THREATS OF EXTREME WEATHER EVENTS

Improving the Resilience of QwaQwa to the Multiple Risks of Climate Change

Volume 1

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

Recent climate projections for the Southern African region strongly indicate that the occurrence of rainfall extremes and prolonged drought periods may increase in the near future. Such extreme events pose a severe threat to water resources, food security, public health, infrastructure, biological diversity, and ecological systems in the region. Changes to the temporal dynamics of flow regimes in rivers as a result of these projected changes could hold important consequences for both humans and riverine biota.

While current research on climate extremes generally focuses on relatively large catchments with a low spatial resolution, information is needed on smaller catchments at detailed spatial resolution as to whether the climate projections for Southern Africa actually display increasing probabilities of sequential extreme events of, for example, torrential rainfall following directly after an extended drought period. Sequential extremes could have severe consequences by triggering cascades of secondary effects such as high sediment yields with impacts on, for example, infrastructural damage to water purification plants.

To improve the resilience against such impacts and to develop efficient coping strategies, new approaches that integrate the assessment of exposure and vulnerability on the one hand, and offer efficient coping strategies on the other, are needed. However, such adaptation strategies must be based on appropriate and reliable downscaled information and include communication technologies with early warning and decision support systems for the population and decision makers concerned. Such risk reduction is all the more important given that weak governance could further increase the exposure to these risks. This failure could hold dire consequences for already vulnerable communities and sectors and, to a large extent, counter socio-economic development efforts by the government and other non-governmental agencies.

AIMS

The overarching aim of this project was to understand how the cumulative impacts of successive extreme weather events may affect the exposure and resilience of local communities in QwaQwa and how these impacts may be ameliorated through risk reduction planning. The objectives of the project were:

1. To determine how the ecological services of river ecosystems in QwaQwa could be impacted by an increase in the occurrence of extreme weather events;
2. To develop an understanding of the impact that secondary effects may have on service delivery and infrastructure development in QwaQwa;
3. To identify the most important hazards and risks for the QwaQwa community in terms of water delivery, human health, and environmental safety;
4. To prepare a tailor-made risk assessment for the QwaQwa area based on downscaled climate and hydrology models specifically developed for the area;
5. To develop a tailor-made disaster risk reduction (DRR) strategy and plan for QwaQwa.

STUDY AREA

The focal area of this study comprised the Phuthaditjhaba urban area and the surrounding villages that make up 30 wards in the area. It is situated in the north-eastern Free State province, bordering KwaZulu-Natal to the south-east and Lesotho on the south-west. The area is located in a relatively narrow valley in a section of the Maloti-Drakensberg mountain range, at an elevation of between 1 675 m to more than 2 200 m above sea level. The mountainous area serves as the headwaters for several streams, including the Mphukojwane, Namahadi, and Metsi-Matso rivers. These streams joins to form the Elands River, and later the Wilge River, a major tributary of the Vaal River. The study catchment forms part the northern Drakensberg strategic water source area.

QwaQwa is one of the four towns in the Maluti-a-Phofung Local Municipality and serves as the administrative headquarters of both the Maluti-a-Phofung Local Municipality and the Thabo Mofutsanyana District Municipality. Phuthaditjhaba, the main urban area, is densely populated and surrounded by informal settlements. Socio-economic development in the area is relatively low. Poverty and unemployment are widespread, with the rural villages being more deprived than the urban areas. The general state of water infrastructure and provision is poor, with large portions of the population lacking piped water, waterborne sanitation, and access to electricity. QwaQwa has been experiencing chronic water scarcity for more than two decades, with public protests occurring regularly. Water insecurity problems came to a head during a severe drought in 2014 to 2016 that exposed the vulnerability of communities in QwaQwa to water insecurity.

METHODOLOGY

The project comprised three components, namely climate and hydrological modelling, ecological risk assessment, and disaster risk analysis and reduction; each of which required different methods. The work was conducted over three phases.

During the first phase, sampling sites were selected on the Namahadi, Metsi-Matso, Mphukojwane, and Elands rivers and were described to serve as a focal point for the different components of the study. During the second phase, the emphasis was on the identification of ecological risks (based on field sampling) and risks to the local communities (based on social surveys through semi-structured questionnaires and interviews). The identified risks were assessed in terms of probability, frequency, intensity, and magnitude against the simulated changes in the local climate and streamflow in the study rivers. During the third and final phase, the risk reduction strategy and plan for the QwaQwa area were developed.

RESULTS AND DISCUSSION

Climate and hydrological modelling

A climate and hydrological model was developed to provide appropriate and reliable downscaled information for QwaQwa.

Climate projections indicated a warming trend for QwaQwa in the immediate and distant future, especially for the lower-lying area of the catchment where Phuthaditjhaba is situated. Mean daily minimum and maximum temperatures are expected to increase by approximately 1.5°C by the mid-2030s, and by more than 4°C by the 2070s. The number of frost days is projected to reduce by more than 40% in the higher-lying parts of the catchment, and by more than 70% in the lower-lying areas. The mean annual evaporation in QwaQwa could increase by 7% in the near future, and by more than 20% in the distant future.

QwaQwa is projected to experience higher rainfall during the rainy season (summer), but relatively less rainfall during the dry season (winter). Rainfall increases will, however, not occur uniformly over the catchment. The projections show that the greatest changes in mean annual rainfall will occur in the mountainous headwater areas, which could receive 30 to 40 mm more rain (a 4% increase from the present) in the near future, and between 140 mm and 185 mm more rain (a 20% increase from the present) in the distant future. Rainfall increases could be lower during dry years and higher during wet years. Dry spells are projected to increase in the immediate future, while wet spells could be fewer. This impact could be more pronounced in the higher-rainfall upper parts of the catchments than in the slightly drier lowland areas.

The hydrological model indicated that the bulk of the runoff in the catchment is generated on the mountain slopes, with these areas producing nearly three times more runoff, on average per year, than the lowland areas. The highest runoff generally occurs in January (summer), while August and September (winter) have the lowest runoff. The mean annual runoff in the catchment is projected to increase by approximately 7% in the highlands and 15% in the lowlands in the near future. In the distant future, runoff could increase by 36% in the highlands and by nearly 70% in the lowlands. Stormflows in the catchment generally occur in summer (rainfall season), when they contribute approximately 70% to runoff. Stormflows are projected to increase by between 13% and 21% annually, with the greatest changes expected for the highland areas. The percentage increase in baseflows, which are the major contributors to total runoff during the dry winter season, are projected to be higher in the lowlands than in the highlands.

Accumulated streamflows are projected to increase in the future, although the increases are not expected to occur uniformly over the catchment. The accumulated streamflows vary greatly between the 19 sub-catchments, depending on the size and rainfall of the sub-catchments. Peak discharges in the catchment generally occur in late summer (February) after thunderstorm activity. The projections indicate that peak discharges could increase in the immediate future (2040s), with the most downstream sub-section of the catchment (lower Elands River) being at risk of flooding in future.

Ecological risk assessment

The ecological risk assessment collected data on physical and chemical water quality, ecotoxicology, and river health. The aim of these assessments was to identify potential hazards to human and environmental health associated with extreme weather events in the study area.

The negative impacts of current anthropogenic activities on the rivers and streams were clear. The results showed that the upper reaches of the rivers, situated predominantly in the more rural and less densely populated areas, were less impacted than the middle and lower reaches, situated in the urban and more densely populated parts of the catchment.

Water quality, in general, deteriorated from upstream to downstream, with the water at the most downstream sites on the Elands River being hypertrophic, acutely toxic, and having high levels of manganese, iron, and a range of emergent pollutants such as dioxins, caffeine, pharmaceuticals, and herbicides. The presence of faecal coliform bacteria, used as an indicator of faecal pollution in surface waters, also increased from upstream to downstream in the catchment. Faecal coliform bacteria concentrations were unacceptably high in the lower Namahadi, middle Mphukojwane, and Elands rivers, where concentrations exceeded the recommended Target Water Quality Range (TWQR) set by the Department of Water and Sanitation by 1 700 times.

This study was the first to detect and confirm the presence of organic micropollutants such as sulfamethoxazole, Bisphenol-4, ibuprofen, carbamazepine, atenolol, nevirapine, efavirenz (or its metabolite 8-OH-efavirenz), and the classical indicator of human impact, caffeine, in the catchment. The data showed that the lower Mphukojwane and the Elands rivers were the most affected, with the substances being present in the low to medium range. This study was also the first to conduct a series of in vitro biotests in the catchment. These tests indicated elevated estrogenic activity in the middle Mphukojwane and Elands rivers, as well as highly increased activity of aryl-hydrocarbon in the Elands River, which can induce inflammatory responses upon exposure and may lead to chronic inflammatory diseases, including asthma, cardiovascular diseases, and increased cancer risk.

The ecotoxicological investigation found the river sediment in the Metsi-Matso, Namahadi, and Elands rivers to be contaminated with chromium above the recommended prohibition level. The Elands River was the most polluted, with chromium and zinc concentrations exceeding the recommended thresholds. A number of metals (aluminium, iron, manganese, copper, and zinc) were detected at elevated concentrations in water samples. The Mphukojwane, lower Namahadi, and Elands rivers were the most impacted, with concentrations for aluminium and iron exceeding the TWQR for both domestic use and aquatic ecosystems at these sites. Acute toxicity tests found that toxicity increased from upstream to downstream, with the sites in the middle and lower reaches being more toxic than those in the upper reaches. There is concern about the water of the Mphukojwane River, with the upper site classified as having high acute toxicity (Class IV) and the middle site as very high acute toxicity (Class V).

Riparian and instream habitats were moderately to seriously modified from their natural state. The scores for instream habitat integrity and fish assemblages were lower than the numerical limits set by the Resource Quality Objectives (as published in the *Government Gazette* in 2016) for the catchment at all the sites, except for the upper and middle Namahadi River reaches. Of particular concern is the severe flow modification in the upper Metsi-Matso due to the lack of environmental flows being released from the Metsi-Matso Dam, severe infestation of black wattle trees at the upper Namahadi, and severe erosion and solid waste disposal at the upper Mphukojwane. Also concerning is the apparent rapid expansion of unlicensed sand mining (mostly for building and brick making) in the instream and riparian zones of streams and rivers in the catchment.

Disaster risk analysis

The disaster risk analysis comprised four sub-components: hazard analysis (hazard identification, probability, frequency, intensity), exposure analysis of key elements, vulnerability or resilience analysis using the community capitals approach, and calculation of the Multi-Hazard Risk Index (MHRI).

The hazard analysis identified four hazards that posed a high risk to communities in QwaQwa, namely water scarcity, drought, floods, and wildfires. All these highly ranked hazards were climate related, which indicates the importance of addressing climate change impacts and climate change-related risks.

The exposure analysis showed that the overall rating of exposure to the identified hazards was high. It highlighted the fact that communities in QwaQwa have very high exposure to water scarcity, and high exposure to the other three hazards (drought, floods, and wildfires). Most of the elements analysed show high exposure to all the hazards, while the population and land use showed very high exposure to water scarcity. Water sources showed very high exposure to wildfires.

The Resilience Index value calculated for QwaQwa was low, which indicated that communities in QwaQwa would struggle to recover from the impacts of extreme weather events and climate shocks. This result emphasises the importance of strengthening resilience in the area by investing in available resources to reduce disaster risk to climate change hazards and impacts.

The MHRI score was high, which indicated that the overall risk to the combination of climate-related hazards identified for QwaQwa was high.

This study took a different approach to traditional vulnerability analyses by using the Community Capitals Framework (CCF). The CCF differs from traditional approaches by identifying a community's unique strengths, and using those to empower communities. For QwaQwa, the social and natural capitals were identified as potential strengths that could be employed to improve resilience to climate-related hazards.

CONCLUSIONS

This study set out to develop an understanding of how the cumulative impacts of extreme weather events may affect the vulnerability of local communities in QwaQwa and how these impacts may be ameliorated through DRR and resilience building. To fully comprehend the extent and impact of climate-related risks in QwaQwa, a downscaled climate and hydrological model was developed for the catchment, an ecological risk assessment was conducted at nine representative sampling sites on the Namahadi, Metsi-Matso, Mphukojwane, and Elands rivers, and a disaster risk analysis was performed. The findings from the three components were then used to develop a tailor-made DRR framework that addresses the specific hazards, exposures, and vulnerabilities of local communities in the study area. The strategies that were developed specifically address the improvement of policy and political issues, local community empowerment, DRR and climate change adaptation, and resilience building to the climate-related hazards. The study followed a systems thinking approach to recommend strategies that are interrelated and interconnected. Recommendations were also made for further research to build on, and improve on, the current project and for the replicability of similar studies in other communities in South Africa. The innovative approach of assessing community assets, instead of community vulnerabilities to extreme climate change events, stands out in this study. The addition of a downscaled climate and hydrological model and an ecological risk assessment to the conventional disaster risk assessment methodology makes this study unique.

RECOMMENDATIONS

Recommendations for future research, based on the experience gained during this project, include:

Climate and hydrological modelling

- Sustained station observation networks are essential for the long-term analysis of local and regional climate trends, as well as for the calibration of satellite-derived climate products. The installation of local weather stations at various altitudes in different parts of the catchment would greatly contribute to future studies.
- Although the water releases from the Fika-Patso Dam are monitored, it does not reflect the “natural” or “uncontrolled” flow in the catchment. Considering the important contribution of streams in the catchment to the Wilge River (via the Elands River), and ultimately to the Vaal River, the installation of streamflow gauging stations in the catchment should be considered.

Ecological risk assessment

- Information on the aquatic ecology of the streams is sparse, fragmented, and uncoordinated. In light of the projected climate and hydrological changes for the catchment, it is clear that there is a dire need for a coordinated and comprehensive ecological assessment of the streams.
- The Resource Quality Objectives (RQOs) gazetted for the Elands River catchment (Republic of South Africa, 2016) are largely lacking for river water quality. The only category for which numerical limits are available is for nutrients (phosphate, nitrite, and nitrate), most probably due to a lack of information for the other categories (e.g. salts, system variables, toxins, and pathogens). The results from this study highlight the urgent need for setting numerical limits for the other classes and for conducting regular water quality monitoring, especially in the Namahadi, Mphukojwane, and Elands rivers.
- This study found that the RQOs set for the river instream habitats (Category C or higher) are not achieved for most of the middle and lower sites. Particularly concerning is the marked increase in illegal sand mining during the course of this study. This is a serious matter that requires urgent intervention by the relevant authorities, as well as further investigation.

Disaster risk analysis and reduction

- Stage 3 and 4 of the United Nations Office for Disaster Risk Reduction's (2016) risk assessment process, including monitoring and evaluation, ought to be commissioned in another research project by the Water Research Commission.
- Further, and more in-depth, research should be conducted on the 17 hazards identified for QwaQwa, but not only on those related to extreme climate change events, since risks are integrated and systematic, with cascading and compounding effects.
- The approach developed and applied in this study should be tested on other climate hotspots; for example, Nelson Mandela Bay District Municipality in the Eastern Cape or eThekwini in KwaZulu-Natal.

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LIST OF ABBREVIATIONS

β-NF	β-Naphthoflavone
4-OHT	4-Hydroxytamoxifen
ACRU	Agricultural Catchments Research Unit
AhR	Aryl-hydrocarbon receptor
AIDS	Acquired immunodeficiency syndrome
Al	Aluminium
As	Arsenic
BOD	Biochemical oxygen demand
BPA	Bisphenol A
BP-4	Bisphenol-4
Ca	Calcium
CAS	Chemical Abstracts Service
CCAM	Conformal Cubic Atmospheric Model
CCF	Community Capitals Framework
Cd	Cadmium
CEM	Centre for Environmental Management
CMIP5	Coupled Model Intercomparison Project Phase 5
CoBRA	Community Based Resilience Analysis
COD	Chemical oxygen demand
CoGTA	Department of Cooperative Governance and Traditional Affairs
Cr	Chromium
CR(VI)	Hexavalent chromium
CSIR	Council for Scientific and Industrial Research
Cu	Copper
CV	Coefficient of variation
DEET	N,N-Diethyl-meta-toluamide
DIN EN	Deutsches Institut für Normung Europaische Norm
DMSO	Dimethyl sulfoxide
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DRR	Disaster risk reduction
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
E2	17ß-Estradiol
EC	Electrical conductivity
EC50	50% effective concentration
ELL	Elands Lower [site code]
ELU	Elands Upper [site code]
EMS	Ethyl methanesulfonate

ESI	Electrospray ionisation
Fe	Iron
Flu	Flutamide
FRAI	Fish Response Assessment Index
GCM	Global Climate Model
hAR	Human androgen receptor
hER	Human estrogen receptor
Hg	Mercury
HGV	Health-oriented Guidance Value
HI	Habitat integrity
HIV	Human immunodeficiency virus
HRU	Hydrological response unit
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometer
IPCC	Intergovernmental Panel on Climate Change
IS	Internal standard
ISO	International Organization for Standardization
ISO/IEC	International Organization for Standardization / International Electrotechnical Commission
KI	Key informant
LC50	Lethal concentration causing the death of 50% of a population
LOQ	Limit of quantification
MAP	Mean annual precipitation
MAR	Mean annual runoff
Mg	Magnesium
MHRI	Multi-Hazard Risk Index
MM	Metsi-Matso Middle [site code]
Mn	Manganese
MNvit	Micronucleus in vitro
MPM	Mphukojwane Middle [site code]
MPN	Most probable number
MPU	Mphukojwane Upper [site code]
MU	Metsi-Matso Upper [site code]
MUSLE	Modified Universal Soil Loss Equation
NbS	Nature-based Solutions
NDMC	National Disaster Management Centre
NGO	Non-governmental organisation
Ni	Nickel
NL	Namahadi Lower [site code]
NM	Namahadi Middle [site code]
NU	Namahadi Upper [site code]

OECD	Organisation for Economic Co-operation and Development
OMP	Organic micropollutant
Pb	Lead
PDI	Peak Discharge Index
PE	Percentage effect
QnCDB	Quinary Catchments Database
RCP	Representative concentration pathway
RPMI	Roswell Park Memorial Institute
RQO	Resource Quality Objective
RSA	Republic of South Africa
SAC_{254}	Spectral absorption coefficient at 254 nm
SANS	South African National Standard
SFDRR	Sendai Framework for Disaster Risk Reduction
StatsSA	Statistics South Africa
T	Testosterone
TDS	Total dissolved solids
Tmin	Minimum temperature
TSS	Total suspended solids
TU	Toxicity unit
TWQR	Target Water Quality Range
UFS	University of the Free State
UN	United Nations
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNEP	United Nations Environment Programme
UNISDR	United Nations International Strategy for Disaster Reduction
USLE	Universal Soil Loss Equation
UV	Ultraviolet
WFI	Water for Injection
WRC	Water Research Commission
WTP	Water treatment plant
WTW	Water treatment works
WWTP	Wastewater treatment plant
YAAS	Yeast-based Anti-androgenic Screen
YAES	Yeast-based Anti-estrogenic Screen
YAS	Yeast-based Androgenic Screen
YDS	Yeast-based Dioxin-like Screen
YES	Yeast-based Estrogenic Screen
Zn	Zinc

LIST OF UNITS

μg	Microgram(s)
μg/L	Microgram(s) per litre
μL	Microlitre(s)
μm	Micrometre(s)
cc	Cubic centimetre(s)
cm	Centimetre(s)
g	Gram(s)
kg	Kilogram(s)
km	Kilometre(s)
km^2	Square kilometre(s)
m	Metre(s)
m^3	Cubic metre(s)
$m^3.s^{-1}$	Cubic metre per second
m^3/a	Cubic metres per annum
m^3/s	Cubic metres per second
$m^3/s.km^2$	Cubic metres per second per square kilometre
m.a.s.l.	Metres above sea level
mbar	Millibar
mg	Milligram(s)
mg/L	Milligram per litre
mg/kg	Milligram per kilogram
ml	Millilitre(s)
ML/d	Million litres per day
ml/min	Millilitre(s) per minute
mm	Millimetre(s)
$mm.h^{-1}$	Millimetres per hour
mm/a	Millimetres per annum
mS/cm	MilliSiemens per centimetre
ng/L	Nanograms per litre
nm	Nanometre(s)
psi	Pounds per square inch
t/ha	Tonnes per hectare
t/ha.a	Tonnes per hectare per annum
$t/km^2.a$	Tonnes per square kilometre per annum
V	Voltage
v/v	Volume per volume

CHAPTER 1: BACKGROUND

1.1 PROJECT BACKGROUND

Recent climate projections for the Southern African region strongly indicate that the occurrence of rainfall extremes and prolonged drought periods may increase in the near future. Such extreme events pose a severe threat to water resources, food security, public health, infrastructure, biological diversity, and ecological systems in the region, as well as changes to the temporal dynamics of flow regimes in rivers. These projected changes could hold important consequences for both humans (e.g. influencing freshwater water supply) and to riverine biota (e.g. influencing habitat availability and quality).

While current research on extremes generally focuses on relatively large catchments with a low spatial resolution, information is needed at detailed spatial resolution on smaller catchments as to whether the climate projections for Southern Africa actually display increasing probabilities of sequential extreme events of, for example, torrential rainfall following directly after an extended drought period. Sequential extremes could have severe consequences by triggering cascades of secondary effects such as high sediment yields with impacts on, for example, infrastructural damage to water purification plants.

To improve the resilience against such impacts and to develop efficient coping strategies, new approaches that integrate the assessment of exposure and vulnerability on the one hand, and offer efficient coping strategies on the other, are needed. However, such adaptation strategies must be based on appropriate and reliable downscaled information and must include communication technologies with early warning and decision support systems for the population and decision makers concerned. Such adaptation strategies are all the more important given that weak governance could further increase the exposure to these risks, and that both the water management sector and local municipalities in South Africa are poorly prepared for expected medium- and long-term changes associated with climate change in that these sectors are failing to integrate information on climate change into their management strategies and systems in a systematic manner (Mukheibir, 2008; Ziervogel *et al.*, 2008; Ziervogel *et al.*, 2010). This failure could hold dire consequences for already vulnerable communities and sectors and, to a large extent, counter socio-economic development efforts by the government and other non-governmental agencies.

Climate change is expected to have a marked impact on the flow regimes of rivers, which could either be reduced or enhanced markedly over the next 30 or so years; changing perennial rivers to non-perennial, and semi-permanent rivers to ephemeral or episodic rivers, or vice versa (Döll and Schmied, 2012; Van Vliet *et al.*, 2013; Gudmundsson *et al.*, 2021; Tanner *et al.*, 2022). It is therefore vital to understand how changes to the timing, seasonality, incidences, and magnitudes of high and low flows, or periods of flow intermittence, could increase the vulnerability of aquatic biota and river ecosystems to climate-induced changes. Of special interest are the potential effects on the ecosystem services (e.g. freshwater for household use, water for irrigation, dilution of pollution, etc.) delivered by these rivers. Much of South Africa lacks large freshwater bodies and many areas rely on groundwater and/or direct abstraction from rivers for freshwater supply. A change, especially a reduction, in annual and seasonal runoff could therefore not only severely affect freshwater biota, but also the communities that rely on these water sources. This study investigated the risk factors associated with the projected impacts of the expected future changes in the occurrence of extreme hydro-climatic events (e.g. floods, high-intensity rainfall events, and droughts) on river ecosystems in the QwaQwa area of the Upper Vaal River catchment in the Free State province of South Africa in order to develop a relevant and appropriate risk reduction strategy that would be useful to the local authorities, the water as well as the agricultural and human health sectors, and also to local communities in this area.

1.2 PROJECT OVERVIEW

The overarching aim of this study is to understand how river ecosystem services (including water provisioning) may be influenced by the possible cumulative impacts of successive extreme weather events in future, how these impacts may affect the vulnerability and resilience of local communities in the QwaQwa area, and how these effects may be ameliorated through risk reduction planning (see Table 1.1).

Table 1.1. Project objectives for the study

No.	Description of objectives
1	To determine how the ecological services of river ecosystems in the QwaQwa area could be impacted by an increase in the occurrence of extreme weather events.
2	To develop an understanding of the impact that secondary effects may have on service delivery and infrastructure development in QwaQwa.
3	To identify the most important hazards and risks for the QwaQwa community in terms of water delivery, human health, and environmental safety.
4	To prepare a tailor-made risk assessment for the QwaQwa area based on downscaled climate and hydrology models specifically developed for the area.
5	To develop a tailor-made disaster risk reduction (DRR) strategy and plan for the QwaQwa area.

In order to achieve the aims of the study, the project was divided into three phases: (1) risk analysis, (2) risk assessment, and (3) developing the risk reduction strategy and plan (see Figure 1.1). In the first phase, sampling sites were selected on the Namahadi, Metsi-Matso, Mphukojwane, and Elands rivers and were described to serve as a focal point for the different components of the study. During the second phase, the emphasis was on the identification of ecological risks, based on field surveys, and risks to the local communities, based on social surveys (semi-structured questionnaires and interviews). The identified risks were assessed in terms of probability, frequency, intensity, and magnitude against simulated changes in runoff and accumulated streamflow resulting from projected changes in the climate. During the third and final phase, the risk reduction strategy and plan for the QwaQwa area were developed.

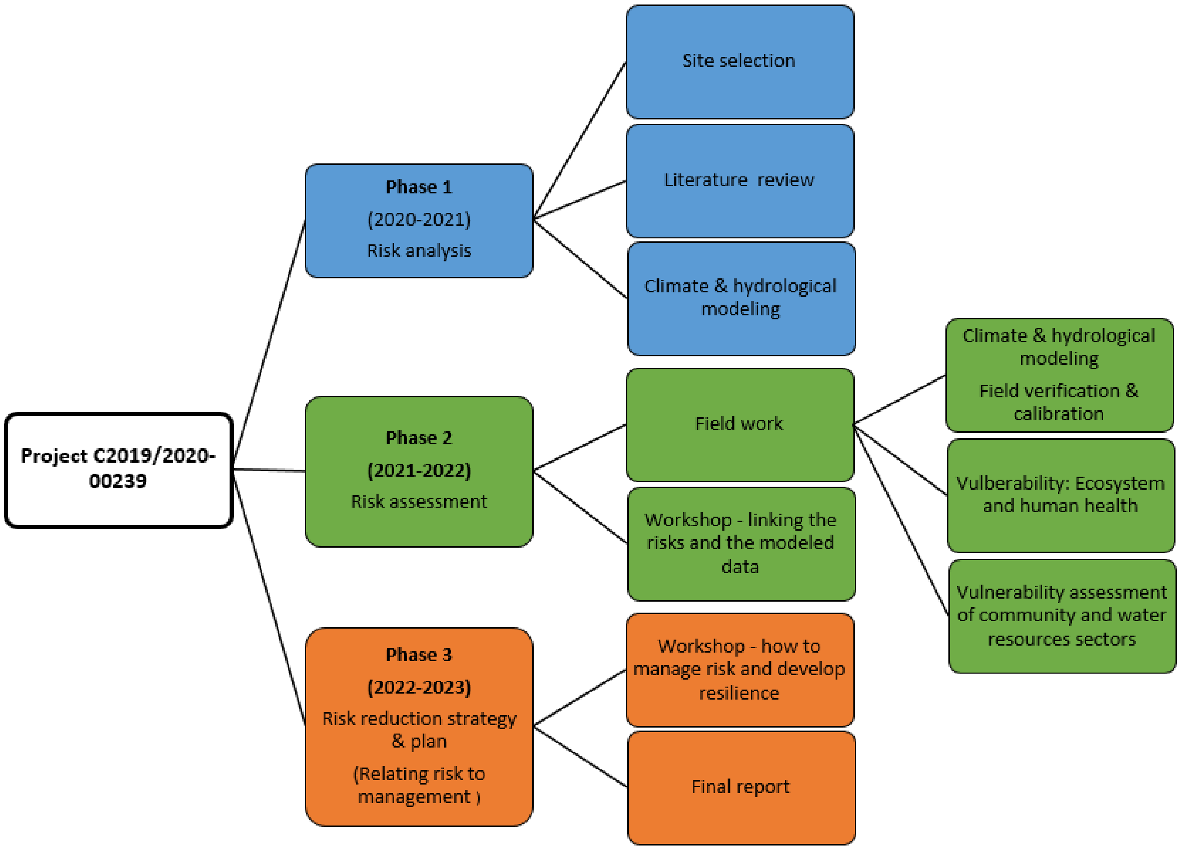


Figure 1.1. A graphic representation of the project outline

1.3 PROJECT TEAM

The multi-disciplinary project team consisted of eight members, who were assisted by four postgraduate students from the University of the Free State (UFS) (see Table 1.2).

Table 1.2. The study team involved in the study and their specific fields of expertise

PROJECT TEAM			
Name	**Role**	**Expertise**	**Institution**
Dr Marinda Avenant	Project leader	Environmental management and aquatic ecology	Centre for Environmental Management (CEM), UFS
Prof. Johanes Belle	Principal researcher	Environmental and disaster management	Disaster Management, Training and Education Centre for Africa, UFS
Prof. Beatrice Opeolu	Principal researcher	Water quality and environmental toxicology	Faculty of Applied Sciences, Cape Peninsula University of Technology
Dr Patricks Voua Otomo	Principal researcher	Environmental toxicology	Zoology and Entomology, UFS
Dr Dirk Jungmann	Principal researcher	Water quality and ecotoxicology	Institute for Hydrobiology, Technical University of Dresden
Dr Hilmar Börnick	Principal researcher	Chemistry	Institute of Water Chemistry, Technical University of Dresden

PROJECT TEAM			
Name	**Role**	**Expertise**	**Institution**
Emeritus Prof. Roland Schulze	Collaborator	Climate and hydrological modelling	University of KwaZulu-Natal
Mr Nick Davis	Collaborator	Climate and hydrological modelling	Isikhungsethu Environmental Services
Ms Ngitheni Nyoka	Student researcher (PhD)	Ecotoxicology	UFS
Ms Fumiso Muyambo	Student researcher (PhD)	Disaster management	UFS
Mr Nduduzo Kubheka	Student researcher (MSc)	Ecotoxicology	UFS
Mr Paul Masoabi	Student researcher (BA Hons)	Africa studies	UFS

1.4 PROJECT LIMITATIONS AND CONSTRAINTS

This project commenced on 1 April 2020 while the country was experiencing a national lockdown (level 5) due to a National State of Disaster being declared by President Cyril Ramaphosa on 23 March 2020 in an effort to curb the spread of the COVID-19 virus. The travel and social restrictions, associated with the National State of Disaster, had a significant impact on the sequencing and alignment of the research activities, as well as the overall progress of the study. The social component of the study, in particular, experienced long delays.

1.5 LAYOUT OF THIS REPORT

The remainder of the report is structured as follows:

- Chapter 2 provides a brief literature background on the impacts of extreme climate events on river health.
- Chapter 3 introduces and describes the study area.
- Chapter 4 discusses the development of the downscaled climate and hydrological and provides a brief overview of the results.
- Chapter 5 reports on the ecological risk assessment, including the key findings.
- Chapter 6 provides an overview of the disaster risk analysis process.
- Chapter 7 presents the disaster risk strategies developed for QwaQwa.
- Chapter 8 concludes the report with lessons learned and recommendations for future research.

CHAPTER 2: RISKS OF EXTREME CLIMATE EVENTS ON SOCIO-ECOLOGICAL SYSTEMS

2.1 INTRODUCTION

The Millennium Ecosystem Assessment, initiated by the United Nations (UN) and published in 2005, was a landmark study that assessed the state of ecosystems globally at the start of the third millennium. The study highlighted the interdependence between the state of ecological systems and human wellbeing by showing the consequences of anthropogenic impacts on ecosystems and their ability to deliver ecosystem services. It furthermore identified five drivers that contributed the most to ecosystem change and degradation in the 20th century, namely habitat change, invasive species, overexploitation, climate change, and pollution (Millennium Ecosystem Assessment, 2005). Of these five drivers, two were believed would become more and more significant in future, namely climate change and pollution (especially enriching from nitrogen and phosphorus). The concept of socio-ecological interdependence has since grown in prominence, and in the new series of Intergovernmental Panel on Climate Change (IPCC) reports the interdependence between climate, ecosystems and biodiversity, and human societies is recognised in the assessment of climate impacts and risks, as well as in the development of climate responses (IPCC, 2022).

2.2 OVERVIEW OF DISASTER RISK, EXPOSURE, VULNERABILITY, AND RESILIENCE

Climate change is perceived by many as the greatest threat the world has ever faced (Jenkins, 2021; UN Office of the High Commissioner for Human Rights, 2022). The impacts from a rapidly changing climate are arguably threatening every aspect of human existence and have been described by the Secretary-General of the UN, Mr Antonio Guterres, as a "crisis multiplier" that could threaten international peace and stability (UN Security Council, 2021). Although climate change is a global phenomenon, not everyone will be equally affected by its impacts. It has been shown that lower-income economies and populations may face the biggest climate risks (World Economic Forum, 2020). Southern Africa, in particular, is considered to be very vulnerable to the impacts of climate change, not only due to its geographical location and climate variability (Scholes and Engelbrecht, 2021), but also because the region has been experiencing climate changes that are more rapid and severe than the global mean (Maúre *et al.*, 2018; Fitchett, 2021). The region's vulnerability is further aggravated by socio-economic factors such as widespread poverty, declining food production and food insecurity, habitat degradation and desertification, poor and ageing infrastructure, increasing pressure on natural resources, weak governance and institutions, the prevalence of HIV/AIDS and other diseases such as malaria, armed conflicts, etc., and recently COVID-19 (United Nations Environment Programme [UNEP], 2013; Niang *et al.*, 2014; World Economic Forum, 2020).

The concept of "risk" has become increasingly prominent in the consideration of climate change impacts over the last decade. In the most recent series of reports published by the IPCC, "risk" is used as a central framework, both for understanding how climate change may impact socio-ecological systems across regions, sectors, communities, and generations, and for developing appropriate responses to these impacts (IPCC, 2022). According to the Sixth Assessment Report of the IPCC (2022), risk, which can be defined as “the potential for adverse consequences for human or ecological systems”, can arise from the dynamic interaction between climate-related hazards, the exposure to these hazards, and the vulnerability of human or ecological systems to these hazards when exposed to them. Climate-related hazards refer to “the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources” (IPCC, 2022). The exposure and vulnerability to such climate-related hazards are not homogenous, and differ within communities and across societies, regions, countries, and even time (IPCC, 2022). Exposure and vulnerability are seen as the key determinants of disaster risk, and climate adaptation should focus on reducing exposure and vulnerability to hazards and building community and system resilience.

The Sendai Framework for Disaster Risk Reduction (SFDRR) 2015-2030 was the outcome of the Third UN World Conference on Disaster Risk Reduction held from 14 to 18 March 2015 in Sendai in Japan. Its main outcome was “[t]he substantial reduction in disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries” (United Nations International Strategy for Disaster Reduction [UNISDR], 2015) and its goal was to “prevent new and reduce existing disaster risk through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience” (UNISDR, 2015). With seven targets and four priority areas, the SFDRR serves as an international yardstick to measure the extent to which countries in the global community have reduced disaster risks, including those emanating from extreme climate events. The goal, Target ‘D’, and Priority 3 of the SFDRR emphasise building community and system resilience to multiple hazards.

2.3 EXTREME CLIMATE EVENTS AND DISASTERS

2.3.1 Risks of extreme climate events and disasters

Human-induced global warming has already resulted in multiple changes in the climate system, including increases in the intensity and frequency of weather extremes (Hoegh-Guldberg *et al.*, 2018). Climate models project that extreme events may become even more prominent in the near to distant future. An extreme climate or weather event may be defined as the “occurrence of value of a weather or climate variable above (or below) a threshold bear of the range of observed values for a particular variable” (IPCC, 2012). Although sparse observational and operational records in Southern Africa limit the ability to detect trends in extreme events with high confidence, there is strong evidence of an increasing trend for hot extremes, erratic rainfall patterns with increasing intensity, frequency of dry spells and droughts, and the magnitude of storms producing flood events (Davis-Reddy, 2017). Such events pose a severe threat to water resources, food security, sustainable energy, public health, infrastructure, biological diversity, and ecological systems in the region (Ziervogel *et al.*, 2014; Van Niekerk and Le Roux, 2017; Bradshaw *et al.*, 2022).

The biggest impact of climate change may not be that single events become more severe, but that more compounding extreme events may occur in regions with naturally high climate variability and vulnerability (IPCC, 2012; Clarke *et al*., 2022). The cumulative impact of successive extreme events could have severe consequences on human and ecological systems; for example, sequential flood events could trigger cascades of secondary effects, such as increased sediment delivery that causes infrastructural damage to water purification plants, and nutrient and pesticide input into surface water systems that lead to deterioration of drinking water quality (Woodward *et al*., 2016). To improve resilience against such impacts and to develop efficient coping strategies, new approaches that integrate the assessment of exposure and vulnerability on the one hand and offer efficient coping strategies on the other are needed (Gallina *et al.*, 2016; Schanze, 2016). Such adaptation strategies must, however, be based on appropriate and reliable downscaled information, and must include communication technologies with early warning and decision support systems for the population and decision makers concerned. It is for all these reasons that a study of the assessment of climate-related extreme events and suggesting risk reduction and resilience-building strategies in QwaQwa by the South African Water Research Commission (WRC) are necessary.

2.3.2 The likelihood of an increase in the frequency of extreme climate events in Southern Africa and the QwaQwa study area

There is evidence that the frequency and intensity of extreme climate events have been increasing globally since the 1950s (Field, 2012; Abrahams *et al.*, 2013; Leigh *et al*., 2015; Garner *et al*., 2015), regionally in Southern Africa (Mason *et al*., 1999; Kruger and Sekele, 2013; MacKellar *et al.*, 2014; Engelbrecht *et al.*, 2015; Davis-Reddy and Vincent, 2017; Perkins-Kirkpatrick and Gibson, 2017), and locally in the Maloti-Drakensberg region (Mohamed and Mukwada, 2019; Mukwada and Mutana, 2023). Climate projections indicate that these extreme events will most likely become more common and more severe in the future, both globally (Abrahams *et al.*, 2013; IPCC, 2014) and in Southern Africa (Field, 2012; Niang *et al.*, 2014; Archer *et al.*, 2018). According to the IPCC (2022), there is high confidence that Southern Africa could experience more heat waves and warm spells that will last longer than in the past. There is medium confidence that droughts over Southern Africa will intensify due to a reduction in rainfall and an increase in evaporation and evapotranspiration, and low confidence that the intensity of rainfall events will increase in the intermediate and long term (Field, 2012). According to regional climate models, shifts in the frequency and variance of extreme climate variables in South Africa could increase in the future (Lumsden *et al.*, 2009; Schulze, 2012).

Mohamed and Mukwada (2019) recently reported a significant increase in the long-term (1960-2016) annual mean maximum and minimum temperatures for the Maloti-Drakensberg region. It was also clear from Mohamed and Mukwada's (2019) study that the frequency of temperature extremes increased significantly over this 56-year period. For the Orange-Senqu River basin, future trends with regard to rainfall and droughts are unclear, with earlier studies (Hewitson *et al.*, 2005; Knoesen *et al.*, 2009; Crerar *et al.*, 2011; see also Dallas and Rivers-Moore, 2014) projecting increased rainfall in summer and autumn (including extreme rainfall events) and decreased short-term droughts, especially in the higher-altitude eastern part of the catchment. A recent study by Abiodun *et al.* (2019) found, however, that drought intensity and frequency could increase over the catchment in the future (under increasing global warming levels) if both rainfall and potential evapotranspiration are considered (instead of only rainfall). Rainfall variability is expected to increase in the future, both within and between years (Knoesen *et al.*, 2009; Crerar *et al.*, 2011; Dallas and Rivers-Moore, 2014), which increases uncertainty of when streamflow could occur.

Mountain regions are considered particularly vulnerable to climate change (Mukwada and Manatsa, 2018). According to Mohamed and Mukwada (2019), such regions have spatially complex patterns. The steep elevation results in vertical gradients of microclimates, which in turn influence species distribution, livelihoods, and the availability of water resources (Mohamed and Mukwada, 2019). Considering the important effect that temperature has on other meteorological variables, the warming trend over the Maloti-Drakensberg region could have a serious impact on water availability through increased evapotranspiration from wetlands, rivers, and dams (Mohamed and Mukwada, 2019). The abrupt temperature shifts noted by Mohamed and Mukwada (2019) could have a negative impact on the already stressed aquatic ecosystems in the QwaQwa area, which would put the already water-stressed QwaQwa community at risk of reduced ecosystem service delivery.

2.3.3 Potential impacts of extreme events on the ecological integrity of rivers

A river's natural flow regime is the key driver of its ecological features and functioning (Poff and Zimmerman, 2010; Arthington, 2012), and alterations to the flow regime could change a river's unique character (Bunn and Arthington, 2002; Postel and Richter, 2003). Streamflow, in turn, is influenced by hydro-climatological processes, and even though river health is determined by many interacting variables (e.g. water temperature, nutrient availability, and intact riparia), changes to the flow regime could alter the physical habitat template of a river, which would result in long-term ecological changes (Garner *et al.*, 2015). Extreme climate events, caused by meteorological anomalies, may therefore act as structuring forces that could change aquatic habitat, biodiversity, and ecological functioning in riverine ecosystems (Humphries and Baldwin, 2003; Heino *et al.*, 2009; Fenoglio *et al.*, 2010; Morrongiello *et al.*, 2011; Abrahams *et al.*, 2013; Filipe *et al.*, 2013; Dallas and Rivers-Moore, 2014; Death *et al.*, 2015; Leigh *et al.*, 2015; Woodward *et al.*, 2016). Understanding the ecological effects of these events on the drivers (e.g. hydrology, fluvial geomorphology, and water quality) of riverine ecosystems is crucially important for predicting how aquatic communities (fish, aquatic macroinvertebrates, riparian vegetation, etc.) and consequently human use of the river would respond to changes. Examples of the negative impacts extreme events may have on river systems are presented in Tables 2.1 and 2.2.

Table 2.1. Potential negative impacts of extreme climate events on physical riverine drivers

Extreme event	Potential impact on driver
Heatwaves	• Increased water temperatures; • Decreased dissolved oxygen (DO) concentrations; and • Increased decomposition of organic matter.
Droughts	• Loss of surface flow, connectivity broken, formation of isolated pools, and eventually dry river beds; • Decreased baseflow due to loss of groundwater inflow from aquifers; • Increased periods of flow intermittence (zero flow); • Increased accumulation of sediment due to flow intermittence; • Declining water quality (salinisation) in isolated habitats; and • Loss of aquatic habitats.
Heavy rainfall and floods	• Increased catchment and channel erosion; • Increased runoff, sediment delivery, and turbidity; • Increased connectivity of aquatic habitats; • Scouring of river substrata and loss of habitat; • Removal of in situ basal resources; e.g. macrophytes and detritus; and • Hypoxic blackwater events due to microbial breakdown of organic matter washed into rivers.
Wildfires	• Formation of hydrophobic soils, leading to lower infiltration and increased runoff and sediment delivery to streams; • Loss of terrestrial and riparian vegetation, which could influence, for example, water temperature and energy input into the river; and • Increased levels of phosphorous and conductivity in some cases.

Source: Whitehead *et al.* (2009); Abrahams *et al.* (2013); Dallas and Rivers-Moore (2014); Jaeger *et al.* (2014); Leigh *et al.* (2015); Death *et al.* (2015); Woodward *et al.* (2016)

Table 2.2. Potential negative impacts of extreme climate events on riverine biota

Extreme event	Potential impact on response
Heatwaves	• Aquatic species are vulnerable when their upper thermal limits are exceeded, especially over a longer period such as a heatwave; • Increased algal growth and incidence of cyanotoxins; • Increased metabolism, especially in poikilothermic species; • Reproduction and sex ratios for some species; and • Changes in community processes and structures.
Droughts	• Longitudinal ecological processes are interrupted; e.g. reduced nutrient input from upstream that results in reduced productivity; • Restriction of migrating and spawning patterns for fish species; • Riparian vegetation separated from channel due to lateral drying; • Loss of riparian vegetation due to a drop in the groundwater level; • Extirpation of fish when refuge pools dry up; • Switch from lotic to lentic conditions, and eventually from lentic to terrestrial conditions (vegetation encroachment into the channel); and • Loss of sensitive species and domination by more tolerant species.
Heavy rainfall and floods	• Displacement of aquatic organisms; • Expansion of invasive species (e.g. exotic macrophytes); • Untimely floods could influence natural reproduction cues and cycles of freshwater biota; and • Changes in food resources.
Wildfires	• Responses linked to increased water temperature, nutrient input, and sedimentation; • Reduction in macroinvertebrate richness and density; and • Dominance by more generalist species.

Source: Heino *et al.* (2009); Fenoglio *et al.* (2010); Abrahams *et al.* (2013); Filipe *et al.* (2013); Dallas and Rivers-Moore (2014); Leigh *et al.* (2015); Death *et al.* (2015); Woodward *et al.* (2016); Tanner *et al.* (2022)

2.3.3.1 Predicting the impacts of extreme events on river ecosystems and river use

The effects of extreme climate fluctuations on riverine ecosystems are poorly understood (Fenoglio *et al.*, 2010; Woodward *et al.*, 2016). Although the physical effects of floods and droughts on river ecosystems are relatively well studied, the biological and indirect impacts (e.g. cost of lost ecosystem services) of these events are less known and uncertain (Filipe *et al.*, 2013; Death *et al.*, 2015). As a result, accurate predictions of biological changes, and the impact these may have on biodiversity and ecosystem services, are difficult to make, and will remain of low confidence without supporting field studies. Other factors that may influence the accuracy of such predictions in South Africa are the high levels of natural variability in some systems (e.g. seasonal and ephemeral systems), a general poor understanding of flow-ecology relationships (for the majority of South African rivers), a poor understanding of life-histories for the majority of aquatic species, a general lack of specialist species in rivers naturally subjected to large disturbances (aquatic communities in these rivers are generally dominated by hardy generalist species), and a deteriorating trend in river health (due to increased anthropogenic pressures and poor river management) that increases the vulnerability of river systems.

2.3.4 Potential impacts of extreme events on water river use and human health

There is high confidence that climate change has the potential to reduce the quantity and quality of freshwater and groundwater resources, especially in semi-arid and arid regions characterised by large spatial and temporal climate variability (Dudgeon *et al.*, 2006; IPCC, 2014; Döll *et al.*, 2015; Kusangaya *et al.*, 2017), such as Southern Africa (Scholes and Engelbrecht, 2021). South Africa depends heavily on surface water sources, which provide 85% of the usable water in the country, and is also the main source of potable water (Colvin *et al.*, 2016). It is therefore of great concern that surface water resources are considered to be at the epicentre of projected climate change impacts (Kusangaya *et al.*, 2017).

Climate change is expected to reduce raw water quality and to pose risks to the quality of drinking water (Döll *et al.*, 2015; Klasic *et al.*, 2017; Van Niekerk and Le Roux, 2017; Wang *et al.*, 2022). According to Döll *et al.* (2015), water quality projections are difficult to make; the following factors, however, may contribute to a deterioration of water quality: increased water temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; increased concentration of pollutants during low-flow episodes; and flood damage to water treatment infrastructure that disrupts municipal water treatment. A brief overview of the impacts of extreme events on the quantity and quality of surface water is presented below.

2.3.4.1 Extreme heat and heatwaves

Extreme heat may cause unusually high air and water temperatures that can change the physical and chemical properties of water (Abrahams *et al.*, 2013; Dallas and Rivers-Moore, 2014; Woodward *et al.*, 2016; Wang *et al.*, 2022). Such changes may include lower DO solubility, higher inorganic salt concentrations, increased pH levels, accelerated release of nutrients from sludge, increased algal growth and the release of cyanotoxins from heat-tolerant cyanobacteria, higher microbial activity, etc. Higher water temperatures may also increase the oxygen consumption and metabolism of aquatic biota, and may cause mortality among riverine benthic invertebrates when individuals are pushed outside of their optimal temperature range (Abrahams *et al.*, 2013; Woodward *et al.*, 2016). Estimating water increases from air temperature projections is, however, complex, since factors such as solar radiation, groundwater input, and shading from riparian vegetation may have an insulating or buffering effect (Dallas and Rivers-Moore, 2014).

2.3.4.2 Storms and floods

Floods generally occur when the volume of water in a river exceeds the capacity of the channel to transport the water downstream. During a flood, the velocity and erosive power of the water increase with growing discharge, which dislodges particles from the river bed and banks and uprooting emerged and submerged vegetation (Abrahams *et al.*, 2013). Floods may therefore increase erosion of the mineral substrate, remove aquatic vegetation, and disperse organic material and debris downstream, before depositing it downstream as the velocity is reduced. Heavy rainfall and subsequent runoff from steep, sparsely vegetated slopes, urban substrates, and overflown sewers may wash large amounts of sediment (as well as pollutants in the sediment such as heavy metals, pesticides, and organic compounds), pollutants (including particulate matter, pathogens, and soluble substances), and organic waste into the river (Wang *et al.*, 2022). The first stormflow of the season is known to be particularly high in pollutants and organic matter and leads to an increase in suspended solids and dissolved organic carbon (DOC) and a decrease in DO concentration (Abrahams *et al.*, 2013). The nutrient loading of water bodies may, in combination with higher air and water temperatures, cause algal and cyanobacteria blooms (Klasic *et al.*, 2017). High flows may also improve water quality by diluting the pollutant load and decreasing electrical conductivity (EC) in the receiving waters.

2.3.4.3 Droughts (and very low flows)

Extreme low flows during droughts can be more detrimental to river systems than high flows, due to a higher risk of ecological change and potentially long-term effects (Abrahams *et al.*, 2013; Woodward *et al.*, 2016). Lower rainfall and increased evaporative demand (linked to warming temperatures) during droughts are projected to reduce soil moisture, runoff, and groundwater recharge, which causes water shortages and low flows in rivers (Scholes and Engelbrecht, 2021). In severe droughts, streamflow may be interrupted, which can cause river fragmentation, longer residence time, and the loss of longitudinal processes (e.g. ameliorating effect of continuous flow on water quality, downstream invertebrate drift, etc.). The lower velocity may cause the deposition of suspended solids, which reduces turbidity. Loss of dilution capacity due to very low or interrupted flows may increase the concentrations of dissolved and particulate matter, as well as other parameters such as water temperature, DO, and EC. Also important to note is that the quality of surface water may change due to a higher proportion of groundwater, which may have lower DO and higher nutrient concentrations (Abrahams *et al.*, 2013). During droughts, the effluents from wastewater treatment plants (WWTPs) have a more pronounced effect on water quality due to the lower dilution and self-purifying capacity of water bodies. This could pose a serious risk to ecological and human health in situations where the WWTPs are not operating optimally.

2.3.4.4 Wildfires

Extreme high temperatures, in combination with droughts and lightning storms, may trigger wildfires (Thompson *et al.*, 2016). Wildfires can generate ash that contains minerals and oxidised organic substances that can increase the total nitrogen, phosphorous, organic carbon, and sediment content of freshwater (Wang *et al.*, 2022). Fires can also accelerate soil erosion and change runoff patterns in catchments by destroying surface vegetation and organic soil material that facilitate water infiltration after rainfall (Scott, 1993; Strydom and Savage, 2016). It has been shown that fires on mountain slopes may reduce infiltration by as much as 50%, which increases the likelihood of flash flooding (Merz, 2004). The increased runoff generated from these burnt slopes increases soil removal, which results in increased sediment delivery to river systems (Strydom and Savage, 2016).

