HYDROLOGICAL MODELLING OF CLIMATE CHANGE IMPACTS FOR DEVELOPMENT OF ADAPTATION STRATEGIES: THE CASE OF LUVUVHU RIVER CATCHMENT, LIMPOPO, SOUTH AFRICA

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

The Limpopo basin is a semi-arid region of South Africa where rainfall patterns are highly variable, unpredictable and unreliable. The effects of the remote El Nino phenomenon in the equatorial Pacific Ocean are significant in the northeast of South Africa resulting in frequent drought. In all South Africa, this region is the most vulnerable to land falling tropical cyclones from the southwest Indian Ocean and the Mozambique Channel. Several modelling studies have found a significant future climate change signal in Limpopo. Whilst rainfall is enhanced in the upper Luvuvhu River Catchment due to orographic effects, a key question is whether this pattern will be altered under climate change.

One of the major challenges with climate change is its impact on water resources and extreme hydrological events. Extreme events such as droughts and floods, significantly affect important sectors such as agriculture, energy, water resources, among others. Variations in catchment water flows are expected to alter water availability for irrigated agriculture, flow availability for dam water supplies, or for water harvesting and storage. There is a need to determine the effects of climate change on water resources to predict the potential impacts on agriculture and domestic/municipal water use. Adaptive responses that reduce vulnerability to current, as well as future climate variability and change, are critical in the context of South Africa's urgent socio-economic developmental needs and threatened ecosystem services.

RATIONALE

Climate variability and change are likely to affect efforts targeted at satisfying the increasing domestic demand and generating income to purchase food for the people, achieve poverty reduction and sustainable development strategies. Climate change is associated with increasing temperatures and alteration in the rainfall patterns resulting in changes in streamflow patterns, increased frequency and severity of climate extremes linked to frequent floods and droughts with severe impacts on soil, water and the plant environment affecting crop production and by extension human health and nutrition. In attempts to protect themselves from these adverse effects of climate change and variability, the affected communities confronted with problems of drought, poor yields or floods, amongst others, have never stopped trying to devise adaptation methods to mitigate impacts related to climate change.

Knowledge of existing adaptation options form the basis upon which practical methods can be identified and developed to protect the communities from adverse effects of climate change and hence reduce their vulnerability through integration of the indigenous knowledge and new techniques. Events associated with climate change, in most cases, take people by surprise as they are usually caught unaware. There are no systems put in place to predict changes that come with climate change. This study, therefore, addressed this problem by modelling alterations in the hydrological system associated with climate change to enable preparedness through the development of adaptation options. A hydrological modelling system that provides future climate change scenarios and predicts the impacts on water resource availability for agriculture and municipal/domestic use is, thus, essential as it will aid in the generation of long-term climate change adaptation options.

OBJECTIVES

The purpose of the study is to investigate the impact of future climate change scenarios on water availability for agricultural and municipal/domestic water uses and develop practical adaptation options for vulnerable communities in Luvuvhu River Catchment. The specific objectives are:

- To predict the effect of future climate change scenarios on water resource availability for agricultural production and domestic/municipal water uses in the catchment.
- To identify and assess adaptation measures for climate change used by communities in the catchment.
- To develop practical adaptation options for future climate change scenarios in consultation with key stakeholders.

METHODOLOGY

Time series analysis techniques were used to analyse the historical climate variability including long-term trends and cyclical patterns in the data. Future climate projections were investigated using regional climate models nested in global climate models from Coordinated Downscaling Experiment (CORDEX). Generally, at regional scales, future projections were mainly based on dynamic model applications that use laws of physics applied to the earth system with a set of complex partial differential equations. Dynamic Regional Climate Models (RCMs) from CORDEX were key in obtaining detailed projections of the climate in South Africa. They were applied at a very high resolution for regions of interest. This reasoning and understanding allowed for future projections using a combination of high-resolution RCMs from CORDEX and low-resolution CMIP5 GCMs.

