_3$), Alkalinity, Calcium, Magnesium, Chloride, Nitrate as Nitrogen (NO_3-N), Ammonia, Sulphate, Phosphate as phosphorus, Iron, Manganese, Fluoride, Aluminium, Copper, and Zinc[7].

Trace metals: Two sets of water samples will be collected for trace metal analysis. One set of samples will be collected at the end of the dry season (August 2021), and one during the wet season (December 2021. These samples were analysed for Phenols, Vanadium, Nickel, Cobalt, Cyanide, Cadmium, Mercury, Lead and Selenium.

Tests for E. coli and Total coliforms were conducted at WASCO in Maseru.

4.2.2 Department of Water Affairs

The Lesotho Department of Water Affairs monitored water quality at three locations in the Hlotse River at about a monthly frequency (Table 4-2, Figure 4-2). The sampling programme ran from 1999 to 2014.

Water samples are routinely analysed for the following constituents: Electrical conductivity (µS/cm), pH, TDS (mg/l), Water temperature (°C), Dissolved oxygen (mg/l), Oxygen Saturation (%),Redox Potential (mV), Alkalinity as $CaCO_3$ (mg/l), Calcium (mg/l), Total Hard as $CaCO_3$ (mg/l), NH4 as N (mg/l), Free Chlorine (mg/l), Total Chloride (mg/l), SiO_4 (mg/l), Sulphate (mg/l), Iron (mg/l), Total Fe (mg/l), Manganese (mg/l), Ortho-phosphate (mg/l), NO_3 as N (mg/l), NO_2 as N (mg/l), Kjeldahl nitrogen (mg/l), Suspended solids (mg/l), Turbidity (NTU), Fluoride (mg/l), and Aluminium (mg/l).

Table 4-2: DWA sampling points on the Hlotse River

Name	Description	# of samples	First date	Last date
CQ14	Hlotse @ Ha Khabo CQ14	76	31 May 1999	6 May 2014
CQ15	Hlotse @ Setene CG25	79	31 May 1999	6 June 2014
CQ21	Hlotse @ Ha Leshoele CQ21	78	31 May 1999	9 April 2013

[7] *Chloride, Ammonia, Copper, Manganese, Zinc and Fluoride consistently tested below the lower detection limit of the water testing laboratory. It was decided to reduce the testing for these constituents to every 3rd month from May 2021 onwards.*

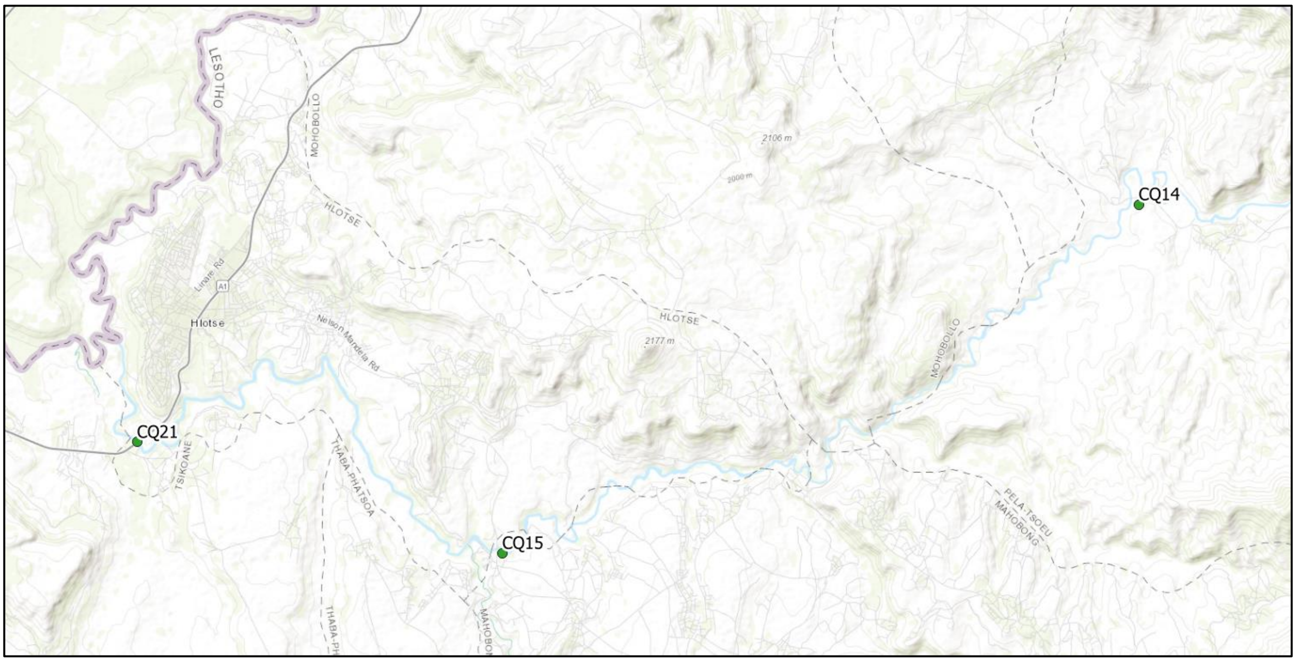


Figure 4-2: Location of the DWA sampling points on the Hlotse River

4.2.3 Lesotho Lowlands Water Development Project

The Lesotho Department of Water Affairs are monitoring water quality in the Hloste River on behalf of the Lesotho Lowlands Water Development Project (LLWDP). Sampling is conducted at a weekly frequency (Table 4-3, Figure 4-3) and was still operational at the time this report was prepared.

Water samples are routinely analysed for the following constituents: Turbidity (NTU), Temperature (°C), pH (in-situ), pH at 25°C (laboratory), EC (µS/cm) (in situ), EC (µS/cm) (laboratory), TDS (mg/l) (in situ), TDS (mg/l) (laboratory), F (mg/l), Cl (mg/l), NO_2-(mg/l), NO_3-(mg/l), PO_4 (mg/l), SO_4 (mg/L), Calcium Hardness (mg/l), Magnesium hardness (mg/l), Total hardness (mg/l), Total Alkalinity (mg/l), Al (mg/l), Fe (mg/l), Mn (mg/l) and TSS (mg/l).

Table 4-3: Sampling points on the Hlotse River for the LLWDP II study

Name	Description	# of samples	First date	Last date[8]
TS1	Hlotse River @ Above Adit TS1	45	11 Feb 2020	30 Mar 2021
TS3	Hlotse River @ Below Adit (TS3)	47	11 Feb 2020	30 Mar 2021
Hlotse A	Hlotse@ Abstraction (Hlotse A)	44	11 Feb 2020	30 Mar 2021
HS2	Hlotse @ Downstream (HS2)	44	11 Feb 2020	30 Mar 2021

[8] *The programme is ongoing.*

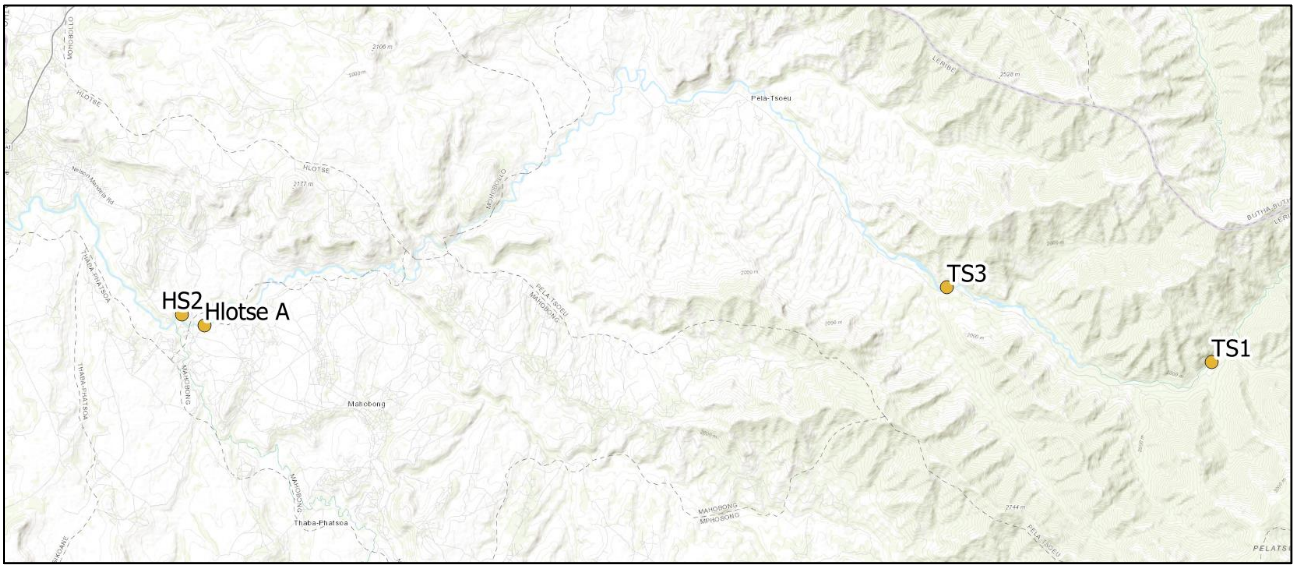


Figure 4-3: Water quality monitoring points on the Hlotse River for the LLWDP II

4.2.4 Lesotho Highlands Development Authority

The Lesotho Highland Development Authority monitors water quality in Katse Dam at the intake to the Transfer Tunnel (Table 4-4, Figure 4-4). This data was important to characterise the quality of water released into the transfer tunnel, and that could eventually be discharged into the upper Hlotse River via the Adit.

The sampling frequency was about monthly up to the end of 2009 after which the frequency changed to quarterly samples. Water quality samples were tested for Dissolved Oxygen, Water temperature, Conductivity, pH, Secchi disk depth, Al, As, B, Br, Ca, Cd, Cl, Co, COD, Cr, Cu, F, Fe, Hardness, K, M-AlK $CaCO_3$, Mg, Mn, Mo, Na, NH_4, Ni, NO_2, NO_3, TP, P, P ALK, Pb, PO_4, S, Si, SO_4, SS, TDS, TKN, TOC, TP, Total Sil, Turbidity, V, and Zn. In-situ physical water quality profiles were also measured from the surface to the bottom and the following measurements were made: Water temperature, Dissolved oxygen, pH, Conductivity, and Total Dissolved Salts.

Table 4-4: LHDA sampling points relevant to this study

Name	Description	# of samples	First date	Last date
Kdamt tower top	Surface water sample at the Katse Dam transfer tunnel intake	186	23 May 1996	8 July 2021
Kdamt tower bot	Bottom water sample at the Katse Dam transfer tunnel intake	179	23 May 1996	8 July 2021

Figure 4-4: LHDA water quality monitoring points in Katse Dam near the transfer tunnel intake

4.2.5 Department of Water and Sanitation (South Africa)

The South African Department of Water and Sanitation (DWS) operates the National Chemical Monitoring Programme (NCMP) throughout South Africa and the chemical analysis data are stored on the Department's Water Management System (WMS) database. The NCMP has two registered water quality sampling points on the Caledon/Mohokare River near the Hlotse River confluence, and at the transfer tunnel outlet (Table 4-5, Figure 4-5) where samples were collected on a regular basis. Table 4-5 shows the sampling point numbers, descriptions of the sampling points, the number of samples collected, the date the first sample was collected, the date of the last sample in the WMS database, and sampling point coordinates. Due to operational problems routine sampling stopped in 2018.

Water samples are routinely analysed for the following constituents: Calcium, Chloride, Dissolved Mineral Salts, Electrical Conductivity, Fluoride, Potassium, Total Kjeldahl Nitrogen, Magnesium, Ammonia, Nitrate and Nitrite nitrogen, Total Phosphate, pH, Orthophosphate, Silica, Sulphate and Total Alkalinity.

Table 4-5: DWS sampling points near the Hlotse River relevant to this study

Name	Description	# of samples	First date	Last date
D2H012Q01	Caledonspoort 190 the Poplars 199 at the Poplars on Little Caledon River (ncwq NCMP)	822	1971-09-24	2018-10-23
D2H035Q01	Caledon River at Ficksburg/ Ficksburg Bridge (ncwq NCMP)	581	1994-08-09	2018-10-23
C8H036Q01	Ash River Tunnel Outlet from Katse at Botterkloof / (NCWQ)	1005	1997-11-12	2018-05-17

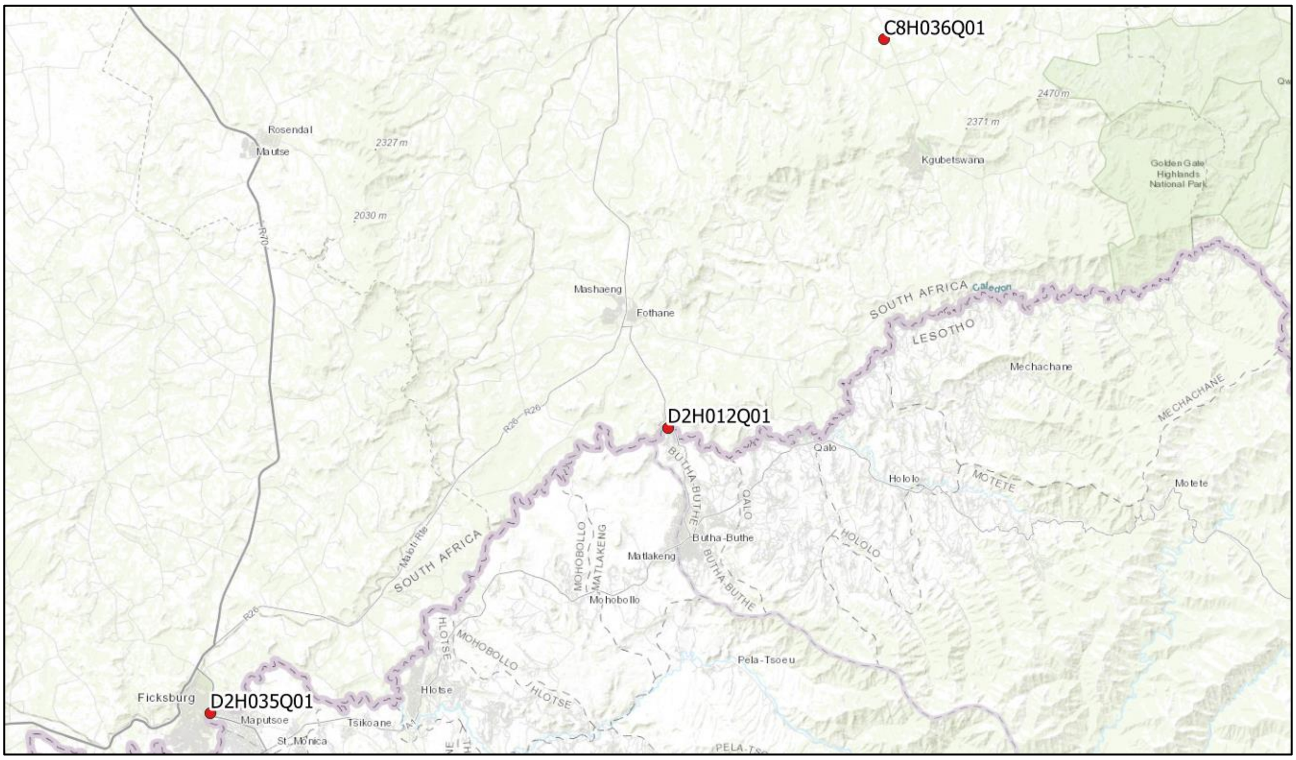


Figure 4-5: South African Department of Water and Sanitation sampling points on the Caledon/Mohokare River and the Katse Tunnel outfall (C8H036Q01)

4.3 Water Quality Constituents of Concern

During the Inception Phase a preliminary list of water quality constituents of concern was developed, recognising that the list could change as the project progressed. Indicators of water quality that would change with changes in the flow regime, include:

- Electrical conductivity or Total Dissolved Solids as indicator of the salinity status of the Hlotse River.
- Dissolved nitrogen (NO_3-N, NO_2-N) and dissolved phosphorus (PO_4-P) as indictors of the nutrient and trophic status of the Hlotse River.
- Water temperature as indicator of the thermal characteristics of the Hlotse River.
- Dissolved oxygen as indictor of the dissolved oxygen status of the Hlotse River.
- Turbidity as indicator of the water clarity and suspended sediment characteristics and underwater light climate of the Hlotse River.

The final list of indicators that was included in the DRIFT model was determined in consultation with the biomonitoring and Drift modelling team.

4.4 Spatial water quality changes

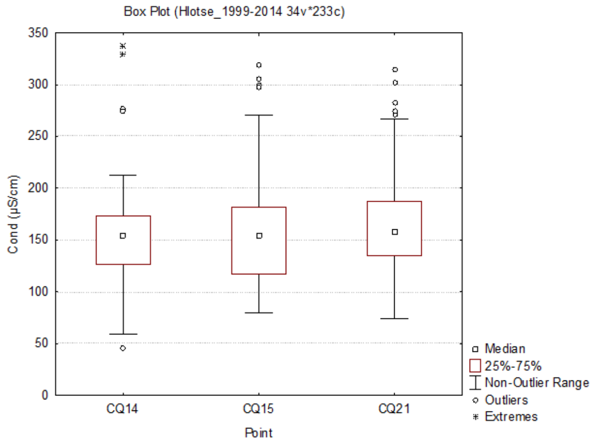
Spatial changes along the length of the Hlotse River were reviewed using historical data collected by the Department of Water Affairs from 1999 to 2014, the data collected for the Lesotho Lowlands Water project from 2019 to 2021, and the baseline data collected in this project.