2.3.5 Management considerations

Managing water resources under a changing climate is particularly challenging due to the high levels of uncertainty; not only due to natural variability and uncertainties around future greenhouse gas emissions and downscaled climate modelling, but also related to other factors such as the difficulty of quantifying potential freshwater-related impacts (Döll *et al.*, 2015). According to Döll *et al.* (2015), these uncertainties make it very difficult to quantify the impact of climate change on freshwater systems in a deterministic way. Döll *et al.* (2015) propose that water managers identify potential hazards and risks (related to freshwaters) for a broad range of possible future hydrological changes and then determine freshwater risks by assessing the consequences of the identified hazards, also taking into account the level of exposure and vulnerability.

As drastic as climate change impacts can be for surface waters, it is important to emphasise that climate change is not the only stressor on these systems. Additional stressors to river functioning include anthropogenic interventions such as a growing water demand, pollution, introduction of alien species, water abstraction, inter-basin transfers, large-scale damming, land use changes, habitat fragmentation, sediment mining, removal of riparian vegetation, etc. (Kusangaya *et al.*, 2017; Best, 2019). The implication of this is that the total risk to river systems is often underestimated (Thompson *et al.*, 2021).

For example, the deterioration of surface water quality due to increased anthropogenic activities, population growth, and climate change has led to an increase in the accumulation of waste and pollutants in water bodies (Wu *et al.*, 2017). Major rivers in Africa, Latin America, and Asia have been identified as the worst hit in terms of pollution load, and this has been on the increase since the 1990s (UNEP, 2016). Locally, pollution due to metal and pesticide contamination causes the most concern. In the eastern Free State especially, metal pollution in the Elands River in Phuthaditjhaba and the Wilge River in Harrismith has recently been linked to failing wastewater treatment works and the lack of proper refuse removal services (Moloi *et al.*, 2020).

Polluted water affects public health directly or indirectly. This is because polluted water not only limits its utilisation value, it also places an added economic burden on society through treatment costs incurred for more polluted the water. Poor water quality also negatively affects the living standards, dignity, and social wellbeing of humans (Council for Scientific and Industrial Research [CSIR], 2010; Apeh and Ekenta, 2012; Cullis *et al.,* 2018). Polluted water affects human health in many ways. Waterborne diseases such as diarrhoea, cholera, and bacterial infections are particularly endemic in many parts of the world, including South Africa. These waterborne diseases, especially those leading to diarrhoea, are suspected to cause three to five million deaths yearly among children. These diseases remain among the leading causes of deaths and disability worldwide and continue to dominate the global burden of water-related diseases (CSIR, 2010; Yang *et al.,* 2012). Additionally, Yang *et al.* (2012) reported that although substantial advances in biomedical sciences and public health measures have facilitated control of many infectious diseases in the past century, the world has witnessed an increasing incidence and geographical expansion of emerging and re-emerging infectious diseases.

CHAPTER 3: CASE STUDY: QWAQWA

3.1 BACKGROUND

QwaQwa, a former homeland area for Sesotho-speaking people at the foot of the Maloti-Drakensberg mountain range in the north-eastern corner of the Free State province, South Africa, has been plagued by water insecurity for more than two decades (see Figure 3.1). Phuthaditjhaba, QwaQwa's urban centre, falls under the jurisdiction of the Maluti-a-Phofung Local Municipality, which is responsible for providing basic services to communities, including water and sanitation (see Figure 3.2). The municipality has, however, a poor record of service delivery. Service delivery protests by communities in the Maluti-a-Phofung Local Municipality have been occurring since 2004, with limited or no access to safe drinking water as one of the main grievances (*Mail & Guardian*, 2004; Gouws *et al.*, 2011; Mdlalane, 2020). Nearly 80% of houses in the urban centre are connected to the municipal water supply (Statistics South Africa [StatsSA], 2011), but this percentage is expected to be considerably lower for informal settlements on the outskirts of town and rural villages higher up in the mountains. Access to the municipal water network does not necessarily guarantee access to clean water, since prolonged interruptions in the water supply have become a common occurrence in QwaQwa (Sekhele and Voua Otomo, 2023). Water insecurity problems came to a head during a severe drought in 2015/2016 that caused a drastic decline in the water levels of the Fika-Patso and Metsi-Matso reservoirs, the main water supply in QwaQwa, which necessitated the Maluti-a-Phofung Local Municipality to erect communal water tanks and deliver water with hired water trucks (Macupe, 2020; Mocwagae, 2020; Mukwada and Mutana, 2023). Despite these efforts, many poor households that were unable to afford buying drinking water were forced to rely directly on potentially polluted local rivers and streams for access to water (Khalane, 2020). Alarmingly, the frequency and intensity of severe droughts are expected to increase in the catchment in the immediate future (Abiodun *et al.*, 2019; Mukwada and Mutana, 2023). Together with other risk factors such as projected increases in minimum and maximum temperatures, as well as evaporation, lower rainfall during the dry winter season, more dry spells and fewer wet spells (see Chapter 4), reduced streamflow in the headwater streams (Mukwada and Mutana, 2023), continued influx of people into the area (StatsSA, 2011), widespread environmental degradation in the catchment (Avenant, 2022), high levels of poverty and unemployment (Noble and Wright, 2013; Melore and Nel, 2020), poor governance and gross mismanagement of resources (Sekhele and Voua Otomo, 2023), insufficient water infrastructure and maintenance, underperforming WWTPs, and improper sewage sludge disposal (Sekhele and Voua Otomo, 2023), communities in QwaQwa remain highly vulnerable to water insecurity – even during years with average or above-average rainfall.

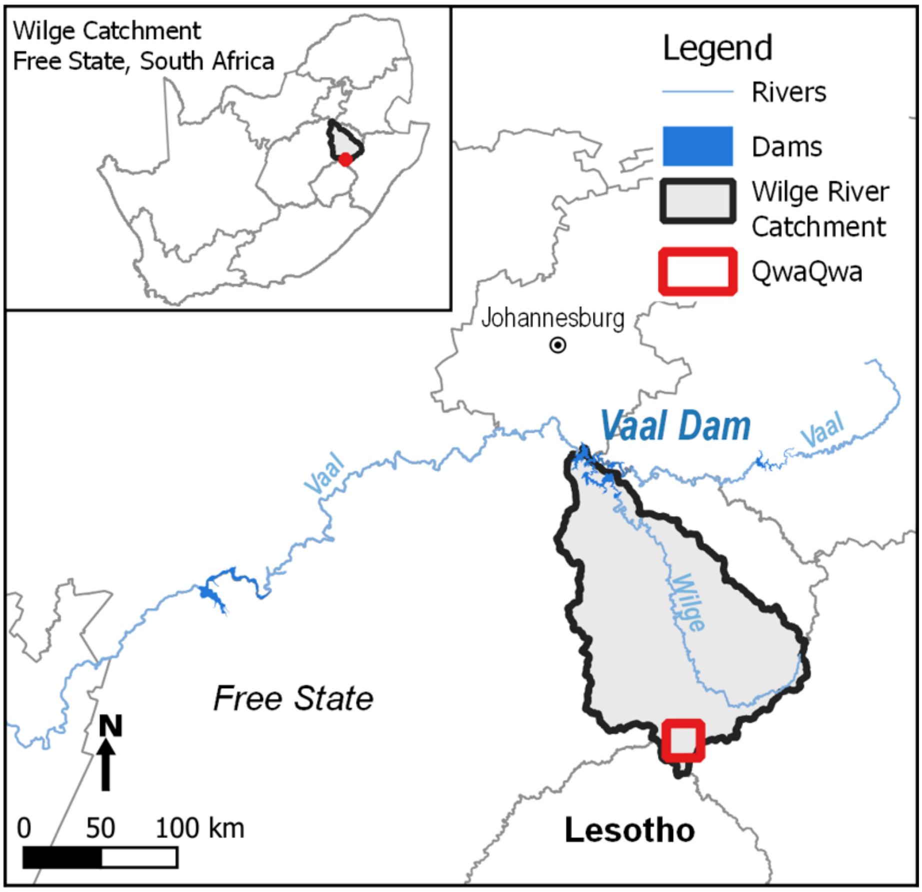


Figure 3.1. Map showing the position of the study area within the Wilge River catchment

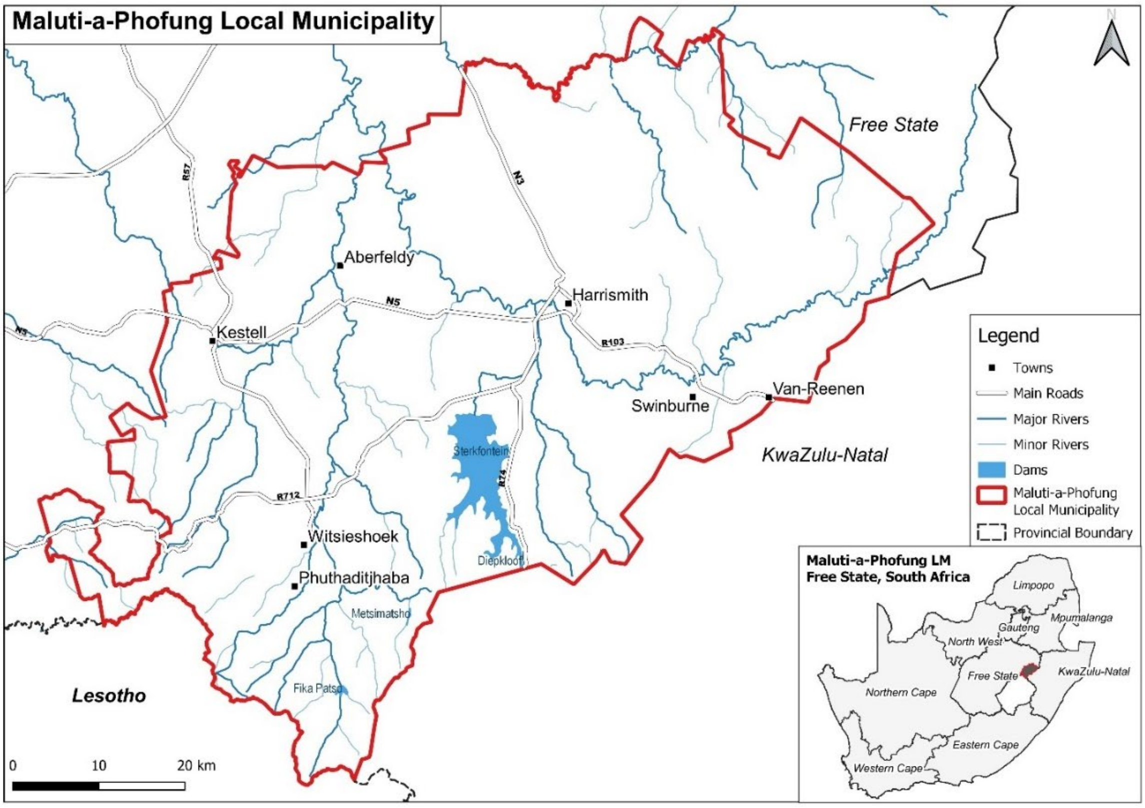


Figure 3.2. Map showing the boundaries of the Maluti-a-Phofung Local Municipality

3.2 DIFFERENT SCALES OF SAMPLING AND SITE SELECTION

3.2.1 Scale of sampling

Data collection for the three components of the study – climate and hydrological modelling, ecological risk assessment, and disaster risk assessment – was conducted at different spatial scales. Whereas the climate and hydrological modelling mainly focused at higher (larger) hierarchical scales, such as quinary catchment, river segment, and hydrological response unit (HRU) level, the ecological work was conducted at lower (smaller) scales, such as river reach, morphological unit, and hydraulic biotope level (based on the hierarchical geomorphological classification for South African rivers by Rowntree and Wadeson, 1999). Due to the fact that the ecological sampling focused on the lowest spatial level in the catchment, the site-selection process was predominantly driven by ecological requirements (see Section 3.2.2).

The purpose of the field sampling was to identify potential risk factors linked to field-based knowledge of the selected rivers in the study area, and to serve as focus points for the downscaled climate and hydrological modelling, as well as the social surveys.

3.2.2 Site selection

A total of nine sampling sites were selected for study on the Metsi-Matso, Mphukojwane, Namahadi, and Elands rivers. These rivers, which drain the mountainous areas around Phuthaditjhaba and the surrounding rural villages, were chosen in order to screen the greater QwaQwa area. The sites were selected to represent both sparsely inhabited and relatively undisturbed areas, and densely urbanised zones with a diversity of anthropogenic activities, as well as to represent both elevated areas on hilly slopes and flatter lower-lying downstream areas.

Based on the project proposal and available budget, it was decided to select two sampling sites on each of the Metsi-Matso, Namahadi, and Mphukojwane rivers: one relatively undisturbed site in the upper reaches and one more impacted site in the middle or lower reaches. An additional site was added on the Elands River to reflect the impacts downstream of where the abovementioned rivers join. Other criteria that guided site selection included the accessibility to sites, suitability for sampling, ecological representativity, the presence of critical habitats, and the availability of historical data on the specific river reaches.

In preparation for site selection, a comprehensive literature review was conducted to identify if, and where, previous studies had been conducted in the study area. This was important for obtaining background information on the catchment and various rivers, to collect existing information and ecological data, and to allow for continuity of study where possible. Next, a range of maps representing the physical and ecological characteristics of the catchments (e.g. topography, climate, land use, and ecoregions) were prepared to identify river reaches that would satisfy the primary criteria of the study. In addition, Google Earth (web-based; version 9.165.0.1) was used to investigate land uses and upstream anthropogenic impacts (e.g. weirs, dams, agricultural fields, sand mining, and informal settlements) in the catchment and to identify potential sites in the selected reaches and catchment sections. In a next step, the potential sites identified during the desktop study were visited by a core team during a ground-truth survey on 6 October 2020. Where necessary, alternative sites were identified and assessed. During the final step, the selected sites were verified during a field visit on 25 February 2021, in preparation for the first sampling visit in April 2021.

3.3 DESCRIPTION OF STUDY AREA

3.3.1 Physical environment

QwaQwa is situated in the north-east of the Free State province, bordering on KwaZulu-Natal to the south-east and Lesotho on the south-west. The area is located in a relatively narrow valley in a section of the Maloti-Drakensberg mountain range, at an elevation of between 1 675 to more than 2 200 metres above sea level (m.a.s.l.) (see Figure 3.3). The mountainous area serves as the headwaters for several streams, including the Mphukojwane, Namahadi, and Metsi-Matso rivers, which join to form the Elands River, and later the Wilge River. The Wilge River is an important source of water for the Vaal Dam complex, contributing 36% of surface water to the Upper Vaal River catchment (mean annual runoff [MAR] = 868 m^3/a; Department of Water Affairs and Forestry [DWAF], 2004).

3.3.1.1 Climate

Annual temperatures in QwaQwa range from -5°C in mid-winter to 35°C in mid-summer (Department of Water Affairs, 2011). The mean annual temperature is lower in the higher-lying mountainous areas (13°C) and higher in the lower-lying Phuthaditjhaba area (14°C) (see Figure 3.4). Frost occurs in winter, with occasional snowfall in the higher-lying areas (DWAF, 2004).

QwaQwa falls within the summer rainfall region of South Africa. Rainfall is strongly seasonal, with most of the rain occurring between October and March (DWAF, 2004). Rainfall is the highest in the high-altitude headwaters of the streams (mean annual precipitation [MAP] >950 mm), and decreases gradually towards Phuthaditjhaba (MAP <750 mm) (see Figure 3.4). Longer-term meteorological data (1986-2016) show that Phuthaditjhaba received a mean annual rainfall of 629 mm over the last three decades (Agricultural Research Council Institute for Soil Climate and Water, 2016).

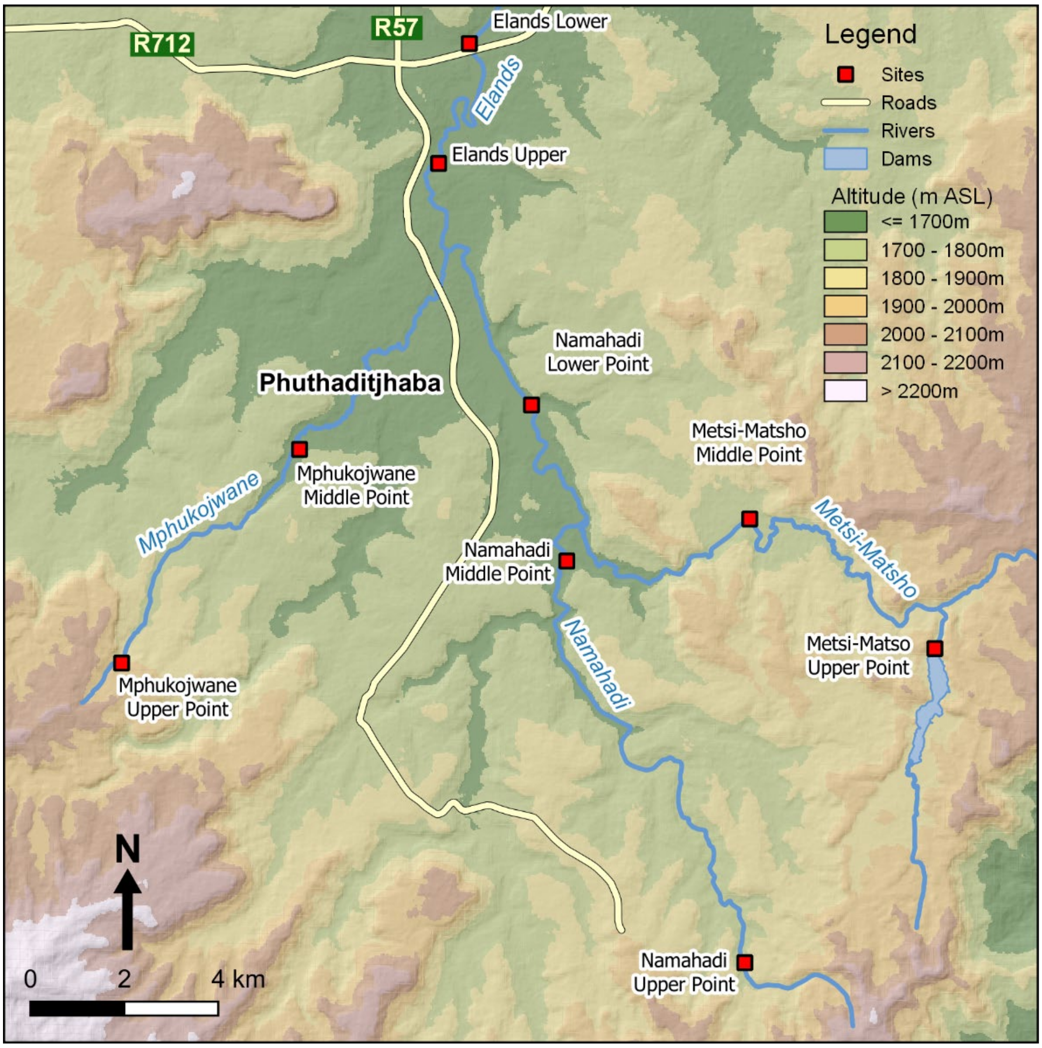


Figure 3.3. Topography of the study area

3.3.1.2 Geology, soil, and erodibility

The study area is mainly underlain by the Karoo Supergroup (Hobbs *et al.*, 2013). The Mphukojwane, Namahadi, and Metsi-Matso rivers have predominantly basalt at the origin of the rivers, with arenite and mudstone in the downstream areas (CEM, 2003). The soils comprise mainly of shallow lithosols, representative of the Glenrosa and Mispah soil forms (CEM, 2003).

The topography of the QwaQwa area is mostly steep due to the mountainous slopes of the Maloti-Drakensberg mountains. This makes the area vulnerable to erosion, which can be aggravated by some land uses and overgrazing. Using an Erodibility Index that considers a combination of factors such as the slope, soil type, rainfall intensity, and land use, the sensitivity of an area to erosion can be expressed (Rooseboom *et al.,* 1992). The headwaters of the study rivers have moderate sediment potential (Erodibility Index value of 10), while the downstream areas have a high sediment delivery potential (Erodibility Index value of 8) (CEM, 2003).

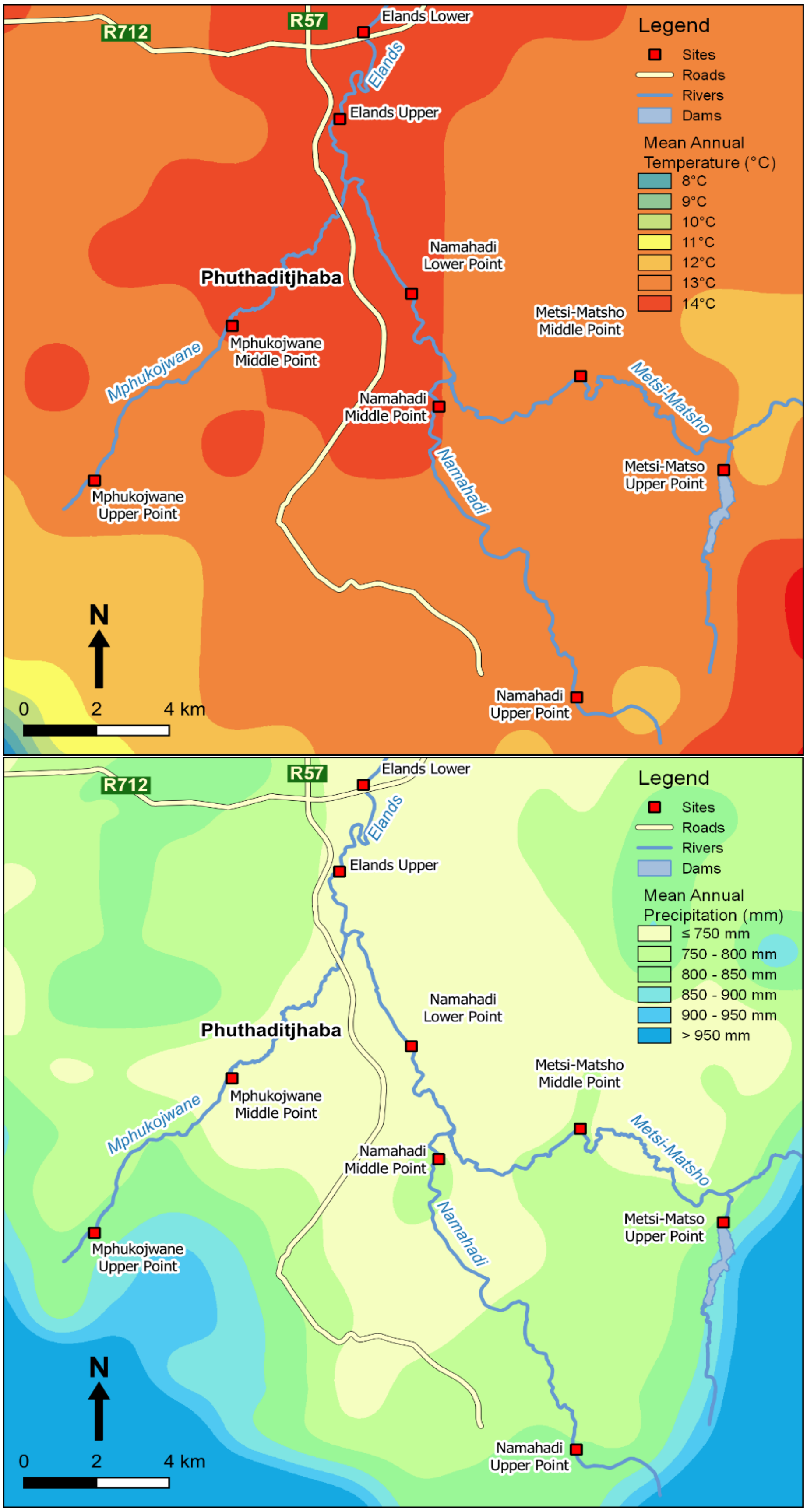


Figure 3.4. Mean annual temperature (top) and mean annual precipitation (MAP) (bottom) of the study area

3.3.1.3 Vegetation and land use

QwaQwa falls within the Drakensberg Afromontane region of Southern Africa. The vegetation comprises predominantly mountain grassland types interspersed with patches of Afromontane forest. The Namahadi River originates in uKhahlamba Basalt Grassland vegetation type, whereafter it flows through the Northern Drakensberg Highland Grassland, Basotho Mountain Shrubland, and Eastern Free State Sandy Grassland vegetation types (see Figure 3.5). The Metsi-Matso and Mphuhokjwane rivers originate in Northern Drakensberg Highland Grassland vegetation type and run through the Eastern Free State Sandy Grassland type in their lower reaches before joining the Elands River.

Land use in the area is predominantly urban (both formal and informal) and agricultural (cattle and goats) (see Figure 3.5). The rural areas around Phuthaditjhaba are extensively used for grazing (Taylor, 2023). Environmental degradation due to overgrazing, soil erosion, veld fires, and soil mining for building is widespread in these areas (Melore, 2017; Melore and Nel, 2020).

The local rivers play an important role in the water supply to domestic, agricultural, and industrial users in the area. The water quality in the river is impacted by diffuse urban runoff (informal and formal settlements), point source discharges (municipal wastewater), and industrial effluent from Phuthaditjhaba (CEM, 2003).

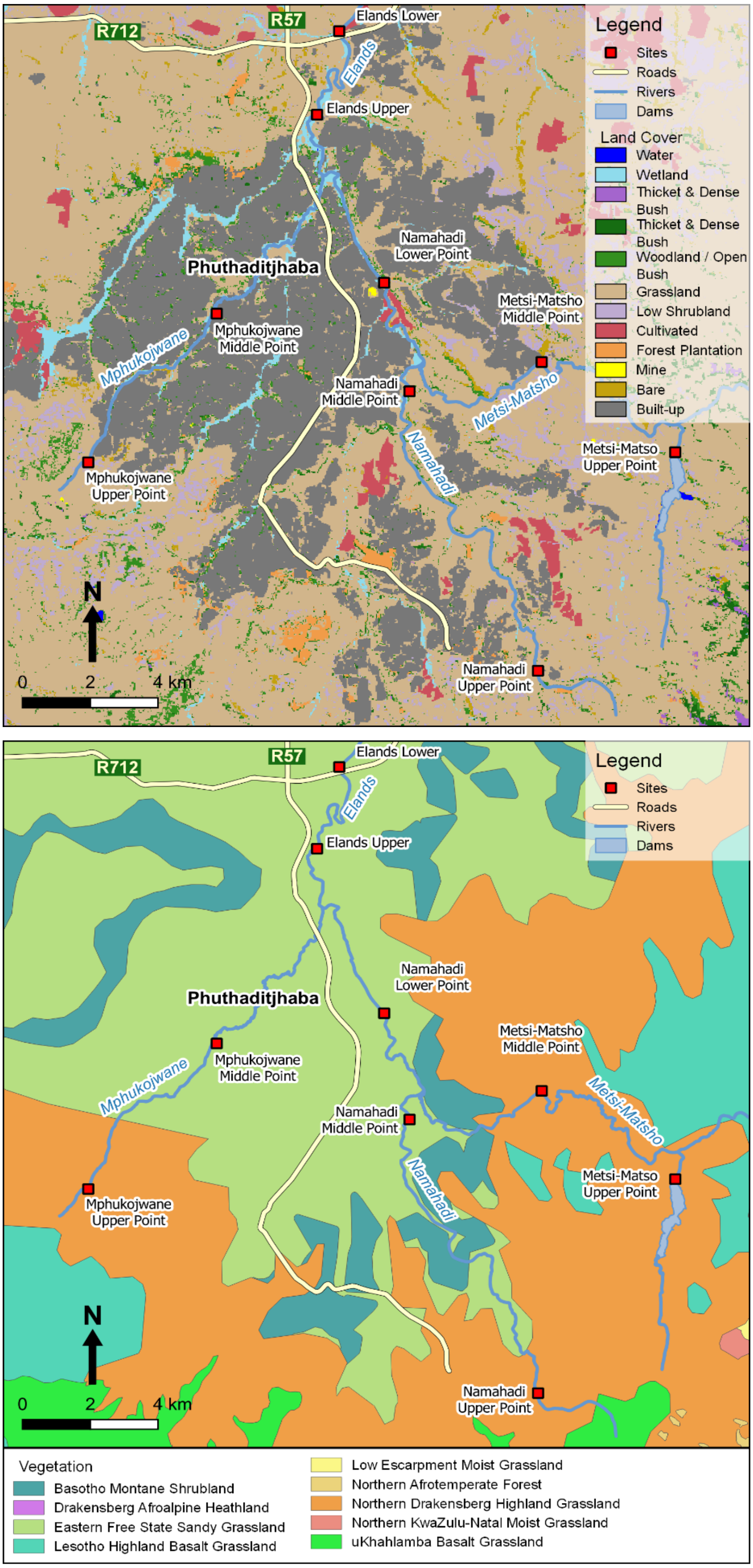


Figure 3.5. Vegetation (top) and land cover types (bottom) in the study area

3.3.2 Socio-economic environment

3.3.2.1 Brief history of QwaQwa

QwaQwa became a self-governing homeland for South Sotho people in 1974 (Slater, 2002). The population of QwaQwa grew from 24 000 in 1970 to approximately 300 000 in 1908, and approximately 450 000 in 1989 (Slater, 2002). The rapid population growth was mostly due to immigrants from white-owned farms. Initially, these immigrants could choose, with the permission of the local chiefs, where they wanted to settle. However, as the area became increasingly more crowded, immigrants settled in the smaller villages surrounding Phuthaditjhaba. These immigrants received a plot on which an informal dwelling could be erected, with no access to agricultural land or basic services. The majority of immigrants in the villages had no access to piped water, sanitation, or electricity, and depended on the rivers and streams for their drinking water. Phuthaditjhaba provided better access to improved living conditions and employment opportunities than the more rural villages, and as a result three industrial areas were established in the 1980s, which provided 27 000 jobs by 1992 (Pickles and Woods, 1992; Slater, 2002). QwaQwa was deregulated as a homeland during the transition from the former regime to the new democratic dispensation in South Africa. The withdrawal of government subsidies after 1994 caused many industries to close down or to relocate to other urban centres. This resulted in widespread job losses, with high levels of poverty, unemployment, and income inequality prevailing in QwaQwa (StatsSA, 2011).

3.3.2.2 Present situation

QwaQwa is one of the four towns in the Maluti-a-Phofung Local Municipality; the other three are Harrismith (53 km north-east of QwaQwa), Kestell (36 km north-west of QwaQwa), and Tshiame (41 km north-east of QwaQwa) (Mocwagae, 2020). QwaQwa serves as the administrative headquarters of both the Maluti-a-Phofung Local Municipality and Thabo Mofutsanyana District Municipality. The area has a large number of informal households located at the edge of the urban sections of Phuthaditjhaba and sprawled across the slopes to an altitude of 1 646 m.a.s.l. (Melore, 2017). Land use in the area comprises mostly urban activities (both formal and informal) and agriculture (cattle and goat rearing) (CEM, 2003).

Phuthaditjhaba is the business centre of QwaQwa (see Figure 3.6), and one of the most densely populated areas in South Africa with approximately 22 294 people per km^2 (Mukwada and Mutana, 2023). The population is growing at a rate of 0.87%, with the present population of 56 251 projected to increase to 78 361 by 2050 (StatsSA, 2011). The majority of the people are black African (99%), with Asian, coloured, and white groups contributing 0.5%, 0.2%, and 0.1% to the population respectively (Melore, 2017). Illiteracy is relatively high (22% of the population), with 8.9% of people older than 20 years being unschooled (Melore, 2017).

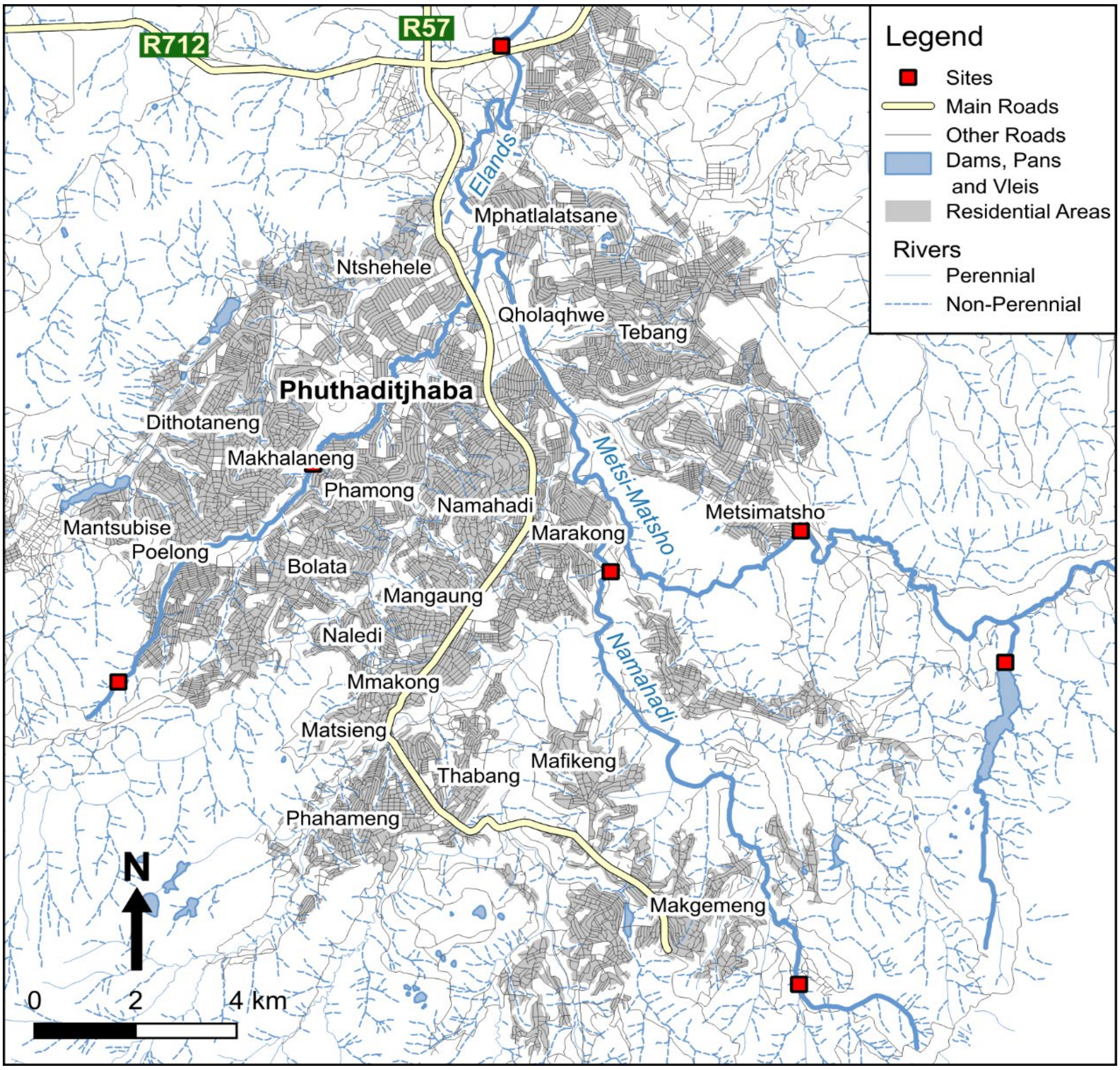


Figure 3.6. Residential areas in the study area

The dependency ratio in QwaQwa is high and continues to grow (Melore, 2017). The economically active population (15-64 years) increased from 4.9% in 2001 to 5.3% in 2011, while the proportion of the population older than 64 years increased from 60.6% in 2001 to 62% in 2011 (StatsSA, 2012). According to Noble and Wright (2013), 36.8% of the population of QwaQwa live with material deprivation, 56% with employment deprivation, 22.8% with education deprivation, and 61.4% with environmental deprivation. Around 74.9% of the population of QwaQwa live on the lower poverty line (R604) and 83.4% in the upper poverty line (R1 113) (Melore and Nel, 2020). Approximately 52% of income is from social grants, while 34% comes from daily labour wages (Melore, 2017).

Unfortunately, all of these socio-demographic indicators highlight the high vulnerability of communities in QwaQwa to climate-related hazards.

3.3.2.3 Water crisis in QwaQwa

QwaQwa has been experiencing a chronic water crisis since 2015 (Sekhele and Voua Otomo, 2023). According to Mocwagae (2020), the water crisis has been long in the making, which started with insufficient water planning since the founding of QwaQwa as a homeland in 1974. Factors such as poor infrastructure, poor maintenance and neglect, poor service delivery and gross mismanagement by the local authority, and climate variability all contributed to the present situation where the Maluti-a-Phofung Local Municipality has not been able to sufficiently provide water of good quality to the local community (Macupe, 2020; Mdlalane, 2020; Mocwagae, 2020; Kleynhans, 2021; Sekhele and Voua Otomo, 2023). The water crisis in QwaQwa made national headlines during the 2014 to 2016 drought. The poor state of water service delivery was compounded by a severe drought that resulted in very low dam levels (the Fika-Patso Dam, which supplies 80% of water in QwaQwa, was at 10% capacity level) (Mocwagae, 2020). The Maluti-a-Phofung Local Municipality responded to the severe water shortages by allocating the available water to critical sectors, such as health facilities, and hiring water tankers to deliver water to communities (Kings, 2017; Masuabi, 2020; Karrim, 2020). According to Motaung (2022), wards received water on a weekly basis, with residents having to fetch water from the tankers. Other strategies included the activation of boreholes and distribution of plastic water tanks. The Free State government responded to the crisis by allocating additional funding (of R1.6 billion) to repair pipelines between the Fika-Patso Dam and water reservoirs supplying households (Mocwagae, 2020), while the national government pledged emergency relief funds (R200 million) and 5 000 water tanks to be strategically placed in the catchment. At the community level, residents with the means to buy water did so, while those with access to cars fetched water from neighbouring towns (Macupe, 2020). Residents who could not afford to buy water resorted to fetching water from the rivers for drinking and domestic uses. However, these strategies offered only short-term solutions and are not sustainable on the long term. The 2014 to 2016 drought exposed the high vulnerability of communities in QwaQwa to climate-related hazards.

3.3.2.4 Water infrastructure and services provision

The general state of infrastructure and service provision in the area are relatively poor, with approximately 68% of households not having piped water in their homes, 70% are without access to waterborne toilets, and 11% are without access to electricity (StatsSA, 2011). The road networks and drainage systems are poor, or largely lacking, especially in the informal settlements (Melore, 2017). Furthermore, the mountainous landscape makes the cost of infrastructure provision and maintenance high, with the local authorities struggling to cover these costs due to limited financial capacity (Melore, 2017; Melore and Nel, 2020).

The main source of domestic water is the Fika-Patso Dam (full supply capacity: 29.43 million m^3) on the Namahadi River (Department of Water and Sanitation [DWS], 2017). The dam, which came into operation in 1986, supplies 85% of water in QwaQwa. The older Metsi-Matso Dam (full supply capacity: 4.5 million m^3), operational since 1976, and the Sterkfontein Dam (full supply capacity: 2 616.95 million m^3), operational since 1974, supply the remaining 15% water to QwaQwa (Mocwagae, 2020). The Sterkfontein Dam was established in 1968 to augment the water supply to Johannesburg through the Tugela-Vaal transfer scheme (Orange-Senqu River Commission, 2013).

The three bulk water schemes that provide water to the QwaQwa area are:

- the Fika-Patso scheme, which provides drinking water to the western, central, and northern areas of QwaQwa;
- the Metsi-Matso scheme, which provides drinking water to the south-eastern areas of QwaQwa; and
- the Sterkfontein scheme, which is being developed to augment bulk water to the Fika-Patso scheme. The first phase, commissioned in 2013, supplies bulk water to Tshiame, Mokgholokweng, and the special economic zone, while the bulk water supplies to the northern areas of QwaQwa commenced in 2014 (Free State Department of Cooperative Governance and Traditional Affairs [CoGTA] and Chell Engineering, 2018). A pipeline from the Sterkfontein Dam to the area is planned at a cost of R2.1 billion (Khalane, 2020).

According to the DWS (2017), the demands on the Fika-Patso and Metsi-Matso dams are limited by the capacities of the two water treatment works (WTW) receiving water from the dams. The Fika-Patso WTW has a capacity of 41 million litres per day (ML/d), while the Metsi-Matso (Makwana) WTW has a capacity of 10 ML/d. Although the capacity of the Makwana WTW was increased from 5.08 ML/d to 10 ML/d in 2016, there is a strong possibility that the WTWs would not be able to meet the average annual daily demand due to increased demand, especially during winter and drought situations (DWS, 2017). This implies that any future growth in demand needs to be supplied by the Sterkfontein scheme (DWS, 2017). As a further step to relieve the pressure on surface water resources, groundwater resources are being explored with several boreholes being drilled in the area (CoGTA, 2020).

The water crisis in the area is creating a huge financial burden on the Maluti-a-Phofung Local Municipality, which has spent close to R30 million between 2016 and 2019 on tankers to provide water to residents (Khalane, 2020). According to members of the Maluti-a-Phofung mayoral committee, the main problems include old and decaying infrastructure, the failure to clean blocked waterways, as well as poor revenue collection and usage by the municipality.

Serious problems with water purification and distribution have been reported, especially in 2016 and 2017 when acute water shortages were experienced (*Bloemfontein Courant*, 2016; Kings, 2017; Mocwagae, 2020). The critical state of the WTW in QwaQwa was confirmed by the 2022 Blue Drop Report (DWS, 2022a), which found that no water quality monitoring was conducted for drinking water by the water services authority. This non-compliance presents a serious health risk to the residents who receive water from these supply systems. This is very concerning, considering the poor water quality of the rivers in the catchment (Sekhele and Voua Otomo, 2023). The WWTPs in QwaQwa are also in a poor state, with dysfunctional processes, improper sewage sludge disposal, and frequent infrastructural failures (Moloi *et al.*, 2020; DWS, 2022b; Sekhele and Voua Otomo, 2023). The poor quality of wastewater effluents poses a serious risk, not only to public health, but also to the ecological integrity of natural water resources (Edokpayi *et al.*, 2017; Steffen *et al.*, 2022).

3.3.2.5 Vulnerability and the potential impact of climate change on services

The top three long-term risks identified by the 2023 Global Risks Report (World Economic Forum, 2023) are related to climate change: (1) failure to mitigate climate change, (2) failure to adapt to climate change, and (3) natural disasters and extreme weather events. The fourth risk, biodiversity loss and ecosystem collapse, is strongly linked to climate change. The fact that weak governance could further increase the exposure to these risks was also raised by the report. Studies have shown that both the water management sector and local municipalities in South Africa are poorly prepared for expected medium- and long-term changes associated with climate change (Mukheibir, 2008; Ziervogel *et al.*, 2010). For example, neither the Thabo Mofutsanyane District Municipality nor the Maluti-a-Phofung Local Municipality have conducted any scientific risk assessment, nor do they have functional disaster management plans in place (Maluti-a-Phofung Local Municipality, 2018). A district disaster risk assessment was, however, initiated by the District Disaster Management Centre in 2021.

CHAPTER 4: DEVELOPMENT OF A DOWNSCALED CLIMATE AND HYDROLOGICAL MODEL FOR QWAQWA

4.1 INTRODUCTION

This component of the study investigated the risk factors associated with the projected impacts of expected future changes on the occurrences of hydro-climatically driven events, especially the more extreme ones, such as extremes of temperatures, soil water conditions, extreme rainfall events (including sequential extremes), floods (including multiple day floods), meteorological, as well as hydrological, droughts of varying severities and durations, and soil loss (in both tonnes and tonnes per hectare [t/ha]). The focus was on terrestrial and river ecosystems in the QwaQwa area of the Upper Vaal River catchment in order to develop relevant and appropriate risk reduction strategies useful to the local authorities, to the water and agriculture sectors, as well as to local communities in the study area.

The hydrological component was undertaken in light of projected climate change, which is expected to have a marked impact not only on extremes, but also on the flow regimes of QwaQwa's rivers, such as changes to annual flows, low flows, the variability of flows, the seasonality of flows, and periods of intermittence, which could affect river discharges and affect the vulnerability of aquatic biota and river ecosystems. Ultimately, it was important to interpret the results from this component by considering the potential effects of the projected changes on the ecosystem services delivered by these rivers, and on communities that rely on these water sources.

This chapter presents only an extract from a more comprehensive report on the development of a downscaled climate and hydrological model for QwaQwa, including detailed results and projections for the sub-catchments of the study area (see Volume 2 of this report).

4.2 METHODOLOGY FOLLOWED FOR DEVELOPING THE DOWNSCALED CLIMATE AND HYDROLOGICAL MODEL

4.2.1 Historical databases used

The University of KwaZulu-Natal's Centre for Water Resources Research's Quinary Catchments Database (QnCDB), which contains 50 years (1950-1999) of data on daily rainfall, daily maximum and minimum temperature, daily reference potential evaporation, daily solar radiation, and daily maximum and minimum relative humidity, was used as the core database for the baseline (i.e. historical) studies. Additionally, the outputs from a one arc minute (i.e. ~1.7 x 1.7 km) hydro-climate database, developed in WRC Project K5/1490, were used for the more localised studies. These outputs consist of rainfall information (Lynch, 2004), as well as temperature and temperature-derived information (Schulze and Maharaj, 2004).

4.2.2 Climate change databases used

Downscaled and bias-corrected daily hydro-climatic outputs were available at quinary catchments spatial resolution from six Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Climate Models (GCMs) from WRC Project K5/2833 (Wolski *et al.*, 2022, in Schütte *et al.*, 2022). The six downscaled and bias-corrected GCMs used to produce daily outputs were the following:

- Australian Community Climate and Earth System Simulator;
- Geophysical Fluid Dynamics Laboratory Coupled Model;
- National Centre for Meteorological Research Coupled Global Climate Model, version 5;
- Max Planck Institute Coupled Earth System Model;
- Norwegian Earth System Model; and the
- Community Climate System Model.

This ensemble of very high-resolution climate model simulations of present-day climate and projections of future climate changes over South Africa were produced by the CSIR (Engelbrecht *et al.*, 2019; Engelbrecht *et al.*, 2020), and are termed Conformal Cubic Atmospheric Model (CCAM) projections. As in previous work at the CSIR, the CCAM regional climate model was used to develop the downscaled projections. The six GCM simulations from the CMIP5 archive, based on the emission scenarios described by representative concentration pathways (RCPs) 4.5 and 8.5, were first downscaled to a 50 km spatial resolution globally. The selection of these six GCMs was based on their ability to provide a reasonable representation of the El Niño-Southern Oscillation phenomenon for Southern Africa. The simulations span the period 1961 to 2100, with this study utilising the RCP 8.5 low mitigation scenario for three time periods, namely:

- the *Present*, represented by the 30-year period from 1961 to 1990;
- the *Immediate Future*, represented by 2016 to 2045; and
- the *Distant Future*, represented by the period 2071 to 2100.

Daily rainfall and minimum, as well as maximum, air temperature projections were bias corrected to the resolution of the QnCDB with the methods described in Wolski *et al.* (2022) for all 5 838 quinaries covering South Africa, Eswatini, and Lesotho. The datasets relevant to the QwaQwa study area were isolated, with the data then analysed for the selected hydro-climatic variables selected for this study, and with the data then used as climate input into the Agricultural Catchments Research Unit (ACRU) model to determine climate change impacts on hydrological responses in QwaQwa.

4.2.3 The hydrological model used: Agricultural Catchments Research Unit (ACRU)

The daily time-step process-based and multi-purpose ACRU agro-hydrological model (Schulze, 1995; Smithers and Schulze, 1995; updates) was applied in this component of the study.

4.2.3.1 ACRU model attributes

The ACRU agro-hydrological modelling system (Schulze, 1995; Schulze and Smithers, 2004; continual updates), which has been, and is currently being, used extensively in water resources and climate change studies in Southern Africa, is centred around the following objectives and attributes (see Figures 4.1 and 4.2):

- It is a daily time-step and conceptual-physical model;
- with variables (rather than optimised parameters values) estimated from physically based characteristics of the catchment; and
- with the model revolving around daily multi-layer soil water budgeting.

As such, the model has been developed essentially into a versatile simulation model of the hydrological and related system (see Figure 4.2), structured to be highly sensitive to climate drivers and to land cover, land use, and management changes on the soil water and runoff regimes, and with its water budget being responsive to supplementary watering by irrigation, to changes in tillage practices, to enhanced atmospheric carbon dioxide concentrations associated with climate change, or to the onset and degree of plant stress, which may change with global warming.

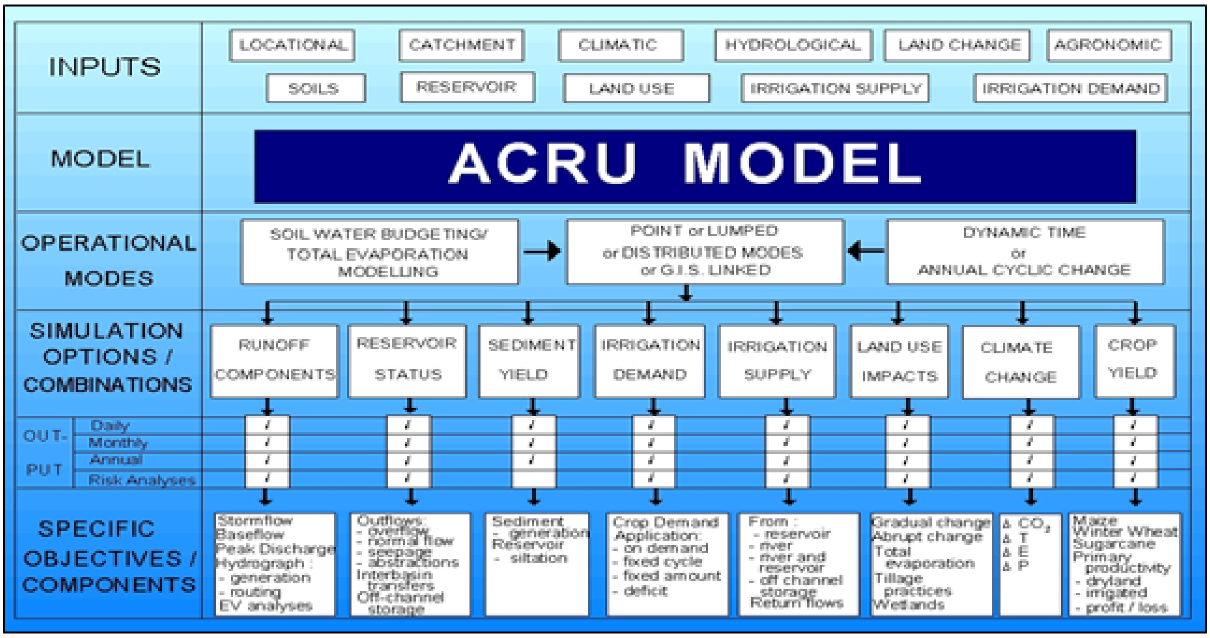


Figure 4.1. General structure and multi-purposeness of the ACRU model

Source: Schulze (1995)

ACRU is a *multi-purpose* model that integrates the various water budgeting and runoff production components of the terrestrial hydrological system (see Figure 4.1). It can be applied as a versatile model for design hydrology (including flow routing through channels and dams), crop yield estimation, reservoir yield simulation, ecological requirements, wetlands hydrological responses, riparian zone processes, irrigation water demand and supply, water resources assessment, planning optimum water resource utilisation/allocation, conflict management in water resources, and land use impacts – in each case with associated risk analyses – and all of which can respond differently with climate change.