However, for hydrological modelling, Conformal Cubic Atmospheric Model (CCAM) projections were used to drive the Soil and Water Assessment Tool (SWAT) hydrological model. CCAM projections at 8 km resolution are ideal for small catchments such as the Luvuvhu. The projections were based on both low mitigation (RCP8.5) and high mitigation (RCP4.5) greenhouse gas emission scenarios.

Historical data on rainfall, temperature, relative humidity, solar radiation and wind speed acquired from various rainfall stations were prepared in a format that suits the SWAT model input data requirement. Hydrological and meteorological data were collected from the Department of Water and Sanitation (DWS) and the South African Weather Service, respectively. During the model setup, the catchment was divided into sub-basins based on topography and drainage pattern and into hydrologic response units (HRU) based on unique combinations of soil and land use. The SWAT model was embedded into an ArcGIS interface making it able to handle large data sets in varied geographic scales. Near future (2021-2050) and far future (2051-2080) scenarios for streamflow were predicted based on the CCAM projections (hydrometeorological) obtained from CSIR. Water requirements for selected crops under changing climate conditions were estimated.

The sub-catchments that drain into Albasini and Nandoni Dams were delineated in ArcGIS to enable estimations of near and far future inflows into the dams. Annual cumulative monthly inflows for Albasini and Nandoni Dams were computed from monthly inflows for April of the previous year to March of the current year for the periods April 2021 to March 2050 (near future) and April 2051 to March 2080 (far future). A year was considered to be the period from April of the previous year to March of the current year to obtain the total inflows into the dam on the decision date (1 April of the current year) for reservoir operation (water allocation purposes). Regression analysis was conducted using the Data Analysis tool of Microsoft Excel to determine trends for near and far future cumulative annual inflows and their significance. The significance of each of the trends was tested at a significance level (α) of 0.05.

Water requirements for selected crops for three 10-year periods (2010-2019, 2050-2059 and 2090-2099) within Luvuvhu River Catchment were estimated based on temperature data from CCAM stations, crop coefficients (K_c), duration of different growth stages and estimated reference evapotranspiration (from Hargreaves equation). Projected future water requirements for some of the regional water supply schemes within Luvuvhu River Catchment were obtained from all towns' reconciliation strategies for northern region reports from DWS through the link www6.dwa.gov.za/DocPortal/. The projections were from 2007 to 2030.

Existing climate change adaptation options were reviewed to improve and/or integrate into a climate change adaptation plan developed in this study. Stakeholder consultation workshops were conducted for identifying implementable climate change adaptation options. The identified options were prioritised in consultation with the stakeholders using a multi-criteria decision analysis (MCDA) method within the CLIMACT Prio tool Excel Spreadsheet. MCDA allows for consideration of stakeholders' preferences in the scoring and weighting of criteria making it suitable for stakeholder engagement.

RESULTS AND DISCUSSION

Results of this study have shown significant changes to the present-day climate of the Luvuvhu River Catchment. Since about 2010, mean monthly surface air temperatures have been consistently higher than a 1981-2010 long-term mean with significant impacts on evaporation from exposed soils and surface water bodies. Because of high inter-annual variability, long-term rainfall trends were not statistically significant. However, the changes in the annual cycle are clear with a delay in the mean onset extending the dry season. The prolonged dry season has implications on fire regimes in grasslands in the drier lower catchment which is dominated by smallholder farmers. Climate change has exacerbated the impact of El Nino droughts, as El Nino itself evolves due to climate change.