Box-and-whisker plots were used to compare the water quality collected at the different sampling points. A box-and-whisker plot is a method of presenting the statistical characteristics of a data set. A data set consisting of, for example, all the electrical conductivity measurements recorded at a monitoring point is analysed for its statistical properties. The minimum, maximum and the 25th, 50th and 75th percentile values are determined. The 25th percentile, for example, means that 25 percent of the observations were below that value. In the box- and-whisker plot, the lower and upper sides of the box represent the 25th and 75th percentile values, indicating that 50% of all the observations fall within that range (the box). The 50th percentile, also called the median, indicates average conditions and falls somewhere within the box. The whiskers extend from the box to the minimum and the maximum value, or the non-outlier range. The size of the box, the inter-quartile range (25 – 75th percentiles), gives an indication of the variability in the data: a small box implies a small variation in the data; a large box implies a large variation in the data. The position of the median within the box is an indication of the skewness of the data.

4.4.1 Department of Water Affairs data (1999 to 2014)

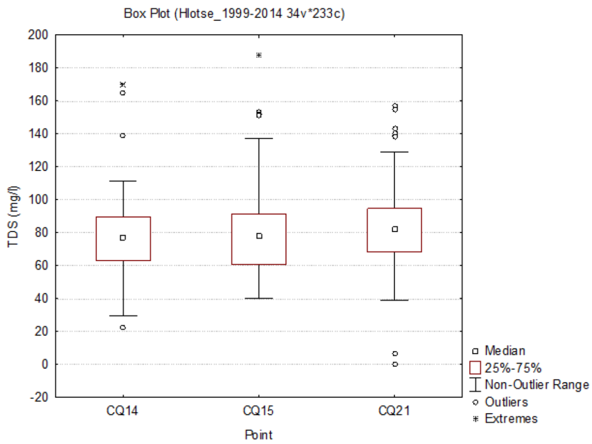
Electrical conductivity

Over the data period, there was almost no difference in the median Electrical Conductivity between sampling points CQ14, CQ15 and CQ21 although higher concentrations were recorded on occasions at CQ14 and CQ15.



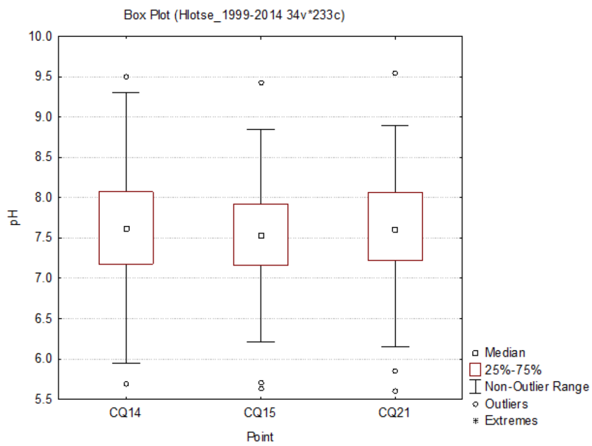
Total dissolved solids

Similar to Electrical Conductivity, there was almost no difference in the median TDS concentrations between sampling points CQ14, CQ15 and CQ21 although slightly higher concentrations were recorded on occasions at CQ14 and CQ15.



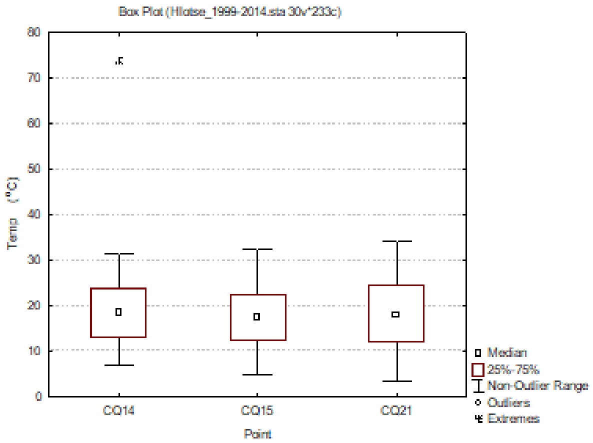
pH

The pH values at CQ14, CQ15 and CQ21 were very similar over the 1999-2014 data period. Fifty percent of all the observations were between 7.2 and 8.0 at all three sampling points.



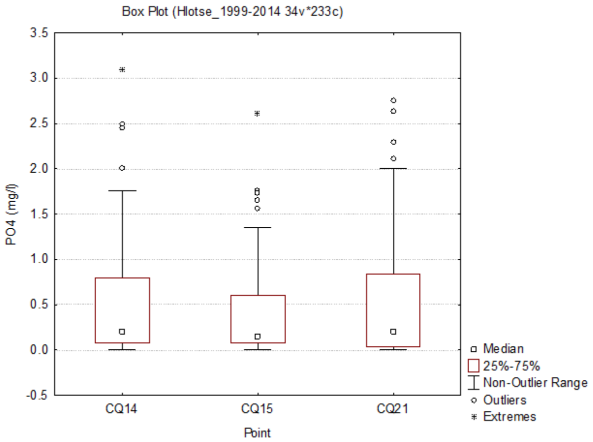
Water temperature

Overall, there appears to be little difference in water temperature between the three monitoring points although it appears that the variability increases slightly in a downstream direction. There are, however, strong seasonality in the temperature data (refer Section 4.5).



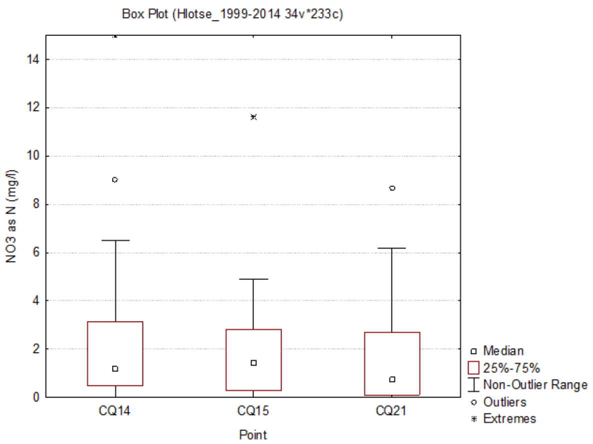
Orthophosphate

Overall, the median orthophosphate concentrations were low although concentrations as high as 0.7 mg/l were recorded for about 75% of the time. This is regarded as high for river systems.



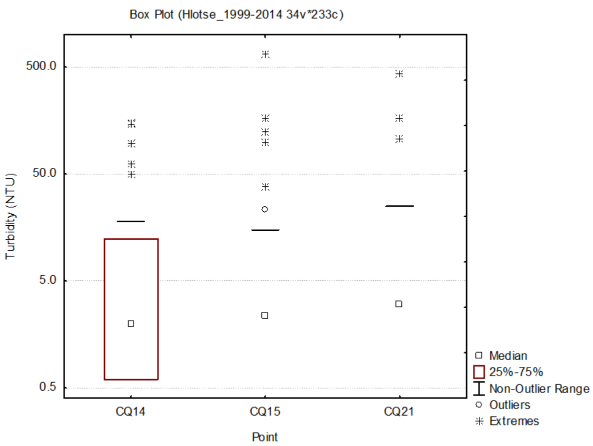
Nitrate nitrogen

The median Nitrate concentrations were about 1mg/l with median nitrate concentrations at CQ21 being lower than at CQ15. It was expected that the discharge of wastewater from the Hlotse WWTW would have resulted in elevated nitrate concentrations at CQ21 but this does not appear to be the case in Hlotse.



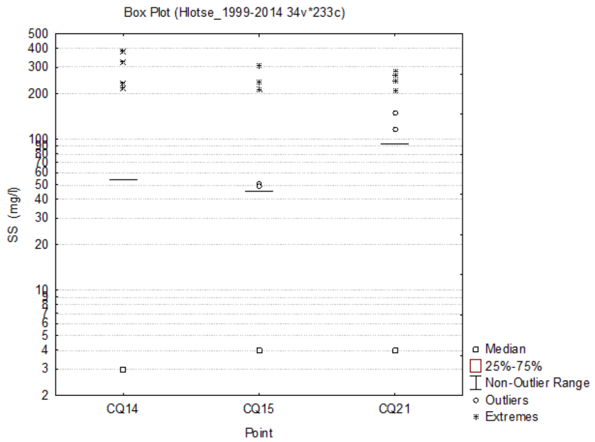
Turbidity

There appears to be an increase in the median turbidity in a downstream direction (please note the logarithmic Y-axis scale.



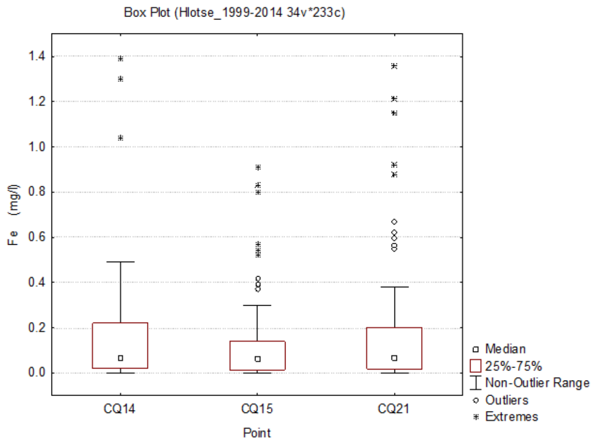
Suspended solids

The median suspended sediment concentrations increase between CQ14 and CQ15 but then appears to stabilise.



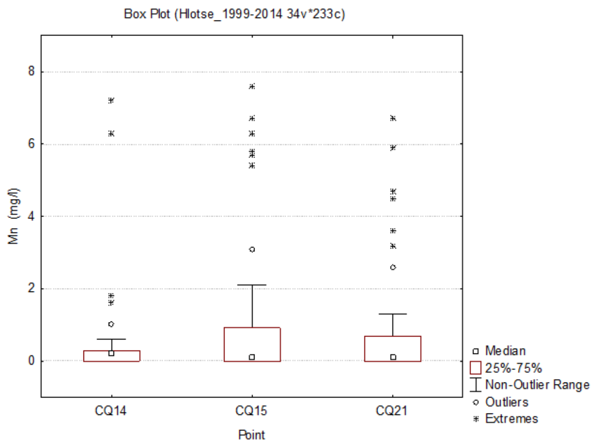
Iron

The median Iron concentrations is quite similar at all three sampling points.



Manganese

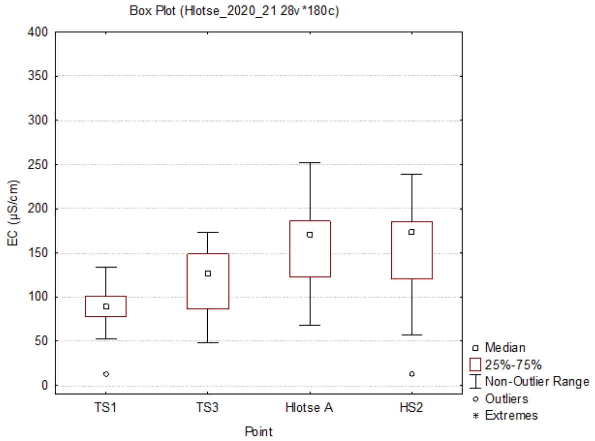
Manganese concentrations increased in a downstream direction even though the median concentrations appears to be quite similar at all three sampling points.



4.4.2 Lesotho Lowlands Water Development Project (1999 to 2021)

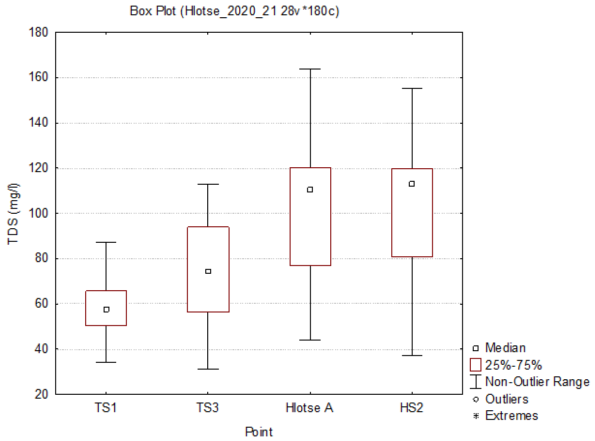
Electrical Conductivity

Electrical conductivity, as indicator of salinity, increase in a downstream direction. It is low in the upper reaches of the Hlotse (TS1). There appears to be little difference in salinity between Hlotse A and HS2, sampling points upstream and downstream of CQ15, the DWS sampling point at the flow gauging site at Setene.



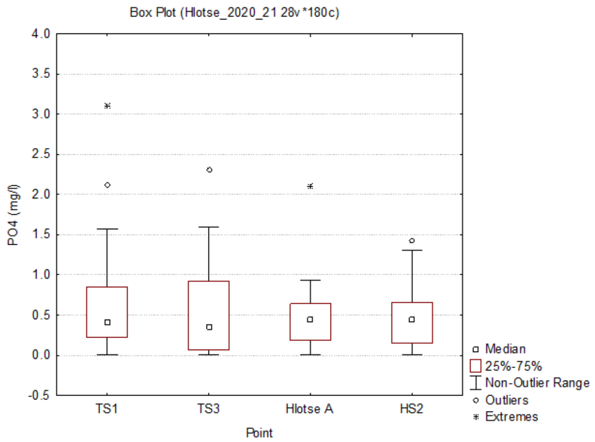
Total dissolved solids

Total dissolved solids exhibit the same spatial pattern as Electrical Conductivity.



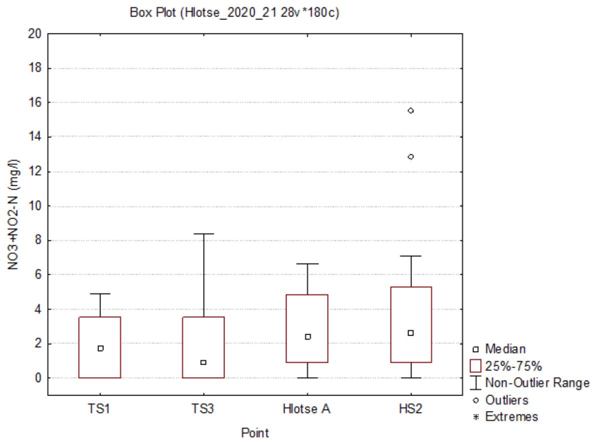
Orthophosphate

Orthophosphate concentrations appears to be elevated with no strong spatial change in a downstream direction. It was expected that concentrations would have been lower at TS1 that is situated just downstream of the Tsehlanyane National Park.



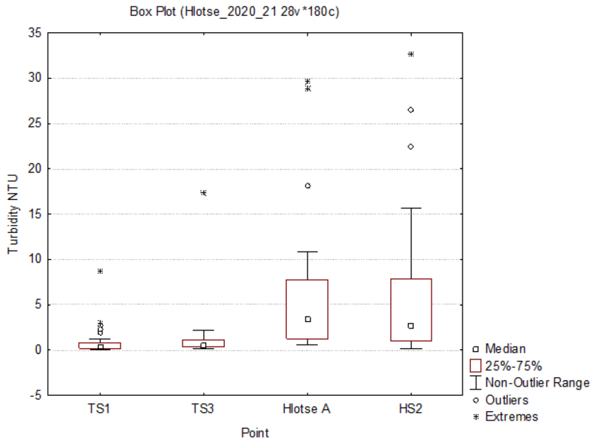
Nitrate plus nitrite nitrogen

NO_3+NO_2-N concentrations appears to increase slightly in a downstream direction.



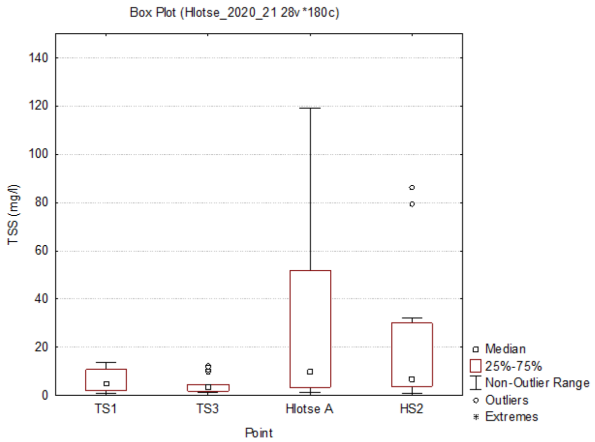
Turbidity

Turbidity measurements were low in the upper reaches of the Hlotse River (TS1 and TS3) and higher at Setene (Hlotse A) and downstream of Setene (HS2). The Malaoaneng River and Maoamafubelu River joins the Hlotse River upstream of these two sampling points.



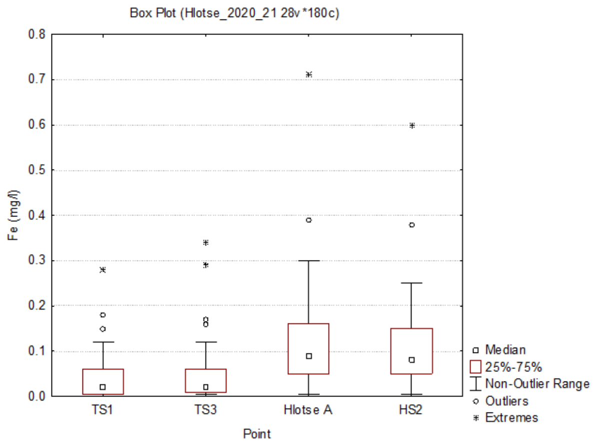
Total Suspended Solids

Total suspended sediment concentrations appear to be higher at TS1 than at TS3. This is unexpected as the land use in the Tsehlanyane National Park is mostly natural veld. Elevated TSS concentrations were observed at the abstraction points (Hlotse A) and downstream of that that site at HS2.