ACRU can operate at multiple scales as a *point* model or as a *lumped* small catchments model, on large catchments or at national scale as a *distributed* cell-type model with flows taking place from "exterior" through "interior" cells according to a predetermined scheme, as is the case in the QwaQwa, simulations, with the facility to generate individually requested outputs at each sub-catchment's exit.

The model includes a *dynamic input option* to facilitate modelling of hydrological responses to climate or land use or management changes in a time series, be they long-term/gradual changes (e.g. urbanisation changes over time, or climate trends over time), abrupt changes (e.g. construction of a dam), or changes of an intra-annual nature (e.g. crops with non-annual cycles).

The ACRU model has been linked to the QnCDB (Schulze and Horan, 2010) for applications at a range of scales in South Africa, Lesotho, and Eswatini for climate change impacts and other studies.

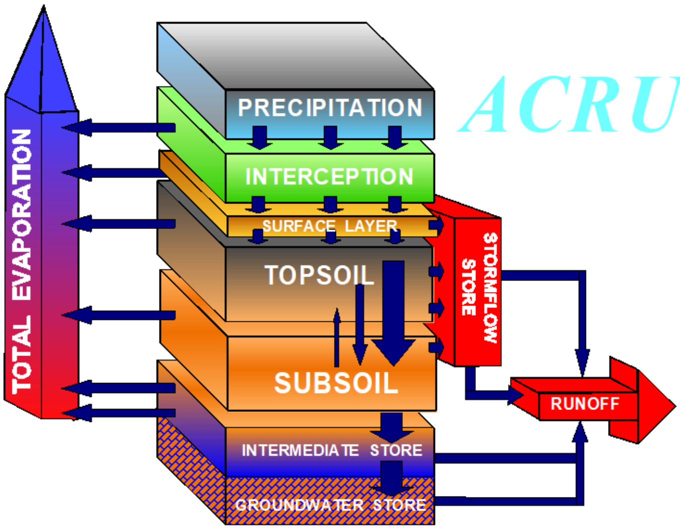


Figure 4.2. Schematic of major processes represented in the ACRU model

Source: Based on Schulze (1995)

4.2.3.2 General structure of the ACRU model

Multi-layer soil water budgeting by partitioning and redistribution of soil water is depicted in a highly simplified schematic in Figure 4.2. Rainfall and/or irrigation application that is not abstracted as interception or converted to stormflow (either rapid response or delayed) first enters through the surface layer and "resides" in the topsoil horizon. When that is "filled" to beyond its drained upper limit (field capacity), the "excess" water percolates into the subsoil horizon as saturated drainage at a rate dependent on respective horizon soil textural characteristics, wetness, and other drainage-related properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed its drained upper limit, saturated vertical drainage/recharge into the intermediate and eventually groundwater stores occurs, from which baseflow may be generated at an exponential decay rate that is dependent on geological or aquifer characteristics, as well as the groundwater store.

Unsaturated soil water redistribution, both upwards and downwards, also occurs, but at a rate considerably slower than the water movement under saturated conditions, and is dependent on, inter alia, the relative wetness of adjacent soil horizons in the root zone. Evaporation takes place from water previously intercepted by the crop's or vegetation's canopy, as well as simultaneously from the various soil horizons, in which case it is either split into separate components of soil water evaporation (from the topsoil horizon only) and plant transpiration (from all horizons in the root zone), or combined, as total evaporation.

Evaporative demand on the plant is estimated, inter alia, according to atmospheric demand (through a reference potential evaporation) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density within the respective horizons, except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

It is vital in agro-hydrological modelling to determine at which point in the depletion of the plant-available water reservoir plant stress actually sets in, since stress implies soil water extraction below optimum, the necessity to irrigate, a reduction in crop yield, and lower runoff potential. In modelling terms, this problem may be expressed as the critical soil water content at which total evaporation, *E*, is reduced to below the vegetation's maximum evaporation, E_m (formerly termed "potential evapotranspiration"). *E* equals E_m until a certain fraction of maximum (profile) available soil water to the plant, *PAW*, is exhausted (see Figure 4.3). The critical soil water fraction at which stress commences varies according to atmospheric demand (the hotter it is, the sooner stress commences) and the critical leaf water potential of the respective vegetation; the latter being an index of the resilience of the vegetation to stress situations. Plant stress, and a reduction in evaporative losses, however, also occur when the soil is too wet; i.e. soil water content exceeds *PAW*. Furthermore, plant stress, when the soil dries out, can be either mild or severe, as illustrated in Figure 4.3. The various levels of stress are defined as follows:

- Excess *soil water stress* occurs when actual soil water content θ exceeds that at the drained upper limit θ_{DUL}; i.e. $\theta > \theta_{DUL}$
  and total evaporation, *E*, drops to below its maximum, E_m.
- No *soil water stress* occurs when the plant can transpire at its maximum rate (i.e. $E = E_m$) with the soil water content then below that of the *DUL*, but exceeding the soil water content at a specified fraction of *PAW* at which plant stress commences, namely θ_{fs}, which in the case where it has been set at 0.4 *PAW*, $\theta_{DUL} > \theta > \theta_{fs}$
  or $\theta_{DUL} > \theta > 0.4(\theta_{DUL} - \theta_{PWP}) + \theta_{PWP}$
  where θ_{PWP} = *soil water content at the permanent wilting point*.
- Mild *soil water stress* is experienced when soil water content is below the stress fraction, θ_{fs}, but the plant is still transpiring at more than 20% of its maximum evaporation; i.e.
  $\theta_{fs} > \theta > 0.2\ E/E_m$
  $\theta_{fs} > \theta > 0.6\ (\theta_{fs} - \theta_{PWP}) + \theta_{PWP}$
- Severe *soil water stress* is defined as the soil water content at which total evaporation has been reduced to below 20% of maximum evaporation; i.e.
  $\theta < 0.2\ E/E_m$
  which in this case equates to $\theta < 0.6\ (\theta_{fs} - \theta_{PWP}) + \theta_{PWP}$

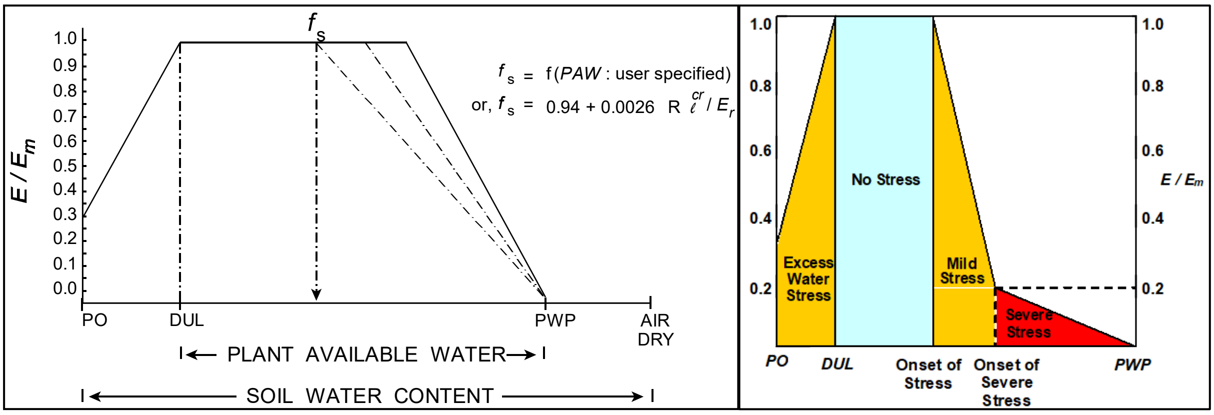


Figure 4.3. Interrelationships used in ACRU between soil water content and the ratio of E : E_{tm}

Source: Schulze (1995; 2008)

The ratio of E : E_{tm} expresses the level of plant water stress (right) and different levels of stress experienced by plants (left).

4.2.3.3 Generation of stormflows with the ACRU model

Stormflow Q is defined as the water that is generated from a specific rainfall event, either at or near the surface in a catchment or sub-catchment, and contributes to flows of streams within that catchment/sub-catchment (see Figure 4.4). It is largely from stormflow events that, for example, reservoirs are filled and design runoffs for selected return periods are computed. Furthermore, the soil detachment process in the production of sediment yield from a catchment is highly correlated with the volume of stormflow from an event. Important statistics on stormflows include annual means, inter-annual variabilities, magnitudes in wet and dry years, and the number of stormflow events per annum that exceeds critical thresholds.

Stormflow can be generated from both the impervious parts of the catchment connected directly to a stream (e.g. paved surfaces, roofs, and permanently saturated areas directly adjacent to a stream – ACRU variable name ADJIMP in Figure 4.4) and from the pervious portions of a catchment. The amount of the stormflow that is generated from the pervious areas (expressed either as a depth equivalent in mm, or as a volume in m^3) in essence depends on the magnitude of the rainfall event (P in Figure 4.4) and how wet the catchment is just prior to the rainfall event.

Stormflow, Q_s, is computed in the ACRU model (Schulze, 1995; updates) in mm equivalents as

$$Q_s = (P_n - I_a)^2 / (P + I_a + S) \quad \text{for } P_n > I_a$$

Where:

P_n = net rainfall (mm); i.e. gross (measured) rainfall minus canopy interception losses

I_a = initial abstractions (mm) before stormflow commences, consisting mainly of the infiltration that occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage

S = the soil's potential maximum retention (mm), which is equated to the soil water deficit and is an expression of the wetness or dryness of the soil

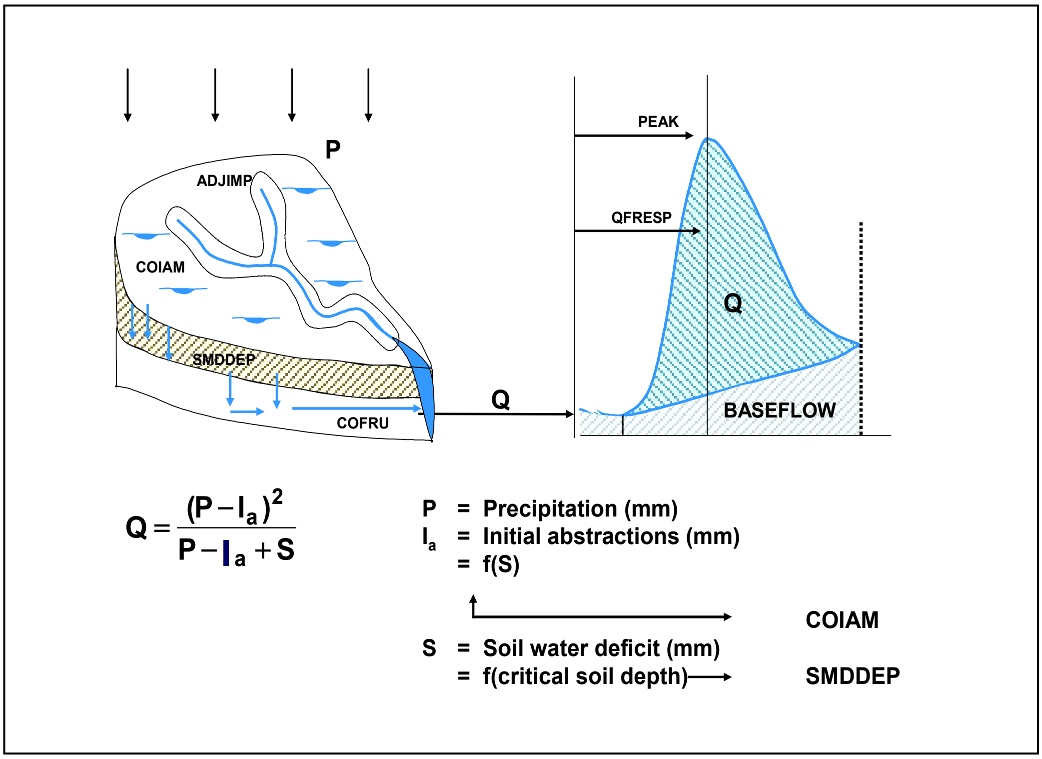


Figure 4.4. Schematic of runoff-generating mechanisms in the ACRU model

In ACRU, the soil water deficit, *S*, is calculated by the daily multi-layer soil water budget, and for computations of stormflow, a critical soil depth, D_{sc} (SMDDEP, in m, in Figure 4.4), is defined from which *S* is determined. The depth of D_{sc} accounts for the different dominant runoff-producing mechanisms, which may vary in different climates, as well as with catchment land uses, tillage practices, litter/mulch cover, and soil conditions. This depth is therefore generally shallow in more arid areas characterised by eutrophic (i.e. poorly leached and drained) soils and high-intensity storms, which would produce predominantly surface runoff, but is generally deeper in high-rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and "push-through" runoff-generating mechanisms predominate. For all hydrological simulations in this report, D_{sc} was defined as the thickness of the topsoil.

A major determinant of initial abstractions is soil water content. In order to eliminate estimations of both I_a and *S* in the equation above, I_a is expressed as a coefficient, *c*, of *S*, where *c* is an index of infiltrability into the soil and varies with rainfall intensity (in the thunderstorm season: smaller *c*), tillage practice, and surface cover / litter / mulch (Schulze, 1995). For all simulations of baseline hydrological responses in this document, the *c* of I_a was input as the value assigned on a month-by-month basis (ACRU variable COIAM in Figure 4.4) by Schulze (2004) for the over 70 baseline land cover types found in South Africa that were defined by Mucina and Rutherford (2006). For simulations with other land uses (including fire and degradation / rehabilitation regimes), the monthly values of the *c* of I_a were taken from Schulze (2008), in which all assumptions are explained.

Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurs, and the fraction that does depends on the size of the catchment, the catchment's slope, and other factors (Schulze, 1995). This necessitates a stormflow response coefficient, F_{sr}, to be input, which controls the "lag" of stormflows and is effectively an index of interflow (ACRU variable name QFRESP in Figure 4.4). In all simulations on all sub-catchments in this report, F_{sr} was set at 0.3 – a value which has been found experimentally to be typical in South Africa for use at the spatial scale of quaternary and quinary catchments (e.g. Warburton *et al.*, 2010) when the ACRU model's flow routing option is not used, as in this case.

4.2.3.4 Generation of baseflows with the ACRU model

Baseflows consist of contributions to runoff from the intermediate/groundwater store that had previously been recharged. These contributions are made up of slow and delayed flows to the catchment's streams. In the ACRU model it is assumed that the groundwater store is always "connected" to the stream system. Unlike many other models that compute baseflow indirectly from total runoff hydrographs with an empirically derived "separation curve", ACRU computes baseflow explicitly from recharged soil water stored in the intermediate/groundwater zone (Schulze, 1995).

The stored water is derived from rainfall of previous events that has been redistributed through the various soil horizons and has drained into the intermediate/groundwater store when the deepest soil horizon's water content exceeds its drained upper limit (field capacity). The *rate of drainage* of this "excess" water out of the deepest soil horizon *into the groundwater store* depends on that horizon's soil texture class, which in this report has been input to vary from catchment to catchment according to soil attributes.

The rate of release of water from the groundwater store into the stream is determined by a release coefficient, F_{bff}, which is dependent, inter alia, on the geology, area, and slope of the catchment. F_{bff} operates as a "decay" function, which is input for a catchment as a single value (COFRU in Figure 4.4), but based on experiences with ACRU in many catchment studies, F_{bff} is not a constant decay function, but is enhanced or decreased internally in ACRU, dependent on the magnitude of the previous day's groundwater store, S_{gwp}, such that empirically

$$F_{bff} = F_{bfi}\ [[[(S_{gwp})^2 - S_{gwp}] / 1000 + 1.3] / 11]$$

Where:

F_{bff}	=	final baseflow release coefficient
F_{bfi}	=	input baseflow release coefficient
S_{gwp}	=	magnitude of previous day's intermediate/groundwater store (mm)

For all simulations in this report, an experimentally determined typical value of F_{bff} of 0.009 (Kienzle *et al.*, 1997) was applied in all quinary catchments in the study area.

4.2.3.5 Generation of peak discharge

The peak discharge is the highest flow rate of a hydrograph (see Figure 4.4). In the ACRU model an estimate of the peak discharge associated with each day's stormflow volume generated for the selected simulation period can be made by assuming a single triangular unit hydrograph. For these simulations, the Soil Conservation Service peak discharge equation (United States Department of Agriculture Soil Conservation Service, 1972), modified significantly by Schulze and Schmidt (1995), is used. In its modified version

$$q_p = 0.2083 Q_s A / 1.83\ L$$

Where:

q_p	=	peak discharge ($m^3.s^{-1}$)
Q_s	=	stormflow depth (mm) from an individual catchment
A	=	catchment area (km^2)
L	=	catchment lag (response) time (h)
	=	$\dfrac{A^{0.35} MAP^{1.1}}{41.67 y^{0.3}\ \bar{I}30^{0.87}}$
1.83	=	a multiplier that was computed assuming high-intensity rainfall to be associated with annual maximum one-day storms over relatively small catchments

with the lag equation having been developed by Schmidt and Schulze (1984) using several hundred hydrographs from over 20 research catchments at seven hydro-climatically divergent regions in the United States of America and South Africa, and in which

A	=	catchment area (km^2)
MAP	=	mean annual precipitation (in mm)
Y	=	mean catchment slope (%), determined in the case of this report from a 200-m digital elevation model
$\bar{I}_{30}$	=	magnitude of the two-year return period 30-minute rainfall intensity ($mm.h^{-1}$)

As is evident from the above equations, Schmidt and Schulze (1984) found that climatic attributes play a major role in determining a catchment's runoff response, or lag, time. For example, they found that a rainfall event's intensity, best represented by the most intense 30-minute period of that event, significantly affects catchment lag time (Schmidt and Schulze, 1984), as did the MAP, which was used as a surrogate variable to describe the retardation of stormflow as affected by a catchment's vegetative cover. Therefore, by using the lag equation above (i.e. *L* =), the potential effects of climate change on catchment lag, and hence peak discharge, can be estimated.

4.2.3.6 Generation of sediment yields with the ACRU model

Complex deterministic models are available to estimate erosion processes and sediment transport. However, these models are limited in their application owing to their reliance on calibration. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is an equation that has received recognition as an empirical method that is useful for planning and design purposes. This method is the foundation for other empirical equations that are then applied at the catchment scale to estimate sediment yield, such as the daily stormflow event-based Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), which has been widely verified worldwide and in South Africa (Kienzle *et al.*, 1997).

Sediment yield at any quinary outlet (or that of any other spatial unit) may be estimated using the ACRU model, with the MUSLE embedded and expressed as:

$$Y_{sd} = \alpha_{sy} (Q_v \, x \, q_p)^{\beta_{sy}} \, K \, x \, LS \, x \, C \, x \, P$$

Where:

Y_{sd} = sediment yield (t) from an individual stormflow event

Q_v = stormflow volume for the event (m³)

q_p = peak discharge for the event (m³/s)

K = soil erodibility factor (t h/N.ha)

LS = slope length and gradient factor (-)

C = cover and management factor (-)

P = support practice factor (-)

While the MUSLE coefficients, α_{sy} and β_{sy}, are location specific (Simons and Sentürk, 1992) and are determined for specific climatic zones, default values set at 8.734 for α_{sy} and 0.56 for β_{sy} were, however, used in sediment yield simulations for this research.

Information needed for each quinary catchment when estimating sediment yield thus includes:

- the stormflow volume for each event (using the equations provided earlier in this section, but with the mm equivalent Q being converted to a volume Q_v in m^3 by multiplying out for area);
- the peak discharge (m^3) for each event (using the equations provided earlier in this section);
- the 30-minute rainfall intensity (mm/h) for the two-year return period, f_{30}, used in the peak discharge equation and computed for historical data, as outlined in Schulze (2012), and for climate change studies in South Africa by techniques developed by Knoesen (2011);
- the soil erodibility factor, K, determined from the Institute for Soil Climate and Water's soil land types and mapped in detail for South Africa by Schulze and Horan (2010);
- the slope length factor, calculated from each quinary catchment's average slope gradient determined from, for example, a 200-m resolution digital elevation model and an equation developed by Schulze (1979) that relates slope gradient to the slope length factor;
- the cover and management factor, C, as determined by Schulze (2004);
- the support practice factor, P, not applicable for these simulations under baseline land cover conditions and thus set to 1; and
- a factor proportioning the amount of the sediment generated from a stormflow event and which reaches the outlet to the respective quinary catchment on the day of the event, in order to account for sediment eroded at one location and which may be stored temporarily, only to be subsequently remobilised several times before reaching the catchment outlet, and generally defaulted to 0.45 in South African studies.

4.2.3.7 *Verification studies on the ACRU model's output*

The ACRU model is arguably the most comprehensively verified (as against calibrated) model in Southern Africa (Schulze, 2022), and in addition to verifications of end-product outputs such as streamflow, its components of baseflow and stormflow or sediment yield and internal state variables such as soil water content have been verified against observed data. In addition to verification studies on South African observations, such studies have also been undertaken on observed catchment data from the United States of America, Canada, New Zealand, Germany, Eswatini, Eritrea, and Zimbabwe.

4.2.3.8 *Model links to databases*

As previously alluded to, the ACRU model has been linked to historical daily climate databases for the 5 838 quinary catchments covering South Africa (Schulze *et al.*, 2010), as well as to daily climate output for present and future scenarios from GCMs, downscaled to quinaries to accomplish the analyses of climate change impacts on climate and water-related variables in QwaQwa.

4.2.3.9 *Baseline assessments and in situ assessments*

To assess the baseline impacts of climate change, model runs were:

- first undertaken with natural vegetation hydrological input and the most recent soils data derived from terrain unit resolution soils parameters, with inputs from historical (baseline) climate data;
- thereafter, simulations using historical climate data were run using hydrological attributes of actual land uses, which were derived from the 2018 National Land Cover, and with key land uses in regard to hydrological responses being:
    - natural vegetation;
    - degraded areas;
    - wetlands;
    - urban areas with different levels of adjunct and disjunct impervious areas;
    - agricultural areas with different crops and levels of management; and
    - dams and irrigation.
- followed by the same runs, but using climate inputs from multiple GCMs and for different future scenarios.

4.2.4 The spatial resolution of the hydrological assessments undertaken in the QwaQwa study area

4.2.4.1 *The quinary catchment: The primary spatial unit of this study*

The primary, and coarsest, spatial unit in this study is the quinary catchment, with three altitudinally delineated quinaries making up a DWS quaternary catchment. In total, 5 838 quinaries cover South Africa, Lesotho, and Eswatini. These quinaries are designated the "upper", "middle", and "lower" quinaries of a quaternary catchment, and within the QwaQwa study area three quinaries of the same quaternary are located, namely Quinaries 1219, 1220, and 1221, as shown in Figure 4.5. Altitude was selected as the key criterion for sub-delineation since it is altitude that largely influences rainfall, as well as temperature and potential evaporation patterns.

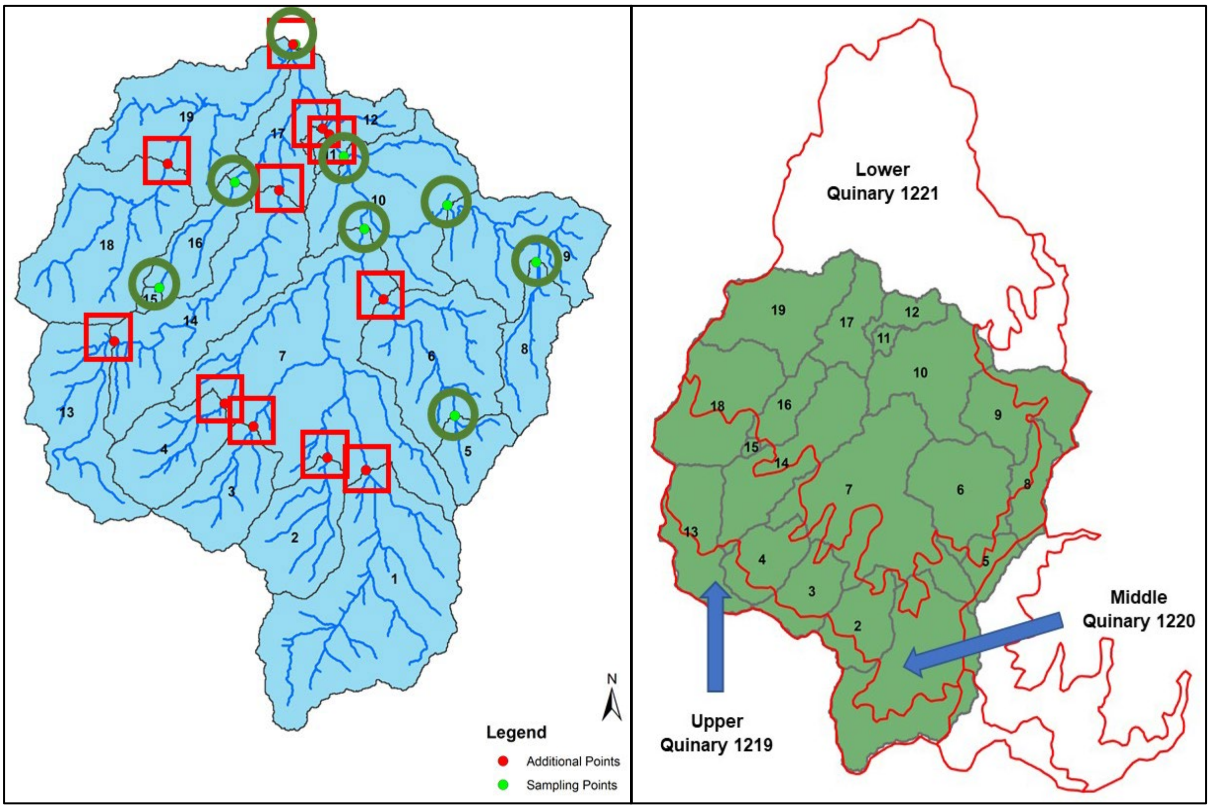


Figure 4.5. Water quality sampling points (green rings), as well as additional quinary-related points identified as sub-catchment outlets for hydrological modelling purposes (red squares; left map), and (right map) the quinary catchments with the sub-catchment numbering system

4.2.4.2 Sub-catchments within the quinaries used for modelling in this study

A key focus, however, of the broader research project into which this report makes inputs revolves around the risks associated with sediments, nutrients, and pesticides that result in the deterioration of, inter alia, drinking water quality and public health. For this reason, seven water quality sampling points were identified within the QwaQwa study area, with these located along three key rivers of interest, namely Namahadi, Metsi-Matso, and the Mphukojwane, all of which originate in the Maloti-Drakensberg mountains near Golden Gate National Park in the Great Escarpment Mountains and Highveld ecoregions, and on the outskirts of Phuthaditjhaba merge to form the Elands River (see Figure 4.6).

The names, coordinates, and altitudes of the seven sampling points, used in the climate and hydrological modelling, are listed in Table 4.1.

Table 4.1. Names, coordinates, and altitudes of the seven sampling points as focus points in the climate and hydrological modelling

No.	Site name	Latitude	Longitude	Altitude (m)
1	Namahadi Upper	-28.6495667	28.6976719	1 783
2	Namahadi Middle	-28.5729722	28.6575556	1 655
3	Metsi-Matso Upper	-28.5886667	28.7379722	1 886
4	Metsi-Matso Middle	-28.5643421	28.6972297	1 766
5	Mphukojwane Upper	-28.5938608	28.7609721	1 875
6	Mphukojwane Middle	-28.5523177	28.7990148	1 680
7	Elands Lower	-28.4970001	28.6283333	1 638

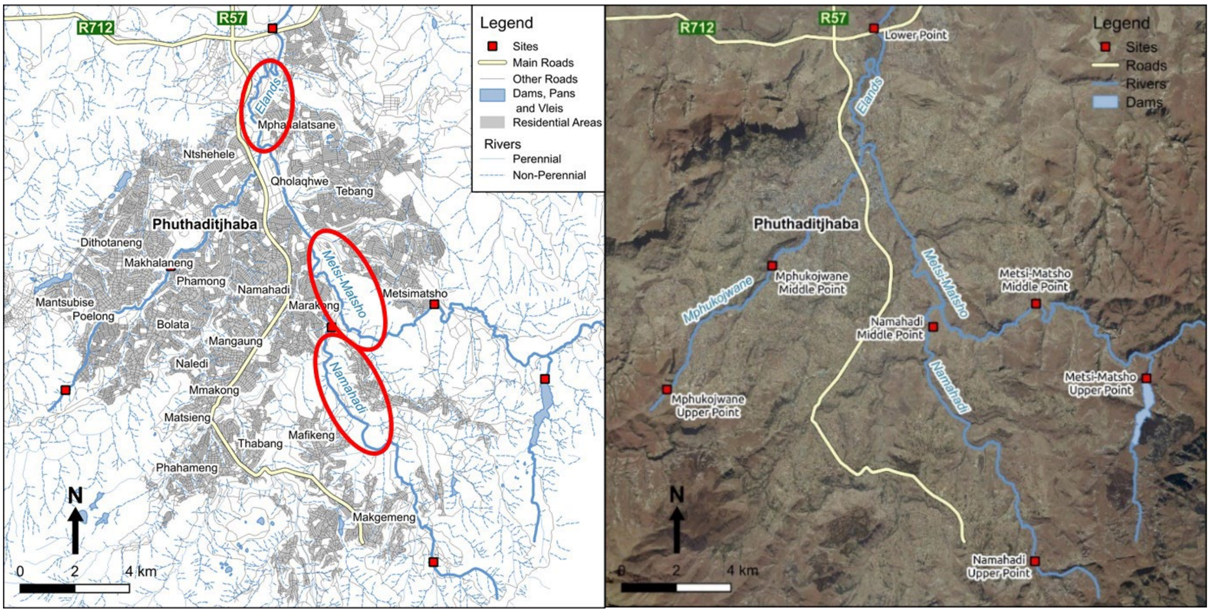


Figure 4.6. The main rivers in the study area in relation to residential areas of Phuthaditjhaba (left), with the location of the seven water quality sampling points located on the Namahadi and Metsi-Matso rivers flowing north-westwards from the south and east, and the Mphukojwane flowing north-eastwards, merging to form the Elands River in the north

With water flows under current and projected future climatic conditions to be modelled with the ACRU model at the seven sampling points, these seven points became logical locations of sub-catchments. However, with much of the hydrological information (such as soils and natural vegetation type) available only at quinary catchment resolution, an overlay of the quinaries with these seven sampling locations yielded a total of 19 modelling sub-catchments, each of which was considered relatively homogeneous with regard to their hydrological responses. The seven sampling and the 12 additional points are shown in Figure 4.6 (on the left), with the sub-catchment numbering system shown in Figure 4.6 (on the right). The flow routing within the study area among the 19 sub-catchments is shown in Figure 4.7, with the locations of the water quality sampling points highlighted in red at the outlets of Sub-catchments 5, 7, 8, 9, 15, 16, and 19.

The mean altitudes and areas of the 19 sub-catchments are provided in Table 4.2, with mean altitudes ranging from 1 677 to 2 521 m.a.s.l. and sub-catchment areas ranging from 1.1 to 72.8 km^2, totalling 501.3 km^2. With only seven of the 19 sub-catchments thus delineated and falling entirely within a specific quinary and the remaining 12 sub-catchments still crossing more than one quinary, the percentages of each sub-catchment within each quinary were calculated, so as to provide area-weight specific model input variables. These percentages per sub-catchment are listed in Table 4.3.

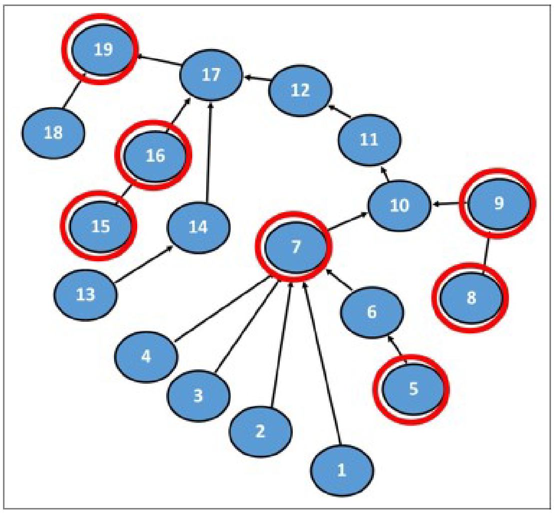


Figure 4.7. The flow routing among the 19 sub-catchments within the study area, with the locations of the water quality sampling points highlighted in red

Table 4.2. Mean altitudes and areas of the 19 sub-catchments identified for QwaQwa

Sub-catchment	Mean altitude (m)	Area (km^2)
1	2 373	64.4
2	2 221	19.9
3	2 246	17.5
4	2 278	18.2
5	2 004	9.2
6	1 817	33.9
7	1 857	72.8
8	1 949	14.5
9	1 931	29.6
10	1 786	36.2
11	1 680	2.3
12	1 756	8.1
13	2 521	28.2
14	1 908	39.1
15	2 000	1.1
16	1 802	12.1
17	1 677	17.3
18	1 921	41.1
19	1 815	35.8

Table 4.3. Percentages of specific quinaries per sub-catchment

Sub-catchment	Upper quinary catchment	%	Middle quinary catchment	%	Lower quinary catchment	%
1	1219	25%	1220	75%		
2	1219	25%	1220	75%		
3	1219	25%	1220	75%		
4	1219	25%	1220	75%		
5	1219	25%	1220	45%	1221	30%
6					1221	100%
7			1220	80%	1221	20%
8			1220	80%	1221	20%
9			1220	50%	1221	50%
10					1221	100%
11					1221	100%
12					1221	100%
13	1219	50%	1220	50%		
14			1220	50%	1221	50%
15			1220	100%		
16					1221	100%
17					1221	100%
18			1220	50%	1221	50%
19					1221	100%

4.2.4.3 Further delineation of sub-catchments within the quinaries into hydrological response units (HRUs) for more detailed modelling in this study

In the final modelling configuration, each of the 19 sub-catchments was further sub-delineated into six interlinked and water-related land use-based HRUs to enable the individual assessment of hydrological responses from, inter alia, natural vegetation, degradation, urban areas, wetlands, dams, dryland agricultural systems, and/or irrigation within a sub-catchment, as well as to enable the assessment of the impacts of land uses of an entire sub-catchment and eventually of the entire QwaQwa system. This configuration facilitated modelling the hydrological responses of individual land uses within each sub-catchment under present and projected future climatic conditions.

4.2.5 Location of the sampling sites

The majority of the sampling sites were located in the lower quinary (1221). Only two sites, Metsi-Matso Upper and Mphukojwane Upper, were situated in the middle quinary (1220) (see Table 4.4 and Figure 4.5). None of the sampling sites were situated in the upper quinary (1219).

Table 4.4. Location of the sampling sites in relation to the quinaries and sub-catchments

Sampling sites	Upper quinary (1219)	Middle quinary (1220)	Lower quinary (1221)	Sub-catchment
Metsi-Matso				
Upstream of MU		X		8
MU		X		8
MM			X	9/10
Namahadi				
Upstream of NU	X			5
NU			X	6
NM			X	7
NL			X	10
Mpukojwane				
MPU		X		15
MPM			X	16
Elands River				
ELU			X	11
ELL			X	19

Site codes: MU = Metsi-Matso Upper, MM = Metsi-Matso Middle, NU = Namahadi Upper, NM = Namahadi Middle, NL = Namahadi Lower, MPU = Mphukojwane Upper, MPM = Mphukojwane Middle, ELU = Elands Upper, ELL = Elands Lower

4.3 RESULTS

A summary of the most important findings and trends is presented in the main report. Detailed results for the climate and hydrological modelling are presented in Volume 2 of this report.

4.3.1 Temperature

4.3.1.1 Historical conditions

There is a clear relationship between temperature (both maximum and minimum temperatures) and elevation in the catchment, which implies that the higher-lying areas are cooler on average than the lower-lying areas. This is evident from the maps in Figure 4.8, which show a distinct north-south trend of temperatures in the catchment, with the north-eastern part having the highest temperatures. In summer, mean monthly maximum temperatures range from less than 19°C in the south-west, to more than 25°C in the north-east of the catchment. In winter, mean monthly minimum temperatures could range between less than -3°C in the higher-lying areas in the south (where snow is common in winter), to more than 3°C in the lower-lying areas to the north (see Figure 4.8). Analysis of the historical data also indicated that the annual maximum temperatures are higher in the lower-altitude lower quinary (where the majority of sampling sites are located), and that differences between the cooler upper and middle quinaries are greater than between the middle and lower quinaries. During very hot years (90^{th} percentile), the annual maximum temperature could be 0.66°C warmer than the median, and during very cold years (10^{th} percentile), the annual maximum could be 0.79°C lower than the median.

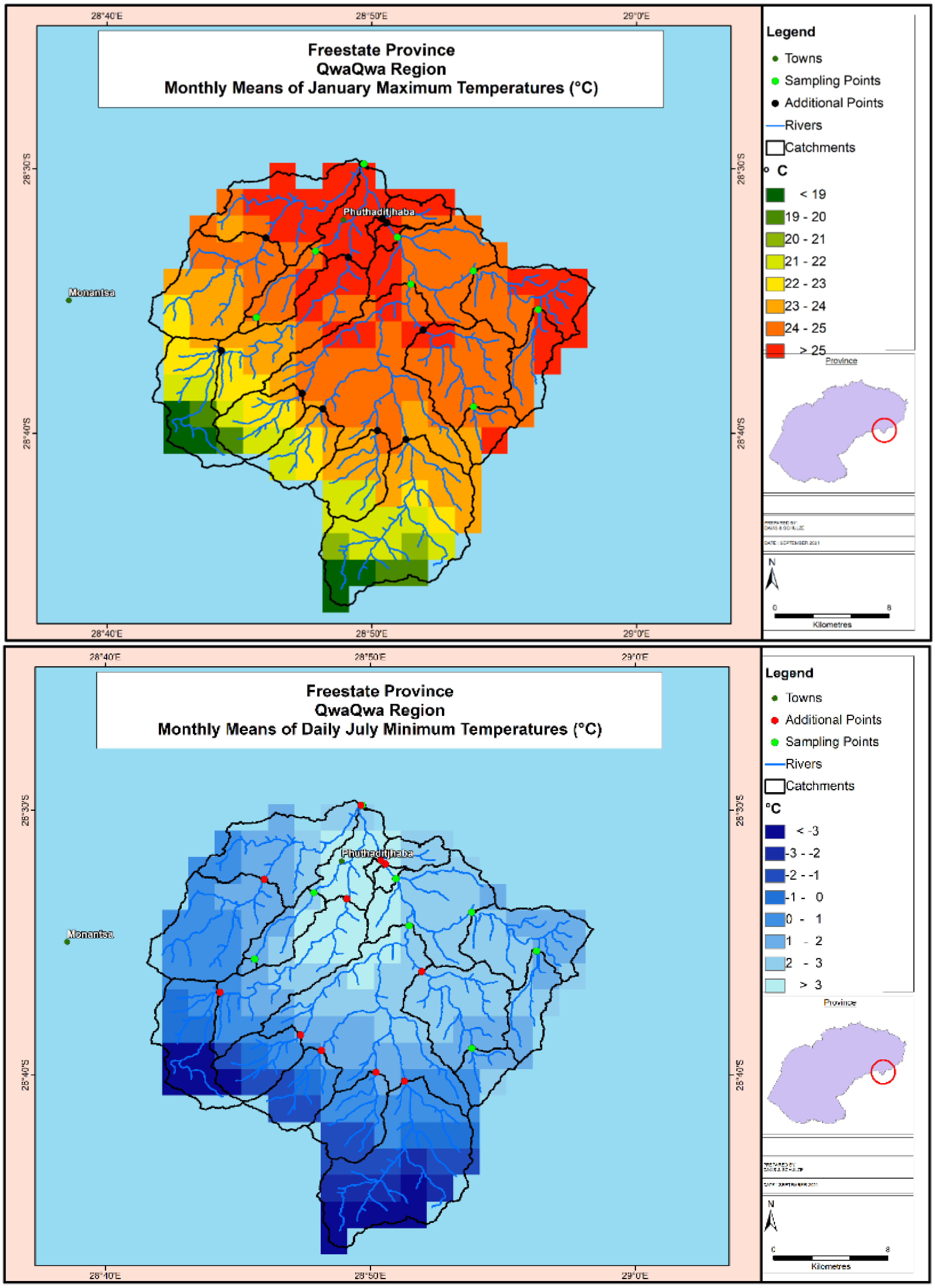


Figure 4.8. Monthly means for historical maximum temperatures for January and historical minimum temperatures for July for QwaQwa

4.3.1.2 Projections for the future

Both day-time maximum and night-time minimum temperatures are projected to increase markedly in the catchment, but not at the same rate, nor with the same spatial patterns. In the immediate future (mid-2030s), the average January maximum temperature could increase by ~1.4°C in the catchment from the defined present, and by more than 4°C in the more distant future (2080s). This means that in summer (January) the mean daily maximum temperatures in the upper quinary could increase from 24.11°C (present) to 25.47°C in the near future (2016-2045) and 28.18°C in the distant future (2071-2100), while in the lower quinary it could increase from 28.27°C to 29.63°C in the near future, and 32.34°C in the distant future. In winter (July), the mean daily maximum temperature in the upper quinary could increase from 11.06°C (present) to 12.69°C in the near future and 15.63°C in the distant future, while in the lower quinary it may increase from 16.84°C (present) to 18.47°C in the near future and 21.41°C in the distant future. In terms of minimum temperatures, the mean daily minimum temperature in winter (July) is expected to increase by 1.39°C (from -2.83°C at present) in the near future and by 3.84°C in the distant future in the upper quinary, and by 1.41°C (from 2.92°C at present) in the near future and by 3.84°C in the distant future in the lower quinary. In summer, the mean daily minimum temperatures are projected to increase by 1.54°C in the near future and by 4.18°C in the distant future in all the quinaries, which indicates that daily minimum temperatures in summer could increase slightly more than the daily maximum temperatures.

The projections also indicate that the number of moderately cold (Tmin<2°C), cold (Tmin<0°C), and very cold (Tmin ≤2°C) days per year could decrease markedly in the future. In the high-altitude upper quinary, the number of very cold mornings could decrease from 94.6 days (historically) to only 52.9 days in future, which is a reduction of 57.4%. The reduction could be even higher in the middle and lower quinaries, where very cold mornings could decrease by 72.4% and 81.8% respectively. Days with frost are expected to decrease by 41.2%, 65%, and 70.8% in the upper, middle, and lower quinaries respectively. This is a concerning result considering the importance of frost as a natural disturbance in grassland ecosystems.

4.3.2 Potential evaporation

4.3.2.1 Historical conditions

Potential evaporation in QwaQwa is very high, with annual averages increasing northwards in the catchment from less than 1 200 mm in the cool, mountainous south-west to more than 1 800 mm over the north (see Figure 4.9). As for temperature, a clear relationship exists between elevation and mean annual reference potential evaporation, with evaporation being significantly higher in the lower-lying parts of the catchment than in the higher-lying areas. Historical data show that annual A-pan equivalent reference potential evaporation in the upper quinary varies between 1 491 mm in a “cool” year (10th percentile) and 1 638 mm in a “hot” year (90th percentile), while it varies between 1 759 mm and 1 946 between cool and hot years in the lower quinary.

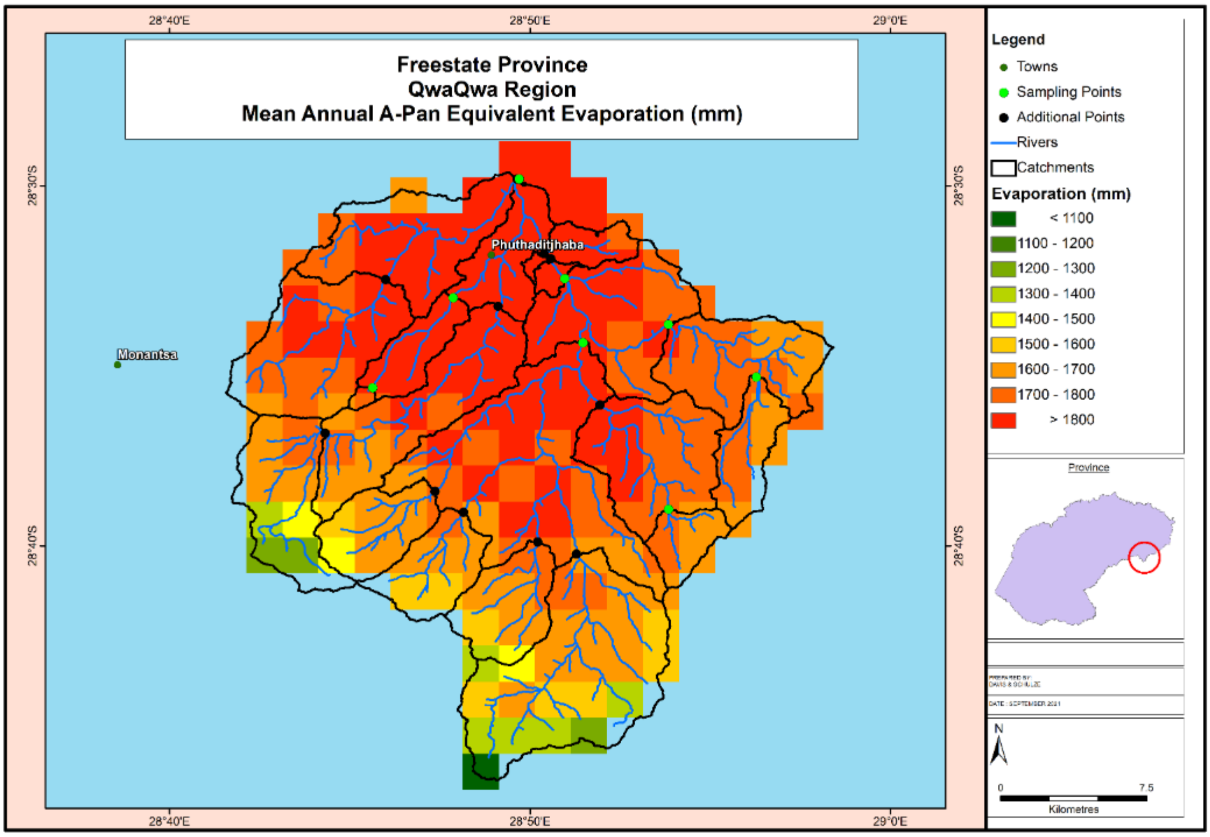


Figure 4.9. Mean annual A-pan equivalent reference potential evaporation (mm) across QwaQwa under historical climatic conditions

Source: Schulze (2008)

On a monthly basis, mean monthly reference evaporation is the highest in December, with 199 mm in the upper quinary, which is equivalent to 6.4 mm/day, and 214 mm; i.e. 6.9 mm/day, in the warmer lower quinary. The lowest average historical reference potential evaporation is experienced in June, when the difference between the cooler upper quinary at 78 mm (~2.6 mm/day) and the hotter lower quinary at 108 mm (~3.6 mm/day) is relatively high.

4.3.2.2 Projections for the future

Mean annual reference potential evaporation in QwaQwa is projected to increase from ~112 mm/a in the upper quinary and ~134 mm per year in the lower quinary in the near future, which represents an increase of approximately 7%. In the more distant future, the increases may range from >350 mm in the cooler upper quinary to ~424 mm in the lower quinary, which represents increases of approximately 22% per year. These projected increases are significant, especially when considering the impact these may have on evaporation from open water bodies, greater irrigation demands, and more rapid drying of soil.

4.3.3 Rainfall

4.3.3.1 Historical conditions

The mountainous areas in the catchment receive higher rainfall than the lower-lying areas, with MAP decreasing from more than 1 100 mm in the highlands (south) to approximately 700 mm in the lowlands (north) (see Figure 4.10). These amounts may, however, vary markedly within and between years. The historical data show that the mean annual rainfall could be approximately 32% lower during dry years (10th percentile) and approximately 37% higher during wet years (90th percentile). For example, the mean annual rainfall in the upper quinary could vary between 699 mm in dry years and 1 423 mm in wet years, whereas it may vary between 528 mm and 1 084 mm between dry and wet years respectively in the lower quinary. The historical data also indicate that years that receive below-average rainfall are more abundant than years with above-average rainfall, and that rainfall variability is higher during the dry season.

The catchment receives its rainfall predominantly in summer, with January receiving the highest rainfall, and June and July the lowest (see Figure 4.11). However, rainfall may vary drastically between years, with an inter-annual coefficient of variation (CV) of between 40% (December) and 170% (July). For example, the mean monthly rainfall may vary between 63 mm in a dry year, compared to more than 330 mm in a wet year (upper quinary).