There is high confidence amongst the models that mean and annual surface temperatures are projected to increase in the future, unlike trends in precipitation which are still less coherent. In the far future climate, the models distinctively projected drying elements over much of the interior of South Africa. The RCMs nested within MPI projected far drier conditions for the Western Cape and south coast for all seasons and in both periods considered. Over the north of South Africa parts, most of the models projected rainfall decreases. The study presented a detailed long-term mean annual and seasonal assessment of rainfall variability using a medium to low and high mitigation scenarios. They were presented on spatial maps. The CCAM projections for temperature and rainfall in the Luvuvhu River Catchment showed high degrees of variability for both near and far future scenarios. Most of the stations indicated that temperature and rainfall will increase and decrease respectively for near and far future. The temperatures are projected to increase by more than 2°C by the year 2076. The SWAT model could predict the peak flood event for the year 2000 in sub-basin 15 which did not have observed data during the flooding period. The annual cumulative inflows for near future for Albasini and Nandoni Dams had increasing linear trends while those of the far future had decreasing trends. Both trends were not statistically significant (p-values were greater than the significance level (α) of 0.05). The year-to-year variations in cumulative inflows indicated that there will be variability in inflows into the dams which will affect water resources availability and allocation.

The results indicated that there is a general increase in the crop water requirements for three selected crops (banana, maize and tomato) for the three 10-year periods (2010-2019, 2050-2059 and 2090-2099) that were analysed. This is related to the expected increase in future temperatures which will increase crop evapotranspiration. An increase in future water requirements for domestic use with time for both low and high population growth scenarios for most of the regional schemes was associated with population increase and/or planned improvement in water services. The future irrigation water requirements will put pressure on available water resources from Albasini Dam. This will be worsened by year-to-year variations of cumulative inflows. The decrease in rainfall in the future is also expected to reduce crop productivity in rainfed agriculture as the irrigation water requirements will increase. The study found that maize, which is a staple food for most of the communities in Luvuvhu River Catchment, had the highest range of changes in crop water requirements, implying food security will be threatened if the irrigation water requirements will not be met.

The future increase in domestic water requirements combined with the need to supplement Giyani regional and Matoks bulk water supply schemes is expected to put severe pressure on the Nandoni Dam system resulting to water supply deficit. Besides, water available for allocation in the study area will also be affected by the reduced capacity of the dams due to sedimentation, evaporation losses from the dams and the changes in downstream (ecological) water requirements. Luvuvhu River Catchment is susceptible to an increase in sedimentation due to the increase in agricultural areas and the clearing of natural forests. Climate change adaptation options were prioritised based on MCDA and the developed climate change adaptation plan were discussed with stakeholders in a feedback workshop. Water conservation and reduction of production space to maximise irrigation were therefore climate change adaptation options with highest scores and priority for implementation for both municipal/domestic and agricultural water use sectors, respectively. Discussions with farmers indicated that they are already implementing some of the adaptation options such as adjusting fertilisers, planting high yielding crop varieties and reducing soil erosion.

CONCLUSIONS

The rate of warming in Limpopo since the turn of the century is alarming with dire consequences on rural livelihoods and water supply. The warmer temperatures are compounding the intensity of extreme events such as heatwaves, droughts, and storms which may lead to flooding. The recent 2014-2016 El Nino-induced drought in the catchment and the February 2019 floods in Thohoyandou are unprecedented. This study has found a warming and drying signal into the far future over the Luvuvhu River catchment which is consistent with several other modelling studies. The rainfall projections are less robust than temperature projections even though they are consistent with global general trends of drying in the subtropics. There was not much comparison between raw Global Circulation Models (GCMs) and RCMs output to determine the greatest source of uncertainty. The projected changes suggest that continuous emission of greenhouse gases may intensify uncertainties amongst models on projections over South Africa.

The hydrological model used in the study could simulate the behaviour of streamflow in the Luvuvhu River Catchment. Streamflow forecasts show a decrease in rare but intense flood events. The projected results show that the areas that are more vulnerable to the effects of climate change on water resources are the ones found downstream of the Luvuvhu River Catchment. The decrease in cumulative inflows for the far future scenario will be worsened by year-to-year variations (variability) in inflows into the dams which will affect water resources availability and allocation. The future irrigation water requirements will put pressure on available water resources from Albasini Dam. The decrease in rainfall in the future is also expected to reduce crop productivity in rainfed agriculture. This will threaten food security if the irrigation water requirements are not met. An increase in domestic water requirements for the future combined with the need to supplement water supply schemes which are outside the Luvuvhu River Catchment is expected to put severe pressure on the Nandoni Dam system resulting to water supply deficit.