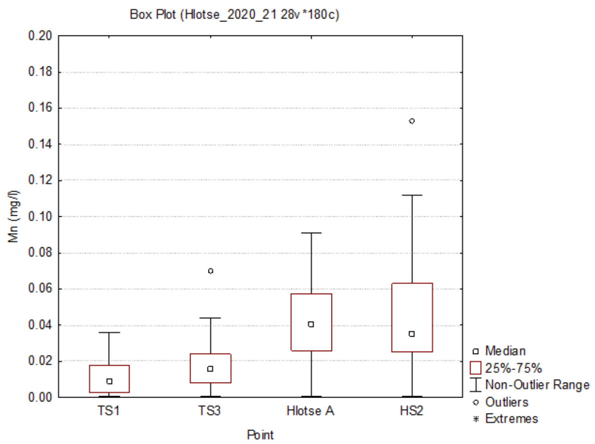
Iron

Iron concentrations were low in the upper reaches of the Hlotse River and increased up to Setene (Hlotse A and HS2).



Manganese

Manganese concentrations were low in the upper reaches of the Hlotse River and increased up to Setene (Hlotse A and HS2).



4.4.3 Baseline monitoring (this project) 2021

Monthly water samples were collected in the Hlotse River with the most upstream sample being near the southern border of the Tsehlanyane National Park, and the last sampling point about 2.4km upstream of the confluence with the Mohokare/Caledon River (Figure 4-1). The major tributaries joining the Hlotse River between the different sampling points are also shown in Figure 4-6.

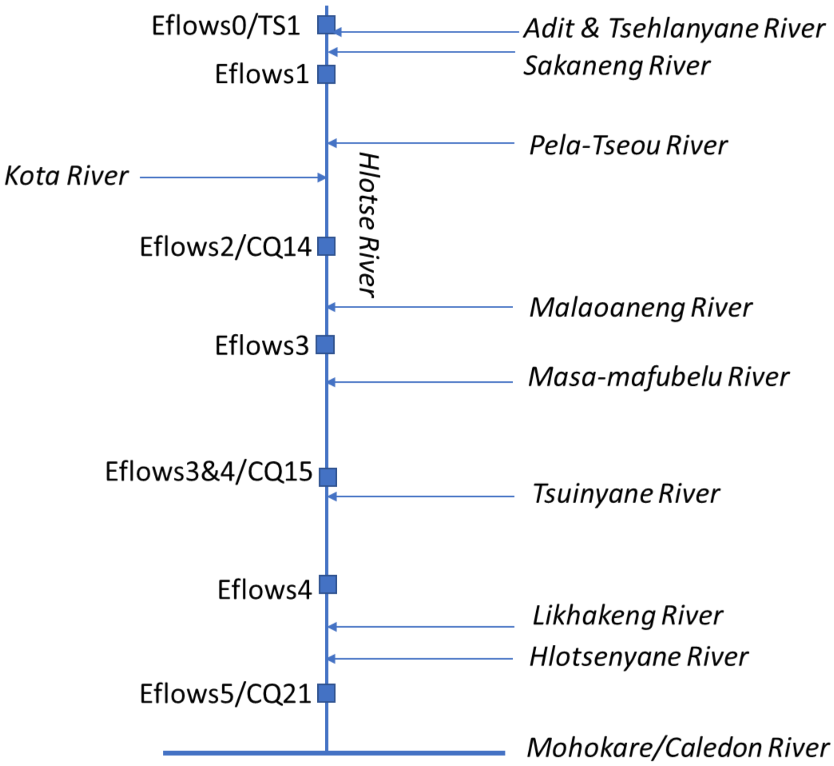
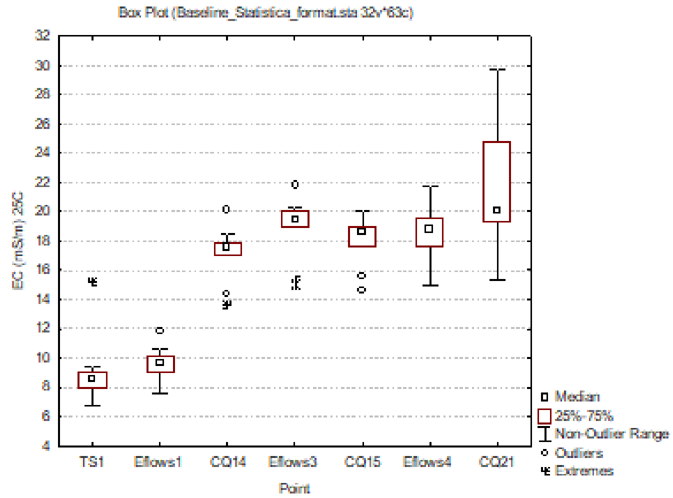


Figure 4-6: Schematic of the Hlotse River showing the location of sampling points and key tributaries

Water quality in the Hlotse River changes in a downstream direction.

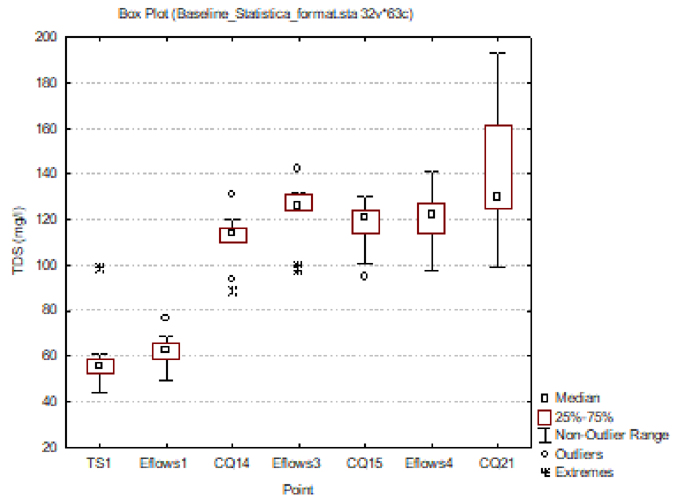
Electrical conductivity

Electrical conductivity at the two most upstream points, Eflows0/TS1 and Eflows1, were quite similar since they are about 3km apart. Between Eflows1 and Eflows2/CQ14, the median EC increases from below 10 mS/m to about 18 mS/m. This is the area in the Hlose valley where extensive agricultural developments start next to the river. Several villages are also located in close proximity to the river and its tributaries. Between CQ14 and Eflows3 the Malauaneng River joins the Hlotse River causing a small but significant increase in salinity. It appears that Morotong River between Eflows3 and CQ14 dilutes the river slightly. The impact of urban runoff from Hlotse is evident at CQ21, increasing the median salinity in the river as well as higher variance in the EC.



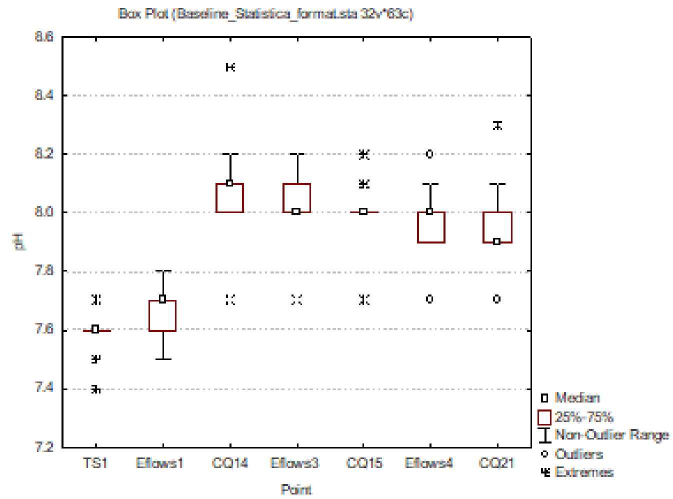
Total dissolved solids

The same pattern of spatial change that was observed in the Electrical Conductivity is evident in the Total Dissolved Solids concentrations.



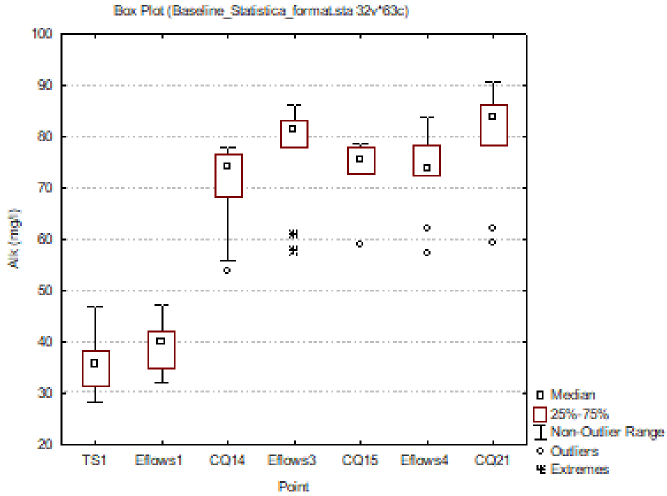
pH

The pH of the two most upstream sampling points, TS1 and Eflows1 is largely natural. Between Eflows1 and CQ14 there is a step increase in pH as the water becomes more alkaline. See also the change in Alkalinity.



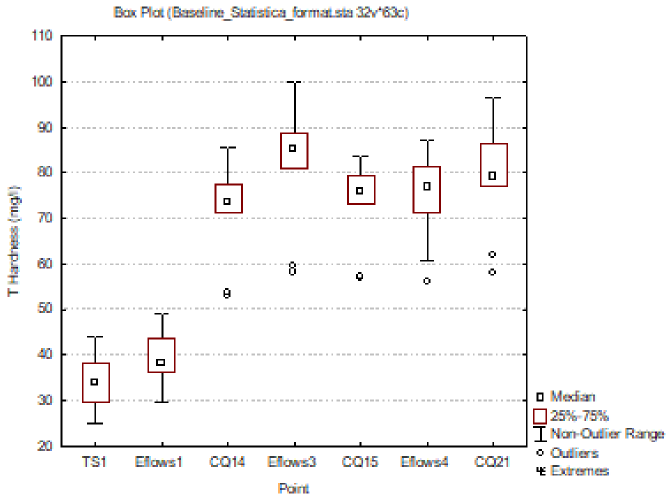
Total alkalinity

The spatial pattern observed in pH is repeated in Alkalinity with a step increase between Eflows1 and CQ14, another increase between CQ14 and Eflows3 (also observed in EC and TDS), some dilution from the Maoamafubelu River between Eflows3 and CQ15, and then a gradual increase up to CQ21 where the impacts of urban runoff might be evident.



Total hardness

Total Hardness follows the same spatial pattern as observed in Alkalinity.

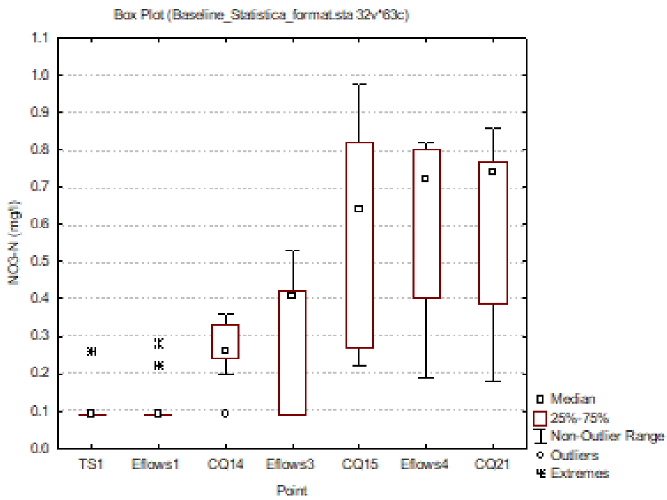


Orthophosphates

During the baseline monitoring, the ortho-phosphate concentrations were consistently below the laboratory detection limit of 0.04 mg/.

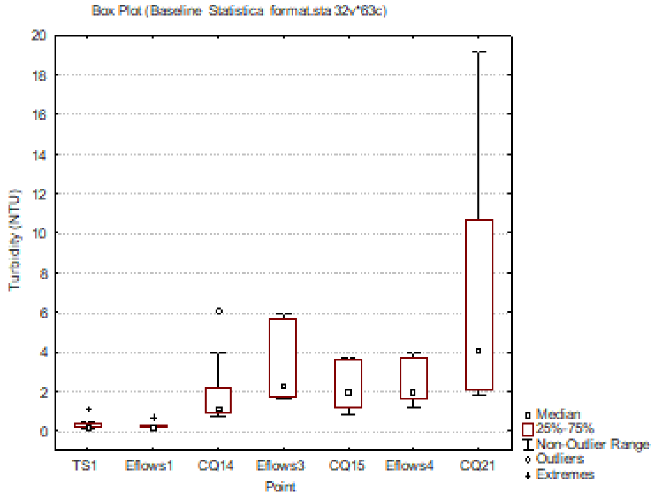
Nitrate nitrogen

Nitrate nitrogen concentrations increased in a downstream direction. It was consistently low in the upper reaches (TS1 and Eflows1). From Eflows2/CQ14 there was a consistent increase in nitrogen concentrations, probably from agricultural activities in the catchment. The highest median concentrations were recorded in the lower reaches of the Hlotse River.



Turbidity

Turbidity in the upper reaches of the Hlotse River is consistently low. There is a moderate increase between Eflows1 and CQ14, a further increase at Eflow3 that could be the result of flows in the Malaoaneng River, some dilution from the Maoamafubelu River between Eflows3 and CQ15, and then an increase at CQ21, probably the result of stormwater runoff from Hlotse town.



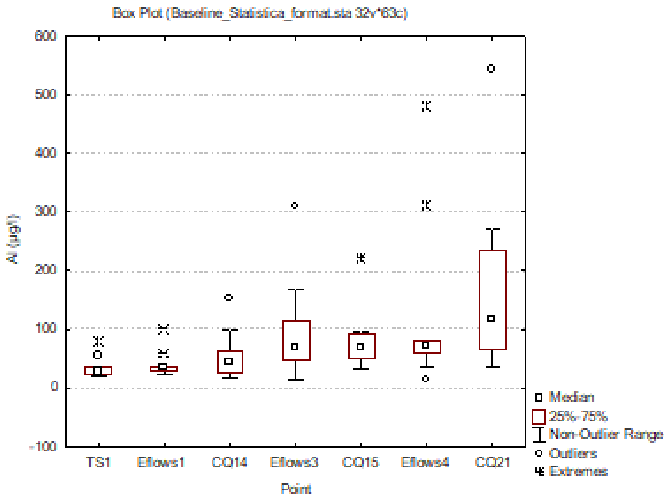
Suspended Sediments

Total suspended sediment concentrations were mostly below the laboratory detection limit of 5 mg/l.

Aluminium

Aluminium concentrations increase in a downstream direction. It is low in the upper reaches of the Hloste River and slowly increase in a pattern similar to turbidity. Aluminium concentrations are related to soil erosion as they make up part of the soil particles suspended in the water.

Iron and Manganese concentrations were mostly below the laboratory detection limits.



4.4.4 Water quality flow relationships

The relationship between flow and water quality was examined using historical water quality data collected at Eflows2/CQ14, CQ15 and Eflows5/CQ21, and baseline flow time series developed for the Hlotse River for this project. The relationships were examined for Electrical Conductivity (Cond µS/cm) as indicator of conservative substances, turbidity (NTU), and the nutrients orthophosphate (PO_4 mg/l) and nitrate nitrogen (NO_3-N mg/l).

Eflows2 / CQ14

Electrical conductivity exhibits an inverse relationship to flow, i.e. salt concentrations reduce as flow increases due to dilution (Figure 4-7). Turbidity appears to exhibit a direct relationship to flow with elevated turbidity at higher flows. However, this relationship is not very strong. Orthophosphate also exhibits a direct relationship to flow at this site because most phosphates are mobilised and washed off the catchment during rainfall-runoff events. Nitrate nitrogen on the other hand exhibits an indirect relationship with flow, probably due to seepage being diluted during elevated flows.

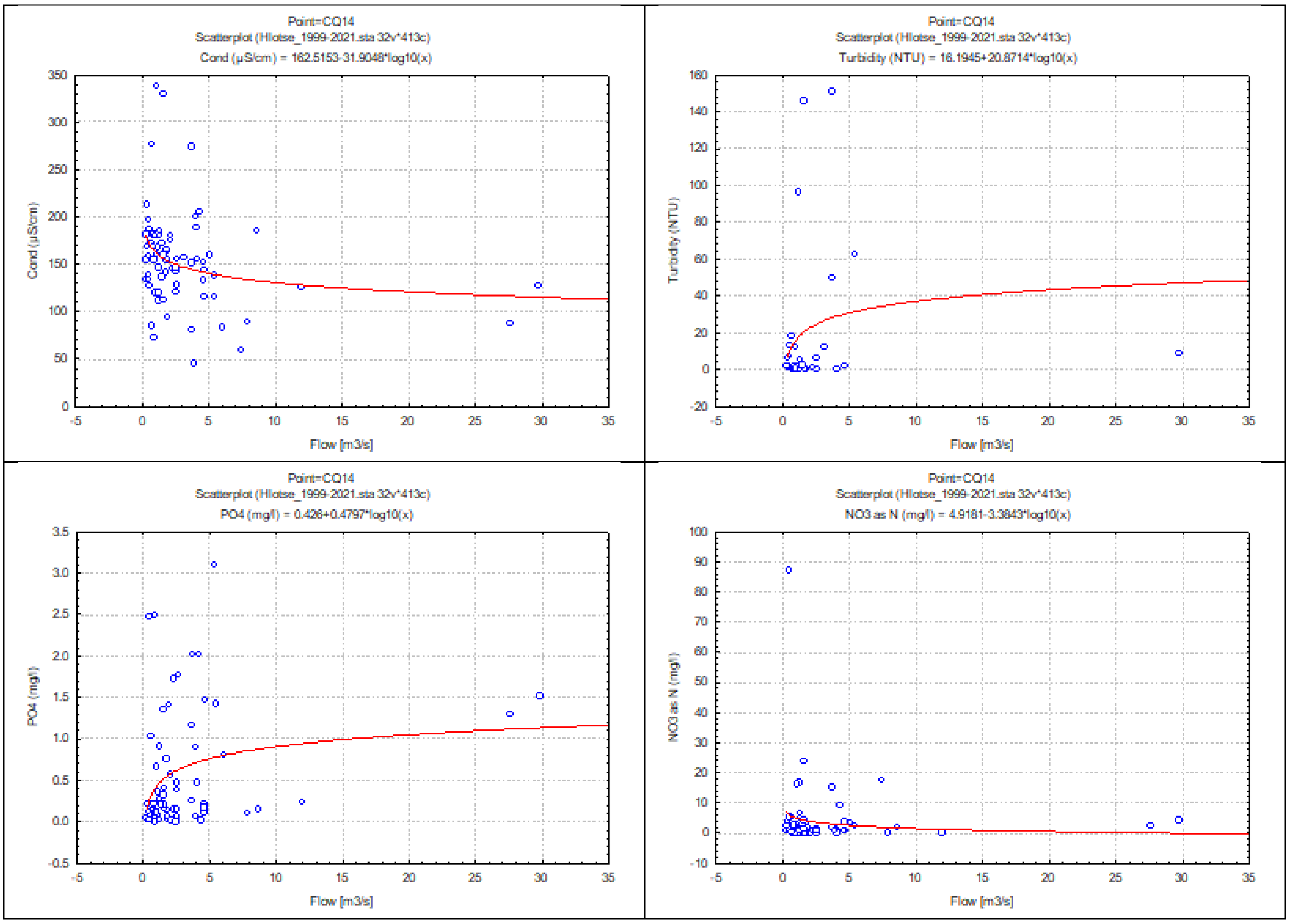


Figure 4-7: Concentration vs flow plots for Electrical Conductivity, Turbidity, Orthophosphate and Nitrate nitrogen concentrations observed at Eflows2/CQ14 from 1999 to 2020

CQ15

Electrical conductivity exhibits an inverse relationship to flow, i.e. salt concentrations reduce as flow increases due to dilution (Figure 4-8). Turbidity appears to exhibit a slight direct relationship to flow. Both Orthophosphate and Nitrate nitrogen exhibit indirect relationship to flow at this site.