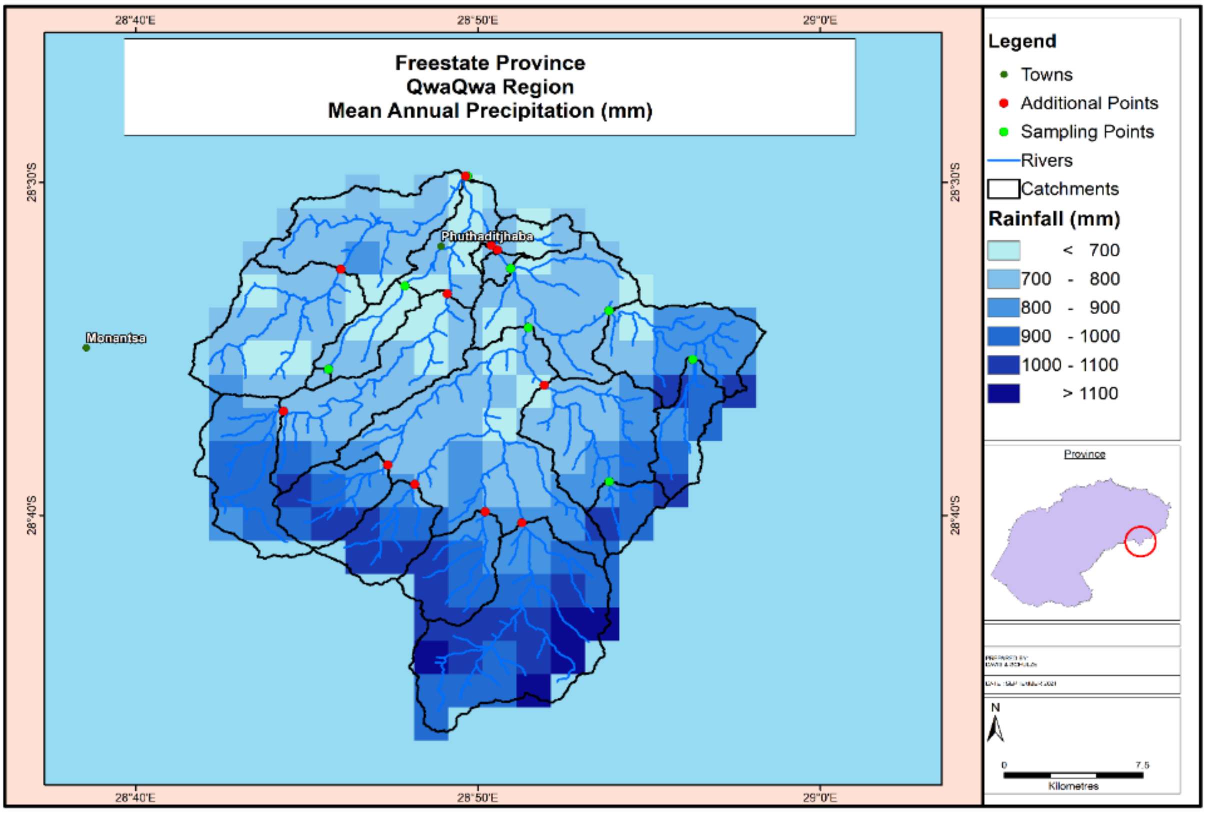


Figure 4.10. Historical mean annual rainfall in QwaQwa

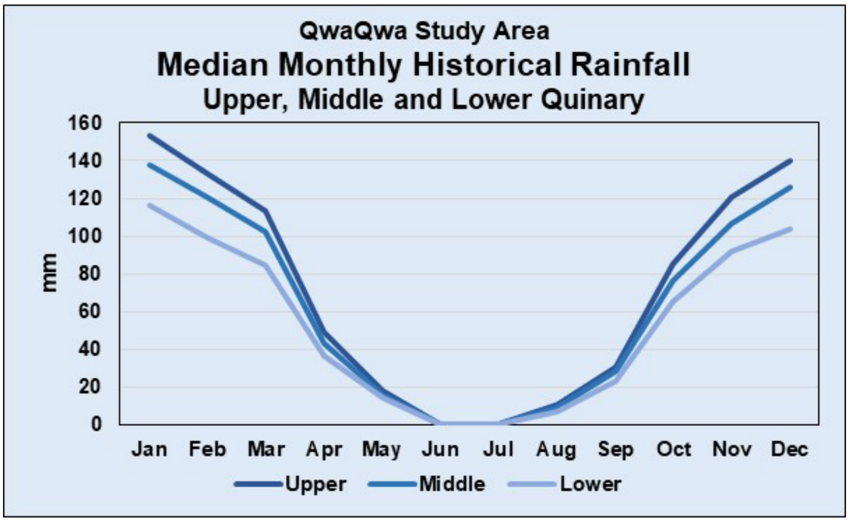


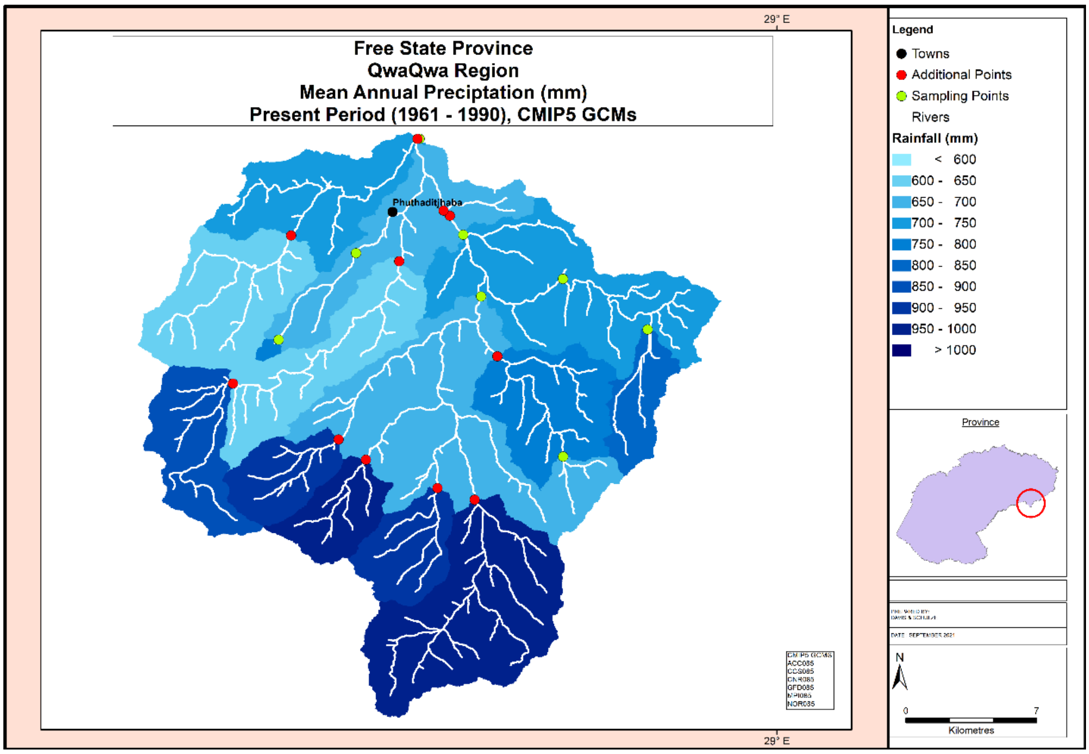
Figure 4.11. Historical median monthly rainfall in the upper, middle, and lower quinaries

In terms of the sub-catchments, the Metsi-Matso River receives the highest mean annual rainfall (>800 mm) and the Mphukojwane the lowest (~700 mm). In the Namahadi, the mean annual rainfall decreases from approximately 785 mm in the upper reaches to 718 mm in the lower reaches.

4.3.3.2 Projections for the future

Rainfall in QwaQwa is projected to increase in the future (see Figure 4.12). Although the differences in mean annual rainfall appear to be small, they become quite significant in dry and wet years. For example, in a dry year, the mean annual rainfall in the upper quinary is projected to increase by approximately 1.7% (12.7 mm) in the near future and by 17.3% (129.6 mm) in the distant future, compared to an average year when rainfall is expected to increase by 4.1% (40.2 mm) in the near future and by 18.5% (185.8 mm) in the distant future. For wet years, projections indicate increases of 2.7% (36.1 mm) in the near future and 17.7% (229.6 mm) in the distant future. The projections also show that bigger changes could occur at the higher altitude in the higher runoff-producing upper quinary (see Figure 4.13). In the wettest year in 10, it also appears, that in terms of rainfall, the GCMs tend to overestimate the rainfall for dry years and underestimate rainfall for wet years. This highlights the fact that the inter-annual rainfall variability may be underestimated by the GCMs. (A detailed discussion of the verification of the results are presented in Volume 2 of the report.)

Figure 4.14 presents the projected changes in the mean annual rainfall for the 19 sub-catchments identified in the study area. Increases within the sub-catchments range between 21 mm (Sub-catchment 18) in the lowlands to 35 mm (Sub-catchment 1) in the mountainous areas.



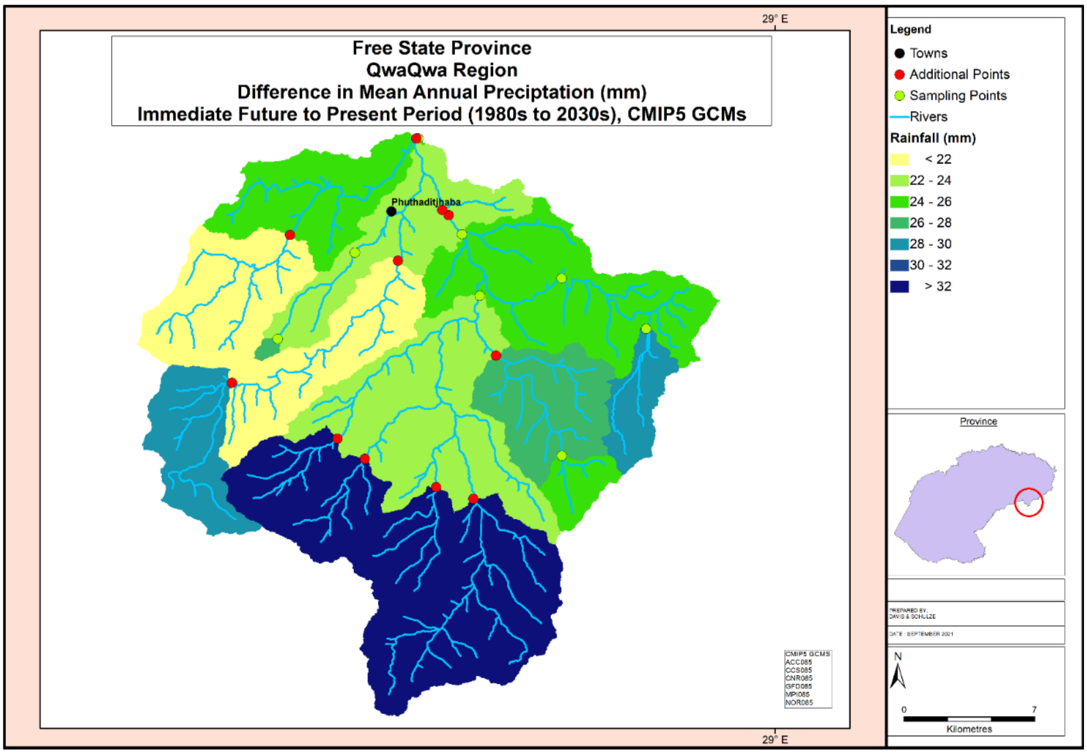


Figure 4.12. MAP (mm) across the 19 QwaQwa sub-catchments for the present period, derived from multiple Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Climate Models (GCMs), and the projected increase from the present to the immediate future

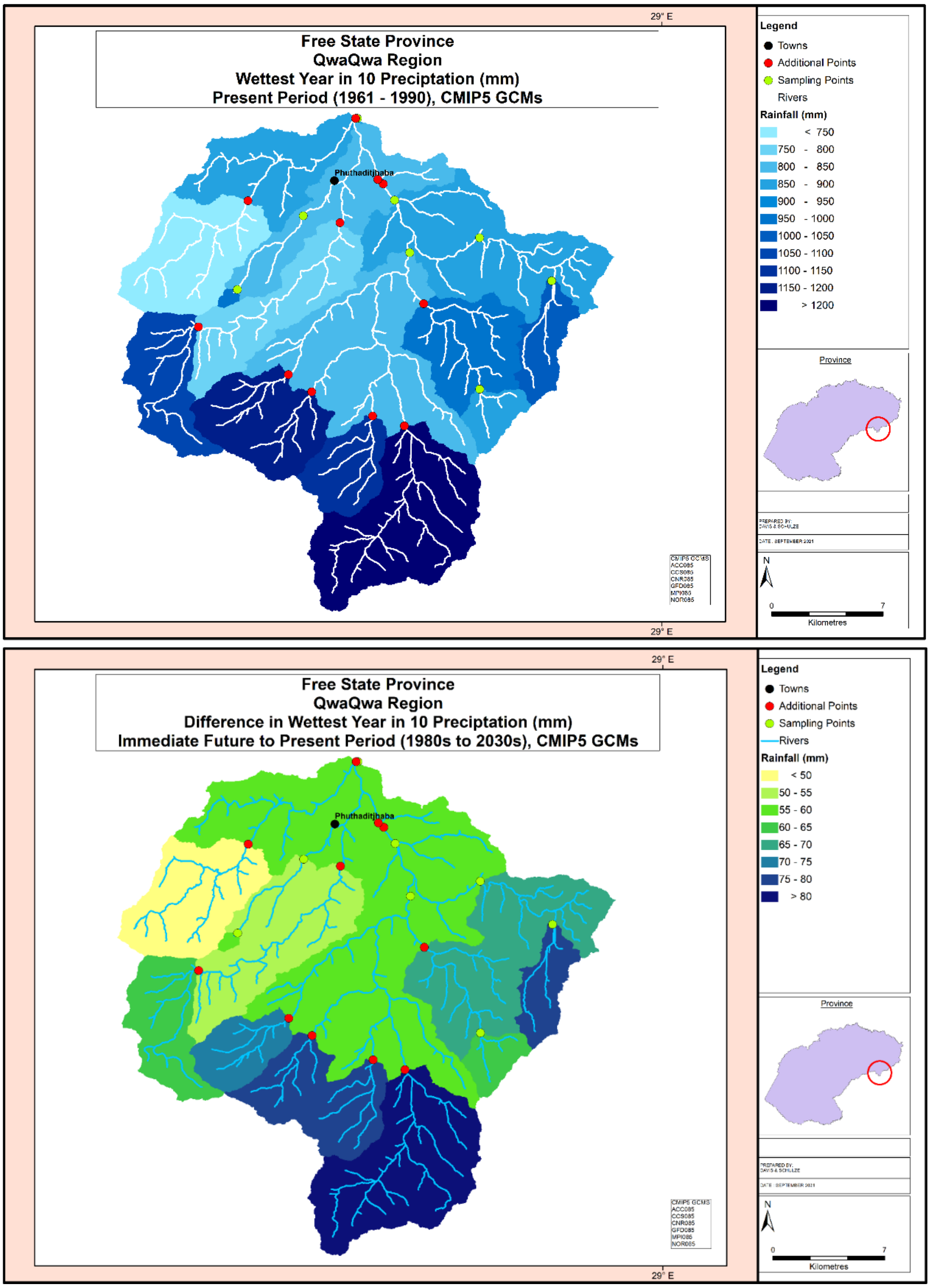


Figure 4.13. Annual precipitation (mm) in the wettest year in 10 across the 19 QwaQwa sub-catchments for the present period, derived from multiple CMIP5 GCMs, and the projected increase from the present to the immediate future

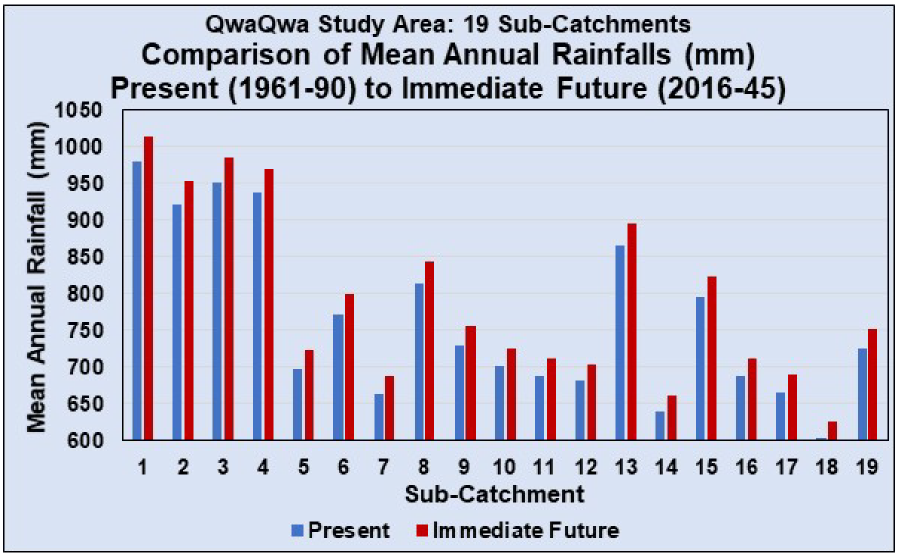


Figure 4.14. Comparison of mean annual rainfall (mm) across the 19 sub-catchments for the present and immediate future periods as derived from multiple CMIP5 GCMs

The wetter higher-lying areas appear to be more sensitive to dry and wet spells than the drier lower-lying areas. The projections indicate that the number of dry spells in the upper parts of the catchment could increase in the immediate future, with the greatest changes being expected for the two- and three-month-long dry spells. In contrast, the number of wet spells are projected to decrease by 15% for two-month, 25% for three-month, and 40% for four-month wet spells in the immediate future respectively. It therefore seems as if more dry spells and fewer wet spells are expected in the near future. This may have severe consequences for agricultural production and water resource management in QwaQwa.

4.3.4 Runoff

4.3.4.1 Historical conditions

The bulk of the runoff in the catchment is generated in the upper quinary (Mean Annual Runoff, MAR, = 505 mm), which delivers nearly three times the runoff generated in the lower quinary (MAR = 177 mm). Interesting to note is that this ratio is higher (6.43 times) during dry years, and lower (2.32 times) during wet years. The historical data show that in dry years, the MAR in the upper quinary may be reduced to 238 mm, compared to 829 mm in wet years. In the lower quinary, the MAR of 117 mm may be as low as 37 mm in dry years and as high as 357 mm in wet years.

The highest runoff generally occurs in summer, with February being the month with the highest median monthly runoff (see Figure 4.15). Considering that median monthly rainfall peaks in January, it is clear that there is a lag of approximately one month between rainfall and runoff in the catchment.

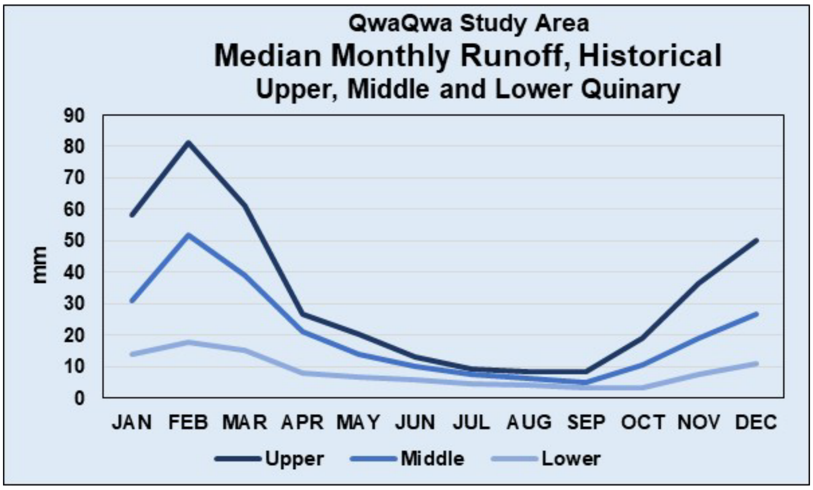


Figure 4.15. Median monthly runoff from baseline land cover under historical climatic conditions for the upper, middle, and lower quinaries in QwaQwa

Intra-annual variability in runoff is high in the catchment, but is lower in the upper quinary (where runoff is higher) and higher in the lower quinary (where runoff is lower).

4.3.4.2 Projections for the future

The projections show that MAR in the upper quinary may increase by nearly 7% from the present day (1961-1990) to the near future (2016-2045), and by up to 35% in the distant future (2071-2100), which indicates an acceleration of climate effects into the future. However, the biggest change is expected to occur in the drier lower quinary, where the acceleration effect of climate change is expected to be even higher than in the upper and middle quinaries. In the lowlands, the MAR is projected to increase by nearly 16% (19.2 mm) in the near future, and by 68% (84.7 mm) in the distant future from present-day conditions (122.9 mm). In dry years (1:10 year low-flow conditions), the MAR in the lowlands could increase by 12% in the near future, and by 65% in the distant future, while in wet years (1:10 year high-flow conditions), it could be 11% and 61% higher in the near and distant futures respectively. These increases are markedly higher than the increases in the mean annual rainfall projected for the lower quinary. These projected changes are seen more clearly when expressed as ratio changes in Figure 4.16, where a ratio change of, for example, 1.6 represents a 60% change. The acceleration of projected climate change as time moves on is clearly evident in Figure 4.17, with the changes from the present to the distant future ratios being several times those of present to the near future.

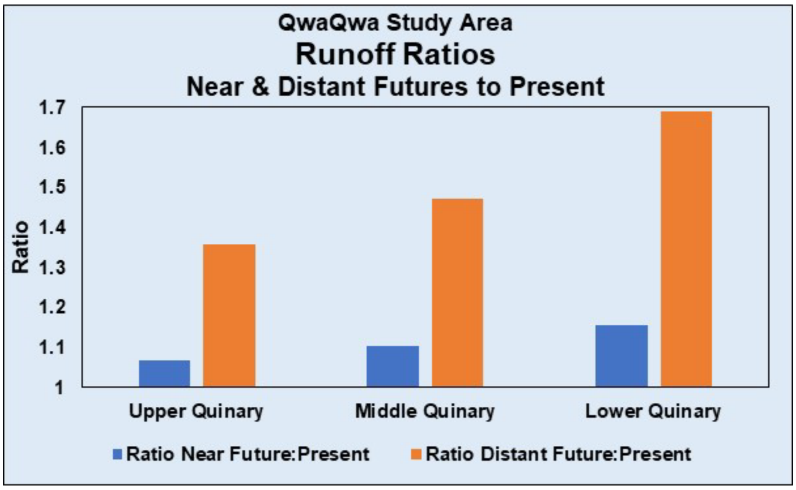


Figure 4.16. Runoff ratios from baseline land cover conditions for the near and distant futures to the present for the upper, middle, and lower quinaries in the QwaQwa study area

The maps in Figure 4.17 present the MAR (derived from multiple GCMs) for the present period spatially (top), as well as the difference between the present and the near future (bottom). The spatial range in MAR under the present climate is from 311 mm in the south-western mountains to 59 mm in the drier north-west. This represents a 5.3 times difference from the highest sub-catchment to the lowest, compared with only a 1.6 times difference in the case of rainfall (979 mm compared to 604 mm), which illustrates the sensitivity of runoff to rainfall. Changes in MAR from the present to the immediate future increase from 29.4 mm in the mountains of the south-west to 14.4 mm in the lower-rainfall lowlands (see Figure 4.17). These changes represent an average increase in MAR of 17.9% in the near future, with the percentage increase being only 9.5% in the mountains, while they go up to 25.9% in the hydrologically more sensitive lowlands, compared with average increases of only 3.5% for mean annual rainfall (range: 3.4-3.6%) and 4.4% (range: 4.3-4.6%) in the wettest year in 10. These statistics once again illustrate the high sensitivity of runoff to changes in rainfall, as well as that the sensitivities are not the same spatially.

It should be noted that although the runoff derived from the GCMs matched the runoff derived from the historical climate data nearly perfectly, the GCM-derived runoff overestimated historically derived runoffs, when averaged over the 19 sub-catchments and expressed as percentages, in the high-flow summer months from December to March, but underestimated runoff in the critical spring period from August to November. A detailed discussion of the validation of the runoff derived from the GCMs are presented in Volume 2 of the report.

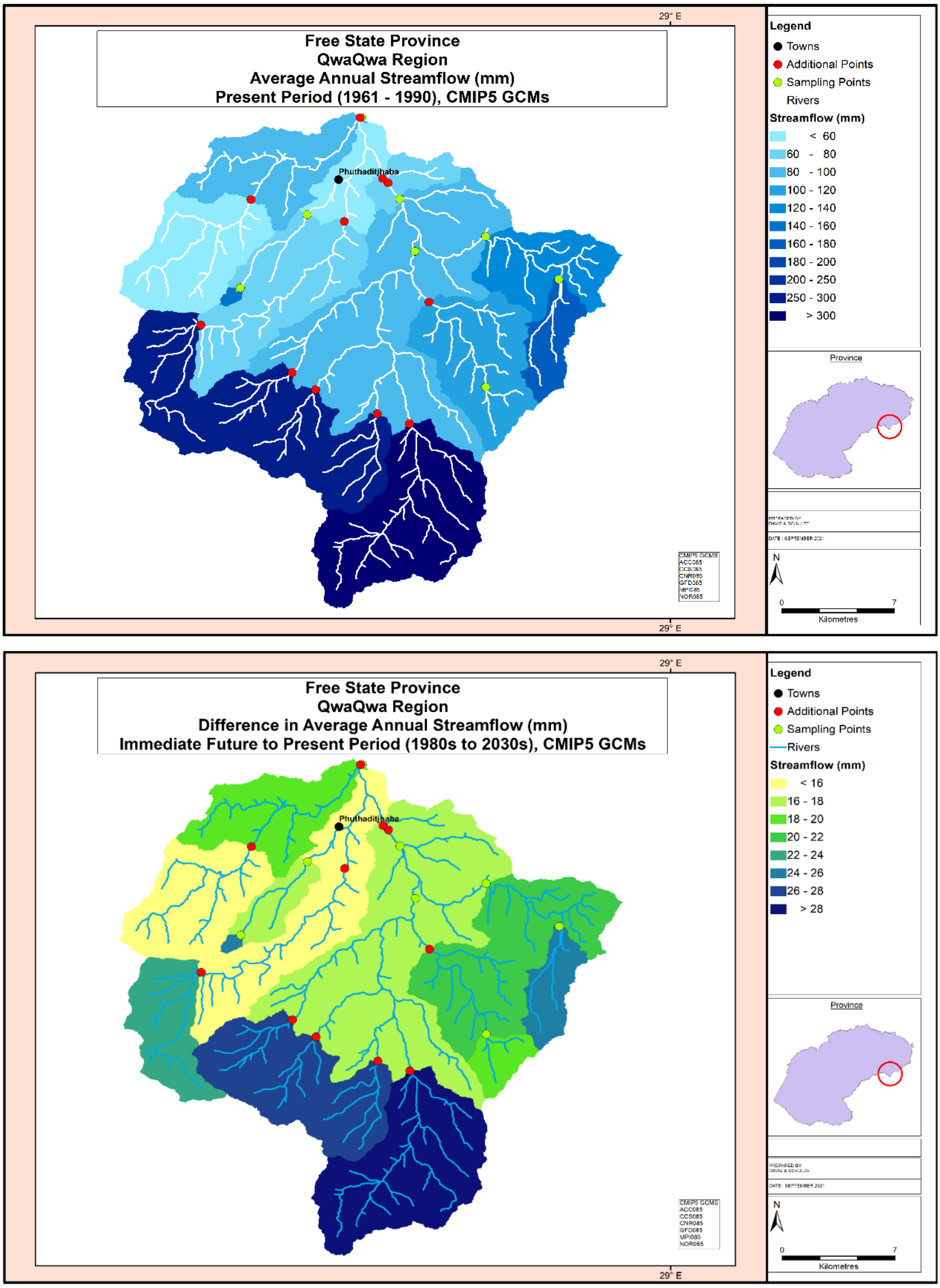


Figure 4.17. Average annual local runoff (streamflow on map, mm) across the 19 QwaQwa sub-catchments for the present period, derived from multiple CMIP5 GCMs, and the projected increase from the present into the immediate future, all under baseline land cover

4.3.5 Stormflows

4.3.5.1 Historical conditions

In QwaQwa, stormflows, defined as the component of runoff generated at or near the surface within a catchment from a specific rainfall event, occur predominantly in summer, particularly in the steeper and higher-lying upper quinary. For example, in January and February stormflow may contribute up to 70% to the total runoff in the upper quinary, compared to less than 30% in winter. In the lower quinary, stormflow contributes approximately 60% to the runoff in summer, and 20% or less in winter.

4.3.5.2 Projections for the future

The average annual local stormflow (mm) across the 19 sub-catchments in QwaQwa for the present period (derived from multiple CMIP5 GCMs) is projected to increase in the immediate future (see Figure 4.18). The average present GCM-derived stormflow simulations range from 202 mm in the mountains to only 45 mm in the lowlands. This represents a decrease by a factor of 4.5 compared with a decrease by a factor of only 1.6 in the case of mean annual rainfall. The projected changes in the mean annual stormflows from the present, represented by the mid-1970s, to the immediate future, represented by the 2030s, are presented in Figure 4.18. The map shows increases into the future, ranging from 28 mm equivalent in the mountains to only 8 mm in the lowlands. However, when expressed as percentage increases, the increase in the mountains is only ~13.6%, compared to an increase of up to 21.8% in the lowlands. However, it should be noted that stormflows seem to be overestimated for the mid-summer months and underestimated from August to November.

4.3.6 Baseflows

4.3.6.1 Historical conditions

Baseflows, defined as the contribution to runoff from earlier rainfall events where rainfall has percolated through the soil horizon into the vadose and groundwater zones, contribute to streamflow when the river channel is connected to groundwater. Baseflows are therefore more evenly distributed over the year and are important for sustaining streamflow during the dry, or non-rainy, season. In QwaQwa, baseflows are higher in wet years than in median and dry years. The historical data also show that baseflows are higher in the upper quinary than in the middle and lower quinaries. It also indicates that baseflows are the main contributor to runoff in the dry season (April to August), whereas stormflows are more dominant during the wet season.

4.3.6.2 Projections for the future

Mean annual local baseflows (mm) are projected to increase across the 19 QwaQwa sub-catchments from the present period (derived from multiple CMIP5 GCMs) to the immediate future for baseline land cover conditions (see Figure 4.18). The average present GCM-derived baseflow simulations of 44.1 mm equivalent (compared to 97.6 mm for stormflows) range from 109.4 mm (compared to 202 mm for stormflows) in the highlands to only 9.8 mm in the lowlands. This represents a decrease by a factor of

11.2 (compared to 4.5 for stormflows and only 1.6 in the case of mean annual rainfall). Baseflows are thus firstly considerably lower than stormflows and, secondly, spatially far more sensitive than stormflows.

The projected changes in mean annual baseflows from the present, represented by the mid-1970s, to the immediate future of the 2030s are shown Figure 4.18. This shows that baseflows are likely to increase in the future, with increases ranging from 1.8 mm in the mountains to 6.1 mm in the lowlands. However, when expressed as percentage increases, it is clear that the increase in the mountains is only ~1.6%, compared with percentage increases of up to 46.9% in the lowlands (see Figure 4.19).

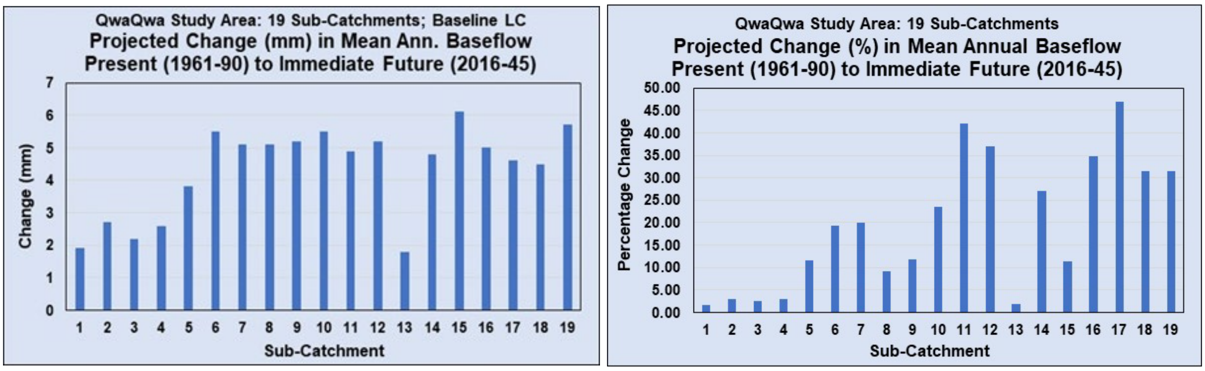
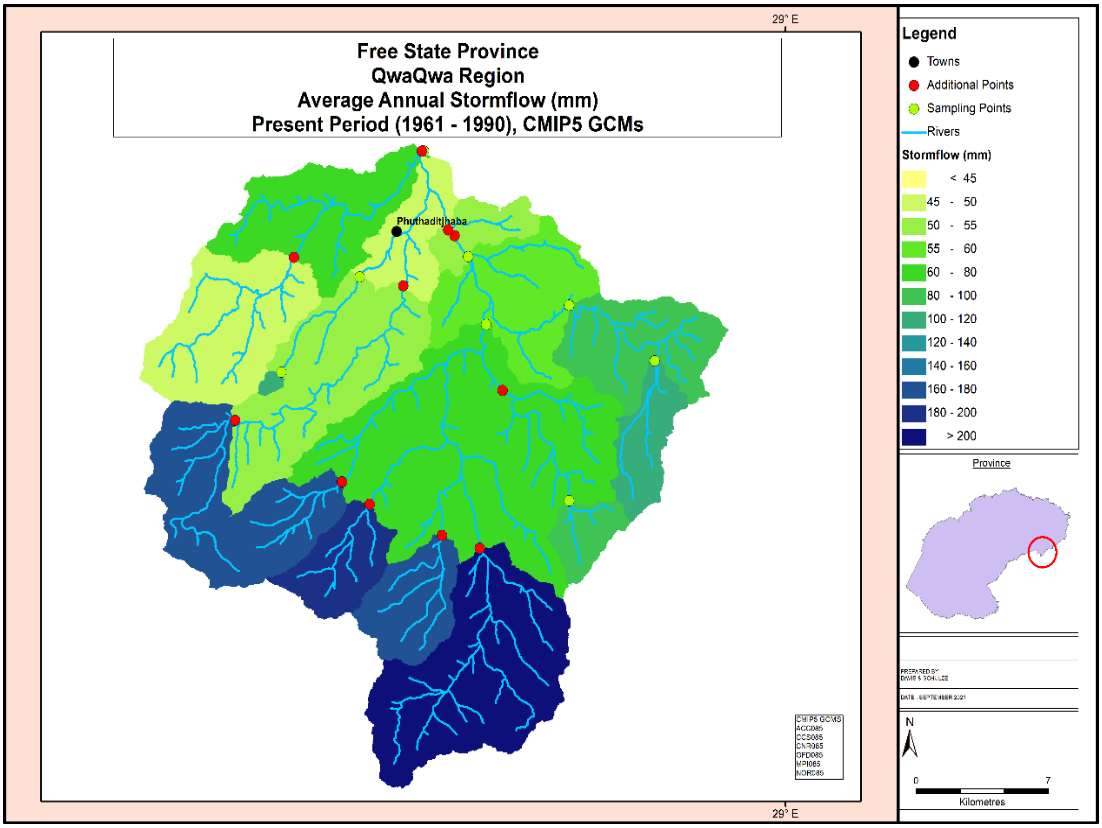


Figure 4.18. Projected changes in mean annual baseflows from the present to the immediate future in mm and as a percentage

The projections also indicate that the recharge to groundwater is likely to increase in the near and distant future, especially in the lower-lying part of the study catchment. Recharge in the lowlands could increase by nearly 7% in the near future and by 38% in the distant future. In the upper quinary, recharge is projected to decrease slightly in the near future and increase by only 1.7% in the distant future.



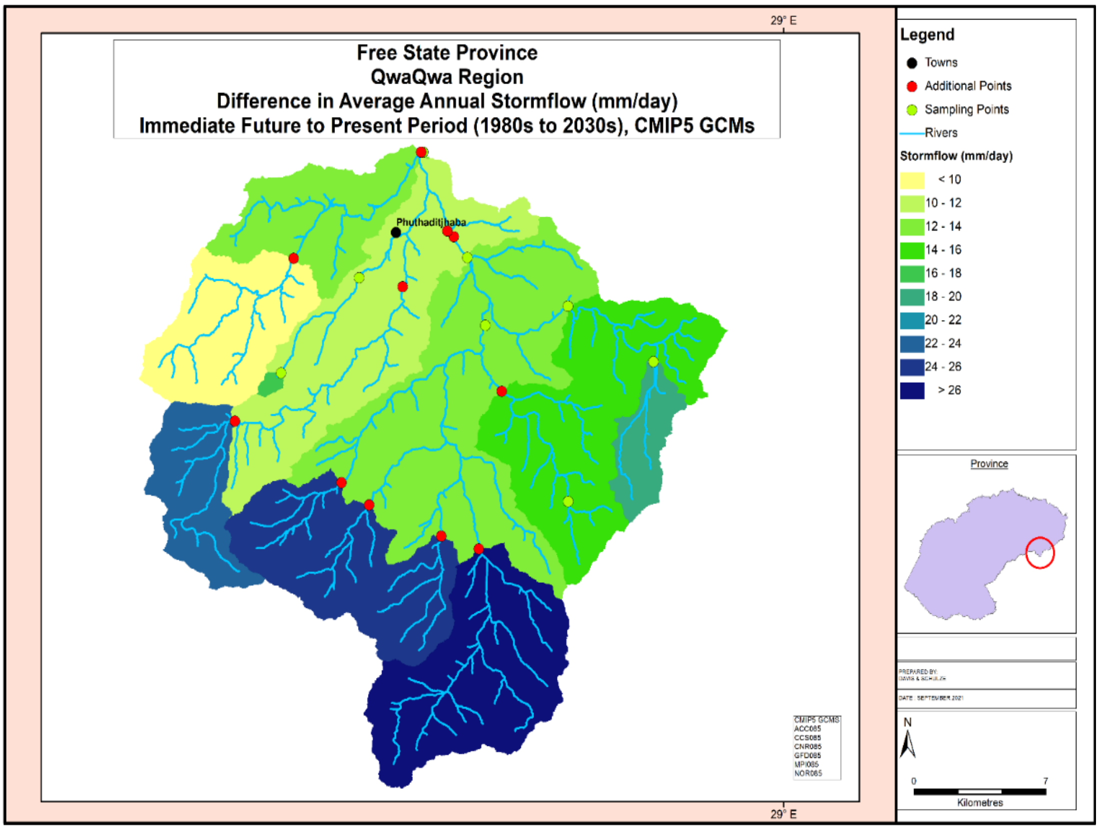


Figure 4.19. Average annual local stormflow (mm), under baseline land cover conditions, across the 19 sub-catchments for the present period, derived from multiple CMIP5 GCMs, and the projected increase from the present into the immediate future

4.3.7 Accumulated streamflow

In streamflow analysis, it is important to remember that the runoff from the upper quinary joins that of the middle quinary to converge downstream with the local runoff from the lower quinary. The accumulated flow from the entire upstream area is referred to as accumulated streamflow.

It is clear from Figure 4.20 that the mean annual accumulated streamflows for the present (as derived from the GCMs) follow the main river system in the catchment, the Namahadi, very closely. The accumulated streamflows vary greatly between the 19 sub-catchments, from 0.17 million m^3/a to 73.47 million m^3, depending primarily on the size and rainfall of the sub-catchments. These GCM-derived statistics compare very favourably with the average accumulated streamflows derived from historical climate data for the same 1961-1990 period, which have a range from 0.18 million m^3 to 73.55 million m^3.

The projections show that the mean annual accumulated streamflows are likely to increase from present conditions into the immediate future (see Figure 4.20), with increases ranging from 0.027 million m^3/a in the small Sub-catchment 15, to 10.53 million m^3/a in the downstream exiting Sub-catchment 19, with an average increase of 2.93 million m^3/a (see Figure 4.21).

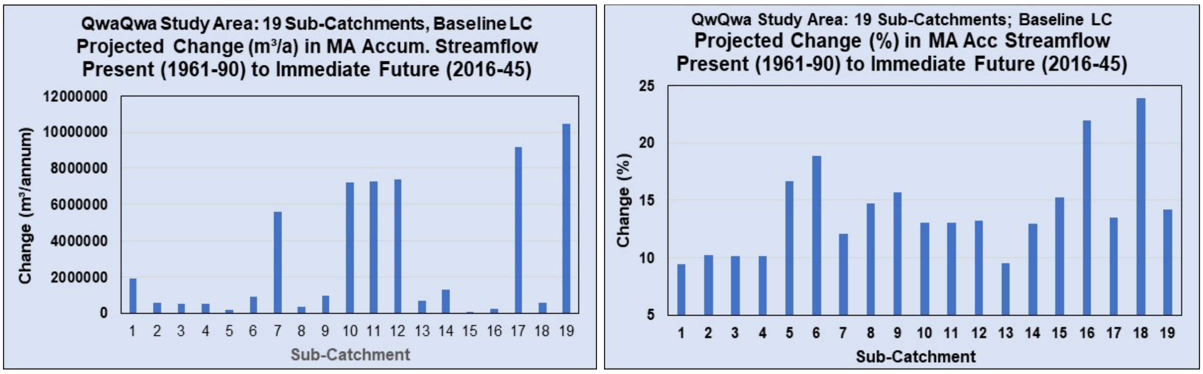


Figure 4.20. Projected changes in mean annual accumulated streamflows from the present to the immediate future in m^3/a and as a percentage, all under baseline land cover conditions

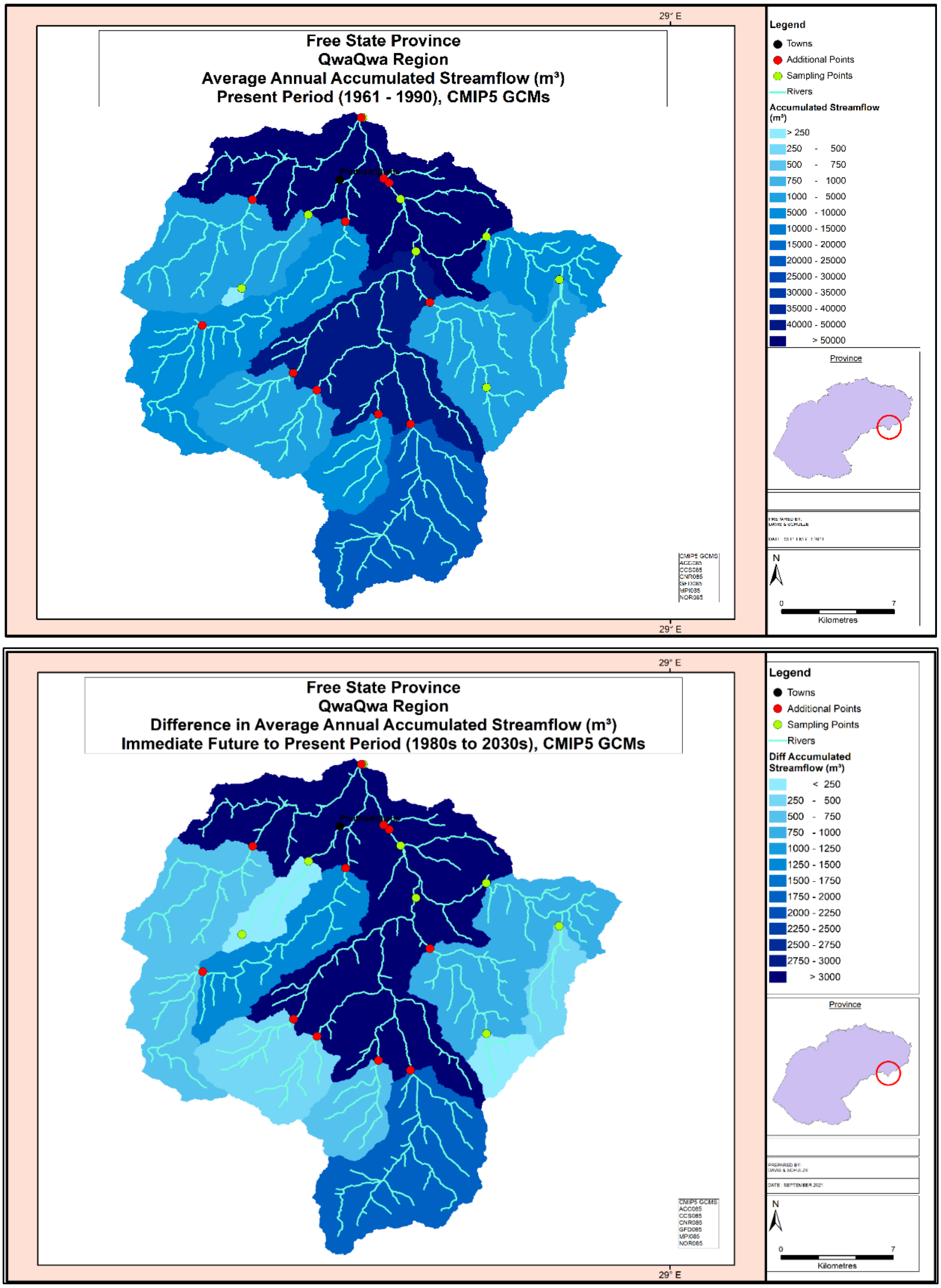


Figure 4.21. Average annual accumulated streamflows, under baseline land cover conditions, across the 19 QwaQwa sub-catchments for the present period, derived from multiple CMIP5 GCMs, and projected increases from the present to the immediate future

4.3.8 Peak discharges

Peak discharges refer to the highest flow of a hydrograph, and is particularly relevant for considering sediment yield in a catchment. Peak discharge is not only a function of stormflow volume in a catchment, but is significantly correlated with catchment area, main channel length, mean slope gradient, and vegetation cover (Fu *et al.*, 2020). Due to these factors being different for the various sub-catchments in the study area, a Peak Discharge Index (PDI) per unit area was used to compare peak discharge between the various sub-catchments.

Figure 4.22 shows firstly that peaks per unit area are considerably higher in the steeper and higher runoff-producing upper quinary than in the middle and especially the flatter lower quinary. Secondly, it shows that the high PDI is particularly a late summer phenomenon, most likely associated with thunderstorm activity, with the highest unit peaks in February, and with a gradual build-up from spring though early summer to late summer.

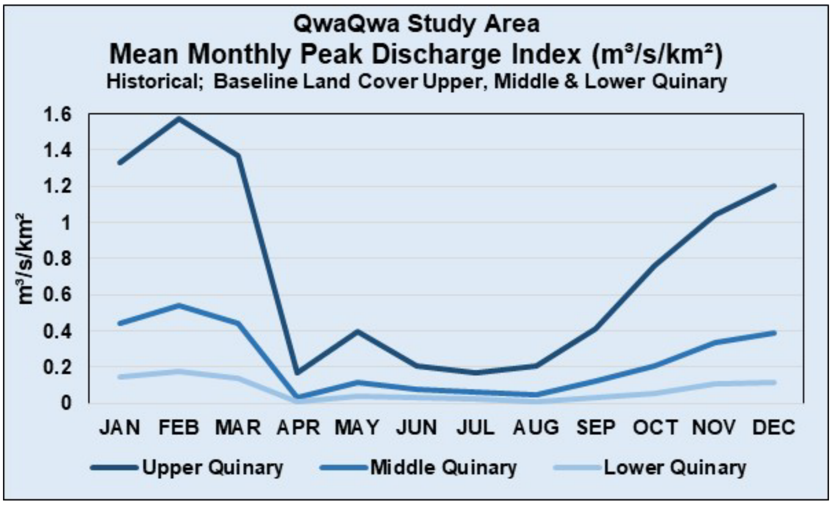
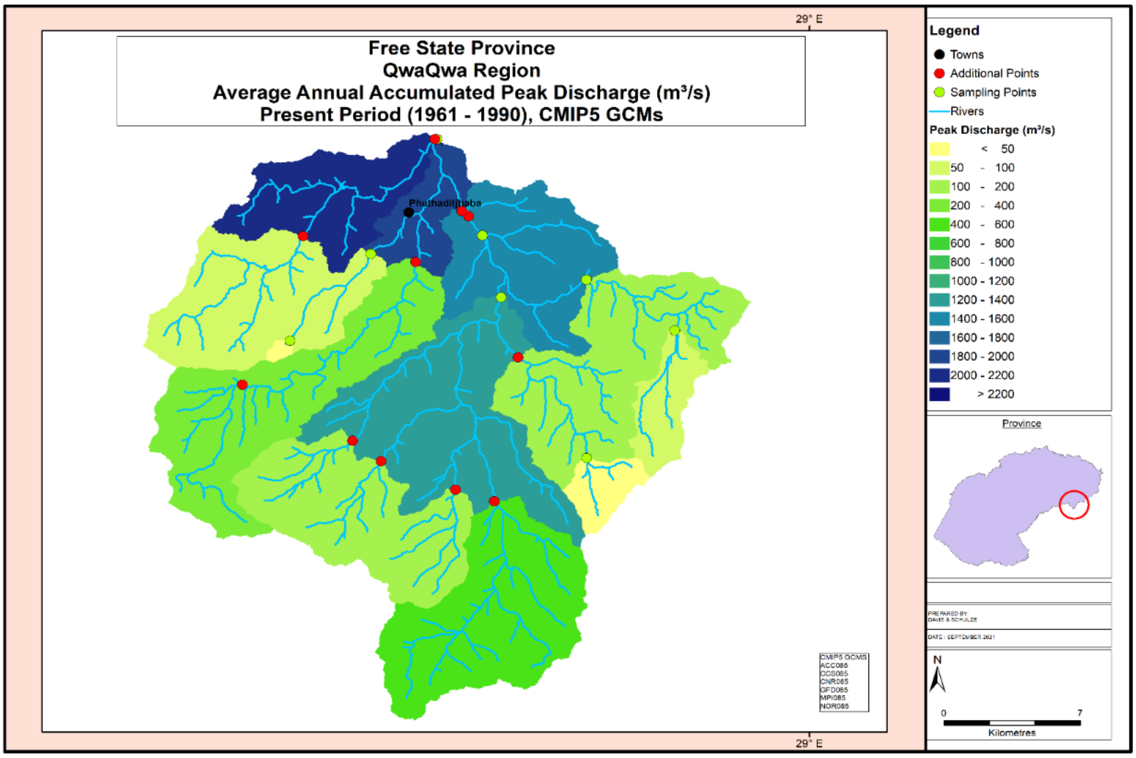


Figure 4.22. Monthly means of the Peak Discharge Index (PDI) under baseline land cover conditions in the upper, middle, and lower quinaries of the QwaQwa study area

It is clearly evident from Figure 4.23 that the accumulated average annual peak discharge under present climatic conditions becomes progressively larger from the various sources in the east, south, and west of the QwaQwa study area to the river exit in the north, where it exceeds 2 200 m^3/s. From the present to the immediate future, Figure 4.23 shows increases in peak discharges in a downstream direction, ranging from <5 m^3/s to >250 m^3/s at its exit from the study area, which indicates that this area might be more prone to floods in the future.



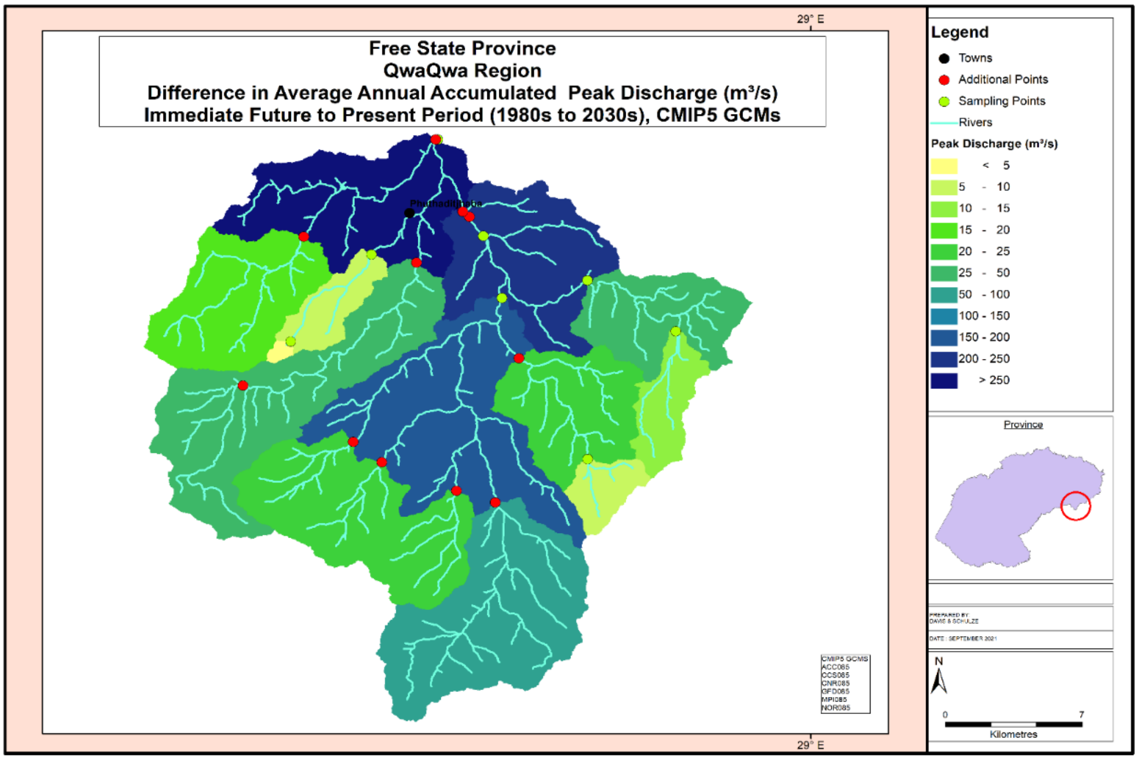


Figure 4.23. Mean annual accumulated peak discharge across the 19 QwaQwa sub-catchments for the present period as derived from multiple CMIP5 GCMs, and projected increases from the present to the immediate future, all under baseline land cover conditions

4.3.9 Sediment yields

4.3.9.1 Historical conditions

The historical data show that there are large differences between the amount of sediment delivered to the river channels in the mountainous, wetter upper quinary and the flatter, drier lower quinary. Under historical climatic conditions, ~2 100 t/km^2.a of sediment are generated in the upper quinary of QwaQwa on average, compared with ~700 t/km^2.a in the middle quinary and only ~100 t/km^2.a in the drier lower quinary (see Figure 4.24). However, in a 1:10 wet year, these values increase from ~2 100 to 4 700 t/km^2.a in the upper quinary, from 700 to 3 200 t/km^2.a in the middle quinary, and from approximately 100 to <400 t/km^2.a in the lower quinary (see Figure 4.24). These increases represent amplifications of 2.2 times in the upper, 4.6 times in the middle, and ~4 times in the lower quinaries. Conversely, in a 1:10 dry year, the tonnages of sediment loss decrease to 1 000, 150, and to around zero for the upper, middle, and lower quinaries respectively.