Water conservation and reduction of production space to maximise irrigation were climate change adaptation options with highest scores and priority for implementation for both municipal/domestic and agricultural water use sectors, respectively. Most of the developed climate change adaptation options have short time frames meaning that their effects are felt immediately after implementation. This will therefore encourage community buy-in and implementation of adaptation options with medium and long time frames.

RECOMMENDATIONS

- Future climate modelling studies can employ new Shared Socioeconomic Pathways (SSPs) which are an improvement of the RCPs used in this study.
- With changes in forestry and urbanization in the catchment, a study is recommended to investigate the sensitivity of the catchment climate to land cover change.
- Studies on the effect of sedimentation on future storage capacities of the reservoirs and water resources availability are essential.
- Pilot studies to test the effectiveness and improve acceptability of the developed climate change adaptation options and plans are essential.

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Stakeholders representing municipal/domestic water use sector	CIVIC, Ward Councils, traditional leaders and VDM officials

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

ARC-ISCW	Agricultural Research Council-Institute for Soil, Climate and Water
AWC	Available water content
CCAM	Conformal Cubic Atmospheric Model
CGCMs	Coupled Global Climate Models
CGIAR-CSI	Consultative Group for International Agricultural Research-Consortium for Spatial Information
CLIMACT Prio	Climate Actions Prioritisation
CMF	Catchment Management Forum
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM	Centre National de Recherches Météorologiques
CORDEX	Coordinated Downscaling Experiment
CRU	Climate research unit
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DALRRD	Department of Agriculture, Land Reform and Rural Development
DEA	Department of Environmental Affairs
DEFF	Department of Environment, Forestry and Fisheries
DEM	Digital Elevation Model
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
GCMs	Global Circulation Models
GHG	Greenhouse gas
GPCP	Global Precipitation Climatology Project
HRU	Hydrological response unit
IPCC	Intergovernmental Panel on Climate Change
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
KNP	Kruger National Park
LEDET	Limpopo Economic Development, Environment and Tourism
MCDA	Multi-criteria decision analysis
MPI	Max Planck Institute
NCEP	National Centers for Environmental Prediction
NSE	Nash-Sutcliffe Efficiency
OLR	Outgoing longwave radiation
PBIAS	Percent Bias
PCPD	Average number of precipitation days
RCMs	Regional Climate Models
RCPs	Representative Concentration Pathways
SANSA	South African National Spatial Agency
SAWS	South African Weather Service
SSPs	Shared Socioeconomic Pathways
SSTs	Sea surface temperatures
SWAT	Soil and water assessment tool
UNDP	United Nations Development Programme
USGS	United States Geological Society
VDM	Vhembe District Municipality

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

One of the major challenges with climate change is its impact on water resources and extreme hydrological events (Anderson, 2011). Projected impacts of climate change are due to changes in rainfall and evaporation rates, further influenced by climate drivers such as wind speed and air temperature as well as soils, geology, land cover and topography across South African water catchments (CSIR, 2009). In the last decade, temperatures have increased to the highest on record and further global warming is expected to lead to increased evaporative losses. Recent trends have shown an increase in heavy precipitation events over subtropical southern Africa (New *et al.*, 2006) and extreme rainfall may occur more frequently in a warmer future climate. Climate change, coupled with population growth, may result in water stress and decreasing annual water per capita (Murray *et al.*, 2012).

Extreme events like droughts and floods, significantly affect important sectors such as agriculture, energy, water resources, among others. Furthermore, extreme droughts resulting in water level drop cause nutrients to be more concentrated. Flooding may cause excess nutrients to be flushed out of the dam. It may also lead to a high influx of soil material from surrounding areas. Variations in catchment water flows are expected to alter water availability for irrigated agriculture, flow availability for dam water supplies, or water harvesting and storage. There is a need to determine the effects of climate change on water resources to predict the potential impacts on agriculture and domestic/municipal water use. Adequate knowledge of historical and future changes in the surface water balance including variables such as precipitation, evaporation and runoff is essential for predicting the reciprocal influence of land surface processes on climate.