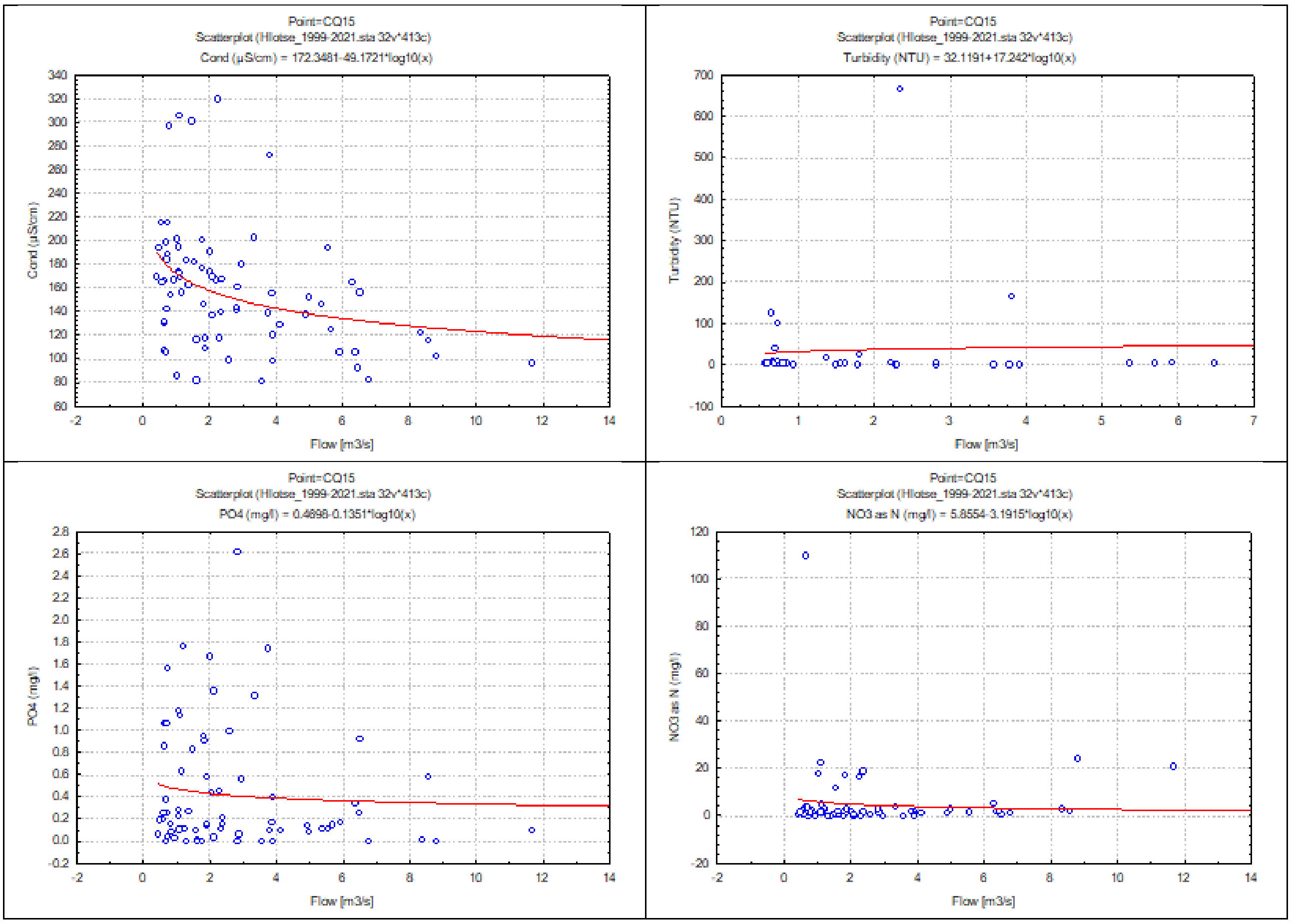


Figure 4-8: Concentration vs flow plots for Electrical Conductivity, Turbidity, Orthophosphate and Nitrate nitrogen concentrations observed at CQ15 from 1999 to 2020

Eflows5 / CQ21

Electrical conductivity exhibits a strong inverse relationship to flow, with lower salt concentrations being measured at high flows due to dilution (Figure 4-9). Turbidity appears to exhibit a weak indirect relationship to flow. Orthophosphate exhibits a direct relationship to flow at this site probably because phosphates are mobilised and washed off the catchment during rainfall-runoff events. Nitrate nitrogen on the other hand exhibits a weak indirect relationship with flow, probably due to seepage or urban runoff being diluted during elevated flows.

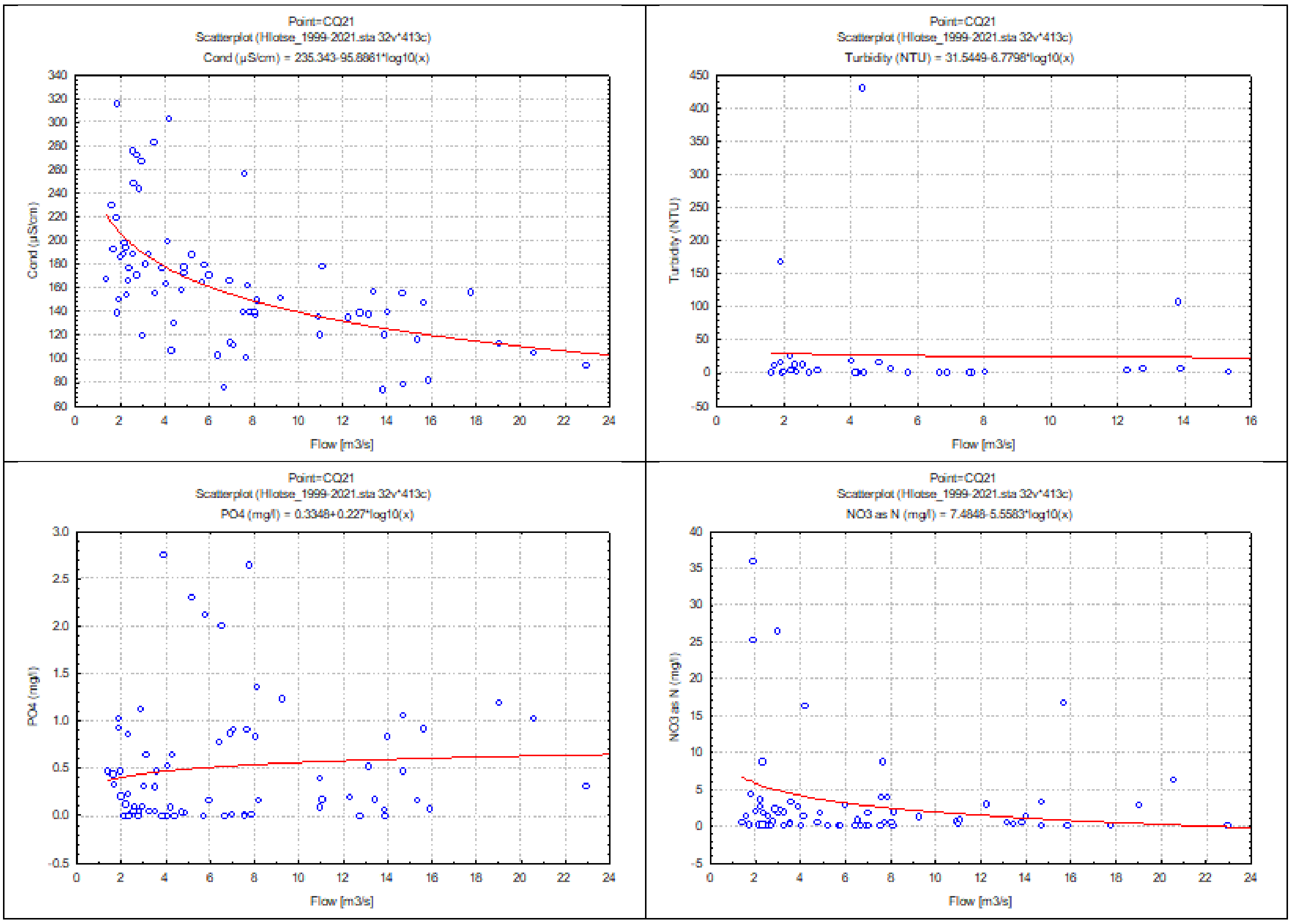


Figure 4-9: Concentration vs flow plots for Electrical Conductivity, Turbidity, Orthophosphate and Nitrate

4.5 Seasonal water quality changes

The seasonal change in water quality was examined for Electrical Conductivity, Turbidity, orthophosphate and nitrate nitrogen using the DWA data for 1999 – 2014.

Eflows2 / CQ14

There was a slight increase in Electrical conductivity during the winter months (May to July) at CQ14. Lower EC's and wider fluctuations were observed during the summer months, probably the result of dilution with elevated flows. There is no clear seasonal pattern in turbidity. Higher turbidity was measured in late summer, January to June, which does not seem to correlate with increased runoff in spring and early summer (August to December). Median orthophosphate concentrations exhibit a weak seasonal pattern with slightly elevated concentrations during the winter months. Elevated concentrations were observed in late summer and autumn (January to May). Nitrate concentrations appears to exhibit weak seasonality with increasing concentrations during the winter and spring months (May to September).

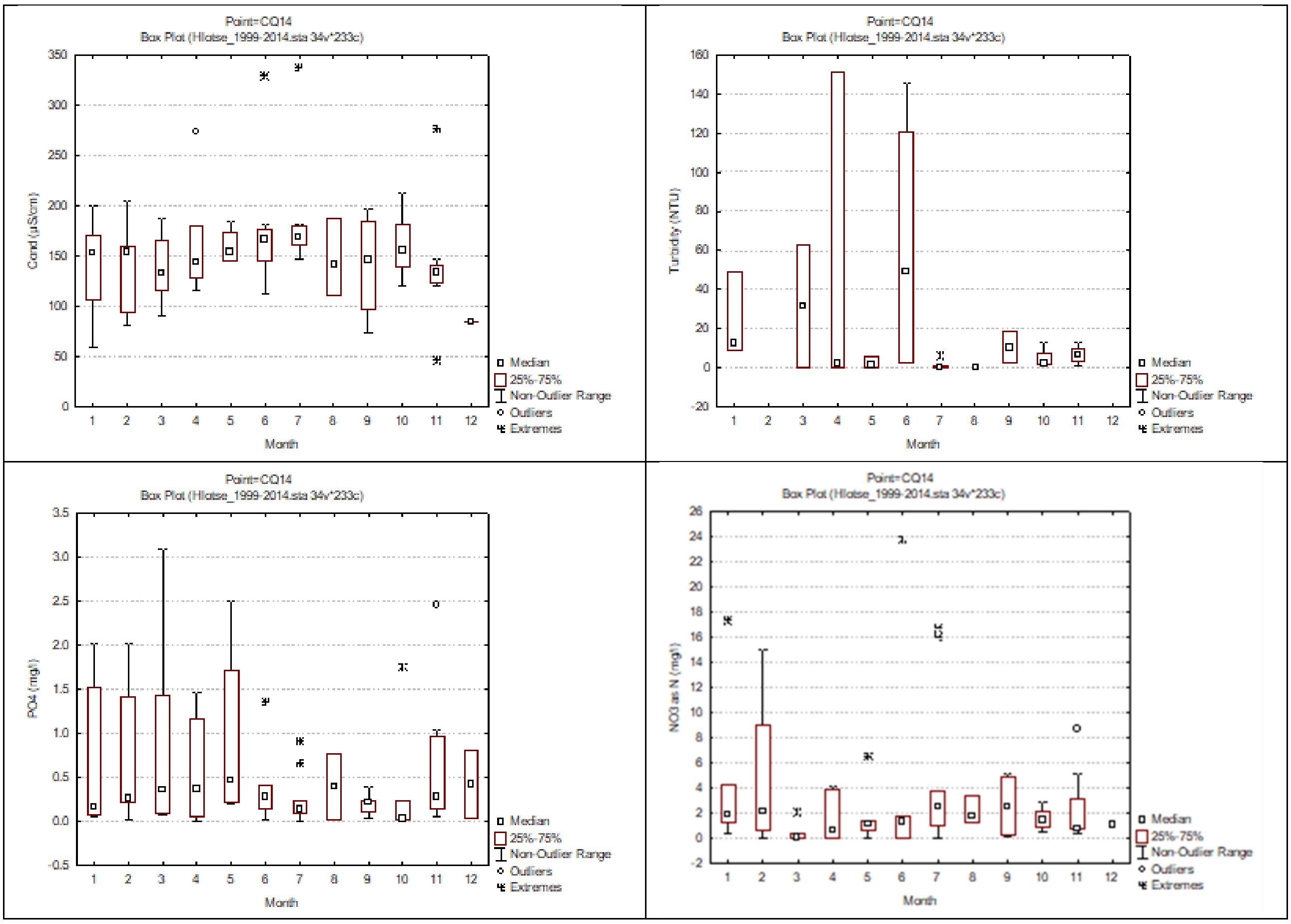


Figure 4-10: Box-and-whisker plots of monthly Electrical conductivity, Turbidity, Orthophosphate and Nitrate nitrogen concentrations at Eflows2/CQ14

CQ15

There is a strong seasonal pattern in Electrical conductivity. Median EC's increase during autumn and the winter months (March to August) and decrease during spring and early summer months. Elevated concentrations and wider fluctuations occurred in late summer (January and February). No seasonal pattern was observed in Turbidity other than high concentrations occurring in January. The median Orthophosphate concentrations appears to exhibit a weak seasonal pattern with slightly elevated concentrations occurring during the winter months. Concentrations fluctuated widely during the summer months. No clear seasonal pattern is evident in nitrate nitrogen concentrations.