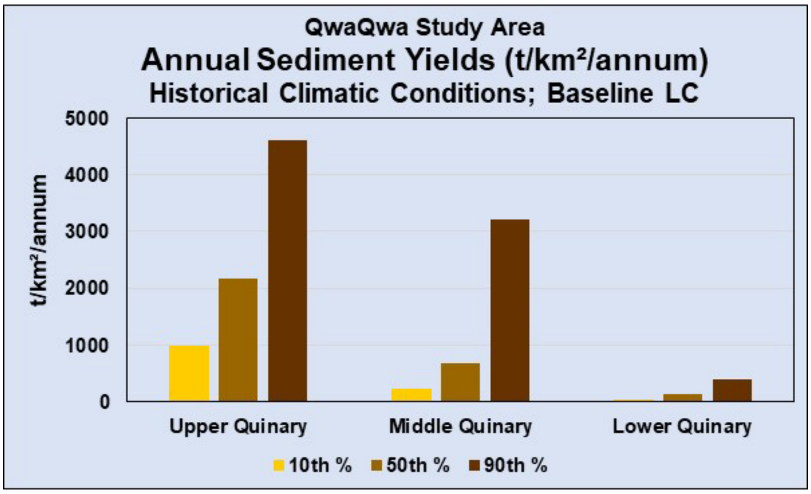


Figure 4.24. Annual sediment yields in t/km^2.a under baseline land cover conditions in the driest year in 10, a median sediment production year, and a 1:10 year high for the upper, middle, and lower quinaries in the study area

On a month-by-month basis, Figure 4.25 shows that the peak sediment-producing month is February, with a rapid decline thereafter. It increases again from August onwards when rainfall events are infrequent and, because of the more frontal type rainfall, of low intensity. The production of sediment is, however, highly variable, with the inter-annual CV in excess of 200% for most months, and up to 500% in April and May. The results indicate that sediment yields are considerably more sensitive to climate than, for example, runoff.

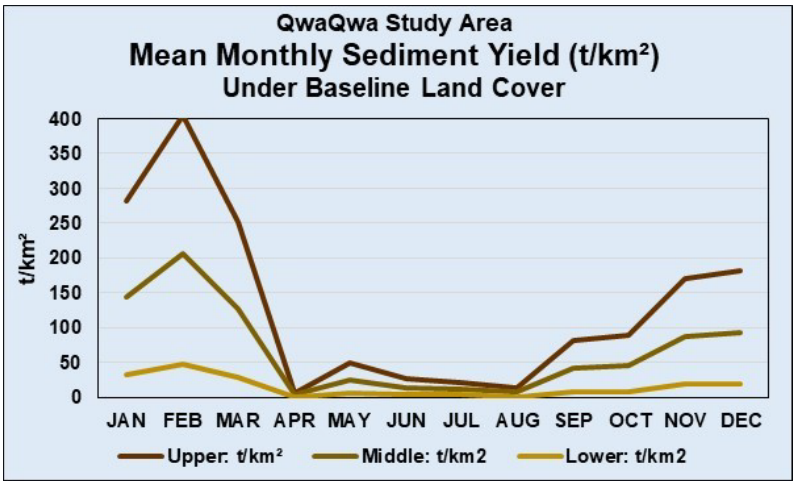


Figure 4.25. Monthly means of sediment yields under historical climatic and baseline land cover conditions from the upper, middle, and lower quinaries in the study area

4.3.9.2 Projections for the future

The average annual accumulated sediment yield is projected to increase from present values across the 19 sub-catchments (Figure 4.26). The top maps in Figure 4.27 represent the present sediment yields, as derived from the GCMs, in tonnes and in t/ha, while the projected increases from the present into the immediate future are shown in the bottom maps in tonnes and in t/ha. The accumulation of sediment yields is clearly visible in the top left map, while the top right map shows which sub-catchments are sensitive to sediment yield production. It is clear that the mountainous areas, with their steep slopes, are particularly vulnerable, as well as some downstream sub-catchments where soil type plays a major role.

The projected changes in mean annual sediment yields from the present into the immediate future (see Figure 4.26), in t/ha.a (bottom right) and as a percentage (bottom left), range from 0.05 to 2.29 t/ha.a with an average of 0.42 t/ha.a, which converts to percentage changes of 7.9% to 25.3% with an average of 20.5%.

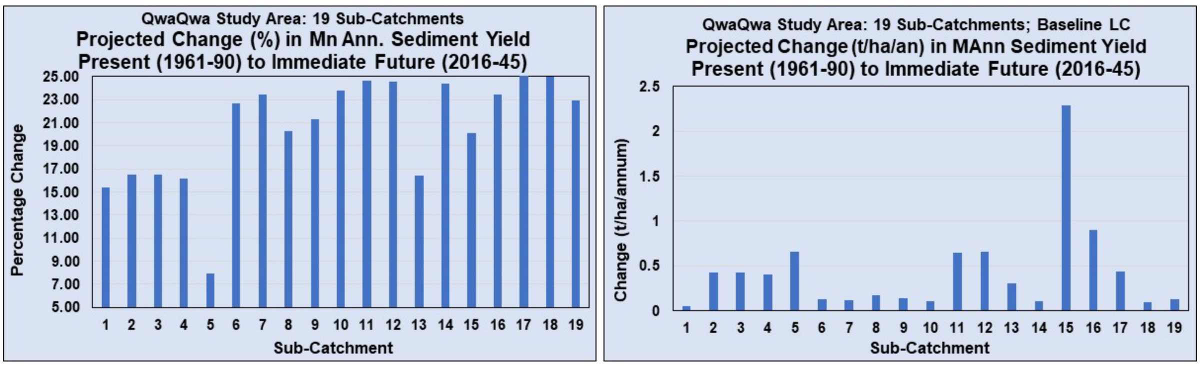


Figure 4.26. Projected changes in mean annual sediment yields from the present to the immediate future in t/ha.a and as a percentage, all under baseline land cover

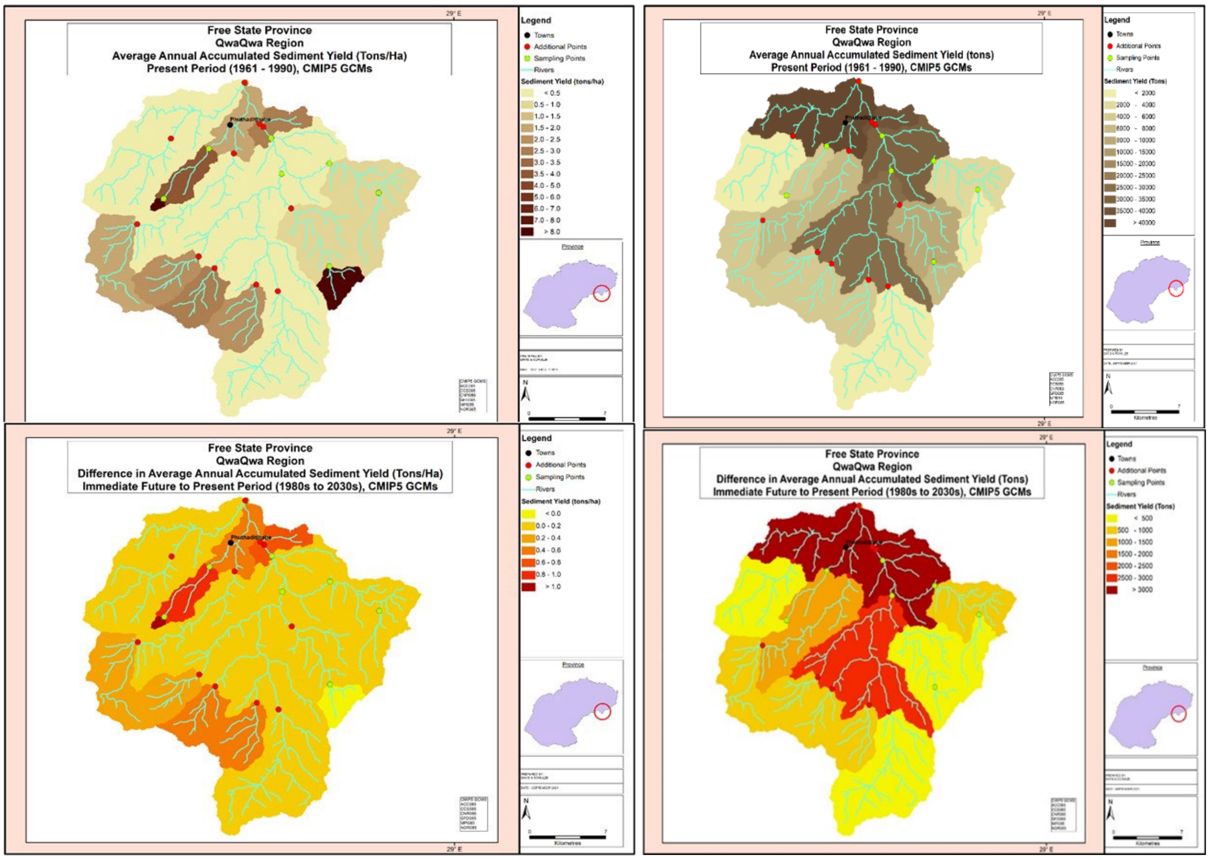


Figure 4.27. Mean annual accumulated baseline sediment yields in tonnes and in t/ha across the 19 sub-catchments for the present period, derived from multiple GCMs, and projected increases from the present to the immediate future in tonnes and in t/ha

4.4 KEY FINDINGS AND TRENDS

The QwaQwa study area, despite being just over 500 km^2 in extent, covers a wide range of altitudes and an associated range of climates across a small space, and with that an amplified range of hydrological responses such as stormflows, baseflows, accumulated streamflows, peak discharges, and sediment yields. This physiographic diversity is rendered even more complex by the overlay of people living in different densities and levels of urban formality across the 19 sub-catchments into which the area was delineated.

Given the above overall perspective, the following observations from hydrologically related modelling were made in the QwaQwa; firstly under baseline conditions of natural vegetation, and secondly considering actual land uses.

4.4.1 Rainfall

The relationships between rainfall and altitude in QwaQwa is complex and non-linear, with the highest rainfall occurring before the highest altitudes.

The highest altitude sub-catchment, Sub-catchment 1, receives a mid-summer monthly January average rainfall of ~170 mm, while the sub-catchment with the lowest altitude, Sub-catchment 17, receives only ~110 mm during January, on average.

Monthly rainfall totals are highly variable from one year to the next, with the CV (%) of monthly rainfall being the lowest in high-rainfall summer months at ~40-50% and the highest in the low-rainfall winter months at ~150%.

Climate change projections of annual rainfall in this area are for an increase of ~8% in the immediate future and ~12.5% in the more distant future. Furthermore, in the future relatively more rainfall is projected in mid-summer and relatively less in the winter months. The highest absolute (i.e. mm) projected change in rainfall in the immediate future in the high-rainfall mountainous sub-catchments is ~30-35 mm per month.

4.4.2 Potential evaporation

Historically, potential evaporation in QwaQwa is the lowest in the cooler higher-altitude upper quinary at 1 550 mm/a, increasing to 1 860 mm in the hotter lower-altitude lower quinary, with the range in the 1:10 hot year from 1 650 to 1 950 mm.

Under climate change conditions, annual potential evaporation is projected to increase by ~7% in the immediate future and by a very marked ~22% in the more distant future.

4.4.3 Runoff

The median monthly runoff is the highest in the high-rainfall upper quinary of the study area, peaking at 80 mm equivalent in February, and the lowest in the drier lower quinary at <20 mm, with February again the month of the highest runoff.

However, the month-month (CV%) of runoff is very high throughout the year – in the range of 60% to 150% – with the highest values at 150% in spring (owing to uncertainty of when the rainy season sets in) and the lowest values in mid-summer with its more predictable rains.

Spatially, the CVs of runoff are the highest in the lower-altitude quinaries with their lower and less predictable runoffs, with values of ~100% in mid-summer months, while, conversely, they are the lowest in the higher-runoff upper quinaries with values of ~70% in mid-summer months.

Projected changes in runoff in the immediate future are expressed in absolute (i.e. mm) terms and/or as relative (%) changes, and while mm (and hence m^3) changes are the highest in the high-runoff mountainous areas, those are also the areas with the lowest percentage increases (~7% in a median year vs ~16% in the lower quinaries).

4.4.4 Baseflows

Baseflows as a contributor to total runoff are relatively (%) higher in the winter months from April to August than in the summer months.

While baseflows derive from drainage of soil water into the groundwater zone, they lag behind drainage, and baseflows are also steadier throughout the year compared to drainage.

Projected changes in baseflows with climate change, as a percentage, are the lowest in the high-rainfall upper sub-catchments of QwaQwa and, conversely, are the highest in the lower-rainfall sub-catchments.

4.4.5 Stormflows

The sediment-laden stormflow component of runoff is the highest in spring and summer and the lowest in winter.

There is a projected annual increase of between 13% and 21% in stormflows in the QwaQwa area in the immediate future, with absolute changes in mm equivalents the highest in the high-altitude mountains at 27 mm, and down to <10 mm in the drier lowlands.

4.4.6 Peak discharge

With peak flows depending not only on rainfall intensity and the catchment's slope, but also on the area of a catchment/sub-catchment, for certain comparative purposes peak discharge was expressed as a PDI in $m^3/s.km^2$. PDIs were found to be approximately three times higher in the upper quinary than in the middle quinary and approximately eight times higher in the upper than in the lower quinary of QwaQwa.

In the immediate future, the biggest changes in PDIs will be in the lower-altitude/lower-rainfall sub-catchments, with the percentage increases in PDIs in the immediate future ranging from 12% to 17%, with significant potential impacts on sediment yields.

4.4.7 Sediment yield

Under historical climatic conditions, on average ~2 100 $t/km^2.a$ of sediment are generated in the upper quinary of QwaQwa compared with ~700 $t/km^2.a$ in the middle quinary to only ~100 $t/km^2.a$ in the drier lower quinary of QwaQwa; i.e. major differences occur between the hilly high-rainfall upper quinary and the flatter, drier lower quinary.

However, in the 1:10 wet year, these values increase from ~2 100 to 4 700 $t/km^2.a$ in the upper quinary to 3 200 $t/km^2.a$ (from 700) in the middle to <400 $t/km^2.a$ (from ~100) in the lower quinary of QwaQwa, with these representing amplifications of 2.2 times in the upper, 4.6 times in the middle, and approximately four times in the lower quinary, while in the 1:10 dry year the tonnages of sediment loss decrease to 1 000 vs 150 to around zero for the upper, middle, and lower quinaries respectively.

Together with the inter-annual CVs (%) of sediment yields being ~500% in the lower and ~350% in the upper quinary, a major conclusion is that sediment yields are considerably more sensitive to climate than, for example, runoff.

In the immediate future, sediment yields in QwaQwa are projected to increase by 15% to 25%.

CHAPTER 5: ECOLOGICAL RISK ASSESSMENT OF THE HEADWATER STREAMS IN QWAQWA

5.1 INTRODUCTION

The bulk of potable water supply sources in South Africa rely on freshwater systems, and particularly rivers (providing 85% of the country's total water consumption) (World Wildlife Fund, 2016). The water quality of a river system is indicative of its ecological health. Rivers are important ecosystems for humans and the general wellbeing of the earth and all its inhabitants. Some communities also depend on river water for their domestic supply. It is particularly important that the water quality of such rivers is regularly monitored and assessed by local communities. Informed policy decisions for sustainable water resources management also require the acquisition of scientific data on water quality (Revermann *et al.*, 2018). This section therefore aims to assess the monitored physico-chemical characteristics of water samples and chemical element analyses of the rivers under study. The ecological health of the rivers was also evaluated using a battery of toxicity tests.

5.2 DATA COLLECTION AND ANALYSES

5.2.1 Components included in the ecological risk assessment

The ecological risk assessment included a range of components under three broad categories: physical and chemical water quality, ecotoxicological tests, and river health concerning the hydromorphological status (see Table 5.1). The aim of these assessments was to identify potential hazards to human and environmental health associated with extreme weather events in the study area.

5.2.2 Field sampling

Two field trips, made by the ecological team, were undertaken to collect data at the selected sampling sites in the catchment in April 2021 and March 2022. During the first sampling visit, data were collected at seven sites. Upon reflection on the success of the first sampling visit, two more sites were added to better account for the individual pollution loads from the various streams in order to improve the characterisation of the identified hazards: Elands Upper was added downstream of where the Mphukojwane joins the Elands River, and Namahadi Middle was added upstream of where the Metsi-Matso flows into the Namahadi River (see Figure 5.1). In addition to the combined field trips, individual data-collection visits were made as required by the respective researchers.

Table 5.1. Components included in the ecological risk assessment of the streams in the study area

Physical, microbial, and chemical water quality	Ecotoxicological tests	River health
System variables Water temperature, pH, DO, total suspended solids (TSS), total dissolved solids (TDS), EC, chemical oxygen demand (COD), biochemical oxygen demand (BOD), redox potential	**River sediment** Reproduction test (*Folsomia candida*) Metal analysis	**Aquatic habitat** Instream and riparian habitat assessment
Anions* Bromide, chloride, carbonate, fluoride, nitrate, nitrite	**River water** Algal growth inhibition test (*Raphidocelis subcapitata*) Acute mortality test (*Daphnia magna*) Protozoan toxicity test (*Tetrahymena thermophila*)	**Aquatic biota** Fish Response Assessment Index (FRAI)
Metals* Al, As, Ca, Cu, Mg, Mn, Fe, Zn	**In vitro tests*** Yeast reporter gene assays Ames test Micronucleus assay	
Organic micropollutants (OMPs)* 35 OMPs were included in the analyses		
Microbial* Faecal coliform bacteria *Escherichia coli*		

*Note: These components were not included in the original scope of the study and were funded from other non-WRC projects/sources.

5.2.3 Description of sampling sites

The geospatial characteristics of the nine sampling sites are presented in Table 5.2.

The source areas of the Metsi-Matso, Namahadi, and Mphukojwane rivers fall in the Eastern Escarpment Mountains 15.03 Level 2 ecoregion (see Figure 5.2). This ecoregion, which occurs in high-altitude mountainous areas, is characterised by high rainfall and moderate to low mean annual temperatures (Kleynhans *et al.*, 2005). Vegetation in these areas consists predominantly of grassland types, including Afro-montane and Alti-mountain vegetation types. The upper sampling points, as well as two of the middle sampling points, are all situated in the Eastern Escarpment Mountains 15.03 Level 2 ecoregion, while the sites in the lower Namahadi and the Elands rivers occur in the Eastern Escarpment Mountains 15.01 Level 2 ecoregion. The geomorphological characteristics of most of the sites resemble the Upper Foothills geomorphological zones (see Figure 5.2).

Even though the Metsi-Matso River is considered to be relatively natural, the Namahadi and Mphukojwane rivers are described as moderately modified and not intact (see Figure 5.3).

No Freshwater Ecosystem Priority Areas were identified in the QwaQwa area (Quaternary Catchment C81F) (Nel *et al.*, 2011).

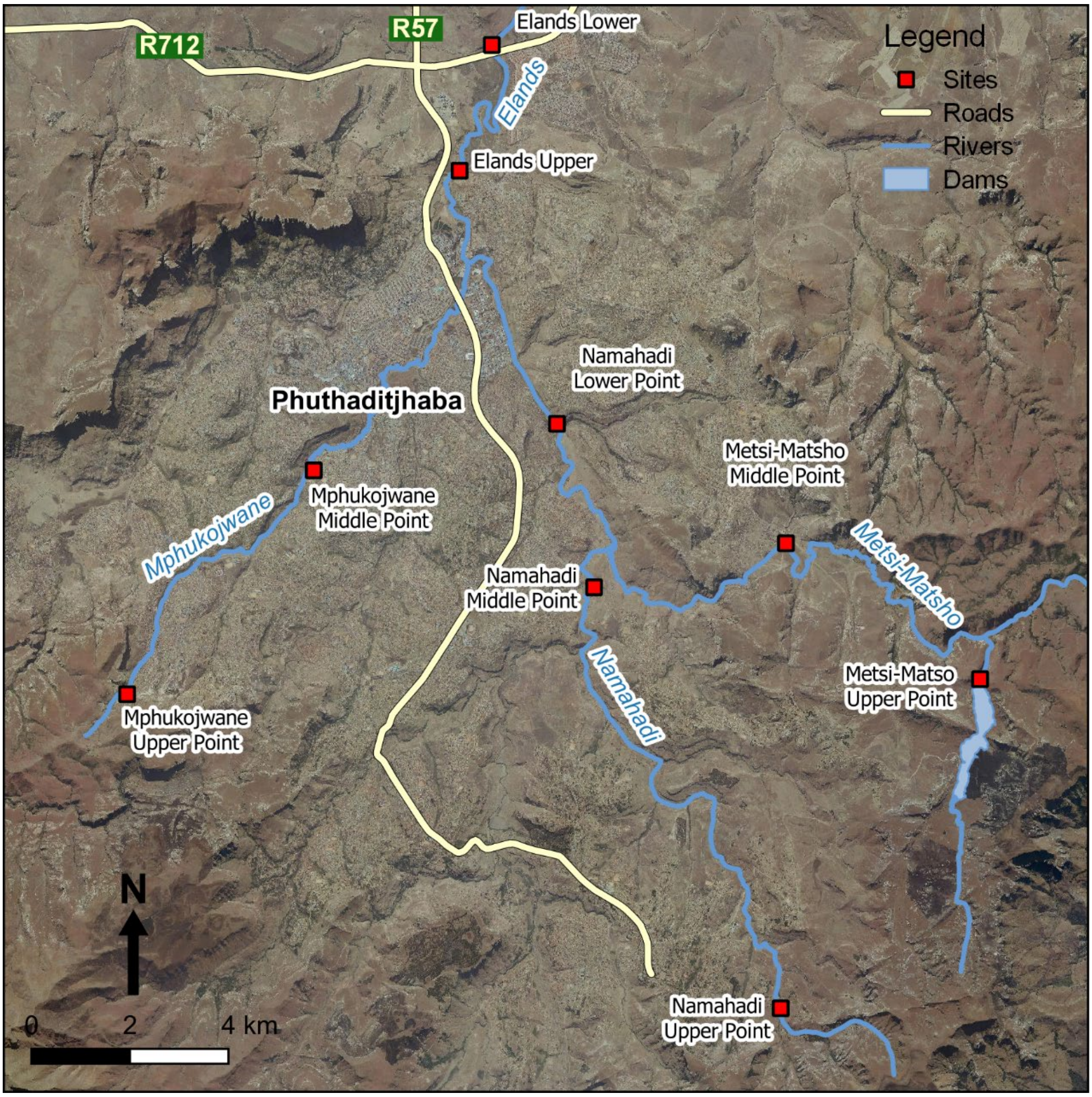


Figure 5.1. Sampling sites on the Metsi-Matso, Namahadi, Mphukojwane, and Elands rivers for ecological sampling

Table 5.2. Summary of the sampling sites on the Namahadi, Metsi-Matso, Mphukojwane, and Elands rivers

Site	ELL	ELU	MPM	MPU	NL	NM	NU	MM	MU
River	Elands	Elands	Mphukojwane	Mphukojwane	Namahadi	Namahadi	Namahadi	Metsi-Matso	Metsi-Matso
Latitude:	-28.47425	-28.497	-28.5523177	-28.5938608	-28.5431111	-28.5729722	-28.6495667	-28.5643421	-28.5886667
Longitude	28.834	28.8283333	28.7990148	28.7609721	28.8493333	28.8575556	28.8976719	28.8972297	28.9379722
Altitude (m)	1 670	1 638	1 680	1 875	1 651	1 655	1 783	1 766	1 886
Ecoregion Level 1	Eastern Escarpment Mountains	Eastern Escarpment Mountains	Eastern Escarpment Mountains	Eastern Escarpment Mountains	Eastern Escarpment Mountains	Eastern Escarpment Mountains	Eastern Escarpment Mountains	Eastern Escarpment Mountains	Eastern Escarpment Mountains
Ecoregion Level 2	15.01	15.01	15.03	15.03	15.01	15.01	15.03	15.03	15.03
Geomorphological zone	Lower Foothills	Lower Foothills	Upper Foothills	Mountain Stream	Lower Foothills	Upper Foothills	Upper Foothills	Upper Foothills	Upper Foothills

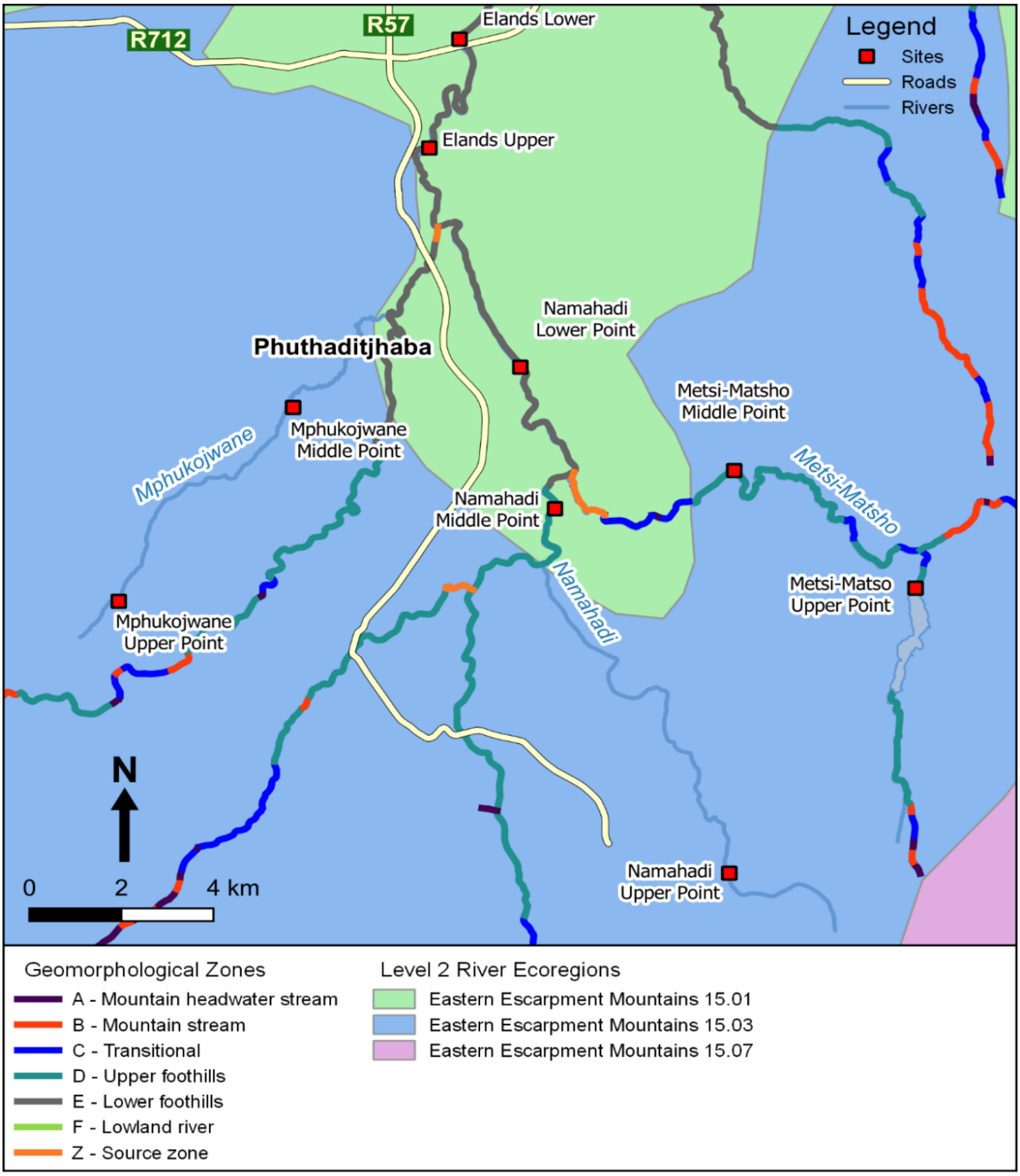


Figure 5.2. Level 2 ecoregions and geomorphological zones at the study sites

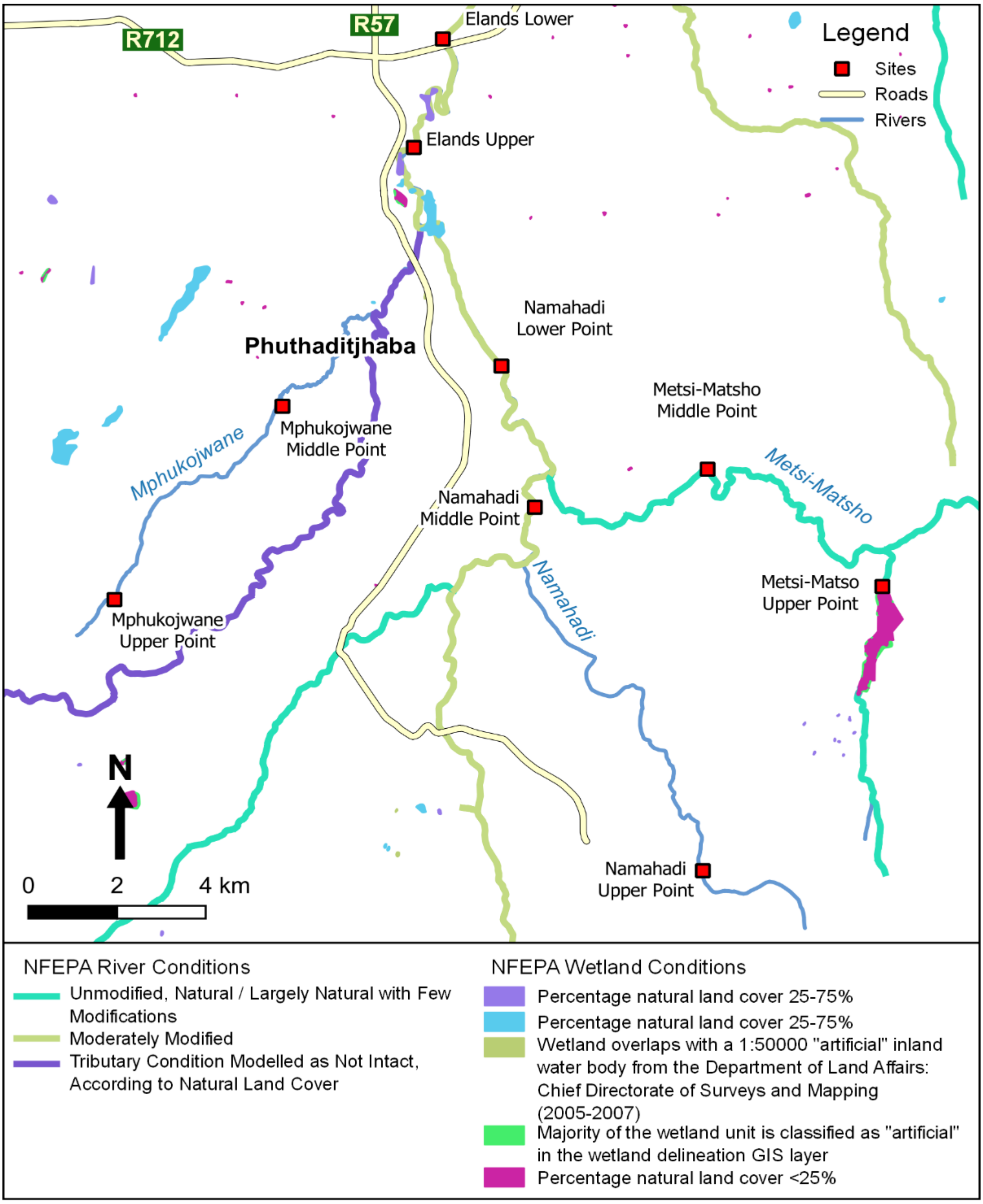


Figure 5.3. National Freshwater Ecosystem Priority Areas river and wetland conditions in the study area

5.2.3.1 Namahadi River

The Namahadi River is a perennial stream originating at an elevation of more than 2 000 m.a.s.l., and the main source of freshwater in QwaQwa. The Fika-Patso Dam, built on the river, has a full supply capacity of 26.3 million m^3, and supplies the western, central, and northern areas of QwaQwa (DWS, 2017). The dam wall, 65 m high and 300 m wide, represents a severe barrier to the natural flow regime and continuity of ecological processes in the river.

(a) Namahadi Upper

Namahadi Upper is situated in the upper reaches of the river, approximately 3.29 km from its origin. The geomorphic features of the river channel resemble an Upper Foothills zone with a moderately steep slope and the river bed dominated by bedrock, boulders, large and small cobbles, and pebbles (see Appendix A: Plate 1). The river channel is between 3 m and 5 m wide, with shallow pools and riffle-rapid sections alternating in this section of the river.

The lower riparian vegetation comprises predominantly of grass with exotic trees (black wattle [*Acacia mearnsii*]) encroaching into the marginal zone of the river. The upper riparian zone is predominantly covered by grass interspersed by small shrubs, with clumps of oldwood (*Leucosidea sericea*). The upland areas are relatively steep with signs of erosion and occasional dongas forming.

This section of the Namahadi River flows past the village of Pitseng. Pitseng is a small village with a population of 131 persons (28 households) (StatsSA, 2011). The nearest dwellings are approximately 130 m away from the sampling point. The villagers use groundwater, stored in reservoirs, for drinking, but use the river for doing laundry.

(b) Namahadi Middle

Namahadi Middle is situated on the Namahadi River approximately 1.38 km upstream of where it joins the Metsi-Matso River (see Appendix A: Plate 2). In this section, the river channel is classified as an Upper Foothills geomorphic zone. The channel has a low gradient and resembles a mixed bed alluvial channel with gravel, sand, and silt dominating the substrate. The channel is between 15 m and 30 m wide, with pool habitat being more abundant than rapid-riffle sections.

The riparian vegetation is dominated by grass, with clutches of reeds, sedges, and shrubs (e.g. *Lavandula* spp.) also present. The upper riparian zone and flood benches are highly disturbed, for example, by the presence of foot paths, gravel roads, and solid waste disposal. The riverbed is highly modified due to several instream structures (upstream weir and low water crossing; downstream road bridge) present at the site.

This section of the Namahadi River flows through urban areas with the Thaba Bosiu residential area on the escarpment above the right river bank, and the Ha-Sethunya residential area on the left bank. The density of people in this part of the catchment is markedly higher than at the Namahadi Upper: Thaba Bosiu has a population of approximately 2 935 people (885 households) and a density of 8 06.51 people per km^2, whereas Ha-Sethunya has a population of 6 678 (1 977 households) and a density of 1 516.2 people per km^2 (StatsSA, 2011). The urban impacts on the river are visible, and include sedimentation of the riverbed, as well as flow and riverbed modification due to instream structures.

(c) Namahadi Lower

Namahadi Lower is situated in the lower reaches of the river, approximately 4.6 km downstream of the Namahadi Middle site and 5.9 km upstream of where the Mphukojwane River joins the Namahadi. This section of the river falls within the Lower Foothills geomorphic zone. The river resembles a mixed bed alluvial channel with gravel, sand, and silt dominating the substrate. The channel is between 12 m and 45 m wide, with pools dominating the aquatic habitat. The riverbed is highly modified due to several instream structures (upstream weir and low water crossing; downstream road bridge) present at the site (see Appendix A: Plate 2, Photos 2-3).

At this point, the Namahadi River flows through very densely populated areas (2 495.9 people per km^2) (StatsSA, 2011), with widespread urban impacts. The river banks are highly impacted by overgrazing, trampling by cattle and small stock, sand mining, and brick making.

5.2.3.2 Metsi-Matso

The perennial Metsi-Matso River originates at an elevation of more than 2 000 m.a.s.l. The river is considered to be largely natural from its origin to upstream of its confluence with the Namahadi River, despite the presence of a relatively large dam in its upper reaches. The Metsi-Matso Dam, built on the Metsi-Matso River approximately 6 983 m from the river's source in the Drakensberg Mountains, contributes to the water provisioning of the QwaQwa area through the Metsi-Matso Dam scheme that supplies drinking water the south-eastern areas of QwaQwa (Free State CoGTA and Chell Engineering, 2018). The Metsi-Matso Dam falls within the Thaba Bosiu and Dinkweng Tribal Councils (DWAF, 2007). Extensive wetlands occur at the dam's upstream end (DWAF, 2007).

(a) Metsi-Matso Upper

The Metsi-Matso Upper site is situated in the river reach immediately downstream of the Metsi-Matso Dam (see Appendix A: Plate 3). The geomorphological characteristics of the river channel represent the Upper Foothills zone. The channel slope is moderately steep, with a mixed bedrock-cobble bed. The flow regime of the river is, however, severely impacted by the presence of the dam (see Appendix A: Plate 3, Photo 1). During the site visit in October 2020, there was no surface flow, which left sections of the river dry (see Appendix A: Plate 3, Photo 5). A number of pools, varying in size, were present in the river channel. When the river flows, these pools should be connected by equally long rapid-riffle sections.

The riparian vegetation is dominated by grass, with trees and shrubs occurring along the river channel. The exotic and highly invasive black wattle (*A. mearnsii*) is present at the dam wall, as well as along the left bank. The vegetation along the edge of dam, upstream of the site, comprises predominantly of wetland species, as well as *Helichrysum* spp.

(b) Metsi-Matso Middle

Metsi-Matso Middle is situated in the middle reaches, approximately 5 km upstream of where the Namahadi River joins the Metsi-Matso River. The river channel resembles the Upper Foothills geomorphic zone, with a moderately steep slope and a mixed bedrock-cobble substrate (see Appendix A: Plate 3). This section of the river consists of pools connected by rapid-riffle sections. At the site, the pool is mainly underlain by silt, while the rapid-riffle section is underlain by bedrock, boulders, and cobbles (see Appendix A: Plate 3, Photo 4).

The riparian vegetation in the river reach comprises predominantly of grass and sedges. At the site, the pool is fringed by sedges (*Cyperus* and *Juncus* spp.) and bulrushes (*Typha capensis*). Downstream of this pool, a rapid-riffle connects it to another pool with a steep right bank covered by various species of trees.

Metsi-Matso Middle is situated on the outskirts of the Metsi-Matso residential area (see Appendix A: Plate 3, Photo 1). Upstream of the site the main impacts on the river include flow and bed modification due to instream weirs and road crossings, as well as faecal contamination due to the watering of stock (Motholo, 2014).

5.2.3.3 Mphukojwane River

The Mphukojwane is a perennial stream that originates on an escarpment (at an elevation of more than 1 900 m) south-west of Phuthaditjhaba. The stream drops over the escarpment to flow northwards for approximately 13 km to join the Metsi-Matso River from the south. Although pristine at its origin, the Mphukojwane River is highly impacted by urban runoff and pollution in the middle and lower reaches (Motholo, 2014).

(a) Mphukojwane Upper

Mphukojwane Upper is situated approximately 1 km downstream from the river's source on the escarpment (see Appendix A: Plate 4). The stream channel is steep, with clear, fast-flowing water. The channel is narrow (1 m to 3 m wide), and resembles a Mountain Stream geomorphic zone type. The streambed is dominated by bedrock and boulders, with step pools and cascades occurring. The riparian zones are dominated by grass, with dense woody vegetation growing next to the stream.

Even though the site appears to be relatively pristine, serious disturbance and erosion occur within the riparian zone approximately 300 m downstream of the site. Here the river flows past the Tseki residential area (right bank) and the upper section of the Poelong residential area (left bank). The density in these residential areas is high at 2 214.4 people per km^2 in Tseki, and 1 269.8 people per km^2 in Poelong (StatsSA, 2011).

(b) Mphukojwane Middle

Mphukojwane Middle is situated approximately 13.2 km downstream of the upstream site. Here the river flows through densely populated areas. Phamong (on the right bank of the river) has a population of 8 010 people (2 288 households) and a density of 2 792.1 people per km^2, and Makhalaneng (on the left bank) has a population of 5 085 people (1 552 households) and a density of 1 542.6 people per km^2 (StatsSA, 2011).

At Mphukojwane Middle, the stream flows through the Eastern Escarpment Mountain 15.03 Level 2 ecoregion. In this section, the stream channel has a lower gradient (than the upstream site) and resembles an alluvial channel with sand and gravel dominating the streambed. At the reach level, pools are more abundant than rapid-riffle series.

The riparian zone is highly disturbed, with deep erosion dongas occurring on the left bank of the river and encroachment by the highly invasive and exotic *A. mearnsii*. Other impacts include bed modification due to sedimentation and instream structures, flow modification due to instream structures, and pollution from urban sources.

5.2.3.4 Elands River

The Elands River has a catchment size of 1 405 km^2 (Republic of South Africa [RSA], 2016). Several streams originating in the mountains above QwaQwa, including the Metsi-Matso, Namahadi, Kollatshwene, and Mphukojwane rivers, join to form the Elands River. The Elands River in turn joins the Wilge River, which is the largest tributary of the Vaal River.

Biomonitoring results from 2002 to 2003 indicated that the river's ecological integrity is "fair" to "poor" (River Health Programme, 2003). These results are supported by Motholo (2014), who found the water in the river to be turbid and highly polluted. Being situated at the downstream end of the rivers that drain the QwaQwa area, the Elands River receives runoff impacted by industrial processes and return flows from water treatment plants (WTPs), as well as from general urban and rural activities. Motholo (2014) also found the aquatic macroinvertebrate community in the Elands River to be dominated by highly tolerant taxa, which reflected the poor water quality of the river.

A gauging station (C8H005) in the Elands River is situated approximately 15 km downstream of the Elands River site.

(a) Elands Upper

Elands Upper is situated 2.3 km downstream of where the Mphukojwane joins the main stem to become known as the Elands River. At this point, the river flows through the Eastern Escarpment Mountain 15.01 Level 2 ecoregion. The river channel resembles a Lower Foothills geomorphological zone with a series of runs, pools, and riffles (see Appendix A: Plate 5).

The riparian zone is highly disturbed, with eroded and unstable river banks and encroachment of alien vegetation into the lower riparian zone. Other impacts include bed modification due to algal growth and instream structures, flow modification due to instream structures, and pollution from urban sources.

(b) Elands Lower

The most downstream site on the Elands River is situated approximately 4.7 km downstream of where the Metsi-Matso and Mphukojwane rivers join to form the Elands River. The site is located at a road bridge where the R712 crosses the Elands River (see Appendix A: Plate 5).

Elands Lower is situated in the Eastern Escarpment Mountains 15.01 Level 2 ecoregion. Here, the geomorphological features of the channel resemble the Lower Foothills geomorphic zone. The channel has a lower gradient and is more slow-flowing than upstream. The riverbed is predominantly alluvial, with sand and gravel being the most abundant substrate types. The channel is markedly wider than at the upstream sites, with aquatic habitat comprising mainly of pools, separated by shorter rapid-riffle sections.

The lower riparian and marginal zones at the site are invaded by exotic trees, including the weeping willow (*Salix babylonica*), poplars (*Populus canescens*), black locust tree (*Robina pseudoacacia*), and black wattle (*A. mearnsii*). The habitat integrity (HI) of the site is also affected by instream modifications such as sedimentation and instream structures (road bridge) that influence the natural riverbed and flow regime of the river.

5.2.4 Description of sampling and analytical methods applied in the study

5.2.4.1 Physical and chemical water quality

(a) System variables

Physico-chemical parameters were measured in situ during field sampling in April 2021 and March 2022. A portable multi-parameter reader (SensoDirect 150 – Lovibond) was used for on-site measurement of pH, DO, EC, TDS, redox potential, and temperature. Prior to sampling, the portable parameter was calibrated according to the manufacturer’s specifications. Samples for COD and other water quality parameters that could not be measured on-site were collected in glass bottles, protected from light to avoid photodegradation, and transported to the laboratory in ice chests. The bottles were labelled appropriately on-site. All field readings were taken in triplicates and so were all the analyses.

The COD and BOD analyses of the samples were conducted by the accredited Institute for Groundwater Studies’ Laboratory Services (UFS campus).

The main anions fluoride, chloride, nitrite, bromide, nitrate, sulphate, and phosphate were analysed by ion chromatography (Dionex Integrion HPIC, Dionex/Thermo Fisher Scientific). The determination of 21 elements, dissolved in water (see Appendix C), was carried out by means of an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (AVIO 200, Perkin Elmer). The DOC was determined as non-purgeable organic carbon with a TOC-5000 (Shimadzu) according to the standard DIN EN 1484:2019-04.

(b) Metals

Water samples were collected in 500-ml plastic bottles that were pre-treated with 10% nitric acid. Unfiltered samples were kept on ice during transportation to the laboratory and stored at 4°C before they were sent for analysis. Analysis was conducted by an accredited commercial laboratory (ISO/IEC 17025:2005), WaterLab (Pty) Ltd, based in Pretoria, South Africa. The samples were analysed, following standard techniques, to determine the concentrations of 66 elements, including heavy metals, and micro and macro nutrients using an ICP-OES (Perkin Elmer, Optima 2100 DV). Analytical accuracy was determined using certified standards (De Bruyn Spectroscopic Solutions 500MUL20-50 STD2), and recoveries were within 10% of certified values.

(c) Organic micropollutants (OMPs)

The selection of target substances for OMP analysis was based on typical representatives of pharmaceuticals, personal care products, industrial chemicals, and pesticides and biocides, which are often still detected in the effluent of WWTPs or are diffusely discharged from agriculture and thus occur globally in polluted rivers. Other environmentally problematic substances such as ethinylestradiol, estradiol or beta-lactam, and tetracycline antibiotics were not included because their relatively high instability leads to their degradation during the transportation of the samples to the analytical laboratory, which takes several days.

Water samples were filtrated immediately after sampling using a 6-ml syringe with attached syringe filter (CHROMAFIL Xtra, Regenerated cellulose, 25 mm, 0.2 µm) that was pre-rinsed five times with sample water. Thereafter, 6 ml of the sample water was filtered in a 40-ml glass vessel (rinsed five times in advance with sample water) for further use. Exactly 5 ml of the filtered sample water was then transferred into a 12-ml glass vessel (pre-flushed with sample water). After the addition of 100 µL of internal standard mixture and intensive shaking, 5 ml of the water sample was filtered through the pre-loaded filter. The first 4 ml was discarded, while the last 1 ml was placed into a designated 2-ml high-performance liquid chromatography vial.

The analytical determination of 35 selected OMPs was carried out via an ultra-high-performance liquid chromatography system (Nexera X2, Shimadzu) with the chromatographic column Luna Omega Polar C18 (100A, 1.6 µm, 100 x 2.1 mm) and the corresponding precolumn SecurityGuard™ ULTRA Cartridge (Fully Porous Polar C18 2.1 mm) in combination with a tandem mass spectrometer (Triple Quadrupol-MS QTRAP 6500+ detector, Sciex) according to a method developed by the Institute of Water Chemistry (Technical University of Dresden, Germany). The injection volume was always 50 µL. The compound separation was performed at a constant flow rate of 0.3 ml/min using a water/acetonitrile gradient. Each eluent was supplemented with acetic acid (0.04% v/v). An analytical standard mix of the OMPs (10 µg/L) was prepared from stock solutions in water/methanol (50% v/v) and diluted for quality control standards (0.1 µg/L) for measurement. An internal standard mix (IS) of 27 isotopically labelled OMPs was prepared equally and all solutions were stored at -18°C. The calibration was carried out for all substances in the range from 10 to 2 500 ng/L. Detection of micropollutants was performed in ESI(-) or ESI(+) mode according to optimised ionisation conditions for each analyte using the following source conditions: IS -4500 V (ESI(-)) or IS +5500 V (ESI(+)), temperature 480°C, curtain gas 40 psi, collision gas medium, and Gas 1 and Gas 2 at 50 psi. The quantitative determination of masses was carried out in multiple reaction monitoring measurements.

5.2.4.2 Ecotoxicological tests

A range of ecotoxicological tests were used to evaluate the effect of river sediment and water samples on exposed organisms by quantifying the effects on their growth inhibition, reproduction, and mortality. For the river sediment, a reproduction test with the springtail *F. candida* was used in combination with metal analysis. For the river water, three aquatic organisms (each representing a respective trophic level) were used, namely *D. magna*, a primary consumer that feeds on algae, *R. subcapitata* (a primary producer), and *T. thermophila* a protozoan (decomposer). Lastly, a range of in vitro assays was used to detect estrogenic and androgenic activity (Yeast-based Estrogenic Screen [YES], Yeast-based Anti-estrogenic Screen [YAES], Yeast-based Androgenic Screen [YAS], and Yeast-based Anti-androgenic Screen [YAAS] tests after ISO 19040-1; 2018), the presence of dioxins (Yeast-based Dioxin-like Screen [YDS]), the mutagenicity (Ames fluctuation test after OECD 471; ISO 11350:2012), and the genotoxicity (micronucleus assay after OECD 487; ISO 21427-2:2006) in the water samples.

(a) River sediment

River sediment samples were collected from the Namahadi, Metsi-Matso, and the Elands rivers. Approximately 5 kg of sediment were collected per site and transported to the laboratory in dark refuse bags (950 x 750 mm). The samples were dried in a Kelvinator incubator at 25^{o}C and passed through a 2-mm sieve to remove coarse debris.

Following the ISO 11267 protocol (International Organization for Standardization, 2014), the springtail *F. candida* was exposed to 0 (control), 50%, 75%, and 100% of the collected sediment samples at 20^{o}C for 28 days. The OECD artificial soil (Organisation for Economic Co-operation and Development [OECD], 2004) was used as the clean (negative) control. Ten live *F. candida* were exposed to 20 g of the different concentrations of the sediment (re)moistened to 50% of its water-holding capacity. The exposures were carried out in four replicates. The experimental organisms were fed 5 mg baker's yeast (Superbake Instant Yeast) per treatment per week. At the end of the exposure period, survival and reproduction were assessed by counting the surviving adults and new offspring.

Metal analysis (water extraction) of the sediment samples was conducted using inductively coupled plasma mass spectrometry. A total of 71 elements including cadmium, lead, iron, mercury, and zinc were assessed. The method used extracts from the metals present in the water phase of the soil. These metals are the ones supposedly bioavailable to the organisms that come in contact with the substrate (Voua Otomo *et al.*, 2011). After metal analysis, elements with sediment concentrations lower than 0.05 mg/kg were considered minor contributors to the potential ecotoxicological effects of the sediment and were not included in subsequent analyses.