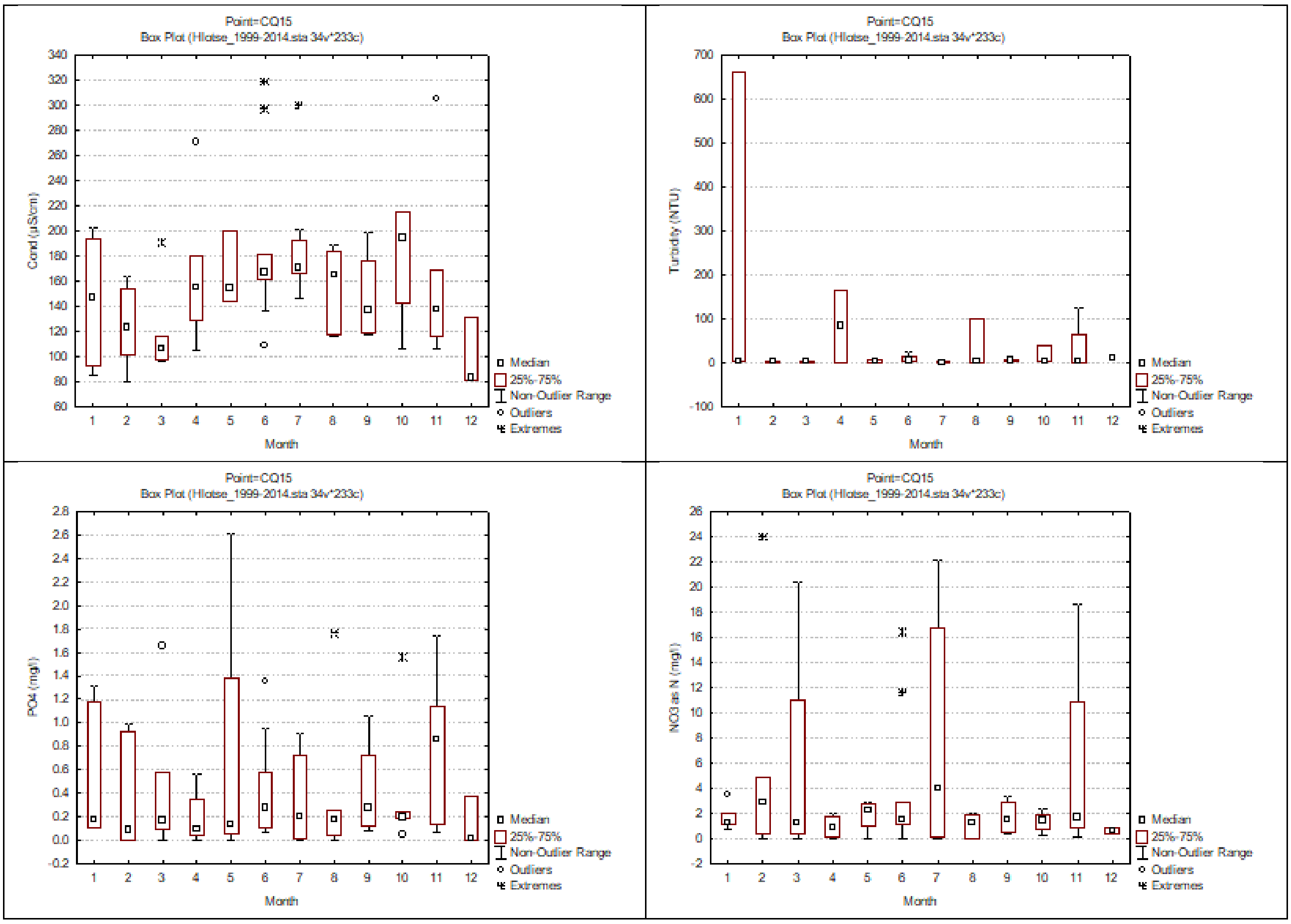


Figure 4-11: Box-and-whisker plots of monthly Electrical conductivity, Turbidity, Orthophosphate and Nitrate nitrogen concentrations at CQ15

Eflows5 / CQ21

There is a strong seasonal pattern evident in the medial Electrical conductivity measurements with concentrations increasing throughout the winter months (April to July/August) and decreasing with the unset of spring and summer. Similar to CQ14 and CQ15, elevated EC's occurred in late summer (January and February) and the reason for this is not clear. No clear seasonal pattern is evident for Turbidity other than elevated measurements during spring an early summer (September and October). No clear seasonal pattern is evident in orthophosphate concentrations at CQ21. This could be the result of urban runoff and treated wastewater discharges from the treatment ponds at Hlotse that are unrelated to rainfall-runoff events. There is no clear seasonal pattern in nitrate nitrogen concentrations other than elevated concentrations observed in December.

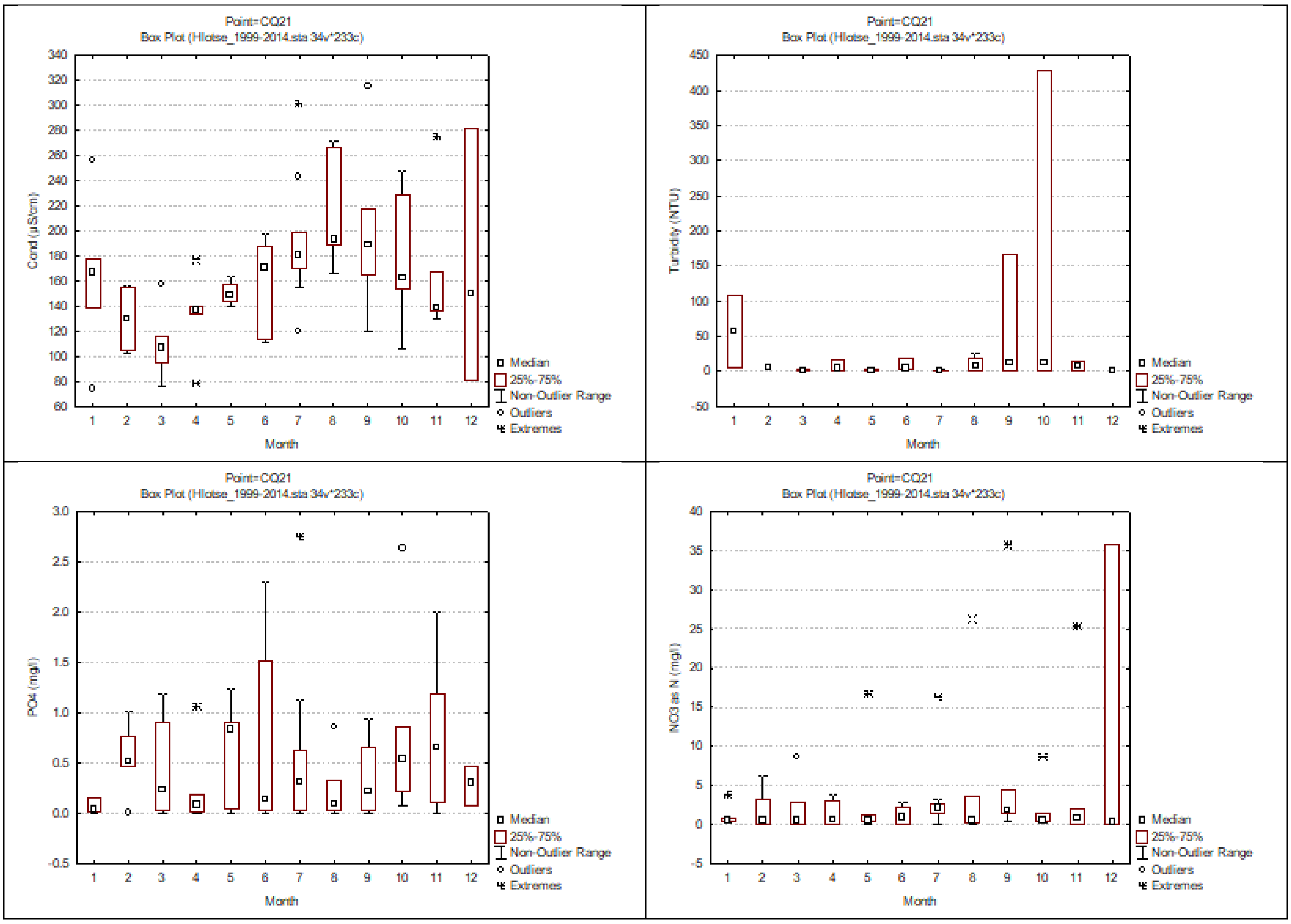
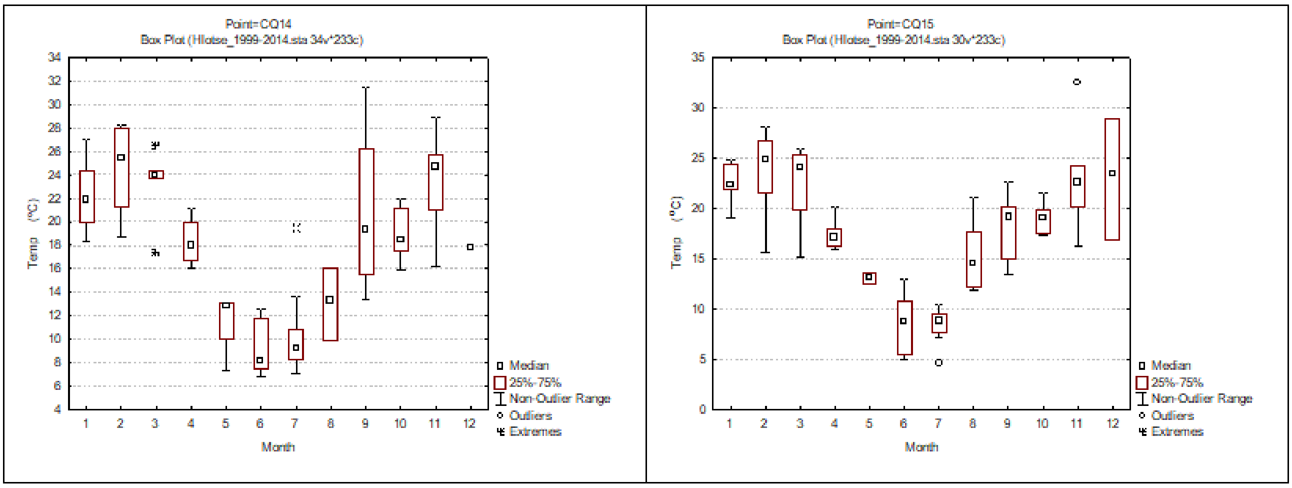


Figure 4-12: Box-and-whisker plots of monthly Electrical conductivity, Turbidity, Orthophosphate and Nitrate nitrogen concentrations at Eflows5/CQ21

Water temperature

As expected, water temperatures at the three sampling points show a strong seasonal trend with the highest median water temperatures recorded at the end of summer (February) and the lowest median water temperatures recorded in mid-winter (June).



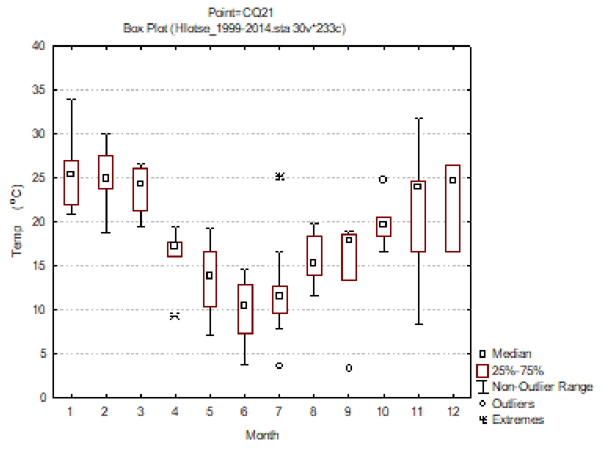


Figure 4-13 Box-and-whisker plots of monthly water temperatures at Eflows2/CQ14, CQ15, and Eflows5/CQ21

4.6 Transfer Tunnel Water Quality

It is envisaged that water will be transferred from Katse Dam into the upper reaches of the Hlotse River during the months of June, July, August, and September. Assessment of the water quality of the transfer water therefore focussed on the reviewing the historical water quality during those months.

The intake tower to the transfer tunnel is situated some 32 river kilometres upstream of the dam wall, and has three intake levels, with the bottom sills located at 2036 masl (top intake), 2019 masl (middle intake), and 2002 masl (lower intake) (Figure 4-14). The full supply level of Katse Dam is at 2053 masl.

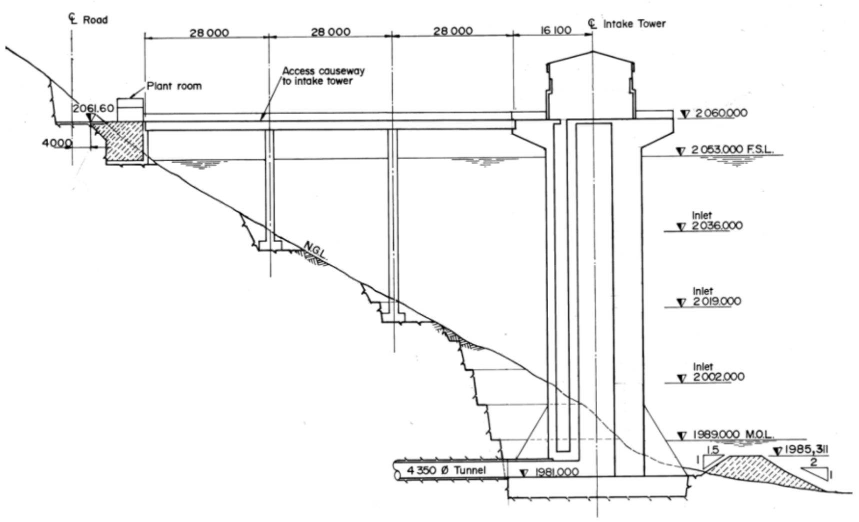


Figure 4-14: Drawing and photograph of the transfer tunnel intake tower in Katse Dam showing the heights of the three tunnel intakes.

Physical water quality

Katse Dam exhibits strong thermal stratification during the summer months (Roos, 2004) but the water column is isothermal during the winter months (June to September). During the summer months the water column separates into a warm surface layer (called the epilimnion), a cold bottom layer (called the hypolimnion), and the thermocline separates the two layers. However, during autumn the first cold spells cool down the surface layer, increasing its density which causes the colder water to sink, eventually resulting in a water column where there is little difference in water temperature between the surface and bottom of the reservoir. i.e. isothermal. This is called autumn turnover and is evident in Katse Dam (Figure 4-15). In terms of water released through the different intakes, there would be little difference in temperature and water quality between the intake elevations during the winter months.

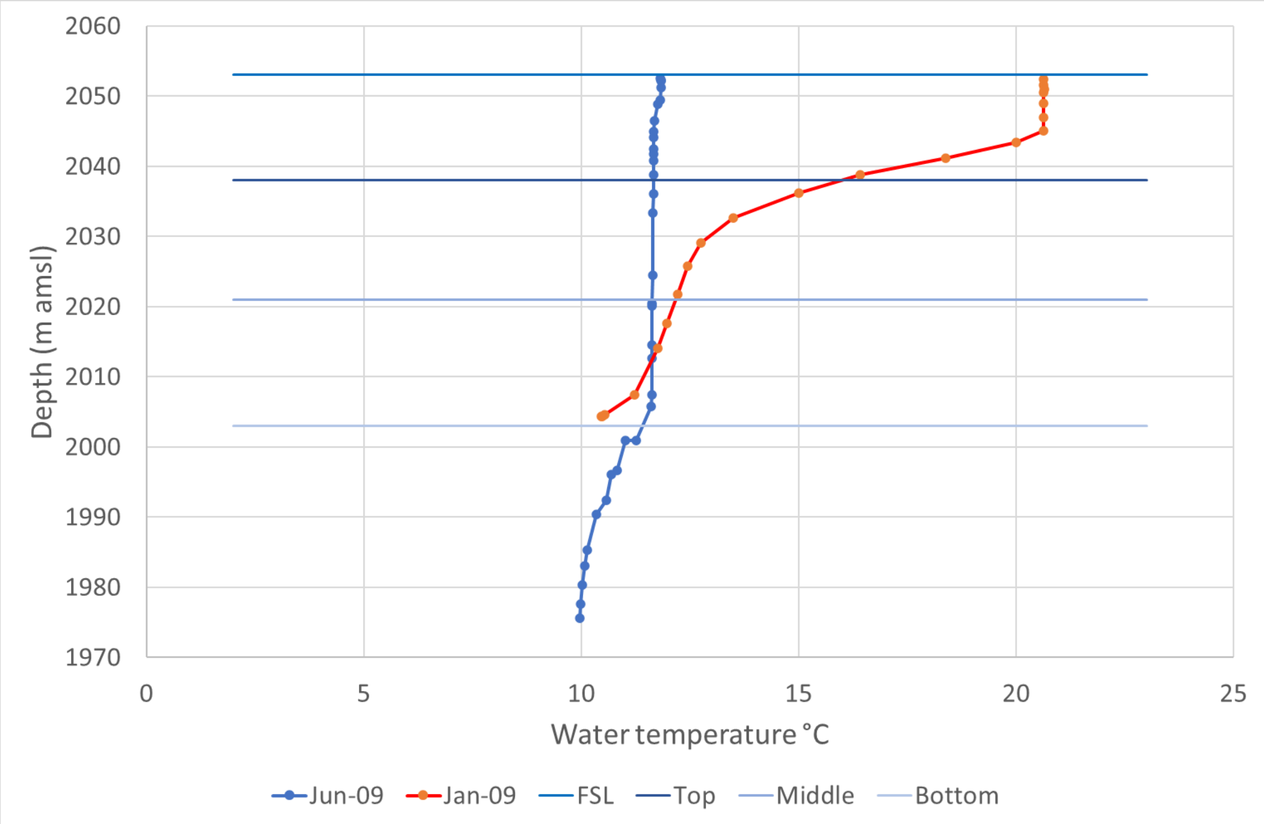


Figure 4-15: Water temperature profiles for summer (January 2009) and winter (June 2009) that illustrates thermal stratification in summer and isothermal conditions in winter at the Tunnel Intakes (LHDA data).

Katse Dam also exhibits strong dissolved oxygen stratification when thermal stratification is present (Figure 4-16). When thermal stratification is present, dissolved oxygen in the warm surface layer is high but in the bottom hypolimnion it becomes depleted resulting in low oxygen or no oxygen conditions. The thermocline (about 10m below the water surface in Katse Dam) is an effective barrier to the transport of oxygen rich surface water to the colder bottom waters. However, during autumn turnover when the water column becomes fully mixed, oxygen is transported into the deeper layers resulting in adequate dissolved oxygen concentrations throughout the water column.