A one-way analysis of variance, followed by Tukey's post-hoc test, was performed to compare juvenile numbers per site (GraphPad Prism version 5.00, www.graphpad.com). Whenever possible, the online median effective concentration (EC50) (AAT Bioquest, https://www.aatbio.com/tools/ec50-calculator) was used to determine the concentration of sediment (in percentage) necessary to inhibit reproduction by 50%.

(b) River water

The determination of river water toxicity was based on three bioassays using aquatic organisms representing different trophic levels.

- Algal growth inhibition test

The OECD 201 algae growth inhibition test method was used to determine the toxicity of samples on a freshwater algal species, *R. subcapitata.* The experiments had five treatments and a control, and each treatment had three replicates.

The statistical design is based on hypothesis testing (hypothesis-based no effect concentration) and regression (egression-based x% effect concentration). Measurements were taken at 24-hour intervals for 72 hours and the results were analysed statistically using ToxRat Professional 3.2 Software.

Algaltoxkit F™ supplied by MicroBiotests Inc. (Belgium) was used for the experiments. The algal beads were de-immobilised according to the manufacturer's instructions. An algal density of $1{\times}10^6$ cell/ml was prepared from the concentrated algal inoculum by measurement of the optical density of the inoculum on a spectrophotometer (Jenway 6300) at a wavelength of 670 nm. Dilution series of the samples were prepared, and each flask was inoculated with $1{\times}10^4$ cells/ml as the test start concentration. The inoculated samples were incubated at 23°C with a sideway illumination of 10 000 Lux for 72 hours. Optical density measurements of the test cells were taken at 24-hour intervals for 72 hours. The obtained data were used to determine yield and growth inhibition of *R. subcapitata* after exposure to the water samples. Data analysis was performed using ToxRat® Professional Software 3.3 for the determination of critical concentrations.

- *Daphnia magna* acute mortality test

D. magna were exposed to the water samples collected for toxicity testing using the ISO 6341 method. Hatching of the ephippia was achieved according to the supplier's (Daphtoxkit F MagnaTM, MicroBiotests Inc., Belgium) instructions. The young daphnids were pre-fed two hours prior to the commencement of experiments to prevent starvation to death. Dilution series of the samples were prepared according to standard procedures. There were five treatments and a control, and each treatment had four replicates. A hatching petri dish was placed on a light table and five actively swimming neonates were transferred into each of the test wells. The multiwall plate was covered and incubated in darkness at 20°C. After 24-and 48-hour incubation, the test plates were scored to determine the number of dead or immobilised daphnids. Neonates that could not swim after gentle agitation of the liquid for 15 seconds were considered immobilised even if they could move their antennae. Experimental data were analysed using ToxRAT® Professional Software 3.3 for the determination of mortality, statistical significance, and critical concentrations.

- Protozoan toxicity test

This test measured the growth inhibition of the ciliate protozoan *T. thermophila* after 24 hours. In this period, normal growing cultures completed at least five generation cycles. The test was performed in disposable 1-cm polystyrene spectrophotometric cuvettes. The tests were performed according to the standard operational procedure manual of the Protoxkit F™ provided by the supplier (Microbiotests Inc., Belgium). The spectrophotometer was zero-calibrated at 440 nm using distilled water. The optical density of each test cell was measured and recorded at 440 nm. At the end of the reading at the initial time (T0), cells were incubated (in darkness) at 30°C for 24 hours. After a 24-hour incubation, the optical density readings were taken again. The data regression analysis was conducted using Microsoft Excel Analysis ToolPak.

(c) In vitro tests

- Preparation of samples

Solid phase extraction was used to concentrate the micropollutants in the water samples for transportation to Germany, where they were analysed. For the solid phase extraction, an aliquot of 1 000 ml surface water was filtered through glass fibre filters (<0.7 µm, 90 mm, Sartorius, Germany) at a low under pressure (-200 mbar) using a vacuum manifolder. A hydrophilic-lipophilic balanced cartridge (200 mg 6 cc, Waters Oasis) was selected. Hydrophilic-lipophilic balanced cartridges were conditioned with 5 ml acetone (analytical grade, purity >99.8%, Carl Roth GmbH, Germany), 5 ml methanol (analytical grade, purity >99.8%, Carl Roth GmbH, Germany) and 5 ml ultrapure water (Millipore® filter systems). After conditioning, the filtered water samples were loaded onto the hydrophilic-lipophilic balanced cartridge with a flow rate of 4.0 to 5.5 ml/min and subsequently washed with 5 ml ultrapure water. Loaded cartridges washed with ultrapure water were gently dried under a nitrogen stream (purity 99.5%, Afrox, South Africa) and afterwards stored at -20°C until elution.

After transportation to the laboratories at Technical University of Dresden, the elution of cartridges was performed in the following way: eluted by 2 ml acetone and 2 ml methanol, completely dried under a gentle nitrogen stream, diluted using 100 µL dimethyl sulfoxide (DMSO) (purity >99.5%, Carl Roth GmbH, Germany), and stored in 1.5-ml glass vials at -20°C until testing in the enrichment factor of 10 000.

- Yeast-based reporter gene assays for endocrine activities

The following yeast-based reporter gene assays were used: YES (agonistic activity of human estrogen receptor [hER] α), YAES (antagonistic activity of hER α), YAS (agonistic activity of human androgen receptor [hAR]), YAAS (antagonistic activity of hAR), and YDS (agonistic activity of human aryl-hydrocarbon receptor [AhR]). The research group of J. Oehlmann (Department Aquatic Ecotoxicology, Goethe University Frankfurt am Main, Germany) kindly provided the applied yeast strains of recombinant *Saccharomyces cerevisiae*. Yeast-based reporter gene assays were conducted as previously described (Abbas *et al.*, 2019; Völker *et al.*, 2016; Wagner *et al.*, 2013; ISO 19040-1). For the various yeast bioassays, the following substances were used as positive control: 17ß-Estradiol (E2, Chemical Abstracts Service [CAS] 50-28-2, purity ≥99%; Sigma-Aldrich, Germany) for estrogenic screen, 4-Hydroxytamoxifen (4-OHT; CAS 68392-35-8; purity >70%, Z-Isomer; Sigma-Aldrich, Germany) for anti-estrogenic screen, testosterone (T, CAS 58-22-0, purity >99%; Merck, Darmstadt, Germany) for androgenic screen, flutamide (Flu, CAS 13311-84-7; Sigma-Aldrich F 9397, Germany) for anti-androgenic screen, and β-Naphthoflavone (β-NF, CAS 6051-87-2, purity ≥98%; purum, Germany) for screening dioxin-like compounds. After exposure for over 20 hours, 4-Methylumbelliferyl β-D-galactopyranoside (CAS 6160-78-7, Carl Roth GmbH, Germany) was admixed and yeast tests were further incubated in the dark to measure enzyme activity by fluorescence after one hour as described by Völker *et al.* (2016). Hormonal equivalence (e.g. 17ß-Estradiol equivalence in ng/L) was calculated as described by previous studies (Völker *et al.*, 2016; Könemann *et al.*, 2018; Kunz *et al.*, 2017).

- Ames fluctuation test

The mutagenicity of native and extracted wastewater samples was assessed using the Ames fluctuation test (ISO 11350; OECD 471) with the *Salmonella typhimurium* strains TA 98 (detection of frameshift mutation) and TA 100 (detection of basepair substitution). The research group of J. Oehlmann (Department Aquatic Ecotoxicology, Goethe University Frankfurt am Main) kindly provided the strains used. Ames fluctuation tests were conducted as described by Magdeburg *et al.* (2014). For testing native samples or extracted samples, overnight cultures were diluted to 1 800 or 180 (TA 98) and 450 or 45 (TA 100) formazine attenuation units in the assay medium. The positive control was carried out using 4-Nitro-Phenylenediamine (CAS 99-56-9, Sigma-Aldrich, Germany) for TA 98 and nitrofurantoin (NF, CAS 67-20-9, Sigma-Aldrich, Germany) for TA 100. DMSO was used as solvent control for extracted samples.

- Micronucleus in vitro (MNvit) assay

The genotoxicity of the water samples was tested with the in vitro mammalian cell micronucleus test MNvit (ISO 21427-2, OECD TG 487) (Sommaggio *et al.*, 2018; Reifferscheid *et al.*, 2007) was conducted with human hepatoma cells (HepG2). HepG2 cells were obtained from the Leibniz Institute Deutsche Sammlung von Mikroorganismen und Zellkulturen (German collection of microorganism and cell culture, cell no. ACC-180, Braunschweig, Germany) and cultured in RPMI1640 medium (with l-glutamine; ROTI®Cell RPMI-1640 CELLPURE®, Carl Roth GmbH, Germany) with 10% new-born calf serum (heat activated; Sigma-Aldrich, Germany) and 1% penicillin/streptomycin (WFI solution; Biochrom, Germany) at 37°C and 5% carbon dioxide. For the MNvit test, HepG2 cells were used between passages 6 to 15 and seeded (6 x 104 cells/ml) onto adhesive microscope slides (Superfrost® UltraPlus by Menzel, Carl Roth GmbH, Germany) in four-well microtiter plates for an incubation period of 24 hours. Cells were then treated with three different concentrations of surface water and in replicates for 24 hours. The negative (solvent) control was carried out in replicates using 5 ml culture medium only (native sample testing), or with addition of 50 µL DMSO (extracted sample testing). The positive (solvent) control was carried out in replicates using 4 ml culture medium and 1 ml ethyl methanesulfonate (EMS, CAS 62-50-0, Sigma-Aldrich, Germany) at 1.75 mg EMS/ml in culture medium only (native samples), or with the addition of 50 µL DMSO (extracted samples). After a 24-hour exposure, treatment solutions were removed from each well, and 1.5% tri-natrium-citrate solution was added. Subsequently, cells were fixed by twice using an iced solution of methanol: acetic acid: formaldehyde at 37% (3: 1: 0.05, v/v/v). After drying, slides were stained twice with 5% Giemsa solution for 15 and 20 minutes respectively. The analysis of MNvit was performed microscopically and mono-, di-, tri- to tetra-, and multi-nucleated cells, as well as micronucleus per dinucleated cell, were counted. Approximately 500 cells per slide, two slides per sample and control, as well as three different concentrations per sample were counted; thus, approximately 1 000 cells per control and 3 000 cells per sample were analysed.

5.2.4.3 River health

Although more components, or index models, are generally used to assess the health, or EcoStatus, of a river, only two of these were applied in this study due to a narrower scope and limited funding.

(a) Instream and riparian habitat integrity (HI)

The assessment of the habitats available to biota is essential during any assessment of biological integrity and provides an indication of the degree to which a river has been modified from its natural state (Barbour *et al.*, 1999). The HI of the study area was assessed according to the methodology described by the DWAF (1999). This rapid HI assessment is a simplified version of the HI approach developed by Kleynhans (1996; 2007). It involves a qualitative assessment of the number and severity of anthropogenic disturbances, and the potential negative impact it may have on the river ecosystem. Disturbances include both abiotic and biotic factors, which are regarded as the primary causes of degradation of the instream and riparian habitat (Belcher *et al.*, 2018). The severity of each impact is ranked using a six-point scale between 0 (no impact) and 25 (critical impact). The assessment is ground-based and focuses on a single site within a local reach. It considers mainly impacts visible at the site, or immediately upstream or downstream of the sampling site and is therefore of a low confidence (DWAF, 1999). The HI assessment for the sites was based on observations made during site visits in February 2021, April 2021, and December 2021, together with Google Earth images and limited literature on the catchment.

The HI assessment assesses both the impacts on the instream and the riparian zones of the river. The total scores for each of these components are then calculated and used to place the HI in a specific HI category (see Table 5.3).

Table 5.3. River health categories

Category	Description	Score of total (%)
A	Unmodified, natural.	90-100
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.	80-90
C	Moderately modified. A loss and change of natural habitat and biota have occurred but the basic ecosystem functions are still predominantly unchanged.	60-79
D	Largely modified. Large loss of natural habitat; biota and basic ecosystem functions has occurred.	40-59
E	The loss of natural habitat; biota and basic ecosystem functions are extensive.	20-39
F	Modifications have reached a critical level and the lotic system has been modified completely with an almost complete loss of natural habitat and biota. In worst instances, basic ecosystem functions have been destroyed and changes are irreversible.	0-19

Source: DWAF (1999)

(b) Fish community health

- Instream fish habitat assessment

An assessment of fish habitat potential was conducted at each of the sampling sites as indicated by the FRAI method (Kleynhans, 2007). Fish habitat potential refers to the potential of a specific habitat to provide suitable conditions for fish species to occur there (Kleynhans, 2007). This assessment considers the diversity of velocity-depth classes present (e.g. slow deep, slow shallow, fast deep, and fast shallow), as well as the various types of fish cover available in each of the velocity-depth classes (e.g. substrate, marginal vegetation, water column, etc.). In addition, qualitative and quantitative information was gathered on habitat condition, flow conditions, water depths, substrate, etc., which are reported for each of the sampling sites.

- Fish community assessment

The FRAI developed by Kleynhans (2007) was used to determine the present ecological status of the fish communities for river reaches represented by the selected sampling sites. The FRAI is based on the environmental intolerances and preferences of the reference fish assemblage believed to have occurred in a reach under natural conditions with the response of the constituent species of the assemblage to particular groups of environmental determinants or drivers (Kleynhans, 2007).

- Reference conditions and data availability

As part of the FRAI, a reference fish assemblage is determined for each sampling site or river reach to be assessed. This list of reference species is generally based on existing or historical fish records and reports, information from other sites in similar ecoregions, and expert knowledge and experience. This information is also used to determine the frequency of occurrence for each reference species under natural conditions. Reference conditions broadly refer to "expectations on the state of aquatic biological communities in the absence of human disturbance and pollution" (Kleynhans, 2007). In the context of this report, it refers specifically to the fish species present in a particular river reach and their frequency of occurrence under reference habitat conditions (Kleynhans *et al.,* 2007).

- Fish sampling

Fish sampling at the study sites was done by electro-narcosis (conducting an electric current into the water, which immobilises the fish momentarily). This method is advised by the River Health Programme (see Kleynhans, 2003) for sampling fast-shallow, fast-deep, and slow-shallow habitats; e.g. riffles, rapids, glides, runs, and shallow pools. A SAMUS 725G backpack-electroshocker, powered by a 12-volt battery, was used to apply the electric current to the water with one sampler with a dip-net to collect the stunned fish.

Fish sampled in the different biotopes at the sampling site were kept in separate plastic buckets until identification and measurements were completed. The distance of the river stretch sampled was recorded at each site. Sampling effort differed between the various sites, depending on the availability of fish habitat at each site. Each fish sampled was identified to species level, weighed (g), and the fork length (mm) noted. Observations were also made on the general health of the collected fish and anomalies were noted.

In addition to the ichthyological data, in situ information was also collected for various physico-chemical variables, including temperature, pH, oxygen saturation, EC, and turbidity. The diversity of fish habitat available at each of the sampling sites was assessed and noted and information on the state of local catchment conditions was assessed as guided by the HI Index (Kleynhans, 1996). Additional information on fish microhabitat that was collected for each biotope sampled included a minimum of 10 random water depths (cm), substrate, fish cover (available at that point), and surface flow (when applicable).

5.2.5 Identification of potential risks to human health and the delivery of ecosystem services

The results from each of the components that formed part of the ecological risk assessment (see Table 5.1) were used to identify potential risks for human and environmental health for each of the sampling sites studied. These risks are presented in Table 5.7. The results from the various components were evaluated according to the recommended thresholds for each specific component.

5.2.5.1 Physical and chemical water quality

(a) System variables

The Target Water Quality Ranges (TWQRs) used by the DWS (DWAF, 1996a; 1996b) were used to evaluate and interpret the general quality of the water samples. If the concentration for a chemical-specific parameter, e.g. EC, was below the TWQR value, it indicates that the parameter was not likely to affect aquatic life or domestic use negatively, and was coded with the colour green (no immediate concern). However, when a value exceeded the TWQR threshold for aquatic ecosystems, but not for domestic use, it was coded yellow (slight concern). In cases where the value exceeded the threshold for domestic use, it was considered a human risk and coded red (serious concern).

(b) Metals

The TWQRs for selected elements were used to evaluate the metal content of the water samples (see DWAF, 1996a; 1996b). If the metal content in the sample was below the TWQR values indicated for aquatic ecosystems (and therefore also domestic use), it was not considered a risk to either aquatic or human life and coded green (no immediate concern). However, when the content was at a concentration equal to TWQR but below the Acute Effect Value, it implied that the pollutants could occasionally affect aquatic organisms and was coded yellow (slight concern). In cases where the metal content exceeded the TWQR or Acute Effect Value concentrations for aquatic ecosystems and domestic use, it was considered to pose a risk to human and environmental health and coded red (serious concern).

(c) OMPs

South Africa's water quality guidelines, published in 1996 (DWAF, 1996a; 1996b), are generally considered to be outdated and do not provide criteria for emerging pollutants and toxic substances that may be present in water bodies. Although the guidelines for domestic use have more recently been refined into the South African National Standard 241 (SANS 241, 2015) for drinking water, it is currently being revised again (Kruger *et al.*, 2022). TWQR limits do not yet exist for most OMPs. For this reason, Health-oriented Guidance Values (HGVs), which were developed by the German Federal Environment Agency, were used for an initial assessment of the trace substance levels detected. The basis of this concept is the general precautionary value of 100 ng/L for previously unevaluated or partially evaluated substances in drinking water, which is derived from studies by Dieter (2014). For those substances for which more extensive toxicological data are available, the HGVs have been updated; in the case of the investigated active pharmaceutical ingredients carbamazepine (0.3 µg/L), diclofenac (0.3 µg/L), and ibuprofen (1 µg/L), an upward adjustment was made.

When concentrations were below the limit of quantification (LOQ), which is generally considered as 10 ng/L, it was coded green, when the concentration was higher than the LOQ but below the HGV, it was coded yellow, and when the concentration exceeded the HGV, it was coded red.

5.2.5.2 Ecotoxicological tests

(a) River sediment

Due to the lack of river sediment quality guidelines in South Africa, the National Action List can provide sediment metal concentration thresholds that are acceptable for disposal in marine environments.

The National Action List can be accessed online at https://www.dffe.gov.za/sites/default/files/docs/marinedisposal_actionlist_technicalreport.pdf. The revised National Action List was approved and standardised by the Department of Environmental Affairs and Tourism. In this National Action List, metals are categorised as Annex I metals (cadmium and mercury) and Annex II metals (arsenic, chromium, copper, lead, nickel, and zinc), based on their toxicity and their concentrations in sediments. Based on their concentrations in the sediment, the metals of interest are classified as Level I (or action level) and Level II (or prohibition level) (see Table 5.4). The sediment quality is judged based on three concentration ranges; i.e. concentrations that fall below the action level, concentrations that fall between the action level and the prohibition level, and concentrations that exceed the prohibition level. These guidelines consider the sediment moderately contaminated if metal concentrations fall between the action level and the prohibition level. The sediment is considered highly contaminated if the concentrations of the metals exceed the prohibition level (see Table 5.4). It is stated in the document that the presence of contaminants in the sediment does not imply that adverse biological effects are exerted on aquatic ecosystems. In this study, the pollutant class was determined based on the total metal concentrations of arsenic, cadmium, chromium, lead, mercury, nickel, and zinc. The metal concentrations in the water phase of the sediments were useful to help flag those metals that might have biological effects on sediment-dwelling organisms.

Table 5.4. Level I and Level II acceptable concentration ranges and thresholds used for the screening of dredged sediment proposed for marine disposal, in mg/kg dry weight, in South Africa

Metal	Action level (mg/kg)	Prohibition level (mg/kg)
Cd	1.5-10.0	>10.0
Hg	0.5-5.0	>5.0
or for a combined level of these metals	1.0-5.0	>5.0
As	30-150	>150
Cr	50-500	>500
Cu	50-500	>500
Pb	100-500	>500
Ni	50-500	>500
Zn	150-750	>750
or a combined level of these substances	50-500	>500

(b) *River water*

To determine the toxicity of the water samples, the endpoints of the three tests were measured with regard to growth inhibition / yield and mortality. Toxicities and lethal concentration / effective concentration values are inversely related; toxicity units (TUs) are thus used to describe concentration-based toxicity measurements. Acute TU is used to express the acute toxicity of concentration-based toxicities. The different classes of toxicity and toxicity values of the samples tested are presented in Tables 5.5 and 5.6. Toxicity values are usually calculated by dividing 100 by the LC50 values of the bioassays. Class weight scores would be evaluated by the allocation of a test score for the effect results of each test of the battery using Equation 1:

$\sum all\ test\ scores\ /\ n$ Equation 1

Where: n = number of tests performed and % class score were calculated using Equation 2:

% Class weight score = Class score ∕ maximum class weight score×100……….. Equation 2

A sample is considered “highly acutely toxic” if the acute TU values, for at least one of the tests, fall between 10 and 100 TU as presented in hazard classification and class weight tables.

Table 5.5. Hazard classification system for natural waters

TU	Toxicity		Symbol
PE<20%	Class I	No acute hazard	☺
20% <PE<50	Class II	Slight acute hazard	☹
50 <PE<100	Class III	Acute hazard	☠
PE=100 in at least one test	Class IV	High acute hazard	☠☠
PE=100 in all tests	Class V	Very high acute hazard	☠☠☠

Source: Adapted from Persoone *et al.* (2003); Kaza *et al.* (2007); Szklarek *et al.* (2021)

Table 5.6. Calculation of the class weight scores

No significant toxic effect	Score 0
Significant toxic effect but <LC/EC50 (≤1 TU)	Score 1
1-10 TU	Score 2
10-100 TU	Score 3
>100 TU	Score 4

Source: Adapted from Persoone *et al*. (2003); Kaza *et al*. (2007); Szklarek *et al*. (2021)

(c) In vitro tests

The limit of quantification (LOQ) was calculated based on the variability of the corrected fluorescence values of all negative controls. The LOQ was derived by inserting the mean response of all negative control values plus (YES, YAS, YDS) respectively minus (YAES, YAAS) three-fold the standard deviation of the mean response of all negative control values in the inverse of the four-parametric logistic function of the respective reference compound. The derived LOQ value was also divided by the final enrichment factor of 20.834. All calculations were performed with the statistical software R (version 4.2.1, 2022-06-23).

For a better overview of the results, a green-yellow-red colour scheme was applied to the results. Equivalence concentration values below the LOQ were assessed as low (green), equivalence concentration values above LOQ but below three times the LOQ, were assessed as moderate (yellow), and equivalence concentration values above three times the LOQ were assessed as high (red).

5.2.5.3 River health

Both the HI Index and FRAI were used to assess the present state of the aquatic habitat and fish communities at the study sites to calculate a total score that is related to an ecological or river health category (see Table 5.3). These categories range from A, which indicates an unmodified or natural condition, to F, which indicates a critical situation where ecosystems have been transformed to the extent that the natural habitat and biota have been almost completely lost and basic ecosystem functions are destroyed (DWAF, 1999).

For the purposes of this study, Category C (moderately modified) was coded as yellow (slight concern), Category D (largely modified) was coded orange (concern), Category E (seriously modified) was coded red (serious concern), and Category F (critically modified) was coded purple (grave concern).

5.3 RESULTS AND DISCUSSION

This section provides a brief summary of the main findings for each of the ecological components. A table with numerical results for the various sampling sites is presented in Appendix C.

5.3.1 Physical and chemical water quality

5.3.1.1 System variables

The values for all eight parameters measured varied across the sampling sites. The values were highly significant for TDS, redox potential, and COD, in that order. The pH values ranged between 7.42 and 10, and the 75th centile value was 9.7. The implication of this result is that the water at the sites was generally high in salts and other contaminants. The sites had also hard water due to the alkalinity values observed.

A significant positive relationship was observed between COD and temperature. This means that warmer freshwater systems will have significantly higher COD. Other strong, but not statistically significant, relationships were revealed in the study. These include COD and TDS (0.72), SAC_{254} and DOC (0.95), DO and EC, as well as a negative correlation between temperature and redox potential. This confirms the importance of temperature as a key driver of freshwater ecosystem dynamics and health.

5.3.1.2 Metals

The concentrations of three of the eight metals included in the assessment exceeded the TWQR limits for domestic use. Aluminium and iron exceeded the limit at both sites in the Mphukojwane, as well as in the lower Namahadi River, while manganese and iron exceeded the limit in the Elands River (see Table 5.7). Aluminium exceeded the TWQR for aquatic systems in the Elands River and the middle Namahadi River, whereas zinc exceeded these limits at all the sampling sites. Arsenic, calcium, and magnesium concentrations were below the TWQRs for aquatic ecosystems and domestic use.

Potential sources of the high metal concentrations include natural sources (e.g. iron and copper could occur naturally in the catchment), agriculture, industrial waste, and WWTP effluent (Galvin, 1996; DWAF, 1996a). Of particular concern is the poor performance of the WWTPs in the catchment that release improperly treated sewage and industrial effluent into the streams (DWS, 2022b). It has been reported that effluent from the Phuthaditjhaba WWTP contained unacceptably high concentrations of magnesium, iron, manganese, zinc, arsenic, cobalt, and copper (Moloi *et al.*, 2020). See Appendix B for potential sources and risks associated with the metal elements recorded in the catchment.

5.3.1.3 OMPs

Fifteen of the 35 OMPs tested for were detected in the water of the catchment at concentrations above the level of quantification (10 ng/L). Of these, Bisphenol-4 (BP-4), caffeine, and 8-OH-efavirenz had the highest concentrations with maximum values of 262, 217, and 195 ng/L respectively. However, concentrations for the majority of the OMPs tested for were in the low to medium range, even at sites in the Mphukojwane and Elands rivers where they were clearly detected. The two sites on the Elands River (lower and upper), together with the Mphukojwane Middle site, had the highest concentrations of OMPs. At all three these sites, the concentrations for BP-4, acetochlor, efavirenz, and 8-OH-efavirenz exceeded the HGV. Caffeine has no relevance to health, but serves as a tracer of human influences.

In the context of the investigations in QwaQwa, increasing urban contaminations in the flow direction of the rivers were clearly indicated by increasing caffeine concentrations. In addition, more basic parameters such as chloride, EC, DOC, or SAC_{254} correlate well with the occurrence of OMPs. It was clear from the results that the water from the sites that were exposed to lower levels of anthropogenic impacts in the upper part of the catchment was less polluted than the water at the sites in the middle and lower parts of the catchment.

5.3.2 Ecotoxicological tests

5.3.2.1 River sediment

After exposing *F. candida* to the sediment samples from the Metsi-Matso, Namahadi, and Elands rivers, all the examined sediments were found to be variably contaminated with chromium. The Namahadi Middle site had the highest concentration of chromium (569 mg/kg), followed by the shared lower site on the Elands River (529 mg/kg). The concentrations of chromium at both these sites were above the recommended prohibition level of 500 mg Cr/kg. The sediment from the upper reaches of both the Metsi-Matso and the Namahadi rivers and the middle reach of the Namahadi River had lower chromium concentrations (416, 400, and 472 mg/kg respectively) but were still above the recommended threshold for the action level (50 mg Cr/kg). Zinc was the second highest concentrated metal in the sediment, measured at 178 mg/kg in the joint lower site on the Elands River. This concentration was also higher than the recommended threshold for the action level (150 mg Zn/kg). Nickel was the third highest concentrated metal in the sediment with a concentration of 68 mg/kg measure at the upper site of the Metsi-Matso River, which was also the only site with a nickel concentration above the recommended threshold for the action level of 50 mg Ni/kg. The bioassay using *F. candida* revealed, using effective concentrations (EC50), that the upper reach of the Metsi-Matso River (EC50=24% sediment) was the most deleterious site for the reproduction of *F. candida*. This site was more than twice more toxic than the Namahadi Upper site (EC50= 60% sediment). Sediments from the middle reaches of both the Metsi-Matso and Namahadi rivers had the same EC50 value of 54%, denoting the same type of pressure exerted by the surrounding peri-urban centre of Phuthaditjhaba. Surprisingly, the shared lowest site (the Elands River) had an EC50 >100% and was the least toxic site in terms of the reproduction of *F. candida*. These findings are discussed in light of the environmental and social dynamics of the QwaQwa region.

The heavy metal contamination observed in this study originated mainly from point pollution sources associated with each river of interest. The Metsi-Matso Upper site is located below the dam. Dam impoundments are known to be a huge disturbance to riverine systems. For instance, a high concentration of chromium observed in this site could be linked to the dam impoundment. The high metal concentrations in sediment from this site were only observed in total metal content and not in bioavailable fractions measured from water extracts. This provides more insight into the historical degradation of the river that was caused by the construction of the dam. In the case of the Metsi-Matso River, the dam was a point source for the sediment degradation in the upper reaches of this river system. The metals may have sunk and persisted in the sediments over a long period, which acted as their repository. The Namahadi Upper site is situated just after the Malemahole tributary running along the Witsieshoek Mountain Lodge. The mountain lodge would be a point pollution source for the Namahadi River since Malemahole is a repository for waste generated by the lodge, which at the time of data collection was said to lack adequate wastewater management facilities. Nevertheless, the heavy metals in the sediments of the upper reaches of the Namahadi River were only detectable in the total metal content. The Elands River was the only site with several known point sources of pollution such as the local WWTP with poor waste management; textile, brick, and cement factories; agricultural waste; as well as urban and municipal waste (Moloi *et al.*, 2020; Mosolloane *et al.*, 2018). Based on the metal analysis, the Metsi-Matso Upper site was more contaminated than the Namahadi Upper site. The middle sites in both rivers were fairly contaminated. The lower site on the Elands River was the most contaminated site. Overall, based on the total metal concentrations, the Metsi-Matso River seemed to have received more anthropogenic influence than the Namahadi River.

Regarding sediment effect on survival and reproduction, the samples did not cause death to *F. candida*. On the contrary, Vezzone *et al.* (2019) observed mortality of collembola (*F. candida*) and earthworm (*Eisenia andrei*) in dredged sediments collected from the Rodrigo de Freitas lagoon, Brazil.

The findings from this study showed that in all sediment samples collected from the rivers of interest, *F. candida* was able to reproduce successfully after 28 days of exposure at 20°C. The EC50 values revealed that the sediment samples from the Metsi-Matso and Namahadi rivers did have an effect on the reproduction of *F. candida* during the exposure period. The EC50 values varied among sites in each river. The Elands River, which was the lowest common point between the Metsi-Matso and Namahadi rivers, recorded an EC50 value greater than 100% (which means that the sediment collected from this shared lowest point did not cause any hindering effect on the reproduction of *F. candida*). The Elands River runs along the industrial area of Phuthaditjhaba, where it receives industrial effluents and untreated sewage waste from the town and its suburbs. The Phuthaditjhaba WWTP is located close to the Elands River. Yet, surprisingly, the EC50 results showed that sediments from the Elands River did not hamper the reproduction of *F. candida*, in contrast to all sediments collected from the upper and middle sites of all rivers of interest. In contrast to this finding, Cloete *et al.* (2017) recorded 76% inhibition of the growth of ostracods after exposure to the downstream site sediment of the Mpumalanga River in the Mpumalanga province, South Africa. The middle parts of the Metsi-Matso and Namahadi rivers recorded the same EC50 values of 54%. The common factor that caused the deterioration of sediments from these sites is the presence of human settlements that contribute to the degradation of river sediments through anthropogenic activities such as dumping of garbage in the waterways, human and livestock faecal contamination, and unmanaged sewage effluent from both municipal waste and WWTPs (Moloi *et al.*, 2020). Based on the bioassays used in this study, the Metsi-Matso Upper site sediment sample was the most deleterious. This did not support the hypothesis that the upper site of a river would be supposedly pristine and have better quality than the downstream sites. Since the Metsi-Matso Upper site was located just below the Metsi-Matso Dam, the degradation of the sediment quality of the Metsi-Matso Upper site could be attributed to dam impoundment effects on rivers and other anthropogenic activities, such as recreation. It was previously reported that man-made structures, such as dams and reservoirs, degrade surface water quality and quantity by altering the natural state of a river and disturbing its physiochemical parameters (pH, salinity, DO, etc.), which cause some pollutants bounded in sediments to be released (Chu *et al.*, 2016; Chen *et al.*, 2018; Liu *et al.*, 2018) and eventually threaten aquatic ecosystems. In terms of sediment quality, the sites along the Metsi-Matso River can be ranked as follows: upper site < middle site < lower site. In the Namahadi River, the sediment from the upper site (EC50 = 60%) was less degraded than the sediment from the middle site (EC50 = 54%), and almost twice as degraded as the sediment from the lower site (EC50 >100%). In terms of sediment quality, the sites along the Namahadi River can be ranked as follows: middle site < upper site < lower site. Based on the reproduction results, the sediment quality of both the Metsi-Matso and Namahadi rivers improved from the upper sites to the lower ones, which means that neither the Metsi-Matso nor the Namahadi River followed the normal river trend where river quality decreases from the upper to the lower reaches of the system.

5.3.2.2 River water

The water from the Namahadi Middle sampling site was considered to be highly acutely toxic and presenting a potential health hazard. Alarmingly, the water at all the sites in the upper sections of the catchment was acutely toxic, except for the upper Namahadi, where it was slightly acutely toxic.

5.3.2.3 In vitro tests

The in vitro biotests found that the water in the catchment had the potential for endocrine disruption and genotoxicity, as well as to cause dioxin-like impacts. The results for the Mphukojwane and the Elands rivers were particularly concerning. The results indicated increased estrogenic activity at the Elands Upper and Mphukojwane Middle sites, as well as highly increased activity of the aryl-hydrocarbon receptor for the Elands River sample. Elevated levels of the aryl-hydrocarbon receptor, which point towards the presence of dioxin-like substances, were indicated for the samples from the middle Mphukojwane, middle and lower Namahadi, and the middle Metsi-Matso rivers.

The increased estrogenic potential indicates pollution with estrogenic substances. Estrogen is an endocrine disruptor that originates from natural endogenous oestrogens or synthetic oestrogens. The compounds have a diverse spectrum of natural and anthropogenic origin and many of these chemicals exhibit estrogenic activity; for instance, industrial chemicals, pesticides, or human medicine, such as oral contraceptives, could be the origin. There are indications that other drugs, such as antiretrovirals used for HIV therapy, may also have an estrogenic effect (Sikora *et al.*, 2010). Dioxins, which may enter the river through industrial effluents and leachate from landfills and storm runoff, are generally highly toxic with negative impacts on human and environmental health impacts.

No anti-estrogenic (YAES), androgenic (YAS), or anti-androgenic activity could be detected at any of the sampling sites.

5.3.3 River health

In a desktop assessment of the Ecological Importance and Sensitivity Categories of quaternary catchments in South Africa, Kleynhans (2002) indicated that the Elands River is of moderate importance (Class C) and moderately sensitive (Class C). The ecological state of the Elands River was estimated to be largely natural (Kleynhans, 2000). No mention, however, was made of the smaller rivers and streams that feed into the Elands River. There is very little ecological information on these streams, and there are, for example, no official biomonitoring sites in the QwaQwa area. Due to these uncertainties with regard to species composition and distribution in the upper catchment, it was not possible to complete the Ecological Importance and Sensitivity Categories assessments for the respective sampling sites with confidence.

5.3.3.1 Instream and riparian HI

The instream habitats at the sampling sites have been moderately to seriously modified from their natural state due to anthropogenic impacts, with the HI scores varying between 35% (Category E; Metsi-Matso Upper and Namahadi Lower) and 64% (Category C; Namahadi Middle). In the Namahadi and Mphukojwane rivers, the level of degradation increased from upstream to downstream, with the upper reaches being moderately modified and the lower reaches being severely impacted. In the Metsi-Matso River, the presence of the Metsi-Matso Dam wall dominates the upper reaches of the river, which severely changed the downstream flow regime and caused increased inundation upstream of the dam wall. The dam has furthermore been stocked with exotic angling fish species such as rainbow trout (*Oncorhynchus mykiss*), which are known to be a very effective predator on the young of indigenous fish species in the tributaries of the Caledon River (Avenant and Kotze, 2004). Even though the Mphukojwane Upper site is situated very close to its source, the human impacts are clearly visible. Of special concern is the dumping of disposable diapers in the stream, both in the upper reaches and downstream. This poses a large risk in terms of the water quality, especially since the stream flows through residential areas.

The scores for the integrity of the riparian zones varied between 28% (Category E; Namahadi Lower) and 65% (Category C; Namahadi Upper). The most important impacts on the riparian zones of the streams are the encroachment of exotic vegetation (notably black wattle, willows, and poplars), extensive erosion, removal of vegetation (for cultivation and livestock grazing), and sand mining (Namahadi Lower). These impacts are of concern, since the degraded river banks could have a severe impact on the instream habitat in the case of increased rainfall and floods under a changing climate.

It is important to note that the Resource Quality Objectives (RQOs) for the instream and riparian habitats in the catchment were set at Category C (≥62%) (RSA, 2016). This implies that the RQOs were attained at six of the eight sampling sites.

5.3.3.2 Fish community health

The present ecological state of the fish communities in the river reaches, represented by the selected sampling sites, varied from moderately modified (Category C; Namahadi Upper and Middle) to critically modified (Category F; Elands Upper). In the Namahadi River, there was a slight decrease in ecological integrity from upstream to downstream. Despite the large impacts on the instream and riparian habitats on the river, especially in the middle and lower reaches, the fish communities persisted. There were signs of recruitment, and the fish specimens sampled showed good external health, even at the Namahadi Lower site where the instream and riparian habitats have been seriously modified. Very few fish specimens were sampled in the Metsi-Matso River. This could be related to the loss of natural flow in the upper reaches and the loss of habitat diversity due to sedimentation in the middle reaches. However, the water of the Metsi-Matso Dam, and possibly also the upper reaches of the river, is oligotrophic with low biological productivity (Barkhuizen, 2015). It could be that the frequency of the occurrence of the expected species was lower than anticipated due to the low productivity, and not only due to external impacts on the river. The sampling sites on the Mphukojwane River showed signs of serious habitat degradation, even in the upper reaches. This was reflected in the low frequency of occurrence and abundances of the expected species. However, there were signs of recruitment at the Mphukojwane Middle site.

The results from the Elands Middle site, located downstream of the outlets of the WWTPs and inflow from the other tributaries, were very concerning. No fish was found in the reach, and the fish community is considered to be critically modified from natural conditions. This is three categories below the RQOs set for the river (RSA, 2016).

5.4 KEY FINDINGS AND POTENTIAL RISKS IDENTIFIED

The ecological risk assessment clearly showed that the upper reaches of the rivers, situated predominantly in rural and less densely populated areas, were less affected by anthropogenic impacts than the middle and lower reaches of the rivers that flow through urban and densely populated parts of the study area.

A clear deteriorating trend from upstream to downstream was observed for most of the ecological components included in the study:

- Water quality, in general, deteriorated from upstream to downstream, with the water at the most downstream sites on the **Elands River** being hypertrophic, acutely toxic, and having high levels of manganese and iron and a range of emergent pollutants such as dioxins, caffeine, pharmaceuticals, and herbicides.
- The concentration of faecal coliform bacteria, including *E. coli*, widely used as an indicator of faecal pollution in surface waters, increased from upstream to downstream in the catchment. Faecal coliform bacteria concentrations were unacceptably high in the **lower Namahadi**, **middle Mphukojwane**, and the **Elands** rivers, where concentrations exceed the recommended TWQR by 1 700 times.
- The cumulative effects of upstream anthropogenic impacts on the Elands River were also reflected by the degraded state of the instream and riparian habitats that were largely modified from their natural condition, as well as the absence of freshwater fish in the upper **Elands River** site.

It was also clear that the pattern of pollution correlated with the respective land uses in the catchment area:

- This study was the first to detect and confirm the presence of OMPs such as sulfamethoxazole, BP-4, ibuprofen, carbamazepine, atenolol, nevirapine, efavirenz (or its metabolite, 8-OH-efavirenz), and the classical indicator of human impact, caffeine, in the catchment. The data showed that the **lower Mphukojwane** and the **Elands** rivers were the most affected, with the substances being present in the low to medium range.
- This study was also the first to conduct a series of in vitro biotests in the catchment. These tests indicated elevated estrogenic activity in the **middle Mphukojwane** and **Elands** rivers, as well as highly increased activity of the aryl-hydrocarbon in the **Elands River**, which can induce inflammatory responses and may lead to chronic inflammatory diseases, including asthma, cardiovascular diseases, and increased cancer risk upon exposure.

A series of ecotoxicological assays and tests confirmed the toxicity of the river sediment and water at some sites in the catchment:

(a) *River sediment*

- The ecotoxicological investigation into the metal content of sediment in the Metsi-Matso, Namahadi, and Elands rivers found that all the sediment samples were contaminated with chromium above the recommended prohibition level. The **Elands River** was the most polluted and showed high concentrations (above the recommended thresholds) of both chromium and zinc.
- Bioassays, using the sediment samples, found the **upper site of the Metsi-Matso** to be the most deleterious to the reproduction of *F. candida*, while the upper site on the Elands River was the least toxic. This was a surprising result, but could be due to the presence of upstream weirs in the lower reaches of the Namahadi that interrupt the downstream movement of sediment in the catchment. Toxicity in the Namahadi River typically increased from upstream to downstream.

(b) *River water*

- Five metal elements were detected at elevated concentrations in the water samples, namely aluminium, iron, manganese, copper, and zinc. The **Mphukojwane**, **lower Namahadi**, and **Elands** rivers were the most impacted, with aluminium and iron concentrations exceeding the TWQRs for both domestic use and aquatic ecosystems at these sites. Copper and zinc concentrations exceeded the TWQRs for aquatic ecosystems in the Mphukojwane and lower Namahadi, while manganese and iron concentrations exceeded the TWQRs for domestic use and aquatic ecosystems in the **upper Elands River**. Zinc exceeded the TWQR for aquatic ecosystem at all sites in the catchment.
- Acute toxicity tests with *D. magna* and growth inhibition tests with *T. thermophilia*, using river water samples, found that toxicity increased from upstream to downstream, with the sites in the middle and lower reaches being more toxic than those in the upper reaches.

- Elevated levels of dioxins / dioxin-like substances were found in the **Metsi-Matso**, **Namahadi**, and **Elands** rivers. Considering the negative health impacts of dioxins on human health and aquatic biota, the high levels in the Elands River are particularly concerning.
- There is concern about the water of the **Mphukojwane River**, with the upper site classified as having **high acute toxicity** (Class IV) and the middle site as having **very high acute toxicity** (Class V).

In terms of general water quality and river health, the following were noted:

- TDS, redox potential, and COD were high at most of the sampling sites.
- A significant relationship between water temperature and COD was identified in the catchment, which indicates that an increase in water temperature could result in higher COD. This is an important consideration given the strong warming trend projected for the catchment in the immediate to the distant future.
- The strong correlations between water quality parameters such as EC, major ions like chloride and sulphate, and DOC and OMPs, imply that elevated values for the first-mentioned parameters may serve as an indication that micropollutants are present in the river water.
- The modified structure and condition of instream and riparian habitats at the sites in the upper, supposedly more “pristine” reaches, are concerning. Of particular concern is the severe flow modification in the upper Metsi-Matso due to the lack of environmental flows being released from the Metsi-Matso Dam, severe infestation of black wattle trees in the upper Namahadi, and severe erosion and solid waste disposal in the upper Mphukojwane. Also concerning is the apparent rapid expansion of unlicensed sand mining (mostly for building and brick making) in the instream and riparian zones of streams and rivers in the catchment.

Table 5.7. Summary of the ecological risks identified in the QwaQwa study area

Ecological risk component	ELL	ELU	MPM	MPU	NL	NM	NU	MM	MU
Physical and chemical water quality									
System variables and nutrients	Nitrates	Sulphates, nitrates, chlorides	EC, sulphates, nitrates, chlorides	EC, phos-phates, nitrates	EC	EC			
OMPs	BP, ibuprofen, bisphenol A (BPA), diclofenac, carbamazepine, sulfamethoxazole, atenolol, nevirapine	BP, ibuprofen, diclofenac, fipronil, DEET, carbamazepine, sulfamethoxazole, atenolol	BP, ibuprofen, diclofenac, sulfamethoxazole, atenolol, caffeine, nevirapine	BP, diclofenac, DEET, caffeine,	BP, diclofenac, caffeine, sulfamethoxazole	BP, BP-4, diclofenac, caffeine, sulfamethoxazole	BP, diclofenac, DEET, caffeine	BP, diclofenac, caffeine	BP, diclofenac, caffeine, atrazine
	BP-4, caffeine, acetochlor, efavirenz, 8-OH-efavirenz	BP-4, caffeine, efavirenz, 8-OH-efavirenz	BP-4, caffeine, efavirenz, 8-OH-efavirenz						
Ecotoxicological tests									
Metal elements									
Sediment	Cr	Cr, Zn	Cr	Cr	Cr	Cr	Cr	Cr	Cr, Zn, Ni
Water		Mn, Fe	Al, Fe	Al, Fe	Al, Fe	Al, Cu, Zn	Cu, Zn	Fe	
Toxicity class									
	Acute hazard	Acute hazard	Acute hazard	Acute hazard	Acute hazard	High acute hazard	Slight acute hazard	Acute hazard	Acute hazard
In vitro tests									
Ames test (TA 98, TA 100)									
Yeast-based tests (YES, YAES, YAS, YAAS, YDS)		YES, YDS	YES		YDS	YDS		YDS	YDS
Microbial pollution									
Faecal coliform bacteria and *E. coli*		Significant risk	Significant risk	Significant risk	Significant risk	Significant risk	Slight risk	Significant risk	
River health									
Instream habitat		Largely modified	Largely modified	Moderately modified	Seriously modified	Moderately modified	Moderately modified	Largely modified	Seriously modified
Riparian habitat		Largely modified	Largely modified	Moderately modified	Seriously modified	Largely modified	Moderately modified	Largely modified	Largely modified
Fish community		Critically modified	Largely modified	Largely modified	Moderately modified	Moderately modified	Moderately modified	Moderately modified	

(Grey: No data; Green: No immediate concern; Yellow: Slight concern; Orange: Concern; Red: Serious concern; Purple: Grave concern)

CHAPTER 6: VULNERABILITY ASSESSMENT / DISASTER RISK ASSESSMENT OF QWAQWA COMMUNITIES

6.1 INTRODUCTION

South Africa is vulnerable to climate change given its water and food insecurity, with potential impacts on health, human settlements, infrastructure, and critical ecosystem services (World Bank, 2021). South Africa is ranked 92 out of 181 countries on the 2020 Notre Dame Global Adaptation Initiative Index, due to a combination of political, geographic, and social factors. This index ranks 181 countries using a score that calculates a country's vulnerability to climate change and other global challenges, as well as their readiness to improve their resilience. The higher the score, the more readily a country is making progress to improve its resilience to climate change (World Bank, 2021).

South Africa submitted its Nationally Determined Contribution to the UN Framework Convention on Climate Change in 2016 and published its Third National Communication in 2018 in support of its efforts to realise the national development goals and to increase resilience to climate change by improving mitigation and adaptation efforts.

The current global trend represents a shift from a strong emphasis on DRR and coping capacities to building household and community resilience using a systemic risk thinking approach. Resilience is a broad and dynamic concept, with no universally accepted definition of the term, which should be context specific and scalable. The Community Capitals Framework (CCF) is increasingly used by researchers to conduct community vulnerability analyses and to develop resilience and development strategies from a systems perspective (Mattos, 2015; Peters, 2016). First developed by Flora *et al.* (2004), the CCF examines seven community capitals, or assets, namely natural, financial, social, political, cultural, human, and built capital (Mattos, 2015). Jordaan (2017) added institutional capital to this list. The term "capital" can be described as "human created assets that are invested to create new resources without consuming the entire asset" (Peters, 2016). Using the CCF approach as a baseline from where communities can improve their responses to shocks is more empowering and inspiring, unlike the vulnerability assessment, which is a more negative approach to community assessment. The increase in the frequency and intensity of hazards and disasters calls for more holistic and dynamic approaches to deal with disaster risks, including those exacerbated by climate change. It is therefore very important to build community resilience to multi-hazards using a systems thinking approach.

In line with international best practices, it is important to focus on reducing disaster risk and building community resilience, which will also support South Africa's National Development Plan 2030, the SFDRR, the Paris Agreement on Climate Change, and the Agenda 2030 for Sustainable Development.

6.2 RISK ASSESSMENT METHODOLOGY

6.2.1 Understanding risk

The United Nations Office for Disaster Risk Reduction (UNDRR, 2016) defines disaster risk assessment as "a qualitative or quantitative approach to determine the nature and extent of disaster risk by analysing potential hazards and evaluating existing conditions of exposure and vulnerability that together could harm people, property, services, livelihoods and the environment on which they depend". The disaster risk assessment process, as supported by the Disaster Management Act, No. 57 of 2002 (RSA, 2002), as amended Act No. 16 of 2015, is depicted in Figure 6.1. The disaster risk assessment process involves four stages, namely (1) identification of risk factors, (2) estimation of the level of the risk, (3) evaluation of the risk, and (4) monitoring the risk reduction strategies, as shown in Figure 6.1. Risk analysis is a sub-process of risk assessment that involves the identification of risk factors and the estimation of the level of disaster risk. For the purposes of this study, a risk analysis was conducted.

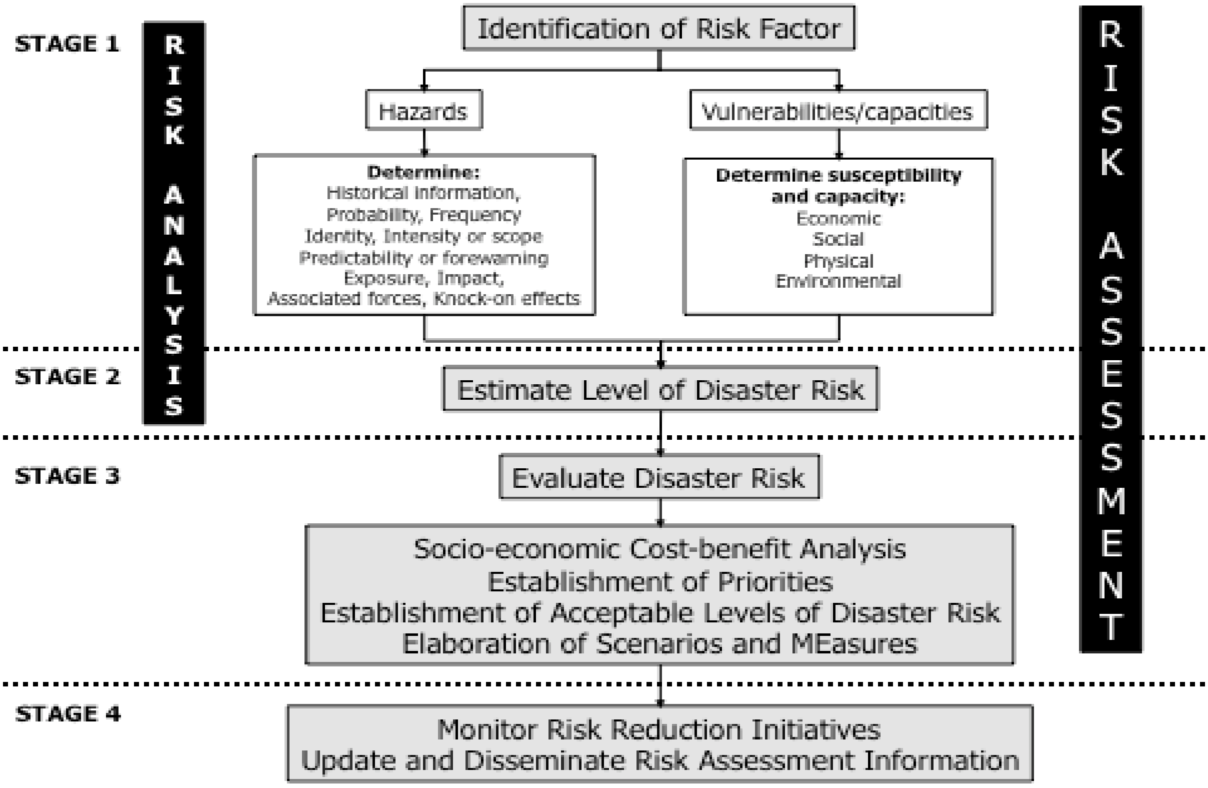


Figure 6.1. Disaster risk assessment methodology

Source: RSA (2002)

6.2.2 Risk equation

Risk assessment methodology differs extensively among scholars and professionals (National Disaster Management Centre [NDMC], 2016) due to the different theoretical interpretations of disaster risk. The formula most commonly applied to assess risk is **R = H x E x V/ C**, where:

R = Risk
H = Hazard

E = Exposure
V = Vulnerability
C = Coping Capacity

For a comprehensive risk assessment, each component of the risk equation is assessed in detail, using various indicators to arrive at a final risk matrix, risk prioritisation, scenario mapping, and risk reduction strategies accompanied by cost-benefit analyses for the various DRR options. This study deviated slightly from the general approach. It adopted a different approach to calculating risk, guided by the CCF, which is more empowering on the premise that any vulnerable community has some available assets on which to improve and build resilience; as opposed to looking at the weaknesses of the community in terms of their vulnerabilities assessment (Mattos, 2015).