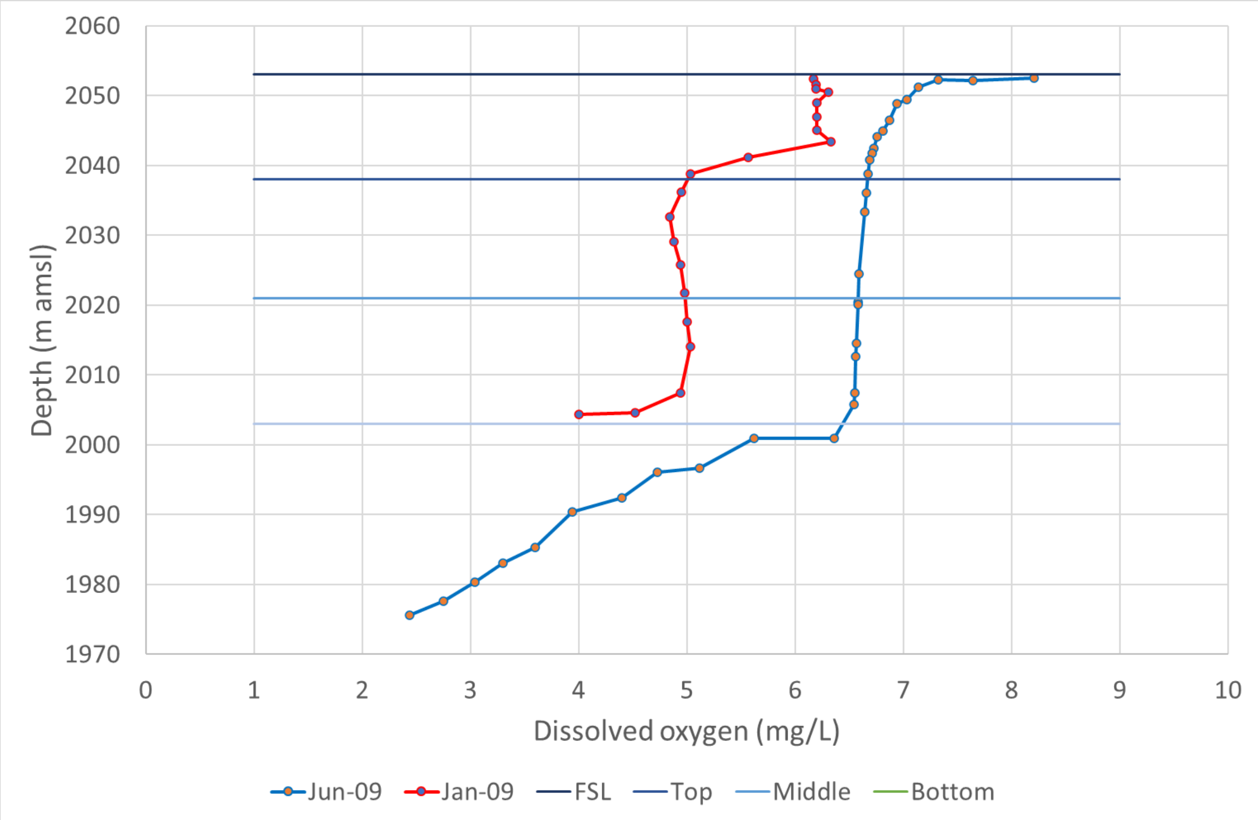


Figure 4-16: Dissolved oxygen profiles for summer (January 2009) and winter (June 2009) that illustrates DO stratification in summer and isothermal conditions in winter at the Tunnel Intakes (LHDA data).

To calculate the average water quality for the months of June to September, the profile data at the Intake Tower were examined and the temperature, dissolved oxygen concentration, pH and Electrical Conductivity at each intake were extracted (Table 4-6) and the summary statistics were calculated. In most cases, only the profiles collected in July were used as the other sampling months fell outside of our focus period (June – September).

In general, the median water temperature of the abstracted water would be about 10.2 °C, the dissolved oxygen concentration would be about 7.4 mg/l, the pH was about 7.9, and the Electrical conductivity was about 5.7 mS/m.

Table 4-6: Physical water quality data and summary statistics during the winter months at the height of the tunnel intakes (LHDA data)

Summary statistics			**Temperature [C]**	**DO [mg/l]**	**pH**	**EC [mS/cm]**	**EC [mS/m]**
		Min	9.03	3.47	7.27	0.053	5.3
		Median	10.23	7.355	7.88	0.057	5.7
		Max	14.72	9.33	10.23	0.154	15.4
Date	**Dam level [m]**	**Intake**	**Temperature [C]**	**DO [mg/l]**	**pH**	**EC [mS/cm]**	**EC [mS/m]**
19-Jul-05	2032.83	Middle	9.12	9.33	7.27	0.06	6
23-Aug-05	2029.863	Middle	9.94	7.4	7.82	0.059	5.9
03-May-07	2050.573	Top	14.72	7.27	8.22	0.067	6.7
03-May-07	2050.573	Middle	13.73	3.47	8.09	0.063	6.3
23-Jul-08	2047.55	Top	10.18	7.19	7.65	0.056	5.6

Summary statistics			Temperature [C]	DO [mg/l]	pH	EC [mS/cm]	EC [mS/m]
		Min	9.03	3.47	7.27	0.053	5.3
		Median	10.23	7.355	7.88	0.057	5.7
		Max	14.72	9.33	10.23	0.154	15.4
Date	**Dam level [m]**	**Intake**	**Temperature [C]**	**DO [mg/l]**	**pH**	**EC [mS/cm]**	**EC [mS/m]**
23-Jul-08	2047.55	Middle	10.14	7.23	7.61	0.056	5.6
19-Aug-08	2047.32	Top	10.12	8.03	8.38	0.056	5.6
19-Aug-08	2047.32	Middle	9.88	7.48	8.36	0.055	5.5
28-Jun-09	2052.49	Top	11.66	6.67	7.74	0.056	5.6
28-Jun-09	2052.49	Middle	11.63	6.58	7.73	0.056	5.6
27-Aug-09	2050.623	Top	10.04	9.12	7.92	0.055	5.5
27-Aug-09	2050.623	Middle	9.89	8.66	7.85	0.054	5.4
21-Jul-11	2049.57	Top	10.35		7.91	0.057	5.7
21-Jul-11	2049.57	Middle	10.33		7.88	0.057	5.7
18-Jul-12	2041.58	Top	9.98	7.9	9.95	0.057	5.7
18-Jul-12	2041.58	Middle	9.75	7.34	10.23	0.056	5.6
24-Jul-13	2044.831	Top	10.25	7.51	10.13	0.053	5.3
24-Jul-13	2044.831	Middle	10.23	7.3	9.92	0.053	5.3
23-Jul-14	2042.552	Top	9.25	8.66		0.062	6.2
23-Jul-14	2042.552	Middle	9.03	8.38		0.061	6.1
08-Jul-15	2045.098	Top	10.47	7.39	7.84	0.058	5.8
08-Jul-15	2045.098	Middle	10.44	7.22	7.81	0.053	5.3
06-Jul-16	2031.108	Middle	10		7.59	0.059	5.9
05-Jul-17	2020.859	Bottom	11.34	6.69	8.15	0.055	5.5
03-Jul-19	2013.366	Bottom	10.52	6.79	7.74	0.086	8.6
06-Jul-21	2039.79	Top	12.3	7.37		0.154	15.4
06-Jul-21	2039.79	Middle	12.04	6.89		0.154	15.4

Chemical water quality

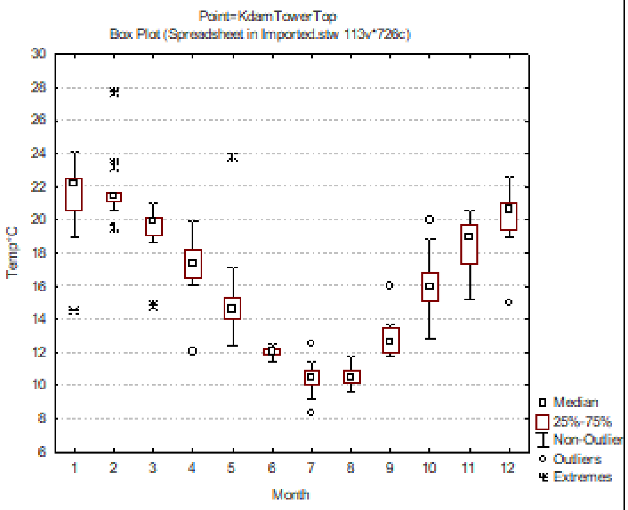
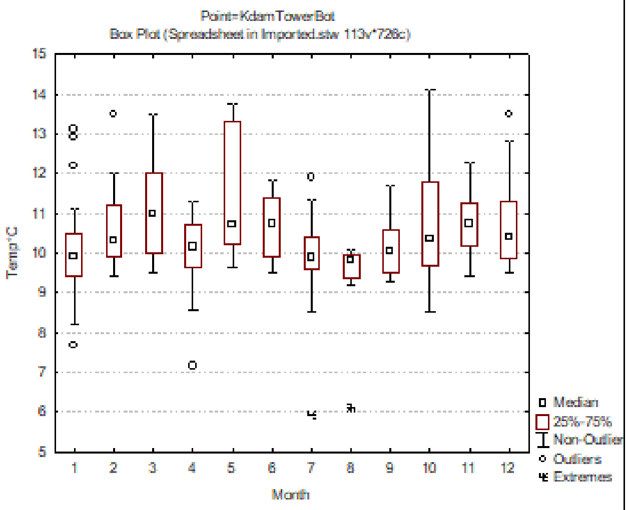
Two water samples are collected at the Intake Tower, one near the surface and one near the bottom. To calculate the summary statistics at the tower, the surface and bottom samples were lumped together for the months of June to September. The winter profile data showed that there was little difference in the physical water quality between the intakes and lumping the surface and bottom samples together for calculating the summary statistics is probably a fair reflection of quality that will be discharged into the upper Hlotse River (Table 4-7).

Table 4-7 : Summry statistics of surface and bottom layer samples collected at the Katse intake tower during the months of June to September, 1996 to 2021 (LHDA, 2021).

Constituent	N	Mean	Median	Min	Max	25%tile	75%tile	Var.	Std.Dev
DO mg/l	104	7.4594	7.72500	1.16000	13.00	6.73500	8.55000	5	2.130
Temp °C	112	10.65	10.41	5.90000	16.00	9.88000	11.70000	2	1.344
Conductivity mS/m	116	6.7158	6.20000	3.30000	12.00	5.70000	7.94000	2	1.517
pH	116	7.8244	7.70000	6.61000	10.04	7.40000	8.08500	0	0.668
Secchi m	55	4.8591	5.00000	1.00000	8.00	4.00000	6.00000	2	1.502
Al mg/l	117	0.0621	0.05000	0.00125	0.49	0.01250	0.05000	0	0.090
As mg/l	12	0.0040	0.00400	0.00400	0.00	0.00400	0.00400	0	0.000

Constituent	N	Mean	Median	Min	Max	25%tile	75%tile	Var.	Std.Dev
B mg/l	117	0.0266	0.01250	0.00150	0.10	0.00500	0.05000	0	0.025
Br mg/l	76	0.1263	0.12500	0.05000	0.25	0.12500	0.12500	0	0.041
Ca mg/l	117	8.9074	8.90000	5.80000	15.00	8.00000	9.70000	2	1.373
Cd mg/l	116	0.0125	0.00150	0.00000	0.05	0.00125	0.02500	0	0.014
Cl mg/l	75	2.5237	2.50000	0.79000	10.00	2.50000	2.50000	2	1.388
Co mg/l	117	0.0221	0.00750	0.00200	0.07	0.00750	0.05000	0	0.019
COD mg/l	112	14.879	5.00000	5.00000	470.00	5.00000	14.00000	2031	45.066
Cr mg/l	117	0.0159	0.00750	0.00250	0.09	0.00500	0.02500	0	0.014
Cu mg/l	117	0.0235	0.01500	0.00400	0.08	0.00500	0.05000	0	0.020
F mg/l	80	0.1542	0.07000	0.00750	3.70	0.03750	0.08000	0	0.556
Fe mg/l	117	0.0940	0.03000	0.00300	2.84	0.02500	0.06000	0	0.279
Hardness mg/l	111	35.27	35.00	23.00	62.00	32.00	38.00	26	5.120
K mg/l	117	0.4453	0.41000	0.05000	1.50	0.15500	0.70000	0	0.299
M-AlK $CaCO_3$ mg/l	112	38.85	36.00	22.00	255.00	34.00	38.50	468	21.632
Mg mg/l	116	3.2483	3.20000	1.90000	6.20	2.95000	3.50000	0	0.523
Mn mg/l	117	0.0517	0.03000	0.00000	0.66	0.00890	0.05000	0	0.096
Mo mg/l	117	0.0182	0.00750	0.00250	0.05	0.00500	0.03000	0	0.017
Na mg/l	117	1.8767	1.70000	0.25000	8.10	0.75000	2.60000	2	1.305
NH_4 mg/l	115	0.0769	0.03000	0.02000	1.10	0.02500	0.10000	0	0.118
Ni mg/l	117	0.0301	0.00750	0.00250	0.17	0.00750	0.05000	0	0.033
NO_2 mg/l	110	0.0240	0.01500	0.00000	0.11	0.01500	0.03000	0	0.020
NO_3 mg/l	112	0.2751	0.17000	0.00000	5.20	0.10500	0.26000	0	0.605
TP mg/l	8	0.2025	0.23000	0.05000	0.34	0.12500	0.26000	0	0.094
P mg/l	88	0.1754	0.13000	0.02000	0.74	0.02050	0.25000	0	0.161
P ALK mg/l	61	2.5000	2.50000	2.50000	2.50	2.50000	2.50000	0	0.000
Pb mg/l	117	0.0281	0.01500	0.00400	0.15	0.00400	0.05000	0	0.036
PO_4 mg/l	114	0.0430	0.02750	0.00000	0.18	0.02500	0.05000	0	0.034
S mg/l	90	1.2886	1.20000	0.00000	5.70	0.89000	1.60000	1	0.768
Si mg/l	80	6.3031	6.40000	0.58000	18.00	5.85000	6.90000	7	2.700
SO_4 mg/l	86	4.0343	2.50000	0.45000	10.00	2.50000	5.10000	5	2.201
SS mg/l	105	354.46	11.000	0.00000	14540.0	5.00000	47.00000		1675.9
TDS mg/l	108	62.259	60.00	0.00000	230.00	51.500	68.50000	922	30.365
TKN mg/l	104	2.1301	1.40000	0.00000	22.29	0.50000	2.20000	10	3.088
TOC mg/l	26	2.1038	2.10000	1.00000	5.20	1.80000	2.30000	1	0.729
TP mg/l	3	0.0883	0.09000	0.05000	0.13	0.05000	0.12500	0	0.038
Total Silica mg/l	61	12.71	14.00	2.40000	16.00	12.00	15.00000	10	3.168
Turb NTU	109	441.0	1.80000	0.32000	35150.0	0.87000	19.00000		3400.45
V mg/l	116	0.0254	0.01500	0.00500	0.07	0.01500	0.05000	0	0.017
Zn mg/l	117	0.0270	0.02500	0.00400	0.14	0.00750	0.05000	0	0.022

An examination of temperature, dissolved oxygen, and electrical conductivity recorded for the surface and bottom water samples (Figure 4-17), indicate that the surface water temperatures vary widely over a season, ranging from greater than 20°C in summer dropping to about 10°C in winter, whereas the bottom water samples show only a small variation over a season, ranging between 10-11°C. The dissolved oxygen in the surface waters is generally high (> 7mg/l), peaking in September each year. The DO in the bottom layers tend to be low during the summer months when the dam is stratified (between 2-4 mg/l) and increasing during the winter months as the dam becomes fully mixed transporting dissolved oxygen from the surface layers into the deeper layers, peaking in August and September just before the unset of summer thermal stratification. There is little difference in electrical conductivity in the surface and bottom water samples, with EC being slightly higher in the surface water samples.

<table>
<tr><th>Surface</th><th>Bottom</th></tr>
<tr><td>
</td><td>
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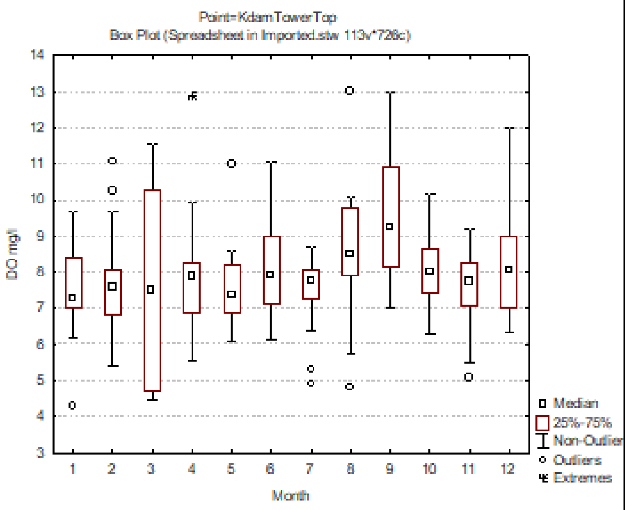
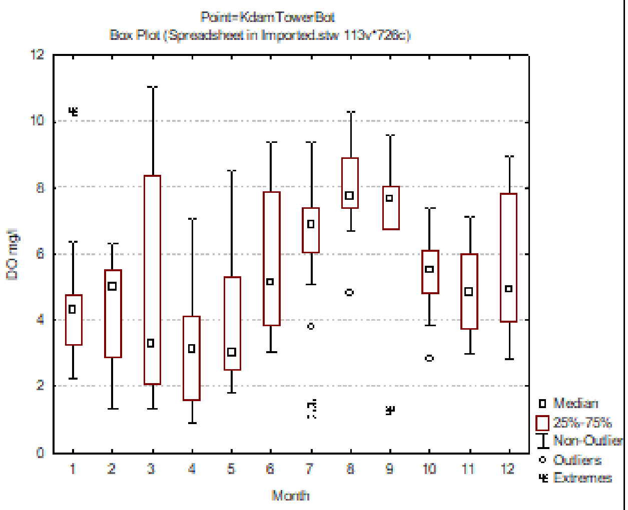
<tr><td>
</td><td>
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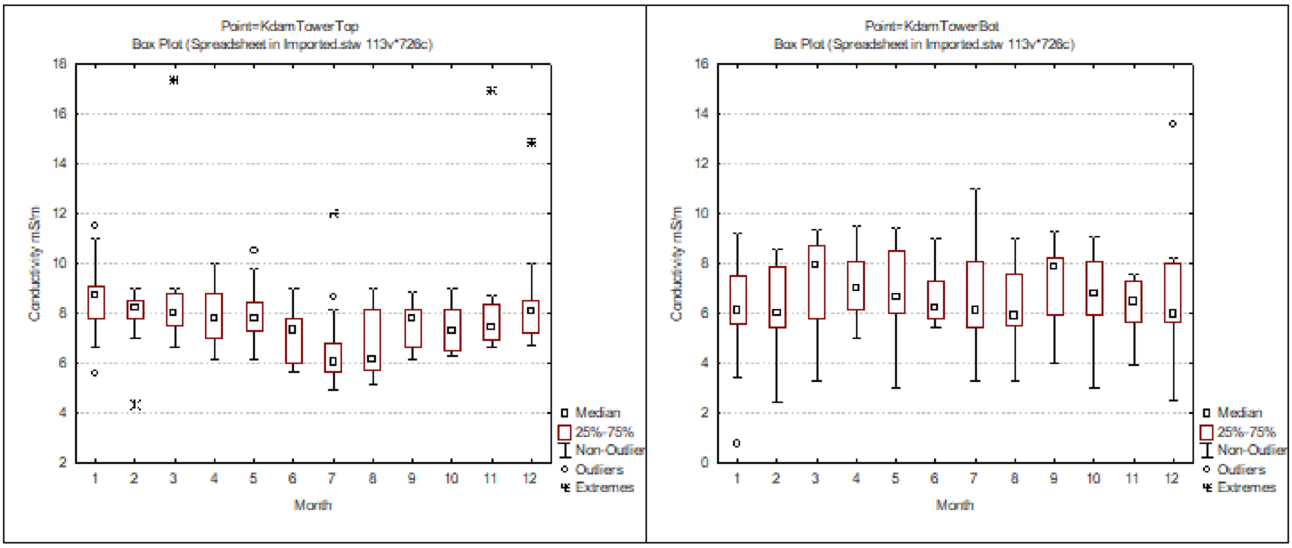

Figure 4-17: Monthly box and whisker plots of water temperature, dissolved oxygen and electrical conductivity of surface and bottom water samples (1996-2021)

The question is whether there would be a change in quality between the water that enters the tunnel in Katse Dam and is discharged at the Hlotse Adit. The length of 4.35m diameter tunnel between the Katse Intake Tower and the connection to the adit is 27996m and the water velocity used in the design of the release infrastructure is 3.23 m/s (Giji, 2021). This means a parcel of water would spend 2.41 hours in the tunnel before it is diverted into the adit from where it flows in a 1.849 km pipeline to the outflow into the Ts'ehlanyane stream. It is the opinion of the author that a water residence time of 2.4 hours is unlikely to change the physical or chemical properties of the water that enters the tunnel in Katse Dam. It is probably safe to assume that the quality of water that enters the tunnel in Katse Dam would be that same as is discharged into the Hlotse River.

4.7 Fitness for use assessment

The water quality observed during the 2021 baseline monitoring were compared to the aquatic ecosystem water quality guidelines that were developed for the Orange-Senqu River by ORASECOM (Appendix Table 5; ORASECOM 2009) and for Lesotho (Fichtner 2013).

The Commissioner of Water was instrumental in the development of water quality standards and guidelines for Lesotho and that project was completed during the last quarter of 2013 (Fichtner 2013). Many of these new guidelines were aligned with the ORASECOM guidelines. For example, the new Lesotho water quality guidelines for Aquatic Ecosystems are the same as the ORASECOM aquatic ecosystem guidelines.

The water quality criteria for determining the fitness for use of water is a function of the use of that water. The fitness for use can range from being 100% or ideally fit for a specific use, to being completely unfit for that use. The fitness for use of a water resource is expressed as (ORASECOM 2009, Fichtner 2013):

- Ideal – the use of water is not affected in any way; it is regarded as 100% fit for use; also referred to as the desirable water quality or target water quality range.
- Acceptable – slight to moderate problems may be encountered
- Tolerable – moderate to severe problems are encountered, usually for a limited period only
- Unacceptable – water cannot be used for its intended use under normal circumstances

The fitness for use criteria and boundary values for aquatic ecosystems are presented in Table 4-8.

Table 4-8: Fitness for use classification for Aquatic Ecosystems (ORASECOM 2009, Fichtner 2013)

Parameter	Ideal	Acceptable	Tolerable	Unacceptable
Phosphates (mg/l)	0.01	0.03	0.130	> 0.130
pH	8	9	10	> 10
Electrical conductivity (mS/m)	30	55	85	>85
Unionised ammonia (µg/l)	15	58	100	>100

Electrical Conductivity as indicator of salinity was below 30 mS/m at all the monitoring points on the Hlotse River. The water would therefore fall within an ***Ideal*** category in terms of fitness for aquatic ecosystem requirements. In the A-F ecological classification used in South Africa, the water would be classified as being in a class A (DWAF, 2008).

The **pH** in the Hlotse varied between 7.4 and about 8.2. The two upstream sampling points (Eflows0/TS1 and Eflows1) has pH values lower than 7.6 and it can be classified as being in an ***Ideal*** category or Class A. The remainder of the sampling points had pH values between 8.0 and 8.4. These waters would be classified as being in an ***Acceptable*** category, or B class (8.0 to 8.8, DWAF, 2008).

Orthophosphate concentrations in the Hlotse River were low and consistently below the laboratory detection limit of 0.04 mg/l. The waters would probably be classified as being in an ***Acceptable*** category, or B class (DWAF, 2008).

The **Nitrate nitrogen** concentrations in the Hlotse River was low. There are no aquatic ecosystem fitness for use guidelines for Total Inorganic nitrogen (TIN). Using the South African guidelines (DWAF, 2008), Nitrate concentrations at the two upstream sampling points, Eflow0/TS1 and Eflows1, these sites would be classified as being in a A class (<0.25 mg/l). The next two points, Eflows2/CQ14 and Eflows3 would be classified as being in a A/B class (0.25-0.70 mg/l). The remaining sampling points (CQ15, Eflows4 and Eflows5/CQ21) would be classified as being in a B class (0.70-1.00 mg/l).

For **Turbidity** there are no quantitative guidelines for aquatic ecosystems, only descriptive ones (DWAF, 2008). Based on the descriptions, Eflows0/TS1 and Eflows1 would be classified as in an A class (no change), Eflows2/CQ14 would be classified as A/B class (small change), and CQ15, Eflows4 and Eflows5/CQ21 would probably fall within a B class (Moderate change) (DWAF, 2008).

Water quality in the Hloste River is regarded as being Ideal to Acceptable for aquatic ecosystems.

4.8 Water quality modelling

4.8.1 Introduction

The HEC-RAS model that was configured for the hydraulic analysis was extended and configured to also simulate water temperature and general water quality for the Hlotse River for the reach from the Hlotse Adit to the Caledon River confluence.

The current version of the HEC-RAS model can perform detailed temperature analysis and transport of limited number of water quality constituents (EC/TDS, Algae, dissolved oxygen, carbonaceous biochemical oxygen demand, dissolved ortophosphate, dissolved organic phosphorus, dissolved ammonium nitrate, dissolved nitrate nitrogen, dissolved nitrite nitrogen, and dissolved organic nitrogen). The water that will be transferred from Katse Dam during the winter months (June to September) would be characterised by adequate dissolved oxygen concentrations, warmer water temperatures than experiences in the Hlotse River at the Adit inflow, low nutrient concentrations, low phytoplankton concentrations, and low suspended sediment concentrations. Water quality would change as it flows towards the confluence with the Mohokare/Caledon River. This change in quality will be simulated with the HEC-RAS model. The selection of variables to be simulated will be informed by the availability of data, both for the transferred water, and the receiving Hlotse River.

Preliminary application of the model was performed to confirm the proper operation of the water quality component of HEC-RAS, identify any data deficiencies that may exist, and to identify important model parameters that may have the greatest impact on model predictions.

In order to run the water quality component of the HEC-RAS model the following is required (USACE, 2016):

- For all water quality models, a calibrated steady flow model or a calibrated unsteady flow model is required. The unsteady flow model HEC-RAS model that was set up for the Hlotse River is described in the Hydraulics Report (Multiconsult, 2022). This formed the
- The first step in modelling water quality is to undertake the water temperature modelling because all the other processes are dependent on water temperature. The requirements for modelling water temperature are:
  - A water temperature time series at all hydraulic boundaries (all the modelled inflows)
  - An initial water temperature in each river reach
  - Meteorological time series of
    - Solar radiation or the latitude and longitude of the study area
    - Air temperatures
    - Relative humidity (or vapour pressure, dew point temperature, wet bulb temperature)
    - Wind speed
    - Cloudiness
    - Atmospheric pressure (or it can be estimated from the site elevation)
- For the Arbitrary Constituent Modelling (conservative substance) the following is required:
  - Time series of constituent concentrations at all hydraulic boundaries
  - Initial concentrations in each river reach
  - Estimated rate constant(s) for the constituent being modelled
- For the nutrient modelling, the following is required:
  - A complete set of water temperature model inputs as described above
  - Time series of nutrient concentrations at all the hydraulic boundaries
  - Initial nutrient concentrations in each model reach

4.8.2 Modelling water temperature in the Hlotse River

The requirements for modelling water temperature are:

- A water temperature time series at all hydraulic boundaries (all the modelled inflows)

- An initial water temperature in each river reach
- Meteorological time series of:
  - Solar radiation or the latitude and longitude of the study area
  - Air temperatures
  - Relative humidity (or vapor pressure, dew point temperature, wet bulb temperature)
  - Wind speed
  - Cloudiness
  - Atmospheric pressure (or it can be estimated from the site elevation)

4.8.2.1 Sourcing meteorological data for the temperature modelling

In order to model water temperature in the Hlotse River, sub-daily inputs are required to model the diurnal changes in water temperature. These were sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land hourly data (Table 4-9).

Table 4-9: Sources of meteorological data used in the HEC-RAS water temperature model

Timeseries	Data source
Solar radiation	Estimated from the latitude and longitude of the study area
Air temperatures 2m °C	Downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land hourly data for 1982 to 2020 for the CQ14 area
Relative humidity (as dew point temperature °C)	Downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land hourly data for 1982 to 2020 for the CQ14 area
Wind speed m/s	Downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land hourly data for 1982 to 2020 for the CQ14 area. Downloaded the 10m u-component and 10m v-component speeds. Average windspeed were calculated as… Mean Windspeed = SQRT($u^2 + v^2$)
Cloudiness	Set as a constant
Atmospheric pressure	Downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land hourly data for 1982 to 2020 for the CQ14 area

4.8.2.2 Estimating local runoff and tributary inflow temperatures

The HEC-RAS model also requires a water temperature time series at all hydraulic boundaries (all the modelled inflows). The tributary water temperatures (WT) were estimated from the air temperature (AT) and a relative humidity (RH) obtained as part of the meteorological data set, using a regression model developed by River-Moore and Dallas (20XX) for upland rivers:

WT = -5.07 +0.68(AT) + 1.27*SQRT(RH)

The relative humidity (RH) was estimated from the air temperature (AT) and dewpoint temperature (DT) using the August-Roche-Magnus approximation:

RH = 100*(EXP((17.625*TD)/(243.04+TD))/EXP((17.625*T)/(243.04+T)))

The water temperature time series for all the tributary and local inflows were the same.

A water temperature of 17 °C was used as the initial water temperature in each of the modelled river reaches at the start of a model run. Thereafter river water temperatures responded to the model formulations, tributary inputs, and meteorological conditions.

- The timeseries of water temperatures of the Katse Dam transfers were generated using the average water temperatures recorded in the top and bottom samples collected by LHDA at the intake tower (

Table 4-10).

Table 4-10: Average monthly water temperatures in the Kaste Dam transfer water

Month	Average of Temp °C	Min of Temp °C	Max of Temp °C
1	15.62	7.68	24.11
2	16.49	9.40	27.71
3	15.47	9.51	20.96
4	13.73	7.16	19.92
5	13.74	9.65	23.82
6	11.36	9.50	12.55
7	10.15	5.90	12.46
8	10.00	6.10	11.77
9	11.74	9.26	16.00
10	13.21	8.54	20.00
11	15.48	9.42	20.53
12	15.61	9.50	22.60

4.8.2.3 Calibration of the water temperature model

In the monitoring data collected by DWA from 1999 to 2014, the years 2004 and 2005 had the most complete monthly temperature records. The modelled water temperatures were therefore compared to those observed records. Initially the model tended to overestimate the river water temperatures. The Shortwave Radiation were reduced by 25% to compensate for topographic and riparian vegetation shading. A better fit was obtained between the modelled and observed data. The model was successful in modelling the seasonal and diurnal fluctuations in water temperatures at the three points where historical water temperature data was available (Figure 4-18 to Figure 4-20).

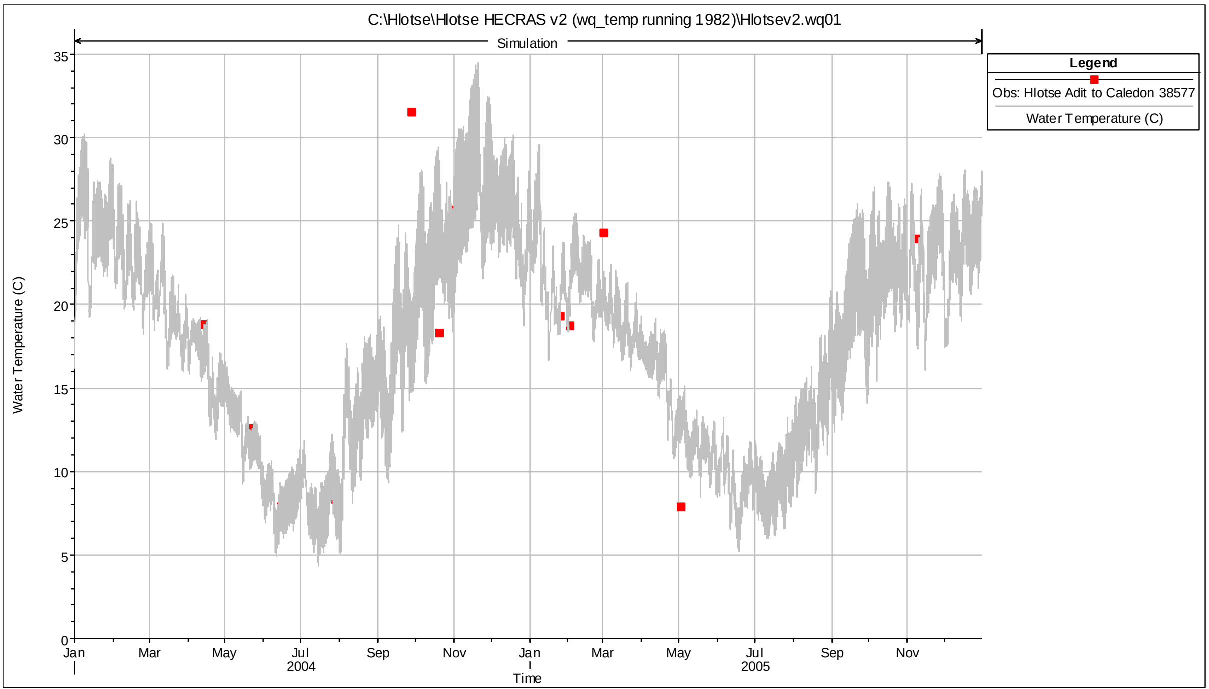

Figure 4-18: Comparison of modelled and observed water temperature data for the period 2004 – 2005 at Flows2/CQ14

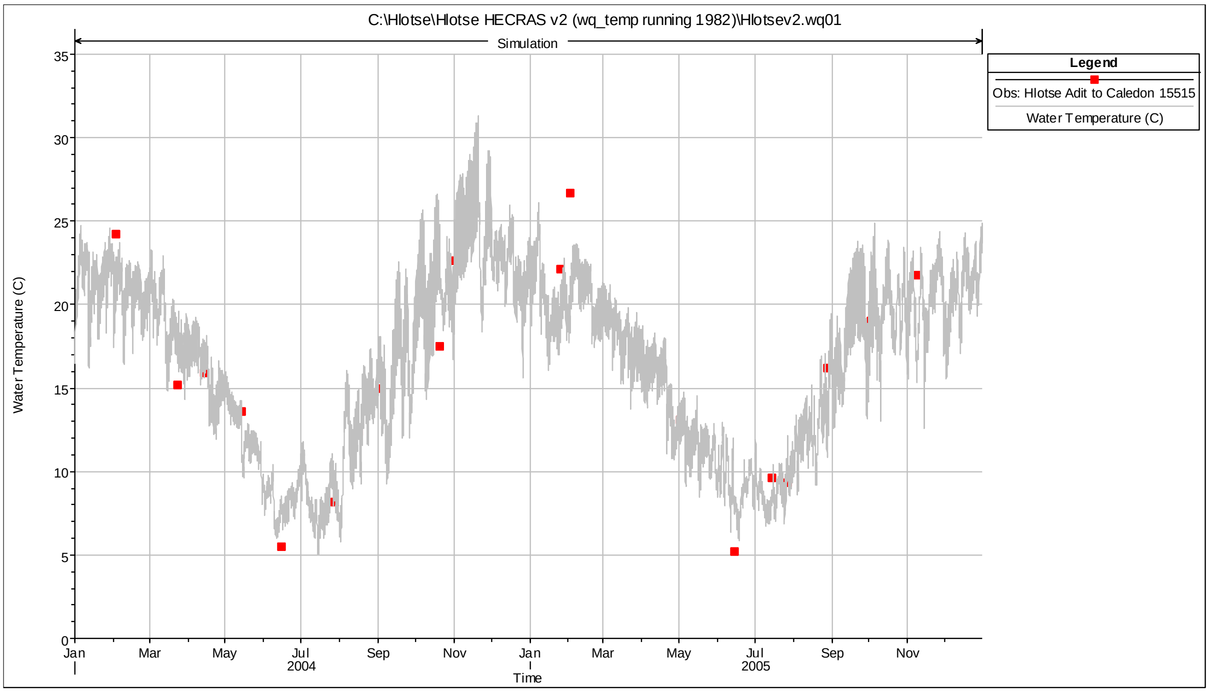

Figure 4-19: Comparison of modelled and observed water temperature data for the period 2004 – 2005 at CQ15