6.2.3 The Community Capitals Framework (CCF) and other relevant frameworks

The CCF is increasingly being used by researchers to conduct community vulnerability analyses and developing resilience and development strategies from a systems perspective (Mattos, 2015; Peters, 2016). As stated earlier, the term "capital" refers to an asset created by humans in order to invest and create new resources without consuming the entire asset (Peters, 2016). Although the term "community capital" is used, it could also refer to community assets, as some capitals, such as natural capital, are not often created but are available to communities as an endowment (Belle *et al.*, 2017). The various capitals are interrelated and their availability, in terms of quantity and quality, increases community resilience, while their absence, or inadequacy, increases community vulnerability.

Another relevant framework to assess vulnerability by evaluating community assets is the Community Based Resilience Analysis (CoBRA).

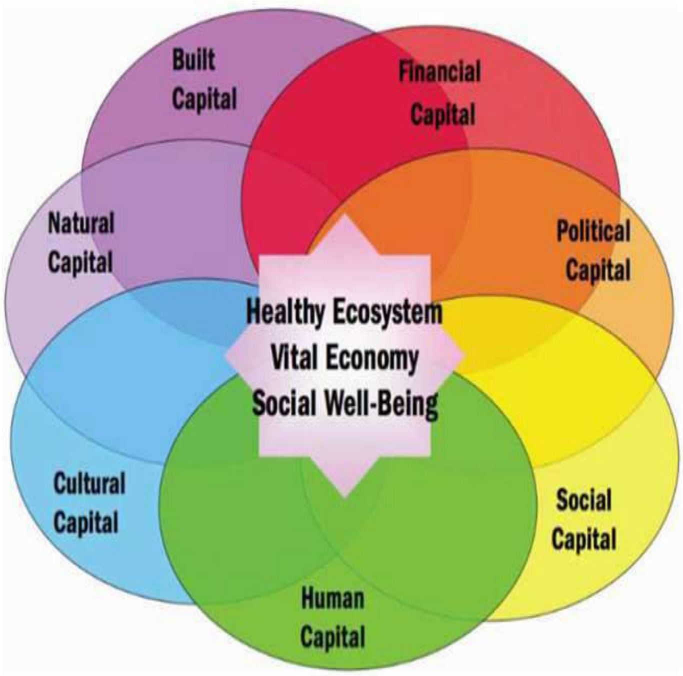


Figure 6.2. Community capitals used to analyse resilience

Source: Peters (2016)

6.2.4 Community Based Resilience Analysis (CoBRA)

The CoBRA conceptual framework was first used to assess the impacts of community-based DRR interventions to build local resilience in drought-stricken areas in the Horn of Africa in order to establish if the humanitarian intervention led to community resilience building (see Figure 6.3; United Nations Development Programme [UNDP] Drylands Development Centre, 2014). The CoBRA identifies both contextual and universal characteristics of resilience, using mostly qualitative and process-orientated tools to identify the key building blocks of community resilience (see Figure 6.3). The framework also analyses community- and household-level characteristics of resilience, which can then be used to develop indicators for quantitative impact assessments. In this research, the outcomes of the CoBRA were used to describe the outcomes and the level of community resilience in QwaQwa.

The UNDP Drylands Development Centre's (2014) CoBRA framework is very similar to the Department for International Development's (2011) Tango Resilience Assessment Framework, which is not expanded upon in this report.

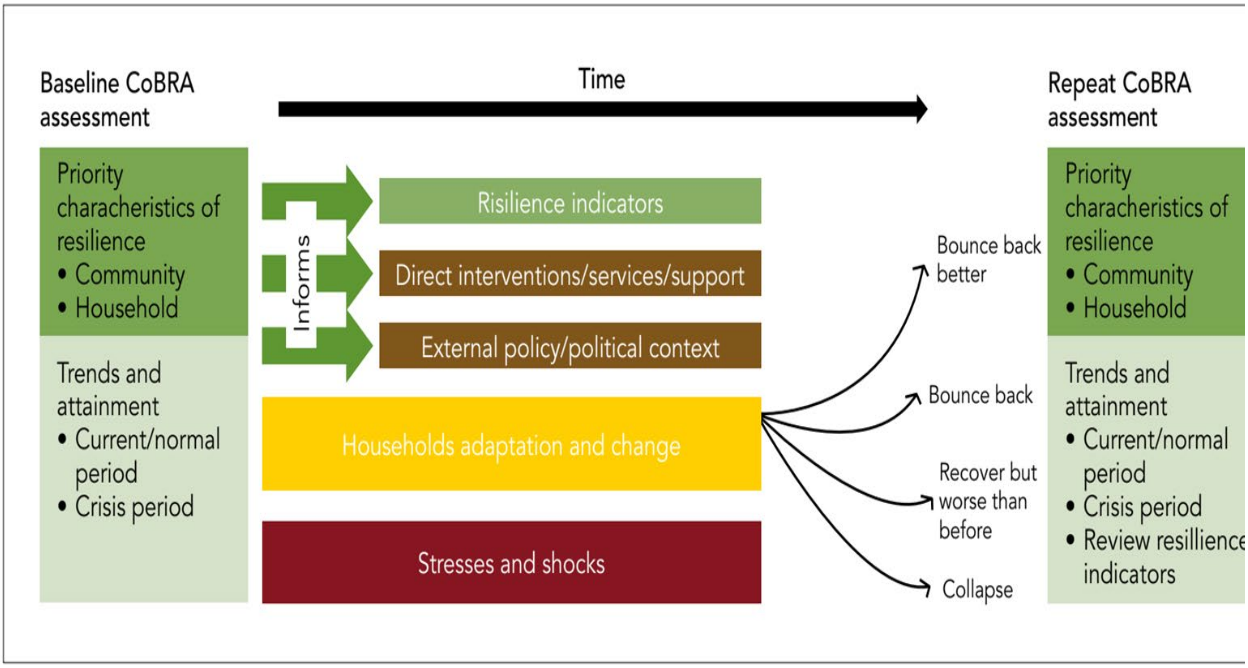


Figure 6.3. The CoBRA framework

Source: UNDP Drylands Development Centre (2014)

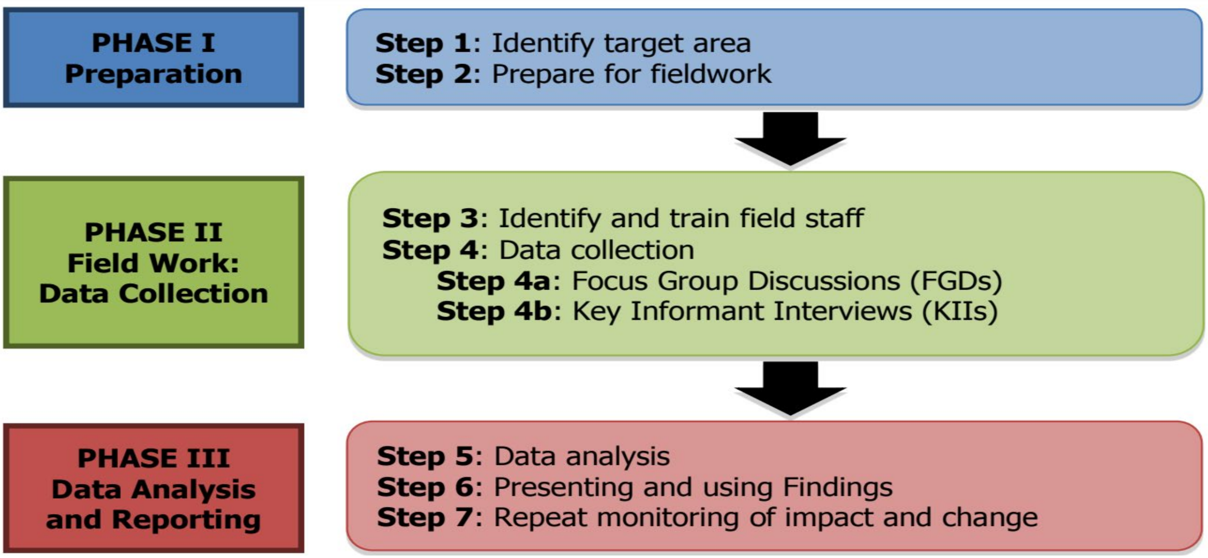


Figure 6.4. Steps in undertaking a CoBRA

Source: Fitzgibbon *et al.* (2014)

More capitals are generated when invested, but they are depleted when they are not sustainably used, which may lead to the weakening of a community's resilience (Mattos 2015; Emery and Flora, 2006). According to the CCF, risk results from an interaction among hazard, exposure, and capitals (resilience), which is expressed as follows:

$$Risk = \frac{Hazard \times Exposure}{Capitals}$$

6.3 DATA COLLECTION AND ANALYSES

Field data collection was divided into four phases. The first phase was the identification and collection of information from relevant key informants (KIs). The KIs included disaster risk management institutions, government departments, non-governmental organisations (NGOs), schools, churches, etc., as guided by the NDMC (2016) guidelines on relevant key stakeholders to include in a disaster risk management assessment. In the second phase, data were collected via household surveys in the QwaQwa area. The third phase was field observation by the researchers, which was integrated with the data collected during the first two phases. The fourth phase comprised a workshop that was conducted with key stakeholders in QwaQwa to validate the data collected during the earlier phases and to obtain more inputs, which were built into the final research report findings.

Quantitative and qualitative data were collected concurrently during the study. The quantitative data were analysed using the Statistical Package for Social Sciences, while the qualitative data were analysed using thematic analysis.

6.3.1 Data collection

6.3.1.1 Key informant (KI) interviews

KIs were identified and contact persons and their email addresses and phone numbers were obtained. A detailed interview guide, containing the questions and instructions, was prepared. The interviews were conducted during a fieldtrip to the study area by Prof. Belle, Ms Muyambo (PhD student), and a research assistant from 13 to 15 December 2021. During this field visit, rapport was established with the identified KIs to allow for follow-up, and observations were noted. Many challenges were experienced during the field visit; for example, many officials were still working from home and were therefore unavailable, heavy rain was experienced during the visit, KIs' reluctance and apprehension to share information with the researchers due to the fear of being victimised, social restrictions due to fears of contracting COVID-19, as well as the festive mood due to the proximity to the Christmas holiday season. Some KIs were unavailable due to the fact that the local elections of November 2021 brought many changes to government offices and new portfolios were still to be filled. The schools were also about to close; there was thus a challenge to meet the principals of selected schools. Prof. Belle was invited to attend the Thabo Mofutsanyane District Disaster Advisory Forum on 12 January 2022 and used this opportunity to speak and to make follow-ups with the relevant stakeholders. Despite all these efforts, the KI response rate was low.

6.3.1.2 Household surveys

QwaQwa comprises 30 wards that were targeted for the household survey in early 2022. The November 2021 local elections made it difficult to obtain the contact details of the newly elected ward councillors, who were the first target for the household survey. Due to the elections, some ward councillors were changed and the municipality and Election Commission Office were still busy updating the list of newly elected and returning ward councillors. Despite these challenges, 246 households, representing all 30 wards, were sampled. These also included the various villages in close proximity to the ecological sampling sites identified (see Section 5.2.3). Simple random and snowballing sampling were used.

6.3.1.3 Field observations

The researchers made three visits to the study area in total: the first to make contact and conduct interviews with the identified KIs, and two to conduct the household surveys. During each of these visits, field observations related to climate and water issues were made by the researchers.

6.3.1.4 Stakeholder validation workshop

A multi-stakeholder validation workshop was held on 24 November 2022 at Letsheng Lodge in QwaQwa. This workshop was attended by more than 25 participants from diverse institutions, such as different government departments, the local municipality, NGOs, civil society organisations, and traditional authorities. The aims of the workshop were to give the research team an opportunity to present their findings on the research project (the results from all three components, namely climate and hydrological modelling, ecological risk, and disaster risk analysis, were presented), to solicit final inputs from stakeholders, and to validate the key findings.

6.3.2 Data analyses and results

6.3.2.1 Hazard analysis

The aim of this section is to present the results of the hazard analysis in the study area. Hazard analysis is part of risk analysis, as depicted in Figure 6.1. The NDMC (2016) defines hazard analysis as "outlining the nature of each hazard in terms of its defined characteristics". It includes the identification, ranking, analysis, and prioritisation of hazards.

(a) Hazard identification

The selection of hazards was guided by literature, field observation, their apparent connection with climate change, and consultation with experts. The 17 hazards that are most likely to occur in the area are presented in Table 6.1.

Table 6.1. Identified hazards

Hazards		
Floods	Pests	Air pollution
Wildfires	Lightning	Land pollution
Drought	Erosion	Strong winds
Heat waves	Water pollution	Hail
Animal diseases	Water scarcity	Snow
Human diseases	Earthquakes	

(b) Hazard ranking

During hazard ranking, the identified hazards were graded according to their prevalence. The key stakeholders, who were the KIs who participated in this portion of the study, ranked the identified hazards from 1 to 5, where 1 indicates a hazard that was least common, 2 – not so common, 3 – average, 4 – common, and 5 – most common. The rating was based on their expert knowledge, experience, and perception. As shown in Figure 6.5, water scarcity topped the list with a rating of 4.4. This was followed by drought (3.1), floods (2.6), and water pollution (2.4). Wildfires received an overall rating of 1.8.

The multi-hazard analysis focused on these 17 hazards, using commonly shared indicators, probability, area covered, magnitude, frequency, intensity, and predictability. Table 6.2 presents the Hazard Index and rating for each hazard.

The study then focused on climate-related hazards. Figure 6.5 presents the four hazards that were included in the overall risk analysis.

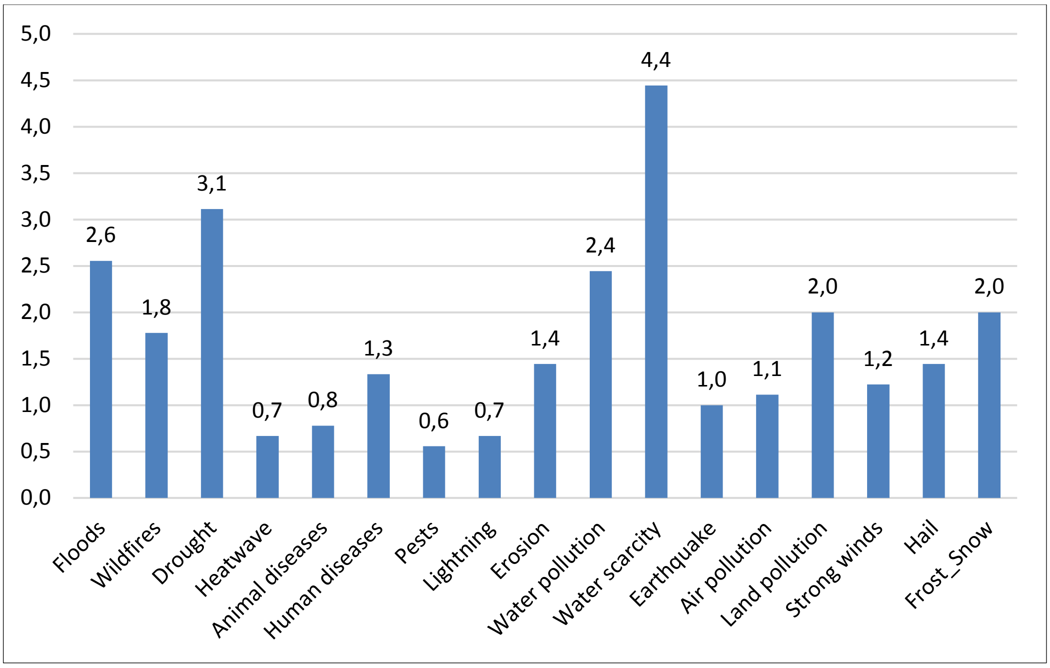


Figure 6.5. Hazard ranking

Table 6.2. Hazard Index and rating

Count	Hazard	Average score / Hazard Index	Hazard rating
1	Drought	3.7	High
2	Extreme cold	3.7	High
3	Floods	3.6	High
4	Strong winds	3.6	High
5	Water scarcity	3.5	High
6	Hail	3.5	High
7	Lightning	3.4	High
8	Frost/snow	3.4	High
9	Heatwaves	3.3	High
10	Wildfires	3.2	High
11	Erosion	2.6	Medium
12	Alien plants	0.9	Very low
13	Land pollution	0.6	Very low
14	Fog	0.6	Very low
15	Human diseases	0.5	Very low
16	Air pollution	0.4	Very low
17	Dust	0.4	Very low

Key: Very low: 0-0.9; Low: 1-1.9; Medium: 2-2.9; High: 3-3.9; Very high: 4-5

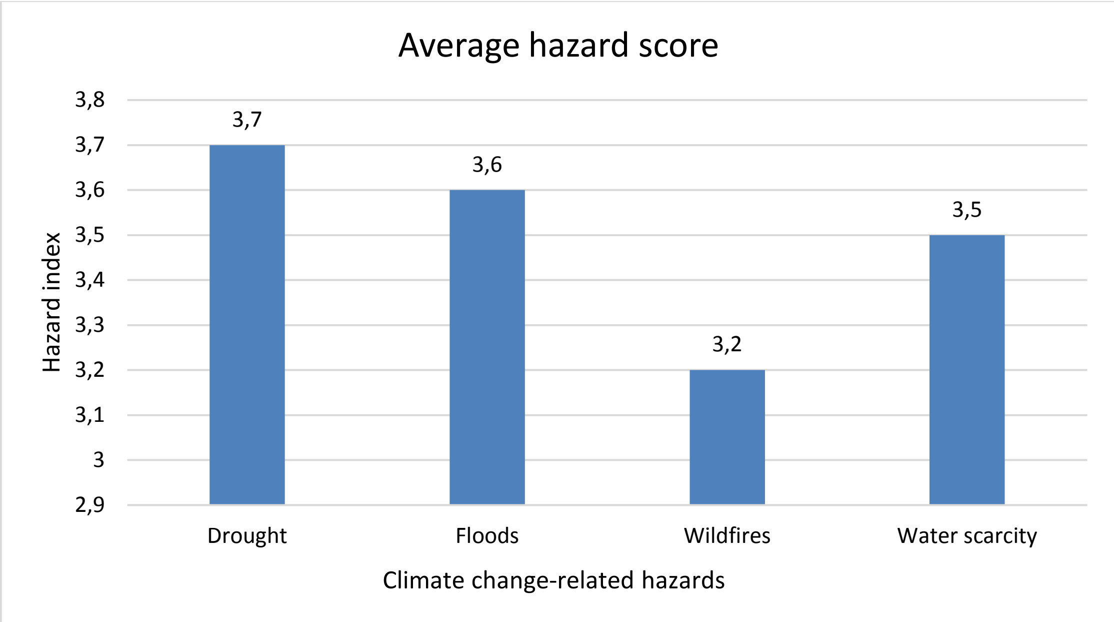


Figure 6.6. Selected climate-related hazards scoring

The overall average score of the selected climate hazards was calculated as follows:

(3.8 D+ 3.6 F + 3.5 WS +3.2F/4) = 3.52

6.3.2.2 Exposure analysis

This section presents the results of the exposure analysis of the critical elements of the four hazards that were prioritised, namely drought, floods, wildfires, and water scarcity. These hazards were included in the risk analysis. Exposure analysis, like hazard analysis, is part of risk analysis, and is defined as the identification of elements that are open to damage, injury, or death from climate change-related events (OECD, 2012; UNDP, 2010). The analysis included the identification of critical elements open to harm from weather events and water scarcity, as guided by literature, field observation, and expert consultations. It was necessary to select elements generic to the hazards in question; hence population, structures, land, and water sources were selected for analysis. The overall exposure per element and for each hazard is presented in Table 6.3.

Most of the elements analysed showed high exposure to all the hazards, while the population and water sources showed very high exposure to water scarcity, and water sources showed very high exposure to wildfires. Only water sources showed low exposure to water scarcity, most probably because of existing water scarcity in the catchment.

Table 6.3. Overall exposure scores and rating

Element/hazard	Drought	Floods	Wildfires	Water scarcity	Average per element
Population	3.7	3.2	2.6	4	3.38
Structures	3.1	3.3	2.6	3.6	3.15
Land	3.7	3.5	3.1	4	3.58
Water sources	3.3	2.8	1.6		2.57
Average per hazard	3.4	3.2	3.07	3.3	Overall exposure = 3.17

Key: Very low: 0-0.9; Low: 1-1.9; Medium: 2-2.9; High: 3-3.9; Very high: 4-5

The next step was to analyse community resilience to common climate-related hazards of drought, floods, wildfires, and water scarcity using the CCF.

6.3.2.3 Resilience analysis

(a) General socio-economic and demographic characteristics of the participants

Table 6.4 summarises the distribution of the study participants according to socio-economic attributes. Socio-economic and demographic characteristics are useful in resilience studies because they provide valuable information that can be used in policy and strategic planning, as well as to guide the identification of target groups for intervention (Sharma *et al.*, 2018).

The socio-demographic summary indicated that there were more males than females in the survey, that the survey population comprised predominantly of youths (younger than 35 years), who were mostly unemployed, educated (high school level and above), single, and living in households where 75% earned an annual income of less than R10 000. This shows a potentially very volatile population, but also a population with untapped potential.

(b) The CCF

The indicators identified for the resilience analysis were based on the CCF (Flora *et al.*, 2004; Jordaan, 2017). These indicators were natural, human, social, financial, infrastructural/built, political, cultural, and institutional capitals. Figure 6.7 shows the average capital score for the six capitals that were measured, which reflects the resilience score. Social capital scored the highest (2.73), followed by natural capital (2.67), human capital (2.1), infrastructural capital (2.36), political capital (2.01), and finally financial capital (1.98).

Table 6.4. Socio-economic characteristics of household survey participants (N = 246)

Characteristics	Sub-characteristics	Frequency	Percentage (%)
Gender	Female	131	53.25%
	Male	115	46.75%
Age group	18-25	70	28.46%
	26-34	69	28.05%
	35-44	38	15.45%
	45-54	25	10.16%
	55-64	24	9.76%
	65+	20	8.13%
Educational level	No formal education	28	11.38%
	Primary school level	20	8.13%
	High school level	109	44.31%
	College level	40	16.28%
	University level	39	15.85%
	Postgraduate level	10	4.07%
Marital status	Single	157	63.82%
	Married	40	16.26%
	Widowed	22	8.94%
	Separated	8	3.25%
	Divorced	3	1.22%
	Living together	16	6.50%
Source of income	Unemployed	96	39.02%
	Social grant	57	23.17%
	Formally employed	42	17.07%
	Self-employed	26	10.57%
	Diverse incomes	2	0.81%
	Employed	12	4.88%
	Others	11	4.47%
Household income range (rands; annual)	No response	3	1.22%
	Under R10 000	184	74.80%
	R10 801-R100 000	42	17.07%
	R101 000-R200 000	10	4.07%
	R201 000-R400 000	7	2.85%

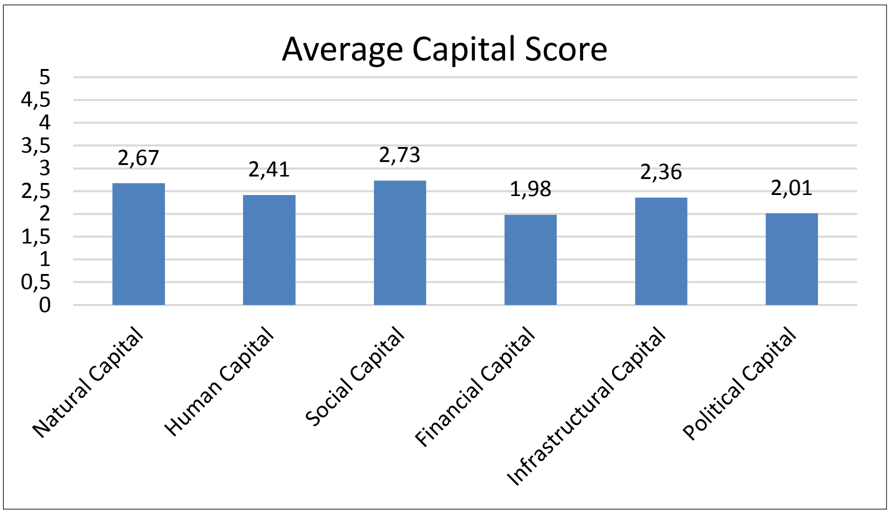


Figure 6.7. Average capital scores for the measured community capitals

To determine the importance of each community capital in influencing the resilience of the QwaQwa communities to climate change impacts, a stakeholder workshop was conducted that assigned weights to each of the capitals. Table 6.5 shows the weighted capitals and the final Resilience Index.

Table 6.5. Weighting of capitals and calculation of Resilience Index

Capital	Capital Index (from analysis)	Average weights (from stakeholders)	Standardised weight factor	Product (weight x Capital Index)	Final Index
Natural	2.60	3.9	0.83	2.158	2.16
Human	2.39	4.1	0.88	2.103	2.10
Social	2.60	3.9	0.88	2.158	2.16
Financial	2.00	3.6	0.77	1.540	1.54
Infrastructural	2.38	4.2	0.90	2.142	2.14
Political	2.02	3.7	0.79	1.596	1.60
Total		**23.4**	**5.0**		**11.7**
Resilience Index = 11.7/6 = 1.95					

The natural and social capitals had the highest scores after weighting (2.16), while financial capital had the lowest score (1.54). Table 6.5 shows that the overall community capital, or Resilience Index score, was calculated by multiplying the standardised weight factor and Capital Index that were obtained from the surveys. The resultant Resilience Index score was 1.95, which indicates low resilience. This implies that communities in QwaQwa will struggle to recover from the impacts of extreme weather events and climate shocks as benchmarked by the CoBRA framework (UNDP Drylands Development Centre, 2014).

Table 6.6. Resilience Index ranking

Capital scoring	Resilience rating	Remarks
Less than 1	Very low resilience	Collapses in case of disaster
1.1-2	Low resilience	Struggles to recover
2.1-3	Medium resilience	Recovers but worse than before
3.1-4	High resilience	Bounces back
4.1-5	Very high resilience	Bounces back better or bounces forward

6.3.2.4 Calculation of the Multi-Hazard Risk Index (MHRI)

The final multi-hazard risk was calculated as follows:

$$\boldsymbol{Risk} = \frac{\boldsymbol{Hazard} \times \boldsymbol{Exposure}}{\boldsymbol{Capitals}}$$

Or:

$$\boldsymbol{RISK} = \frac{(\boldsymbol{Hazard})}{(\boldsymbol{Capitals})} \times \frac{(\boldsymbol{Exposure})}{(\boldsymbol{Capitals})}$$

$$MHRI = \frac{(3.5)}{(1.9)} \times \frac{(3.2)}{(1.9)}$$

$$= 1.8 \times 1.68$$
$$= 3.09$$

Based on the MHRI, QwaQwa exhibits a high risk to the identified climate-related hazards. Considering this in light of the low Resilience Index value (see previous section), efforts should focus on reducing exposure to multiple climate change-related hazards and increasing the resilience of the community, the environment, and structures by improving the existing weak assets.

6.4 KEY FINDINGS AND DISCUSSION

6.4.1 Hazard analysis

Of the 17 identified hazards, 10 were ranked high, one as medium, and six as very low. This ranking followed the South African NDMC's guidelines of 2016. All highly ranked hazards were climate related, which indicates the importance of addressing climate change impacts and climate change-related risks. It is evident from the hazard analysis that the overall risk of the selected climate-related hazards (droughts, floods, water scarcity, and wildfires) was **high** (3.52).

6.4.2 Exposure analysis

The overall rating of exposure to these hazards was also **high** (3.2). Most of the elements analysed showed high exposure to all the hazards, while the population and land use showed very high exposure to water scarcity. Water sources showed very high exposure to wildfires.

6.4.3 Resilience analysis

The Resilience Index of QwaQwa was rated as **low** at 1.9. However, social and natural capitals were ranked the highest in the community survey, while financial capital scored the lowest. The overall Community Capital Index, based on the household surveys, was initially rated as **medium** (2.3), but dropped to a **low** score of 1.95 after the stakeholder weighting was standardised. The CCF approach followed in this study described the cup as "half full", instead of "half empty", as does traditional vulnerability analyses. This serves to empower communities to improve their livelihoods using available resources. Current literature shows an increasing use of the CCF to assess and promote the empowerment of communities (Mulema *et al.*, 2021; Suárez *et al.*, 2021; Lamm *et al.*, 2020; Kline *et al.*, 2019; Himes-Cornell *et al.,* 2018; Belle *et al.*, 2017; Mayunga, 2007). This concept is appropriate to strengthen resilience by focusing on investing in available resources to reduce disaster risk to climate change impacts, especially in marginalised areas such as QwaQwa and similar regions in Africa.

The findings are supported by the risk register of the Maluti-a-Phofung Local Municipality, following a risk assessment that was conducted by the district in 2021. The results of this study are shown in Table 6.7. All the risks ranked as **extremely high** and **high** by the MHRI were climate related. Even "basic service disruptions", ranked as number 2, were mostly linked to the prevailing water crisis, among other causes. This risk assessment did not highlight water scarcity as a major risk, which this research brought to the fore.

Table 6.7. Maluti-A-Phofung Local Municipality risk register

Risk Quantification: Maluti-A-Phofung Local Municipality						
HAZARD CATEGORY	HAZARD				Relative Risk Rating	Relative Risk Priority
SCORE		Hazard Rating	Vulnerability Rating	Capacity Rating		
Natural - Biological	Veldfire	12	12	12	12,000	extremely high
Technological	Basic Services Disruption	11	12	12	11,000	extremely high
Technological	Structural fires	12	9	12	9,000	high
Natural - Hydrom.	Severe weather	10	9	12	7,500	high
Natural - Hydrom.	Floods	10	9	12	7,500	high
Natural - Hydrom.	Drought	8	11	12	7,333	high
Technological	HAZMAT: road	9	10	13	6,923	tolerable
Technological	Illegal dumping	9	10	13	6,923	tolerable
Natural - Biological	Human diseases	11	8	13	6,769	tolerable
Technological	Road incident	10	9	14	6,429	tolerable
Technological	Social unrest/conflict	9	11	16	6,188	tolerable
Technological	Crime	11	8	15	5,867	tolerable
Technological	Major Hazardous Installations (MHI)	5	13	18	3,611	tolerable

Source: Thabo Mofutsanyana District Municipality (2021)

CHAPTER 7: DISASTER RISK REDUCTION (DRR) STRATEGY AND PLAN FOR QWAQWA

7.1 INTRODUCTION

This section presents the proposed strategies for DRR and resilience building, with reference to the literature reviewed, data gathered and analysed for the three components of the study (climate and hydrological modelling, ecological risk assessment, and the community risk analysis), and recommendations by stakeholders and study participants. A summary of the recommendations by the ecological specialists (involved in the ecological risk assessment) and from the household surveys, KI interviews, and stakeholder workshop is presented, in response to the projections and key findings from the downscaled climate and hydrological models prepared for the catchment.

The disaster risk strategies were categorised into eight groups, according to the strengths and weaknesses of each community capital, in order to improve the low resilience of the QwaQwa community to climate change-related extreme events. The eight categories are: (1) natural, (2) human, (3) social, (4) financial, (5) infrastructural, (6) political, (7) cultural, and (8) institutional capitals, based on the CCF (Mattos, 2015; Emery and Flora, 2006; Flora *et al*., 2004).

7.2 INTEGRATED SUMMARY OF THE KEY CLIMATE-RELATED RISKS IDENTIFIED FOR QWAQWA

QwaQwa has been experiencing chronic water scarcity, due to climate variability, as well as poor service delivery and local governance, for the past two decades. This was reflected in the hazard analysis, which identified water scarcity as one of the four highest-ranking hazards; the others being droughts, floods, and wildfires – all of which are climate related. Considering the future changes in climate and river flow, as projected by the downscaled climate and hydrological models developed for QwaQwa, the overall risk of these hazards is, and will remain, high for the local communities and the water resource management sector.

QwaQwa is projected to be decidedly warmer in the immediate to distant future, especially in the lowlands where Phuthaditjhaba is situated. Mean daily maximum temperatures could become approximately 1.5°C warmer in summer and in winter by the mid-2030s, and by more than 4°C for both seasons by the 2070s. Minimum temperatures in winter are also projected to increase, although the expected increase would be slightly less than for the maximum temperatures. It is possible that the number of days with frost could decrease by more than 40% in the higher-lying parts of the catchment, and by more than 70% in the lower-lying areas. This is a concerning result, considering the important role that frost plays as a natural disturbance in the ecology of grassland ecosystems; for example, frost plays a major role in inhibiting tree recruitment in grasslands (Botha *et al.*, 2020). The higher temperatures are also expected to increase potential evaporation, which is already very high, in the catchment. The projections indicate that the mean annual evaporation in QwaQwa could increase by 7% in the near future, and by more than 20% in the distant future. These projected increases are significant, especially when considering the important role that evaporation plays in river hydrology, as well as in water loss from open water bodies, increased irrigation demands, and the more rapid drying of soil. Increased water losses due to the projected higher evaporative demand during the winter months (due to the warmer temperatures), when rainfall and streamflow are naturally low, could increase pressure on water resources in the catchment during this critical time.

Estimating increases in water temperature from air temperature projections is complex (Dallas and Rivers-Moore, 2014). However, it has been shown with high confidence that increases in water temperatures can change the physical and chemical properties of water (Abrahams *et al.*, 2013; Dallas and Rivers-Moore, 2014; Woodward *et al.*, 2016; Wang *et al.*, 2022). For example, warmer water does not only hold less DO than colder water, but can also increase the oxygen consumption and metabolism of aquatic biota, which could result in a further decline of DO concentrations in water (Abrahams *et al.*, 2013; Woodward *et al.*, 2016). This study found that even though the COD was high at most of the sampling sites, it is highly likely to increase in the future; considering that a significant relationship between water temperature and COD was identified in the catchment.

QwaQwa is projected to experience higher rainfall during the rainy season (summer), but relatively less rainfall during the dry season (winter). Rainfall increases will, however, not occur uniformly over the catchment. The projections show that the greatest changes in mean annual rainfall will occur in the mountainous headwater areas, with these areas receiving between 30 mm and 40 mm (4%) more rain in the near future, and between 140 mm and 185 mm (20%) more in the distant future. Rainfall increases could be lower during dry years and higher during wet years. However, verification of the results indicated that the projections may have overestimated the rainfall for dry years and underestimated the rainfall for wet years. This is an important conclusion for water resource managers, since it implies that the dry years may be even drier than projected and the wet years wetter. Also important to water managers is the fact that rainfall in the catchment is naturally highly variable; not only between years, but also within years (runoff and streamflow variability is even higher). This variability is expected to increase in the future, which will increase uncertainty and unpredictability around surface water availability. Another significant result is that dry spells are projected to increase in the immediate future, while wet spells could be fewer. This impact could be more pronounced in the higher-rainfall upper parts of the catchments than in the slightly drier lowland areas. This would have severe consequences for agricultural production and water resource management in QwaQwa.

Most of the runoff in the catchment is generated on the mountain slopes, with these areas producing nearly three times more runoff, on average per year, than the lowlands. The differences between the higher- and lower-lying areas may be even higher during dry years. The highest runoff generally occurs in January (summer), while August and September (winter) have the lowest runoff. MAR in the catchment is projected to increase by approximately 7% in the highlands and 15% in the lowlands in the near future. Into the distant future, runoff could increase by 36% in the highlands, and by nearly 70% in the lowlands. Stormflows in the catchment generally occur in summer (rainfall season), when they contribute approximately 70% to runoff. Stormflows are projected to increase by between 13% and 21% annually, with the greatest changes expected for the highland areas. The percentage increase in baseflows, which are the major contributors to total runoff during the dry winter season, are projected to be higher in the lowlands than in the highlands. It is important to note that baseflows appear to be overestimated by the GCMs for winter, which is the critical period when baseflows dominate streamflow. This could have important repercussions for low-flow water quality assessments, since baseflows generally contain a higher proportion of chemical contaminants. In fact, extreme low flows can be more detrimental to perennial river systems than high flows, due to factors such as the potential for streamflow interruption that causes the river to fragment into a series of isolated pools, the loss of longitudinal river processes, longer residence time of water, and the loss of dilution capacity, which could lead to increases in the concentration of pollutants and toxins in the river water (Abrahams *et al.*, 2013; Woodward *et al.*, 2016). This is especially relevant for the Mphukojwane and Elands rivers, which were found to have high concentrations of toxic constituents (e.g. metals: aluminium, iron, and manganese; OMPs: BP-4, acetochlor, efavirenz, and carbamazepine) and microbes (e.g. faecal coliform bacteria and *E. coli*). Considering the serious problems with water purification, distribution, and the monitoring of drinking water quality in QwaQwa, especially during water shortages, it is clear that the residents who receive water from these water supply systems are at high risk.

Accumulated streamflows in the streams of QwaQwa are projected to increase in the future, although the increases are not expected to occur uniformly over the catchment. The accumulated streamflows vary greatly between the 19 sub-catchments, depending on the size and rainfall of the sub-catchments. It is also important to note that streamflow increases from upstream to downstream as the runoff from the upper quinary joins that of the middle quinary, to converge downstream with the local runoff from the lower quinary. Peak discharges in the catchment generally occur in late summer (February), most often after a thunderstorm event. The projections indicate that peak discharges could increase in the immediate future (2040s), with the most downstream sub-section of the catchment (lower Elands River) being at risk of flooding in the future.

The increase in stormflows and peak discharge could help to improve the water quality of the streams by diluting and flushing out polluted water. On the other hand, these flows could dislodge soil particles, especially from steep and overgrazed slopes, which will increase erosion and sediment delivery to the rivers. The projections indicate that sediment yields in QwaQwa could increase by 15% to 25% in the near future. This is particularly concerning, given the degraded state of the catchment and riparian habitats. For example, the aquatic habitat diversity of the middle Metsi-Matso River has been significantly reduced by sedimentation, with many of the critical habitats, such as riffles, being smothered by sediment. The degradation of riparian and instream habitats by the widespread and uncontrolled sand mining also causes concern, given the projected increases in rainfall, runoff, and stormflows that could wash large volumes of sediment into the rivers.

The higher rainfall and runoff projected for the future could alleviate water scarcity in the catchment, but it is important to note that increases in the annual runoff and streamflow may not necessarily reduce water stress if the infrastructure needed to capture the additional volume of water is not available (Döll *et al.,* 2015). Other factors, such as immigration into the area, higher evaporation from the soil and water bodies, higher evapotranspiration by riparian vegetation, and greater irrigation water demand, may neutralise the expected increases in streamflow. Another concern is the widespread occurrence of alien trees in the catchment and even in the river channel. Of particular interest is the dense clumps of black wattle trees in the upper Namahadi River. These evergreen trees are notorious for reducing water yields (Dye and Jarmain, 2004), as well as during winter, which is the dry season in QwaQwa.

It is clear from the discussion above that the population in QwaQwa is highly exposed to water scarcity, not only in terms of quantity, but also with regard to quality. This was confirmed by the exposure analysis that indicated that communities in QwaQwa have very high exposure to water scarcity, and high exposure to the other three hazards (drought, floods, and wildfires) that are also related to climate change. The resilience analysis showed that QwaQwa has low resilience to climate-related hazards. It is therefore crucially important to strengthen resilience in the study area by investing in available resources to reduce disaster risk to climate change hazards and impacts.

This study has taken a different approach to traditional vulnerability analyses by using the CCF. The CCF differs from traditional approaches by identifying a community's unique strengths, and using those to empower communities. For QwaQwa, the social and natural capitals were identified as potential strengths that could be employed to improve resilience to climate-related hazards.

7.3 REDUCING THE RISKS: RISK REDUCTION STRATEGIES

The proposed strategies are categorised into policy recommendations, recommendations for the empowerment of the local communities, and recommendations to reduce disaster risks and adapt to climate change, as presented in Tables 7.1, 7.2, and 7.3. Considering the prominence of water scarcity as a hazard in the catchment, specific strategies for reducing the risks related to water quantity, water quality, and river health are presented in Table 7.4. **However, it should be noted that these recommendations overlap and interconnect.**

7.3.1 Policy recommendations

Table 7.1 lists policy recommendations for reducing disaster risk in QwaQwa.

Table 7.1. Policy recommendations for reducing disaster risk in QwaQwa

Risk identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
Natural capital			
Inadequate water supply for the population	Water scarcity forces households to use water from unsafe water sources such as rivers. This can result in diseases and health issues	More households may be forced to use water from rivers and other unsafe sources of water due to more frequent dry periods, flooding, and pollution.	Rain harvesting is a feasible, cost-effective, and sustainable strategy to increase household access to water supply during droughts or water infrastructure glitches. Nel *et al.* (2017) report a reduction of up to 69% of municipal water demand when supplementary water is used. Several considerations such as tank size, roof size, and water demand should be taken into account. The initial installation of rainwater harvesting infrastructure could be very expensive for most poor households in QwaQwa; the local authority should therefore work in partnership with the private sector and NGOs to budget for and sponsor such a project. Rainwater harvesting will also contribute to reducing flood risk, saving energy required for tap water, and reducing stormwater runoff. India has recorded several rainwater harvesting success stories (Bansal, 2021). Increase the supply of conventional water supply; for example, water transfer from the Sterkfontein Dam to nearby QwaQwa. Conserve the wetlands that can increase the recharge of groundwater. More groundwater feasibility studies should be conducted and more boreholes should be drilled. According to the National Water Act, No. 36 of 1998, South Africans are provided with free basic water services (RSA, 1998). While the legislation was intended to address inequality and other ills of the apartheid system, it was taken literally and is misused to develop a culture of non-payment and misuse of the basic water and electricity privileges. To address this, residents should adhere to the

Risk identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
			allocated amount and pay if they exceed their allotment. This is supported by scholars such as Maphela and Cloete (2020).
Financial capital			
Lack of access to emergency funds	Inadequate financial capacity to meet urgent financial needs	Increased incidences of flooding and droughts may force households to use their limited finances, which may potentially leave them more financially vulnerable to disaster risks.	The top levels of public management, namely national, provincial, and district municipality, should ensure that more financial and human capitals are directed to the local level, where the actual work of reducing disaster risk and empowering communities occurs. Community members should be encouraged to participate in informal savings groups popularly known as “stokvels” in South Africa.
Infrastructural capital			
Poor land use and zoning	Unsafe locations/ occupations	Higher and more intense rainfall may destroy informal settlements in unsafe locations.	The municipality should update its land use regulations to promote climate resilience and DRR. Land use records should be updated in consultation with the traditional authority to promote collaboration and to reduce the unlawful issuance of land and unplanned settlements. Additionally, a plan should be drawn up and resources allocated for the enforcement of land use planning regulations.
Political capital			
High corruption rate	Mismanagement of public resources Depletion of financial resources for service delivery Discontentment and violent protests	Higher frequency of flooding and drought may lead to the increasing exclusion of needy households from receiving necessary assistance. Water scarcity may result in more violent protests.	The top levels of public management, namely national, provincial, and district municipality, should ensure that more financial and human capitals are directed to the local level, where the actual work of reducing disaster risk and empowering communities occurs. Due to the general lack of confidence in municipal financial management, the organisation should hire professionals or experts who are certified in financial forensics to “provide a wide range of services from complete internal control audits and forensic analysis to general and basic consultations” (Abdulrahman, 2019). The municipality should be held accountable for the mismanagement of public resources and must provide clear and transparent financial statements and

Risk identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
			reports. The South African Constitution, in Chapter 13 in section 215, emphasises the importance of “transparency, accountability and effective financial management of the economy, debt and the public sector” (RSA, 1996); however, this regulation needs to be enforced and those found guilty of fraudulent activities should receive the necessary discipline. The municipality should manage its finances efficiently, exercise financial discipline, and implement systems for effective and timeous revenue collection, efficient debt collection, and timeous payment of its suppliers. Administrators should be guided by municipal regulations in all their work and conduct, and maladministration, nepotism, and corruption should be dealt with according to the established policy. A whistle-blowing system should be implemented to prevent corrupt and fraudulent activities. It should be efficiently and objectively managed to avoid criminalising innocent people. To encourage people to report fraudulent activities, the protection and the preservation of anonymity and confidentiality of whistle blowers are very important.
Political interference	Mismanagement of public resources Misdirection of resources	Climate change will reduce the availability of resources and create more rivalry among political parties, as well as between politicians and administrators.	Politicians must stick to their business and administrators should keep to their administrative work. “Politicians are elected, public administrators appointed; the former make decisions, the later prepare and execute them – that is roughly how the government works and should work” (Bryer, 2021). Politicians should not interfere in the work of the municipality when they provide basic needs to the community.
Cultural capital			
No coordination between traditional and local authority on DRR issues	Inadequate attention to community needs in relation to DRR	Higher incidences of dry periods and flooding may expose the community to more disaster risks, which will result in frustration that	A culture of violence should be discouraged through the effective implementation of the law. Civic education is prescribed to educate the community on peaceful service delivery protests. While protesting is a constitutional right, violence protests that have characterised QwaQwa in the recent past should be discouraged.

Risk identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
		breeds violent protests and crime.	

Institutional capital			
Low involvement of local institutions in DRR	Limited resources to deal with disaster risks Working in silos does not build synergy among DRR role players	The projected greater incidences of flooding and droughts may erode the already limited resources to deal with disaster risks and leave the community struggling to bounce back. Increased use of inappropriate strategies to deal with disaster risks.	South African legislation on DRR, local governance, and water and other natural resources management is well developed; however, there is a need for adherence and effective implementation by political and administrative authorities. Additionally, there should be effective checks and balances by the community and other stakeholders in order to enforce compliance and accountability. The Maluti-a-Phofung Local Municipality's Disaster Management Centre should be fully capacitated in terms of human and financial resources. QwaQwa has the advantage that both the district and local disaster management centres are in the same place. Shared responsibilities and of resources between the centres are recommended. Different department should work together; for example, local government (CoGTA) and the Department of Environment should cooperate and work together in handling issues such as the desilting of the Fika-Patso Dam.

7.3.2 Recommendations for the empowerment of the local communities

Table 7.2 lists recommendations for the empowerment of the local communities in the QwaQwa area.

Table 7.2. Recommendations for local community empowerment

Risk identified (resilience)	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
Natural capital			
Pollution from solid waste (e.g. diapers in rivers)	Human and environmental health hazard	Higher rainfall and stormflows may wash more solid waste into rivers and drainage systems and contribute to more public health issues and flooding.	Informal waste pickers should be integrated into formal waste management in order to complement the municipality's solid waste management activities and reduce costs. The Pune Municipality in India is one example of such an initiative (Gupta, 2012). Guidelines should be developed to effectively integrate unemployed youths to carry out the operation professionally and make waste a resource to enhance community members' livelihoods. A youthful and educated population is one of the greatest capitals that QwaQwa possesses.
Human capital			
Lack of awareness and/or knowledge of disaster risks and DRR	Inadequate preparedness to face disaster risks	The community may not be adequately prepared for extreme weather events such as more intense rainfall, stormflows, flooding, drought, and heatwaves.	Research on communities impacted by disasters has proven the important role that local and traditional knowledge can play in reducing disaster risk and strengthening resilience against the impacts of climate change (Muyambo *et al.*, 2017). Such knowledge, especially on the management of natural resources, should be gathered, taught to communities, and documented for future reference. The traditional authority, as the custodian of such knowledge, should play an active role. Civic education through formal classroom learning and mass media campaigns should be provided to promote understanding of the importance of natural resources such as water, climate change, and citizens' rights and responsibilities and to promote the involvement of the local population in local community development. The UFS in QwaQwa should be more visible and active in DRR and resilience-building initiatives.

Lack of a skilled workforce to cope with climate change risks	Poor maintenance of infrastructure	More infrastructural damage may result from more frequent and intense extreme climate events, which are exacerbated by poor maintenance.	The government should provide continuous skills improvement programmes for its workforce to build capacity and technical, managerial, and leadership skills for more efficient service delivery. Youths who were trained to repair water pipes should be engaged by the municipality, government departments, NGOs, etc. to, for example, repair water leakages that are rampant in the area. The municipality should engage in staff exchange programmes with municipalities in other parts of the country, as well as in other countries, in order to exchange ideas and learn new skills and competencies. This will cater for the shortage of skills in the municipality, as reported in the study. Community capacity building should be promoted to empower the disadvantaged members of the community, including unemployed youths and women, to develop skills that they can use to improve their livelihoods. The proposed waste management project – Nature-based Solutions (NbS) – will be a good entry point.
Inability of people living with disabilities to access resources	Low capacity to prepare for imminent risks. More exposure of people living with disabilities to extreme climate hazards.	Vulnerable groups may suffer more impact from more frequent and intense climate hazards.	The promotion of community-based organisations that target vulnerable groups such as the elderly, people living with disabilities, and other groups to offer meaningful activities, social interaction, and opportunities to participate and contribute to DRR and community resilience.
Social capital			
Lack of community participation in DRR issues	Weak social networks to respond to climate emergencies	Higher frequency and intensity of climate-related hazards will weaken social ties and community support.	Community participation should be promoted because it "is the most effective in ensuring successful DRR initiatives at the local level because communities take ownership of these initiatives and gain a better understanding of their risks" (Nkombi and Wentink, 2022). Community participation is more than just consultative participation; it entails involvement in all stages of community development and DRR initiatives. It also promotes transparency and shared responsibility in the development and implementation of DRR initiatives. An online portal such as a specially created website, Facebook page, or Twitter account can be used to complement traditional means to create an interactive platform. As an example, such an undertaking was successfully launched by the Christchurch

			City Council in New Zealand after the 2010-2011 Canterbury earthquake (UNDP, 2020).
General moderate involvement in social networks	Lack of support in crises	Increasing prevalence of flooding and droughts may leave more households facing disaster risks without adequate social support.	The formation and growth of social networks should be promoted among different groups of people in the community. Social networks are regarded as crucial in coping with and recovering from disasters (Muyambo *et al.*, 2017) because they benefit individuals who may not have any means to cope with catastrophic events to find support from their network. Even people who may not have family will receive support from the groups they belong to. The principles and practice of *Ubuntu* should be promoted.
Financial capital			
Lack of access to emergency funds Lack of access to savings to cope with crises Low participation in informal financial groups (e.g. "stokvels") Low remittance flow from relatives	Inadequate financial capacity to meet urgent financial needs during climate emergencies	Increased incidences of flooding and droughts may force households to use their limited finances and potentially leave them more financially vulnerable to disaster risks.	The promotion of microfinancing to help community members to access micro credit, micro insurance, and other services to help them absorb, transfer, and reduce disaster risk. Community members should be encouraged to participate in informal savings groups popularly known as "stokvels" in South Africa.
Infrastructural/built capital			
Roads in poor condition Poor drainage condition Ageing water infrastructure Silting of dams	Flooding threat to road infrastructure Flooding due to blocked drainage Water scarcity More copper theft, more electricity interruptions, and	Higher and more frequent rainfall may cause more damage to the road infrastructure and worsen access to essential services. Higher and more frequent rainfall and increased stormflows and sediment yield may cause more	The municipality should collaborate or partner with the private sector and NGOs to incorporate community members such as unemployed youths to clean or repair some infrastructure such as drainage systems and roads, which will also help them to earn a decent livelihood and prevent them from resorting to crime. The municipality and other relevant government departments should ensure adequate budget allocation for the maintenance and replacement of ageing infrastructure. Education, better policing, and strict enforcement of the law should curb cable theft, which partly results in more power supply interruptions.