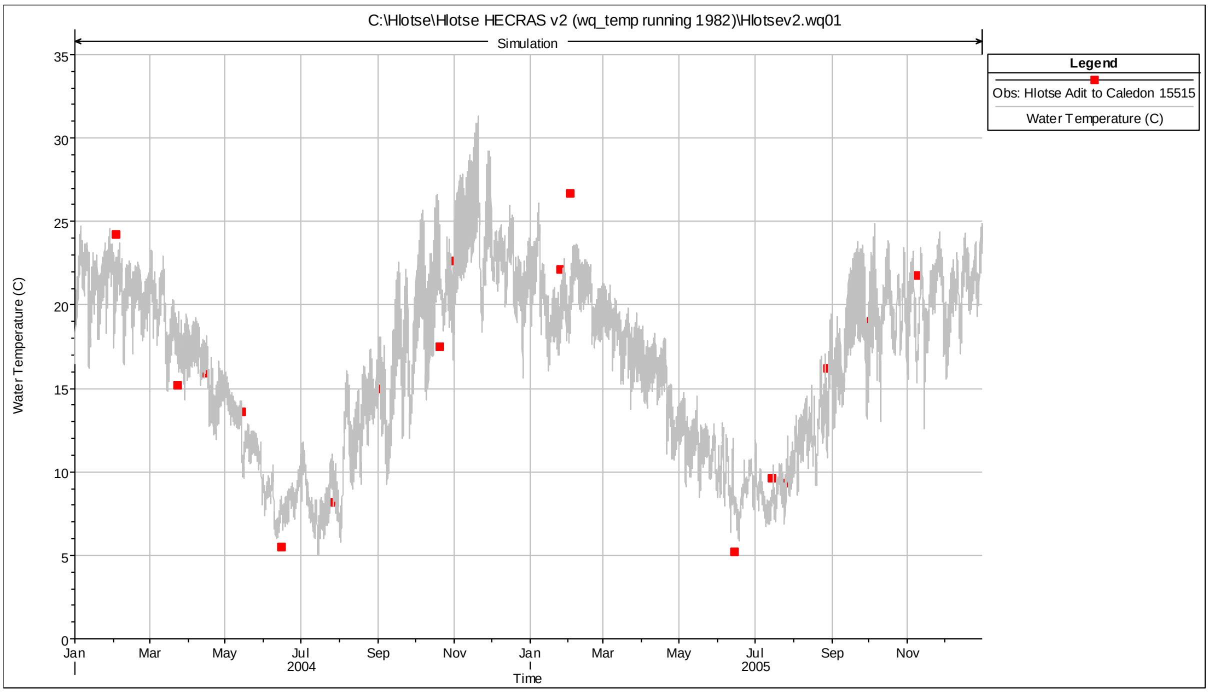

Figure 4-20: Comparison of modelled and observed water temperature data for the period 2004 – 2005 at Flows5/CQ21

4.8.2.4 Simulating scenario water temperatures

The calibrated water temperature model was used to simulate the timeseries of baseline water temperatures for the period 1982 – 2020, as well as the time series of water temperatures for different Katse Dam transfer scenarios.

The model was moderately successful in modelling the average electrical conductivity measurements observed in the Hlotse River at the three points where historical electrical conductivity data were available (Figure 4-21 to Figure 4-23).

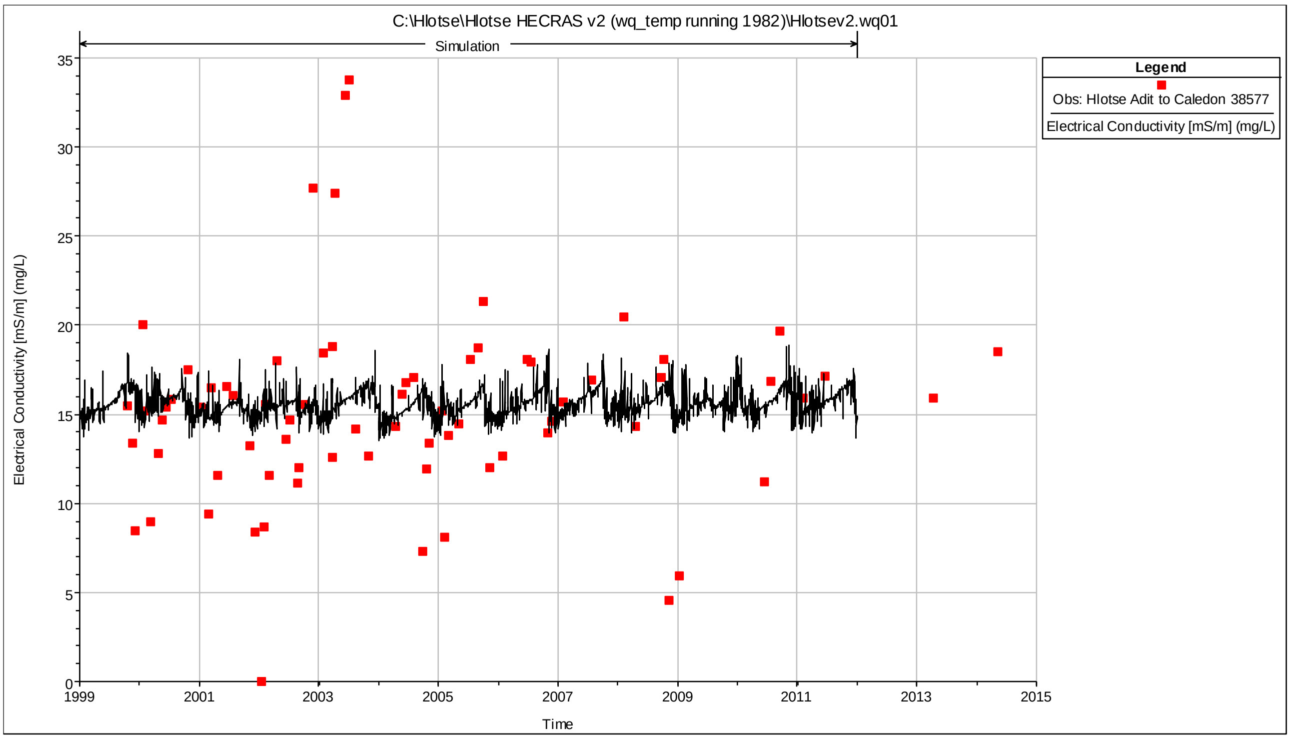

Figure 4-21 Comparison of modelled and observed electrical conductivity data for the period 1999 - 2012 at CQ14

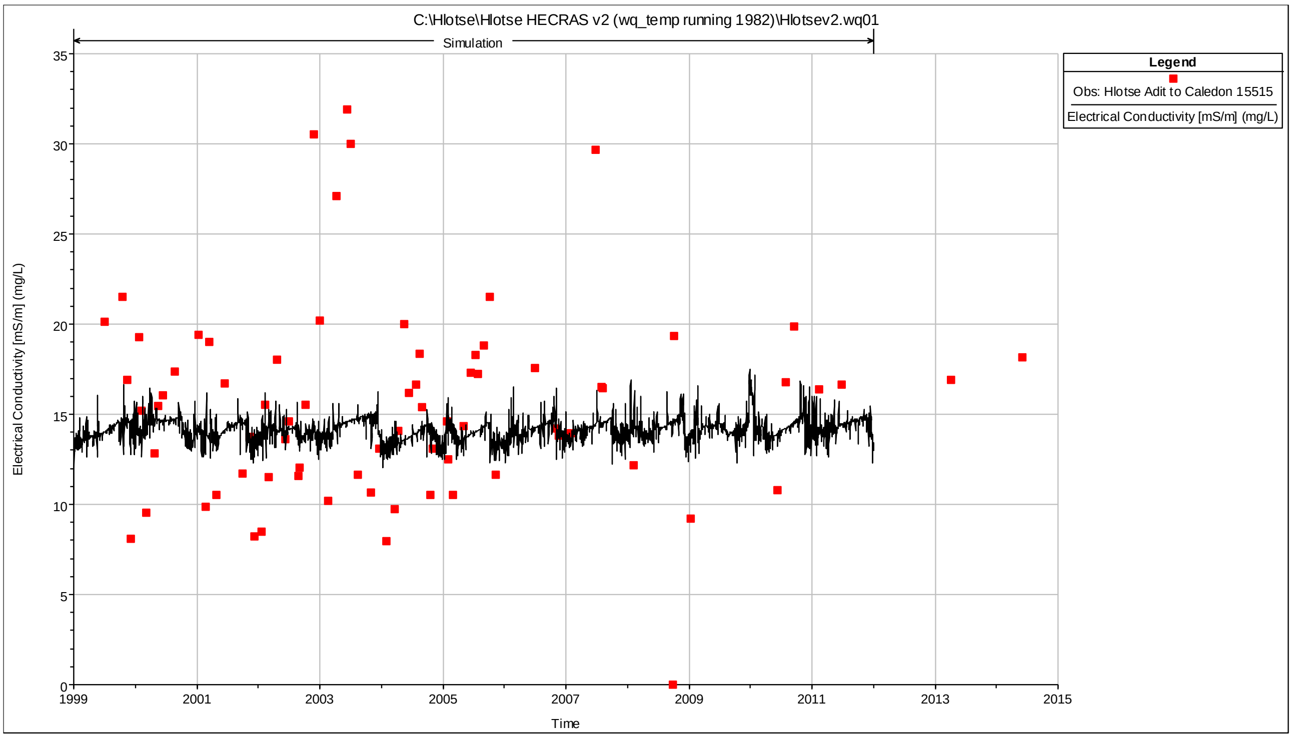

Figure 4-22 Comparison of modelled and observed electrical conductivity data for the period 1999 - 2012 at CQ15

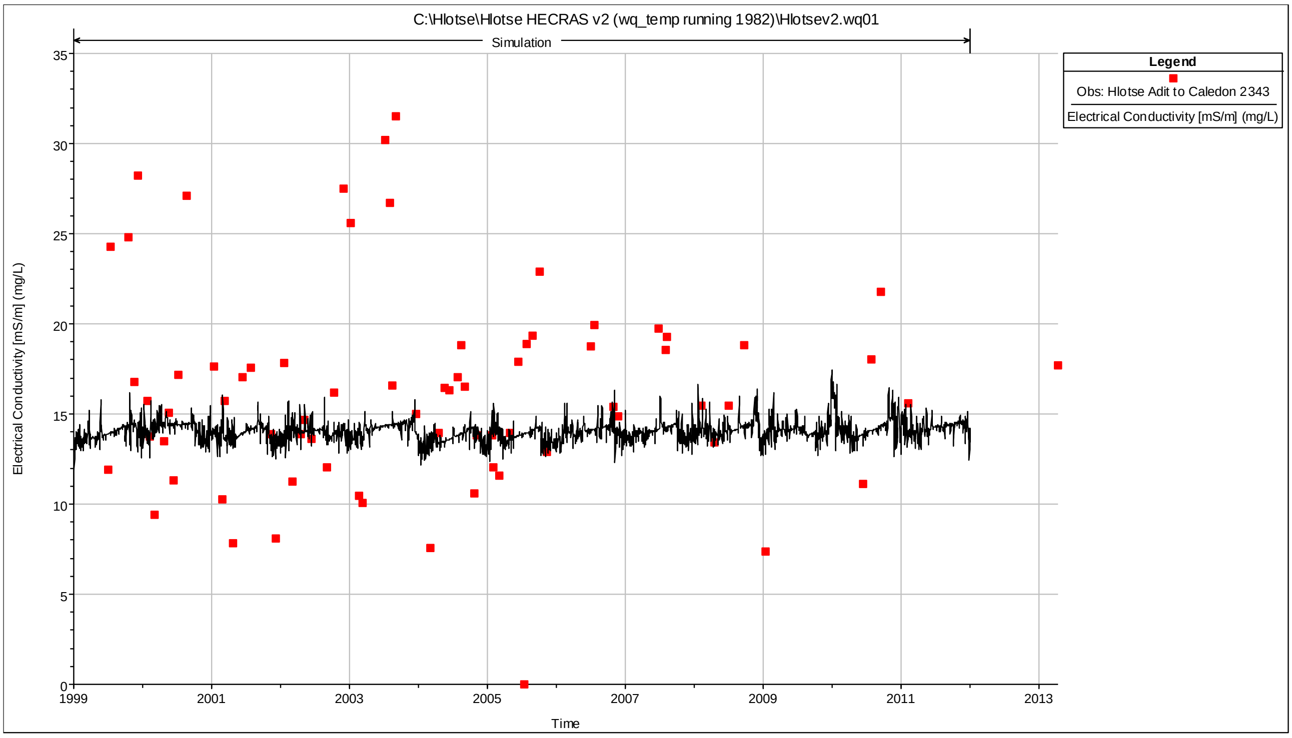

Figure 4-23 Comparison of modelled and observed electrical conductivity data for the period 1999 - 2012 at CQ21

4.8.3 Modelling an arbitrary constituent in the Hlotse River

An arbitrary constituent is one that does not decay over time or undergo any transformations in the river. This is also referred to as a conservative substance and include variables such as Total Dissolved Solids (TDS), Electrical Conductivity (EC) or Chloride. Total dissolved solids (TDS) were selected for modelling an Arbitrary Constituent for the Hlotse River. The HEC-RAS User's Manual recommends this step be taken before modelling more complicated water quality constituents such as nutrients.

The Arbitrary Constituent modelling requires the following:

- Time series of constituent concentrations at all hydraulic boundaries
- Initial concentrations in each river reach
- Estimated rate constant(s) for the constituent being modelled

No water quality data were available for any of the tributaries flowing into the Hlotse River. As Electrical Conductivity acts as a conservative substance, some estimates could be made of the tributary concentrations, assuming a constant concentration, to approximate the average observed concentrations in the Hlotse River. The biggest change in electrical conductivity takes place in the upper Hlotse River between Eflows0/TS1 and Eflows2/CQ14 (Section 4.4.3).

4.8.4 Modelling nutrients in the Hlotse River

Modelling nutrients is complex. For the nutrient modelling, the following is required:

- A complete set of water temperature model inputs as described above
- Time series of nutrient concentrations at all the hydraulic boundaries
- Initial nutrient concentrations in each model reach

The state variables for the nutrient model are:

- Dissolved nitrite nitrogen (NO_2)
- Dissolved nitrate nitrogen (NO_3)
- Dissolved organic nitrogen (Org N)
- Dissolved ammonium nitrogen (NH_4)
- Dissolved organic phosphorus (Org P)
- Dissolved orthophosphate (PO_4)
- Algae
- Carbonaceous Biological oxygen demand (CBOD)
- Dissolved oxygen (DO)

No water quality data were available for any of the tributaries flowing into the Hlotse River. In order to develop a meaningful nutrient model for the Hlotse River, at least some measurements of the state variables in the main tributaries should be undertaken.

5 Conclusions

5.1 Water resources Assessment

For the natural water availability daily discharge series were simulated by the wflow hydrological model over a period the 1982 – 2020 for several scenarios of natural situations and future situations with the Adit and the intake for the water supply. Most of the information for the modelling was based on global data, e.g. for topography, soil type, land use, and the forcing data of precipitation and temperature. The results of the hydrological modelling form the input for subsequent tasks in the project, such as the DRIFT analysis and the hydrodynamic modelling. Simulation were also made for climate change scenarios, using two future time horizons (2041-2070 and 2071-2100) with a warm and a dry scenario.

In addition, an analysis was made of the losses in the river between the Adit and the intake, which were mainly due to evaporation. The total amount of the losses varies over the year with the seasons and is assumed not to surpass 2 – 3 % of the inflow from the Adit.

5.2 Water Quality Assessment

Water quality data collected by DWA, the LLWP and the baseline monitoring undertaken in this project provided good data to assess the water quality characteristics of the Hlotse River.

In general, water quality in the Hlotse River is good. The water quality changes in a downstream direction. From the baseline monitoring that was done it appears that the biggest deterioration in water quality occurs in the upper third of the river, between TS1 and CQ14. Between CQ14 and Eflows3 there was a further deterioration in water quality but not as pronounced. Water quality changes in the lower third of the Hlotse River (CQ15 at Setene to the confluence with the Mohokare/Caledon River) the water quality changes were relatively small. There was strong seasonality in the salts, low concentrations during the summer months due to dilution and concentrations increasing during the dry winter months up to the first spring and early summer rainfalls when salts were diluted once again. In contrast, nutrients appeared to slightly higher during the wet season due to catchment wash-off processes mobilising nutrients and sediments, and lower during the low flow winter months. However, this pattern was not very strong.

Water quality in the Hlotse River is either in an Ideal or Acceptable category with respect to aquatic ecosystem requirements. In the upper reaches of the Hlotse the quality is Ideal for aquatic ecosystems, and it gradually changes to Acceptable in a downstream direction.

The quality of water that will be transferred from Katse Dam during the winter months (June to September) will be very good, the dissolved salts, nutrient concentrations and suspended sediments will be low, and dissolved oxygen concentrations high. The water temperature will be about 3-5°C warmer than the water temperatures in the upper Hlotse at the point of discharge. However, if water is transferred at the end of summer when thermal stratification is present in Katse Dam, then water with low dissolved oxygen concentrations and slightly cooler water temperatures could be discharged into the upper Hlotse River which is not desirable.

The HEC-RAS water quality model can be used to simulate water quality changes in the Hlotse River in response to changes in the catchment or operations of the transfer scheme.

6 Recommendations

DWA had a good water quality monitoring programme active in the Hlotse River. Consideration should be given to restoring the sampling at CQ14, CQ15 and CQ21. Consideration can be given to also continue monitoring at TS1 and Eflows1 to monitor the future impacts of water transfers from Katse Dam. Consideration should also be given to undertaking a water quality survey of the key tributaries of the Hlotse River to characterise their constituent loads to the river. It is further recommended that the water quality data collected during monitoring be reviewed on a regular basis and that quality controls be instituted at the DWA laboratory to identify and verify or correct outliers or incorrect data entries.

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