Irregular electricity supply	more violent protests	drainage blockages that will result in increased flooding and water contamination. Stormflows and sediment yield, especially in peak discharges, may increase the rate of damage to drainage systems. Prolonged droughts and sedimentation affect the quantity and quality of water in dams. Poorly maintained water infrastructure results in pipe and reservoir bursts and water leakages.	
Political capital			
High corruption rate Political interference	Mismanagement of public resources	Higher frequency of flooding and drought may lead to the increasing exclusion of needy households from receiving necessary assistance.	Both politicians and municipal administrators should be educated and trained in climate change issues, DRR, and resilience building, and their responsibilities to the community should guide their actions. One cannot give what one does not have; skills and capacity development should therefore be key. The UFS, and especially the Disaster Management Centre, could play a leading role in community capacity building. “Knowledge is power!”
Low youth participation in decision making Low gender balance in public decision making	Lack of input from the youth in DRR issues, yet the youth are at the greater risk from disasters	Higher frequency of flooding and drought may lead to more youth and gender discrimination in decision making; potentially exposing them to greater disaster risks and causing increased	The untapped talent and energy of the educated but unemployed youth should be developed through income-generating projects and skills and leadership development programmes to reduce marginalisation, poverty, and frustration. The youth are important in DRR and resilience building because of many reasons; among which is the possibility of long-term benefits to the community (Rahman, 2020).

	Exclusion of women from DRR	dissatisfaction among the excluded groups.	Decision making and project designs and implementation should take into account gender issues.
Cultural capital			
The traditional authority does not play any role in DRR	Inadequate attention to community needs in relation to DRR	Higher incidences of dry periods and flooding may expose the community to more disaster risks due to the limited role played by the traditional authority in DRR.	For it to be relevant in DRR and resilience building, the traditional authority should be visible in the community and acquaint itself with the climate change-related issues that affect the community. DRR issues should also be included in some of the community gatherings called by traditional leaders.
No coordination between traditional and local authorities on DRR issues	Lack of coordination in decision making	Higher incidences of dry periods and flooding may expose the community to more disaster risks due to the lack of coordination between traditional and local authorities.	The traditional authority should make use of its representation in the municipality to speak for the development of the community instead of personal advancement. As custodians of the land, the traditional authority should promote the sustainable use and conservation of vital ecosystems such as the wetlands.
Institutional capital			
Lack of feedback from research institutions	Limited knowledge of current disaster risks	Higher frequency of weather events such as intense rainfall, stormflows, high temperature increases, and dry periods may be overwhelming to the community if no feedback on previous or ongoing research is given.	Institutions that conduct research should return to the study area to present their findings and recommendations to the stakeholders for consideration and possible adoption of recommended strategies. Continuous assessment of implemented strategies should be done through follow-up research. This is why this research team organised a final workshop with the relevant stakeholders to share and validate the study’s findings. A similar follow-up workshop at a later stage is recommended.

7.3.3 Recommendations to reduce disaster risks and adapt to climate change

All the abovementioned recommendations would assist in reducing disaster risks, adapting to climate change, and building community resilience. In addition, the following strategies are proposed:

Table 7.3. Recommendations for reducing disaster risk and developing climate change adaptation in QwaQwa

Risk identified (resilience)	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
Natural capital			
Soil erosion Deforestation Loss of wetlands	Reduced soil fertility Increased chance of flooding Increased chance of flooding and drought damage Poor water quality Reduced agricultural yield and increased food insecurity	Higher and more intense rainfall may contribute to more soil erosion and contribute to poor crop yields. Increased rainfall and runoff may result in more severe flooding due to loss of wetlands. Higher evaporation and dry spells may increase drought impacts and more intense flooding due to the loss of wetlands, which will have serious impacts on the community and their livelihoods.	NbS are recommended as an alternative to engineered interventions because they can contribute to climate change mitigation, adaptation, and resilience by supplying ecosystem services to the community. NbS are less expensive, community driven, and provide a win-win opportunity. NbS have successfully been used in other settings to reduce the exposure of critical elements to climate change impacts, reduce sensitivity of climate hazards, and increase adaptive capacity (Belle, 2016; Seddon *et al.*, 2020). Some of the activities that should be carried out are: • Protect the land against land degradation through the conservation of the present natural ecosystem, as well as reforestation and afforestation. • Restore rivers through the removal of silt, invasive plants, and solid waste deposits. • Proper wetland management (rehabilitation and restoration) will contribute to flood, drought, and wildfire reduction and provide socio-ecological benefits. • Agroforestry reduces both exposure and sensitivity to weather events, as well as providing timber, fruit, fuelwood, and other income sources (Belle, 2016; Quandt *et al.*, 2017).

Infrastructural capital			
Inadequate and aged water pipes Roads in poor condition Poor drainage condition	Flooding is a threat to ageing water pipes Flooding is a threat to road infrastructure Flooding due to blocked drainage systems	Higher and more intense rainfall may increase damage to ageing water pipes and result in more disruptions to water supply. Higher and more frequent rainfall may cause more damage to road infrastructure and worsen access to essential services. Higher and more frequent rainfall and increased stormflows and sediment yield may cause more drainage blockage, which will result in increased flooding, water contamination, and dam silting. Stormflows and sediment yield, especially in peak discharges, may increase the rate of damage to drainage systems.	• The municipality should take stock and assess the current infrastructure, and update its database. • Local authorities should plan, invest, design, and build infrastructure that can resist multiple climate change-related events that might occur. Climate-resilient infrastructure protects lives and saves money. Resilient infrastructure usually requires a significant amount of capital investment, but the savings in repairs and replacements are often attractive (Ulm and Manav, 2021). • A maintenance plan must be developed that includes day-to-day repairs of reported malfunctioning or broken-down infrastructure, drainage systems, roads, water leakages, and dam silting. The local community should take proper care of the existing infrastructure and assist in their maintenance.
Institutional capital			
Moderate access to early warning systems Moderate to low response to early warning systems	Low capacity to prepare for imminent risks	Increasing frequency of weather events such as intense rainfall and stormflows may overwhelm an unprepared community due to limited access to early warning systems.	Early warning information, even about water cuts, should be sent via mass communication channels, such as social media and cell phone networks, because the majority of people have access to cell phones with this basic service.

7.3.4 Recommendations to reduce disaster risk and build resilience against the ecological risks identified in the QwaQwa study area (whole catchment)

Table 7.4 lists strategies for reducing disaster risks related to water scarcity (quantity and quality) in QwaQwa.

Table 7.4. Strategies for reducing disaster risks related to water scarcity in QwaQwa

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
Pollution			
Elevated heavy metal concentration in river sediment and water (Al, Cr, Fe, Mn, and Zn exceeding the recommended guidelines for aquatic ecosystems and domestic uses of water)	Human health impacts Health impact on aquatic biota The hardness of the water in QwaQwa decreases the bioavailability of metals to aquatic life Fish, especially benthic feeders, can take up metals via the gut (from the sediment) and gills (from water) Human health effects from eating fish with elevated concentration of metal elements due to bio-accumulation	Higher and more intense rainfall may wash more sediment containing heavy metal elements into rivers, especially from bare and eroded areas in the upper and middle quinaries. Heavy rainfall increases the solubility of metals in the water, which increases the uptake of metals by fish through their gills. Copper toxicity to fish (e.g. *Clarias gariepinus*) has been shown to be enhanced by increasing water temperature. Increasing metabolic rate due to rising water temperature may change LC50 values for aquatic species.	Effective water treatment to remove metal elements from raw and wastewater streams. Resume regular water quality monitoring protocols as required by law. Decentralised water treatment units at potential sources of metal elements; e.g. industries. Improve access to safe and clean water for all, especially during drought periods when people from poorer households depend on river water for domestic use. Implement measures to curb sediment delivery (linked to metal elements entering streams) to the river channel: • Develop and implement catchment management strategies, in collaboration with cultural leaders, to address overgrazing in the upper reaches of the catchment. • Enforce existing legislation to curb the growth in unlawful and unlicensed sand mining in the riparian zones of streams. Resume biomonitoring of rivers and streams in the catchment, including monitoring the recruitment and external health of fish communities and effect-based monitoring. Train staff from local institutions and community members to conduct regular citizen monitoring.

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
High concentrations of certain OMPs / emergent pollutants	Range of human and environmental health impacts (see Appendix B) Environmental impacts of chronic exposure to OMPs and pharmaceuticals still unclear	Dilution due to heavy rainfall and increased runoff leads to higher streamflow. Downstream transportation of highly soluble OMPs during high-flow events. During dry spells, low flow, or absence of flows in combination with higher evaporation could result in a higher concentration of OMPs in river pools.	Although conventional WWTPs cannot eliminate all OMPs (e.g. carbamazepine and nevirapine), they can remove some pollutants (efavirenz, estriol) from raw and wastewater streams. Decentralised water treatment units at potential sources; e.g. hospitals, industries, abattoir, etc. Construct small to medium wetlands for the removal of some OMPs; e.g. pharmaceuticals. Add effect-based techniques to monitoring efforts in the catchment.
Elevated levels of dioxins / dioxin-like substances in the Metsi-Matso, Namahadi, and Elands rivers	Dioxins are highly toxic; may cause reproductive and developmental problems, interfere with immune system and hormones, and are carcinogenic Negative health impact on aquatic biota; e.g. in fish it may cause skin lesions and altered liver function Bio-accumulation in aquatic biota –	Input due to heavy rainfall and increased runoff will lead to higher streamflow. Downstream transportation of persistent substances during high-flow events. During dry spells, low flow or absence of flows in combination with higher evaporation could result in higher concentrations of dioxins in river pools.	Dioxins can be removed through effective water treatment. Activated carbon has proved very successful in removing these harmful substances.

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
	trophic transfer in food web		
Indications of high acute toxicity of some sites in the catchment	Range of human and environmental health impacts (see Appendix B)	Although the projected increase in rainfall and runoff should lead to the dilution of pollution, the increase in dry spells may worsen and concentrate the toxicity of river water.	Further research on the combination of toxic substances that lead to acute toxicity, especially in the Mphukojwane and Elands rivers.
Poor water quality in the middle and lower sections of the rivers; e.g. elevated EC, nitrates, etc.	Various environmental and human health effects (see Appendix B)	Due to a significant correlation between water temperature and COD found in the catchment, increased water temperature could accelerate productivity in the river; e.g. increased algal growth and decomposition of organic matter. Warmer water could lead to lower DO concentration in the water. Increased health risks due to an expected increase in fungal growth in water because of an increase in water temperature. Although the projected increase in rainfall and runoff should lead to the	Improve and restore the functionality of the WTPs and WWTPs. Resume regular water quality monitoring protocols as required by law. Decentralised water treatment units at potential sources of pollution; e.g. industries, etc. Implement measures to curb sediment delivery (linked to metal elements entering streams) into the river channel: • Develop and implement catchment management strategies, in collaboration with cultural leaders, to address overgrazing in the upper reaches of the catchment. • Training staff from local institutions and community members to conduct regular citizen monitoring.

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
		dilution of pollution, the increase in dry spells may worsen and concentrate the toxicity of river water.	
Faecal coliform bacteria and *E. coli* concentrations exceeding recommended guidelines by up to 1 700 times in the lower part of the catchment	Waterborne diseases Aesthetic effects; e.g. bad odours Reduced recreational and cultural uses of streams	Warmer and wetter conditions have been shown to increase the prevalence of waterborne diseases. Poorer households are forced to use untreated water from streams during drought periods, which may become more frequent in the future.	Improve access to safe and clean water for all households. Awareness campaigns to educate communities about the dangers of using water directly from streams and education on easy ways of purifying water before use; e.g. boiling water before use, bleach, etc. Restore riparian zones; macrophytes such as sedges and reeds improve water quality.
Dumping of solid waste into river channels, including used diapers and sanitary pads	Public health and environmental threat due to toxic chemical pollution Bacterial/microbial contamination of water sources due to disposable diapers dumped in rural and urban sections of rivers Attraction of flies and other pest species	Higher frequencies of floods and more intense rainfall events will wash waste downstream, which can cause blockages.	Improved waste removal by the Maluti-a-Phofung Local Municipality; e.g. regular refuse removal and the provision of refuse bags and bins in informal areas. Campaigns to raise community awareness, especially among communities close to rivers. Dedicated effort to educate school children about the negative health and environmental impacts of solid waste disposal. Develop partnerships between the UFS, the DWS, the Maluti-a-Phofung Local Municipality, and schools to establish “clean river” clubs at local schools to teach learners about the advantages of restoring and maintaining river health (using tools such as Mini-Sass, citizen monitoring, etc.). Appoint residents as waste disposal monitors around important areas. Create jobs in waste removal and waste recycling.

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
	Source of microplastic pollution Potential groundwater pollution Decomposition of organic waste releases methane Inhibiting other recreational, cultural, and religious uses of rivers		Ensure waste workers have protective gear (e.g. rubber boots, gloves, etc.) to remove diapers from stream courses. Liaise with companies that produce disposable diapers and sanitary pads to assist with finding solutions to the problem.
Poor performance of WWTPs	WWTPs in QwaQwa are in a critical state – no data are available according to the 2022 Green Drop report. (Efficiency decreased drastically from 2013 to 2022) Wastewater and untreated sewage flow directly into streams and rivers	High water temperatures could have a negative impact on the effectivity of WWTPs; e.g. leading to a deterioration of quality of bacterial floc, increasing the TSS of effluent, etc.	Dedicated effort and political will to improve WWTPs' operations. Train WWTP staff through collaboration between the UFS, DWS, and Maluti-a-Phofung Local Municipality. Implement continuous river monitoring systems to provide real-time data on the effectivity of water treatment processes.

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
	Human health and environmental impacts (see Appendix B)		
Poor delivery of water-related services			
Households without access to clean water and sanitation	Using water from streams for domestic use Health-related impacts due to using untreated water	Poorer households are forced to use untreated water from streams during drought periods, which may become more frequent in the future.	Improve access to safe and clean water for all households. Rainwater harvesting and drilling boreholes for rural communities. Awareness campaigns to educate communities about the dangers of using water directly from streams and education on easy ways of purifying water before use; e.g. boiling water before use, bleach, etc.
Habitat alteration / largely modified instream habitats			
Loss of critical aquatic habitat types and diversity due to siltation	Loss of species linked to specific habitat types; e.g. riffles Lower primary production influences food sources for macroinvertebrate, fish, and other aquatic species Negative impact of fish recruitment due to loss of spawning habitats and smothering of fish eggs and larvae	Higher rainfall and runoff in upper and middle quinaries could increase sediment delivery to rivers. Higher streamflows could help to flush streams.	Implement measures to curb sediment delivery (linked to metal elements entering streams) into the river channel: • Develop and implement catchment management strategies, in collaboration with cultural leaders, to address overgrazing in upper reaches of the catchment. • Enforce existing legislation to curb the growth in unlawful and unlicensed sand mining in the riparian zones of streams. Restore and protect riparian vegetation to reduce the flow of water in the river channel. Restore and protect wetlands in the upper and middle quinaries of the catchment to reduce the frequency and magnitude of floods.

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
Flow modification due to dam walls high up in the catchment	Loss of longitudinal processes in the streams; e.g. nutrient cycling and downstream movement of sediment Loss of surface water connectivity downstream of the dam, which changes a perennial stream to a non-perennial stream Loss of seasonal flows and ecological cues from the river downstream of the dam wall	Intensification of impacts during droughts when flow releases from the dam are less likely; e.g. loss of pool habitat due to lack of surface flow and evaporation may lead to extirpation of aquatic species. Deterioration of water quality in isolated pools remaining in the river channel. Loss of sensitive species and domination of more tolerant species.	Release of ecological flows from the dams in the upper sections of the Metsi-Matso and Namahadi rivers.
Destruction of riparian habitat along the rivers	Loss of habitat for species associated with riparian vegetation Increased delivery of sediment into the river channel Increase in water temperature due to loss of shade Loss of stability of river banks Deterioration of water quality Trampling of river banks due to watering of cattle and small stock at rivers	Riparian areas absorb and dissipate water energy during floods. Degraded riparian zones could result in increased flow speed and volume in the river, as well as erosion and sediment delivery into the channel. During dry periods, degraded riparian areas could result in warmer water, increased loss of soil moisture from river banks, etc.	Implement buffer zones along the streams to protect riparian zones. Develop river restoration projects in critical areas, such as the upper reaches of impacted streams in collaboration with relevant tribal authorities and, for example, Working for Wetlands. Link environmental quality to ecotourism; e.g. create incentives for lodges, especially in the upper parts of the catchment, to improve their operations (e.g. improve wastewater treatment).
Extensive erosion and removal of vegetation due to overgrazing in the catchment	Increased sediment delivery into the river channel	The projected increase in the volume and intensity of rainfall could further increase catchment and channel erosion, as well as runoff, sediment delivery, and turbidity.	Community engagement with tribal authorities. Restoration of areas with serious erosion gullies.

Risks identified	Potential impact	How the impact can be exacerbated/alleviated by climate change	Proposed risk reduction strategy
Encroachment of alien vegetation into the riparian and instream habitats of rivers	Black wattle trees grow fast and are highly invasive. These trees are water thirsty and have been shown to reduce streamflow in rivers	During droughts black wattles can further reduce streamflow/water volume in streams and rivers.	Removal of invasive trees from the river banks, especially in the upper catchments. Investigate the viability of community-based wattle removal.

CHAPTER 8: CONCLUSIONS, LESSONS LEARNED, AND RECOMMENDATIONS FOR FUTURE RESEARCH AND MANAGEMENT

8.1 INTRODUCTION

This study set out to develop an understanding of how the cumulative impacts of extreme weather events may affect the vulnerability of local communities in QwaQwa and how these impacts may be ameliorated through DRR and resilience building. To fully comprehend the extent and impact of climate-related risks in QwaQwa, a downscaled climate and hydrological model was developed for the catchment, an ecological risk assessment was conducted at nine representative sampling sites on the Namahadi, Metsi-Matso, Mphukojwane, and Elands rivers, and a disaster risk analysis was performed. The findings from the three components were used to develop a tailor-made DRR framework that addresses the specific hazards, exposures, and vulnerabilities of local communities in the study area. The strategies that were developed specifically address the improvement of policy and political issues, local community empowerment, DRR and climate change adaptation, and resilience building in the face of climate-related hazards. The study followed a systems thinking approach to recommend strategies that are interrelated and interconnected. Recommendations were also made for further research to build on and improve this project, and for the replicability of similar studies in other communities in South Africa. The innovative approach of assessing community assets, instead of community vulnerability to extreme climate change events, stands out in this study. The addition of a downscaled climate and hydrological model and an ecological risk assessment to the conventional disaster risk assessment methodology make this study unique.

8.2 CONCLUSIONS

8.2.1 Climate and hydrological modelling

A climate and hydrological model was developed to provide appropriate and reliable downscaled information for QwaQwa.

Climate projections indicate a warming trend for QwaQwa in the immediate and distant future, especially for the lower-lying area of the catchment where Phuthaditjhaba is situated. The mean daily minimum and maximum temperatures are expected to increase by approximately 1.5°C by the mid-2030s, and by more than 4°C by the 2070s. The number of frost days is projected to decrease by more than 40% in the higher-lying parts of the catchment, and by more than 70% in the lower-lying areas. Mean annual evaporation in QwaQwa could increase by 7% in the near future, and by more than 20% in the distant future.

QwaQwa is projected to experience higher rainfall during the rainy season (summer), but relatively less rainfall during the dry season (winter). Rainfall increases will, however, not occur uniformly over the catchment. The projections show that the greatest changes in mean annual rainfall will occur in the mountainous headwater areas, which could receive 30 to 40 mm more rain (a 4% increase from the present) in the near future, and between 140 mm and 185 mm more (a 20% increase from the present) in the distant future. Rainfall increases could be lower during dry years and higher during wet years. Dry spells are projected to increase in the immediate future, while wet spells could decrease. This impact could be more pronounced in the higher-rainfall upper parts of the catchments than in the slightly drier lowland areas.

The hydrological model indicates that the bulk of the runoff in the catchment is generated on the mountain slopes, with these areas producing nearly three times more runoff, on average per year, than the lowland areas. The highest runoff generally occurs in January (summer), while August and September (winter) have the lowest runoff. The MAR in the catchment is projected to increase by approximately 7% in the highlands and 15% in the lowlands in the near future. In the distant future, runoff could increase by 36% in the highlands and by nearly 70% in the lowlands. Stormflows in the catchment generally occur in summer (rainfall season), when they contribute approximately 70% to runoff. Stormflows are projected to increase by between 13% and 21% annually, with the greatest changes expected for the highland areas. The percentage increase in baseflows, which are the major contributors to total runoff during the dry winter season, are projected to be higher in the lowlands than in the highlands.

Accumulated streamflows are projected to increase in the future, although the increases are not expected to occur uniformly over the catchment. The accumulated streamflows vary greatly between the 19 sub-catchments, depending on the size and rainfall of the sub-catchments. Peak discharges in the catchment generally occur in late summer (February) after thunderstorm activity. The projections indicate that peak discharges could increase in the immediate future (2040s), with the most downstream sub-section of the catchment (lower Elands River) being at risk of flooding in the future.

8.2.2 Ecological risk assessment

The ecological risk assessment collected data on physical and chemical water quality, ecotoxicology, and river health. The aim of these assessments was to identify potential hazards to human and environmental health associated with extreme weather events in the study area.

The negative impacts of current anthropogenic activities on the rivers and streams were clear. The results showed that the upper reaches of the rivers, situated predominantly in the more rural and less densely populated areas, were less impacted than the middle and lower reaches, which were situated in the urban and more densely populated parts of the catchment.

Water quality in general deteriorated from upstream to downstream, with the water at the most downstream sites on the Elands River being hypertrophic, acutely toxic, and having high levels of manganese, iron, and a range of emergent pollutants such as dioxins, caffeine, pharmaceuticals, and herbicides. The presence of faecal coliform bacteria, used as an indicator of faecal pollution of surface waters, also increased from upstream to downstream in the catchment. Faecal coliform bacteria concentrations were unacceptably high in the lower Namahadi, middle Mphukojwane, and the Elands rivers, where concentrations far exceeded the recommended TWQR set by the DWS by 1 700 times.

This study was the first to detect and confirm the presence of OMPs such as sulfamethoxazole, BP-4, ibuprofen, carbamazepine, atenolol, nevirapine, efavirenz (or its metabolite 8-OH-efavirenz), and the classical indicator of human impact, caffeine, in the catchment. The data showed that the lower Mphukojwane and the Elands rivers were the most affected, with the substances being present in the low to medium range. This study was also the first to conduct a series of in vitro biotests in the catchment. These tests indicated elevated estrogenic activity in the middle Mphukojwane and Elands rivers, as well as highly increased activity of the aryl-hydrocarbon in the Elands River, which can induce inflammatory responses upon exposure and may lead to chronic inflammatory diseases, including asthma, cardiovascular diseases, and increased cancer risk.

The ecotoxicological investigation found the river sediment in the Metsi-Matso, Namahadi, and Elands rivers to be contaminated with chromium above the recommended prohibition level. The Elands River was the most polluted, with chromium and zinc concentrations exceeding the recommended thresholds. A number of metals (aluminium, iron, manganese, copper, and zinc) were detected at elevated concentrations in the water samples. The Mphukojwane, lower Namahadi, and Elands rivers were the most impacted, with concentrations of aluminium and iron exceeding the TWQRs for both domestic use and aquatic ecosystems at these sites. Acute toxicity tests found that toxicity increased from upstream to downstream, with the sites in the middle and lower reaches being more toxic than those in the upper reaches. There is concern about the water of the Mphukojwane River, with the upper site being classified as having high acute toxicity (Class IV) and the middle site as having very high acute toxicity (Class V).

Riparian and instream habitats were moderately to seriously modified from their natural state. The scores for instream HI and fish assemblages were lower than the numerical limits set by the RQOs (as published in the *Government Gazette* in 2016) for the catchment at all the sites, except for the upper and middle Namahadi reaches. Of particular concern is the severe flow modification in the upper Metsi-Matso due to the lack of environmental flows being released from the Metsi-Matso Dam, severe infestation of black wattle trees in the upper Namahadi, and severe erosion and solid waste disposal in the upper Mphukojwane. Also concerning is the apparent rapid expansion of unlicensed sand mining (mostly for building and brick making) in the instream and riparian zones of streams and rivers in the catchment.

8.2.3 Disaster risk analysis

The disaster risk analysis comprised four sub-components: hazard analysis (hazard identification, probability, frequency, and intensity); exposure analysis of key elements; vulnerability or resilience analysis, using the CCF approach; and calculation of the MHRI.

The hazard analysis identified four hazards that posed a high risk to communities in QwaQwa, namely water scarcity, drought, floods, and wildfires. All these highly ranked hazards were climate related, which indicates the importance of addressing climate change impacts and climate change-related risks.

The exposure analysis showed that the overall rating of exposure to the identified hazards was high. It highlighted the fact that communities in QwaQwa have very high exposure to water scarcity, and high exposure to the other three hazards (drought, floods, and wildfires). Most of the elements analysed showed high exposure to all the hazards, while population and land use showed very high exposure to water scarcity. Water sources showed very high exposure to wildfires.

The Resilience Index value calculated for QwaQwa was low, which indicates that QwaQwa communities would struggle to recover from the impacts of extreme weather events and climate shocks. This result emphasises the importance of strengthening resilience in the area by investing in available resources to reduce disaster risk related to climate change hazards and impacts.

The MHRI score was high, which indicates that the overall risk to the combination of climate-related hazards identified for QwaQwa was high.

This study took a different approach to traditional vulnerability analyses by using the CCF. The CCF differs from traditional approaches by identifying a community's unique strengths and using those to empower communities. For QwaQwa, social and natural capitals were identified as potential strengths that could be employed to improve resilience to climate-related hazards.

8.2.4 DRR strategies

A DRR strategy was developed for QwaQwa based on the projected climate and hydrological changes and the findings from the ecological risk assessment and disaster risk analysis. The proposed strategies focused on four areas, namely policy recommendations, recommendations for the empowerment of the local communities, recommendations for DRR and climate adaptation, and recommendations for reducing the risks related to water scarcity (water quantity and quality) and river health.

8.3 LESSONS LEARNED

In terms of the climate and hydrological modelling, the following lessons were learned:

- Land use has been shown to play a significant role in hydrological responses in QwaQwa at the local level; e.g. in streamflows, sediment yields, and especially in peak discharges. Such impacts become muted as catchment size increases. This shows clearly that conducting meaningful hydrological impact studies at quaternary, and even at quinary spatial resolution, identifies little to very little impact of a specific land use. The sub-delineation of quinaries into six land uses / management-based HRUs is seen as a major step forward to meaningful land use impact studies in the South African context.
- Impacts of climate change have much more regional impacts. It is only once climate change impacts are superimposed onto land use impacts that such studies become hydrologically meaningful.
- The hydrological analysis of the impacts of actual land uses such as bare/eroded areas or formal or informal urbanisation, when compared with the natural vegetation they replace, indicates:

  - that the real hydrological impacts of specific land uses need to be determined at the local level; i.e. in situ, at the scale where the actual replacement of a land use takes place; and
  - that on the sub-catchment scale, and even more so at quinary or quaternary resolution, the impacts of individual land uses can become highly muted.
- Local hydrological impacts can be quite dissimilar from one sub-catchment to the next, even within the same study area, depending on the degree/intensity of the specific land use, as well as the local geographical and hydrological characteristics of the natural vegetation they replace, such as soil depth and texture, slope, rainfall interception, and seasonal growth patterns, as well as the surface and aerial characteristics of the vegetation.

8.4 RECOMMENDATIONS FOR FURTHER RESEARCH

The following recommendations are made for future research based on the experience gained during this project.

8.4.1 Climate and hydrological modelling

- Sustained station observation networks are essential for the long-term analysis of local and regional climate trends, as well as for the calibration of satellite-derived climate products. The installation of local weather stations at various altitudes in different parts of the catchment would greatly contribute to future studies.
- Although the water releases from the Fika-Patso Dam are monitored, it does not reflect the "natural" or "uncontrolled" flow in the catchment. Considering the important contribution of streams in the catchment to the Wilge River (via the Elands River), and ultimately to the Vaal River, the installation of streamflow gauging stations in the catchment should be considered.

8.4.2 Ecological risk assessment

- Information on the aquatic ecology of the streams is sparse, fragmented, and uncoordinated. In light of the projected climate and hydrological changes for the catchment, it is clear that there is a dire need for a coordinated and comprehensive ecological assessment of the streams.
- The RQOs gazetted for the Elands River catchment (RSA, 2016) are largely lacking for river water quality. The only category for which numerical limits are available is for nutrients (phosphate, nitrite, and nitrate), most probably due to a lack of information for the other categories (e.g. salts, system variables, toxins, and pathogens). The results from this study highlight the urgent need for setting numerical limits for the other classes and for conducting regular water quality monitoring, especially in the Namahadi, Mphukojwane, and Elands rivers.
- This study found that the RQOs set for the river instream habitats (Category C or higher) are not achieved for most of the middle and lower sites. Particularly concerning is the marked increased in illegal sand mining over the course of this study. This is a serious matter that requires urgent intervention by the relevant authorities, as well as further investigation.

8.4.3 Disaster risk analysis and reduction

- Stage 3 and 4 of the UNDRR (2016) risk assessment process, including monitoring and evaluation, ought to be commissioned in another research project by the WRC.
- That further, and more in-depth, research be conducted on the 17 hazards identified for QwaQwa, but not only on those related to extreme climate change events, since risks are integrated and systematic, with cascading and compounding effects.
- That the approach developed and applied in this study be tested on other climate hotspots; for example, Nelson Mandela Bay District Municipality in the Eastern Cape or eThekwini in KwaZulu-Natal.

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APPENDIX A: PHOTOGRAPHS OF THE NINE SAMPLING SITES ON THE NAMAHADI, METSI-MATSO, MPHUKOJWANE, AND ELANDS RIVERS

Plate 1: Namahadi River

Namahadi Upper site	**Namahadi Middle site**

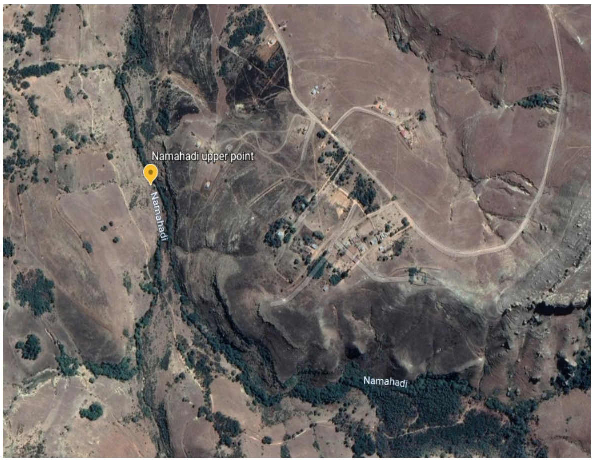

Photo 1: Namahadi Upper: Google Earth image (4.39 km)

Photo 2: Namahadi Middle: Google Earth image (4.1 km)

Photo 3: Namahadi Upper: Upstream view

Photo 4: Namahadi Middle: Upstream view

Photo 5: Namahadi Upper: Downstream view

Photo 6: Namahadi Middle: Downstream view

Plate 2: Namahadi River

Namahadi Lower site

Photo 1: Namahadi Lower: Google Earth image (8.12 km)

Photo 2: Namahadi Lower: Upstream view

Photo 3: Namahadi Lower: Downstream view

Plate 3: Metsi-Matso River

Metsi-Matso Upper site	Metsi-Matso Middle site

Photo 1: Metsi-Matso Upper: Google Earth image (6.6 km)

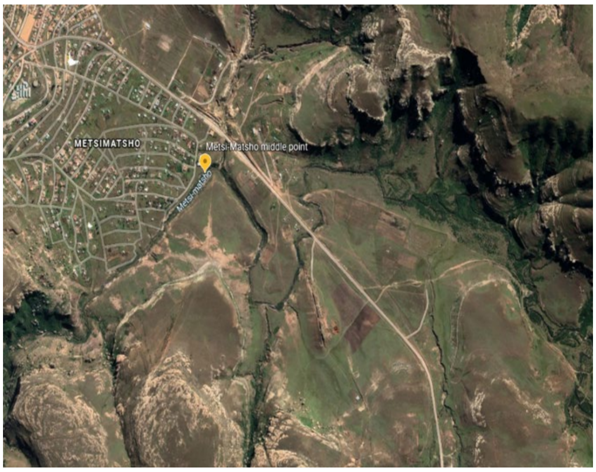

Photo 2: Metsi-Matso Middle: Google Earth image (6.26 km)

Photo 3: Metsi-Matso Upper: Upstream view

Photo 4: Metsi-Matso Middle: Upstream view

Photo 5: Metsi-Matso Upper: Downstream view

Photo 6: Metsi-Matso Middle: Downstream view

Plate 4: Mphukojwane River

Mphukojwane Upper site	**Mphukojwane Middle site**

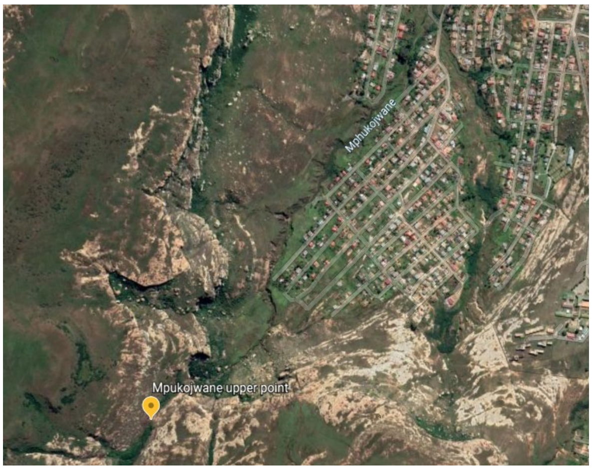

Photo 1: Mphukojwane Upper: Google Earth image (3.9 km)

Photo 2: Mphukojwane Middle: Google Earth image (3.2 km)

Photo 3: Mphukojwane Upper: Upstream view

Photo 4: Mphukojwane Middle: Upstream view

Photo 5: Mphukojwane Upper: Downstream view

Photo 6: Mphukojwane Middle: Downstream view

Plate 5: Elands River

Elands Upper site	Elands Lower site
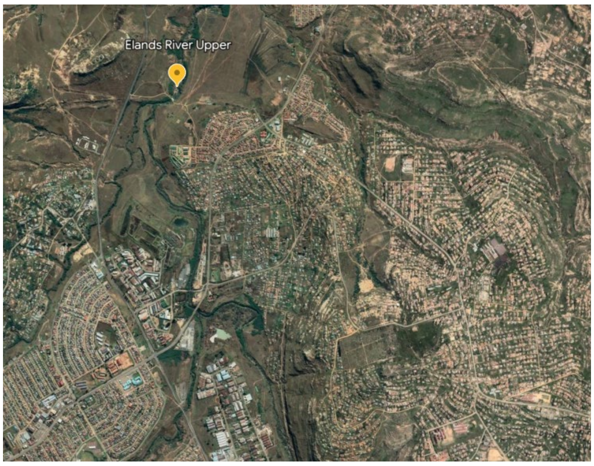	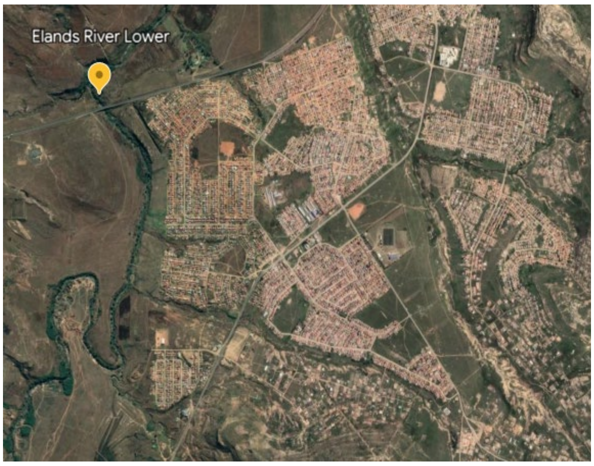
Photo 1: Elands Upper: Google Earth image (11.79 km)	Photo 2: Elands Lower: Google Earth image (9.68 km)
	
Photo 3: Elands Upper: Upstream view	Photo 4: Elands Lower: Upstream view
	
Photo 5: Elands Upper: Downstream view	Photo 6: Elands Lower: Downstream view

APPENDIX B: LIST OF POTENTIAL POLLUTANTS, POTENTIAL SOURCES, AND ASSOCIATED RISKS

Micropollutants	Potential source(s)	Potential risk/effect
Acetochlor	• Herbicide for weed control	• Potential health effects to humans and aquatic biota at high concentrations
Atenolol	• Pharmaceutical	• Ecotoxicology test indicates toxicity to aquatic biota • Atenolol is water soluble and shows rapid degradation in and aquatic environment
Atrazine	• Herbicide for weed control	• Chronic exposure may increase cancer risk • Consider in combination with pH and microbial activity
BPA	• Industrial chemical • WWTP effluent	• Potential endocrine disruptor • Very low acute toxicity for humans • Considered to be an environmental contaminant of emerging concern for a wide range of wildlife, especially aquatic invertebrates and amphibians
Benzophenone	• Industrial chemical ultraviolet (UV) blocker, photo initiator, packaging, etc.)	• Potential negative impact on reproduction of some aquatic organisms
BP-4	• UV filter • WWTP effluent; water recreation	• Potential negative impact on the reproduction of some aquatic organisms
Caffeine	• WWTP effluent • Untreated sewage	• Could be seen as an indicator of untreated sewage • Environmental contaminant – residues are detrimental to aquatic organisms
Carbamazepine	• Pharmaceutical • WWTP effluent	• Persistent contaminant in the environment • Potential impact on embryonic and larval development of fish
DEET	• Insect repellent	• Slightly toxic to birds, fish, and aquatic invertebrates
Diclofenac	• Veterinary pharmaceutical • WWTP effluent	• Average toxicity and high environmental risk • Synergistic effects between diclofenac and sulfamethoxazole
Efavirenz	• Pharmaceutical • WWTP effluent	• Persistent environmental contaminant
Fipronil	• Insecticide	• Highly toxic to fish and aquatic invertebrates
Ibuprofen	• Pharmaceutical • WWTP effluent	• Environmental contaminant toxic to a range of aquatic organisms, influencing, for example, fish reproduction • Metabolites from ibuprofen are more toxic than the parent molecule
Nevirapine	• Pharmaceutical • WWTP effluent	• Persistent environmental contaminant • Potential human health effects • Potential effect on growth of juvenile fish
Sulfamethoxazole	• Pharmaceutical • WWTP effluent	• Low toxicity with low environmental risk • Synergistic effects between diclofenac and sulfamethoxazole

Metal elements	Potential source(s)	Potential risk/effect
Al	• Silicates of Al naturally widespread • Runoff from catchment • Present in water as suspended Al minerals / dissolved Al species • Sewage/WWTPs – Al phosphate is present in sewage • Industrial waste	• Chronic health issues at high concentrations • Consider in combination with pH and fluoride concentration
Cr	• Cr(VI) is highly soluble and mobile in the environment; can move though soil profile into groundwater • Industrial processes (e.g. paints, dyes, metal pickling, ceramics, etc.)	• Long-term exposure increases risk of cancer • Evidence of carcinogenic effects via the oral route
Cu	• Runoff from catchment	• Generally no health effects, but high concentrations may cause gastrointestinal irritation
Fe	• Naturally abundant	• Chronic health effects only at high concentrations • Consider in combination with pH, redox potential, turbidity, suspended matter, Al concentration, and Mn
Mn	• Naturally abundant • Industrial processes	• Health effects only at high concentrations • Consider in combination with pH, redox potential, turbidity, suspended matter, and Al concentration
Zn	• Runoff from catchment • Industrial processes	• Fish highly susceptible to Zn poisoning
In vitro tests	**Potential source(s)**	**Potential risk/effect**
YES (Yeast estrogen screen)	• Birth control pills and other medication in wastewater • Natural oestrogens from soy and dairy products, as well as animal waste	• Estrogen is an endocrine disruptor with potential adverse effects on humans and aquatic biota; e.g. fish
YDS (Arxula-Yeast Dioxin test)	• Industrial processes • Incineration of municipal waste • Leaching from landfills • Stormwater runoff	• Dioxins are highly toxic; may cause reproductive and developmental problems, interfere with immune system and hormones, and are carcinogenic • Negative health impact on aquatic biota; e.g. in fish it may cause skin lesions and altered liver function • Bio-accumulation in aquatic biota – trophic transfer in food web

Water quality	Potential source(s)	Potential risk/effect
Sulphates	• Naturally present in water, soil, and rocks • Industrial processes	• Human health effects; e.g. diarrhoea
Chloride	• Anion of chlorine	• Accelerate corrosions rate in metals • High concentrations may be detrimental to the health of babies
Nitrates	• Naturally present in water and soil • Oxidation of organic material • Effluent from WWTPs • Agricultural and urban runoff	• Increased algal growth and blooms • Uptake of nitrates by plants regulated by temperature and pH • Human health effects
Faecal coliforms and *E. coli*	• Faeces from humans and animals • Untreated sewage	• Waterborne diseases; e.g. diarrhoea • Organic pollution – decomposition depletes oxygen in water • Aesthetic effects; e.g. bad odours • Reduces recreational and cultural uses of streams

Source: Adeola and Forbes (2022); Arnold *et al.* (2013); Arslan *et al.* (2017); Asadgol *et al.* (2019); Batucan *et al.* (2021); Chopra and Kumar (2020); Clara *et al.* (2004); Drzymala and Kalka (2020); Du *et al.* (2017); Joachim *et al.* (2021); Krahnstöver *et al.* (2022); Li *et al.* (2020); Ndlovu and Naidoo (2022); Nibamureke *et al.* (2019); Owen (2017); She *et al.* (2016); Van Vuren *et al.* (1994)

APPENDIX C: RESULTS FROM THE PHYSICO-CHEMICAL, ECOTOXICOLOGICAL AND RIVER HEALTH ASSESSMENTS OF THE NINE SAMPLING SITES ON THE NAMAHADI, METSI-MATSO, MPHUKOJWANE, AND ELANDS RIVERS

Site	ELL	ELU	MPM	MPU	NL	NM	NU	MM	MU
Selected physical and chemical water quality parameters									
System variables (March 2022)									
Temp. (°C)	17.6	16.9	20.4	17.6	21.1	18.5	17.2	22.3	19.8
EC (mS/cm)	179.0	237.0	477.0	201.0	90.6	76.5	61	83.0	16.0
pH	7.7	7.6	6.9	8.4	7.6	7.2	7.8	6.8	6.9
COD	25.2	34.1	28.2	19.8	16.8	19.65	16.2	23.3	19.9
TOC	38.0	40.5	46.5	35.5	31.0	32.5	32.5	37.5	30
DOC (mg/L)	3.22	5.77	5.1	1.58	1.46	2.18	0.81	1.59	1.73
SAC_{254} (1/m)	12.02	18.32	14.4	5.79	4.19	8.96	2.47	5.6	5.00
Nutrients and anions (March 2022)									
Phosphate (mg/L)	1.33	0.28	0.28	0.84	0.42	0.31	0.78	0.28	0.3
Carbonate (mg/L)	5.0	4.8	4.55	4.6	5.5	5.15	5.15	5.25	5.3
Chloride (mg/L)	12.7	18.2	41.2	0.85	2.95	5.65	0.95	1.0	0.9
Fluoride (mg/L)	0.055	0.076	0.074	0.058	0.031	0.035	<0.020	<0.020	<0.020
Chloride (mg/L)	12.70	18.20	41.20	0.85	2.95	5.65	0.95	1.00	0.85
Nitrate (mg/L)	25.4	31.7	25.9	25.3	23.6	30.8	43.6	25.9	25.9
Nitrite (mg/L)	<0.02	<0.02	0.037	<0.02	<0.02	<0.02	<0.02	<0.02	<0.003
Bromide (mg/L)	0.046	0.061	0.092	0.026	0.029	0.037	<0.026	0.028	0.026
Sulphate (mg/L)	12.05	18.37	39.4	9.15	4.83	5.58	3.01	2.21	1.44
Total phosphorus (mg/L)	1.33	0.28	0.28	0.84	0.42	0.31	0.78	0.28	0.28
Soluble reactive phosphorous (mg/L)	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007
Metal elements									
Al		0.148	0.194	0.172	0.169	0.105	-	-	
As		0.001	-	-	0.001	-	-	-	
Ca		26	23	20	18	16	8	7	
Cu		-	0.004	0.002	0.001	-	0.006	0.002	
Mg		9	7	10	8	6	3	3	
Mn		0.610	0.124	0.032	-	0.044	-	-	
Fe		2.140	0.491	0.295	0.462	0.320	0.063	0.428	
Zn		0.026	0.036	0.028	0.027	0.024	0.030	0.023	
Microbial data									
Faecal coliform bacteria (MPN/100 ml)		34 000	340	42	220	39	9	48	
E. coli (MPN/100 ml)		21 000	240	37	190	35	9	46	

	ELL	ELU	MPM	MPU	NL	NM	NU	MM	MU
OMPs									
BP (ng/L)	20	22	22	27	18	18	15	14	10
BP-4 (ng/L)	199	257	262	<10	<10	14	<10	<10	<10
Ibuprofen (ng/L)	71	90	29	<10	<10	<10	<10	<10	<10
BPA (ng/L)	68	<10	<10	<10	<10	<10	<10	<10	<10
Diclofenac (ng/L)	63	56	66	68	65	71	77	62	75
Fipronil (ng/L)	<10	45	<10	<10	<10	<10	<10	<10	<10
DEET (ng/L)	<10	11	<10	23	<10	<10	18	<10	<10
Caffeine (ng/L)	173	217	133	39	34	22	47	68	22
Carbamazepine (ng/L)	38	50	142	<10	<10	<10	<10	<10	<10
Sulfamethoxazole (ng/L)	62	60	97	<10	14	25	<10	<10	<10
Atenolol (ng/L)	20	30	18	<10	<10	<10	<10	<10	<10
Acetochlor (ng/L)	404	<10	<10	<10	<10	<10	<10	<10	<10
8-OH-efavirenz (ng/L)	135	195	125	<10	<10	<10	<10	<10	<10
Efavirenz (ng/L)	126	100	177	<10	<10	<10	<10	<10	<10
Nevirapine (ng/L)	10	<10	29	<10	<10	<10	<10	<10	<10
Atrazine (ng/L)	<10	<10	<10	<10	<10	<10	<10	<10	<10

	ELL	ELU	MPM	MPU	NL	NM	NU	MM	MU
Ecotoxicological tests									
Toxicity of river water									
P. subcapitata (LC50)	146.6	N/A	34.0	ND	ND	N/A	ND	ND	ND
D. magna	80.0	80.0	80.0	80.0	80.0	80.0	30.0	90.0	30.0
T. thermophila	13.2	13.9	31.5	31.1	31.2	100	33.8	34.5	27.8
Class score	51.1	47.0	47.0	55.6	55.6	90.0	13.9	62.3	28.9
Percentage effect	63.9	58.8	58.8	69.5	69.5	90.0	41.1	69.2	96.0
Toxicity class	III	III	III	III	III	IV	II	III	III
In vitro tests									
LOQ YES in ng $E \cdot L^{-1}$	-	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
LOQ YAES in µg OHT L^{-1}	-	5180	5180	5180	5180	5180	5180	5180	5180
LOQ YAS ng $T \cdot L^{-1}$	-	3	3	3	3	3	3	3	3
YAAS µg $Flu \cdot L^{-1}$	-	173	173	173	173	173	173	173	173
YDS µg ß-$NF \cdot L^{-1}$	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

	ELL	ELU	MPM	MPU	NL	NM	NU	MM	MU
River health									
HI Index score (%) (Integrity category)		42.0 (D)	52.0 (D)	60.0 (C)	35.0 (E)	64.0 (C)	63.0 (C)	59.0 (D)	35.0 (E)
Riparian HI score (%) (Integrity category)		45.0 (D)	43.0 (D)	61.0 (C)	28.0 (E)	55.0 (D)	65.0 (C)	55.0 (D)	40.0 (D)
FRAI score (%) (Present ecological status category)		9.8 (F)	51.9 (D)	51.9 (D)	61.9 (C/D)	62.7 (C)	73.8 (C)	57.5 (C/D)	

APPENDIX D: PHOTOGRAPHS OF PROMINENT ANTHROPOGENIC IMPACTS ON THE INSTREAM AND RIPARIAN ZONES AT THE SAMPLING SITES AS OBSERVED DURING THE APRIL 2021 FIELD VISIT

Instream and riparian impacts

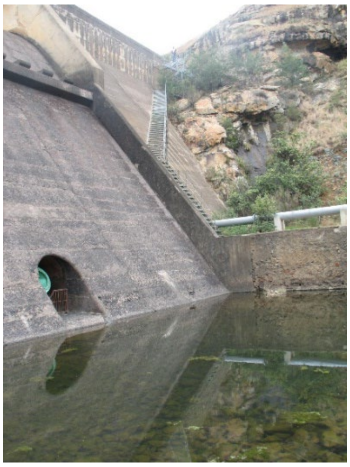

Photo 1: Dam wall at the Upper Metsi-Matso causing serious modification to flow regime

Photo 2: River bank erosion at Metsi-Matso Middle

Photo 3: Exotic black wattle trees at Upper Namahadi

Photo 4: River sand mining at Namahadi Middle (right bank)

Photo 5: Road bridge at Namahadi Middle

Photo 6: Solid waste disposal (diapers) at Mphukojwane Upper

Instream and riparian impacts

Photo 7: Bank erosion at Mphukojwane Upper

Photo 8: Exotic vegetation encroachment into the channel, Mphukojwane Middle

Photo 9: Exotic vegetation encroachment into the channel, Mphukojwane Middle

Photo 10: Solid waste disposal upstream of Mphukojwane Middle

Photo 11: Road bridge at Elands Lower

Photo 12: Exotic willow trees at Elands Lower