Agriculture serves as a source of food, employment, income and foreign exchange earning in Limpopo Province (Oni *et al.*, 2012), and it is hence substantial in improving economic growth and sustaining livelihoods in the province including the Luvuvhu River Catchment. The upper third of the Luvuvhu River Catchment is mainly utilised for commercial agriculture. Intensive irrigation farming is practised in the upper part of the catchment where vegetables, citrus, bananas, mangoes, avocados and nuts are some of the produce grown (Steyn *et al.*, 2010). In the middle and towards the lower reaches of the catchment subsistence agriculture and small scale irrigation are practiced. Small scale irrigation schemes, for example, the Dzindi irrigation scheme utilise run-of-river water and thus changes in river flow dynamics will impact water availability to small scale irrigation. Climate change will, therefore, impact on economic growth and livelihoods in the catchment. The semi-arid nature and highly variable rainfall distribution within the Luvuvhu River catchment are expected to exacerbate the impact of climate change on water resources availability. Dube *et al.* (2014) showed that communities in Thulamela municipality, which is in Luvuvhu River Catchment, are exposed to worst levels of climate change vulnerabilities, have poorest levels of water access and least scope for major future improvements. This shows that the municipal and domestic water supply in these areas will highly be affected by climate change.

United Nations Development Programme (UNDP) proposed that an essential step in the integration of climate change in water resources management is to assess the potential effects of climate change on water availability and extreme hydrological events in different regions to better understand the consequences on vulnerable sectors and societal groups and promote and implement appropriate response measures (Losjo *et al.*, 2006). Most assessments of climate change impacts have been primarily undertaken at macro and regional scales, masking the complex hydrological interactions at the local, catchment scale (Schulze, 2000, 2011). It is therefore crucial to conduct a study at the catchment scale as it will assist in understanding how complex hydrological interactions at catchment scale influence climate change and the impact on water resources availability thereof. In addition, CSIR (2009) reported that the overall impact of climate change on water resources is uncertain, and will vary significantly from place to place within South Africa. Thus, the impacts of climate change on water resources availability will also vary significantly from catchment to catchment. Interactions between changes in water quantity and quality and how they might impact water use, for example, for domestic use have not been fully explored in South Africa (Ziervogel *et al.*, 2014).

There are limited studies that have been done on the impacts of climate change on water resources at a catchment scale. Zhu and Ringler (2010) analysed the impacts of climate change on the hydrological and water resource systems of the Limpopo River Basin and found significant reductions of annual rainfall and water availability by the year 2030. The latter study noted that this will affect river hydrology and can reduce irrigation water supply and reliability, and reservoir storage. DEA (2013) reported that the implications of climate change on water resource availability have not yet been addressed in the Luvuvhu River Catchment. Odiyo *et al.* (2015) determined the long-term changes and variability in rainfall and streamflow in the Luvuvhu River Catchment, South Africa. The study did not link this to the impacts on water resources availability, making it important to study the impact of climate change on water resources availability in Luvuvhu River Catchment. Attempts to link climate change to water resources have been conducted in other countries of the world.

Noting that evaluation of water resources in consideration of future climate change is important for sustainable planning and management of the resource, Obuobie and Bernd (2008) applied the Soil Water Assessment Tool (SWAT), to simulate the present (considered to be 1990-2000) and the future (2030-2039) water resource availability. The study demonstrated how a calibrated and validated model may be used in the prediction of future changes of flow in the rivers resulting from rainfall increases associated with climate change. Several studies have dealt with intra-seasonal rainfall characteristics over southern Africa (e.g. Tennant and Hewitson, 2002; Tadross *et al.*, 2003; Cook *et al.*, 2004; Usman and Reason, 2004; Mwale *et al.*, 2004; Reasona *et al.*, 2005; New *et al.*, 2006, Hachigonta *et al.*, 2008) but the impact of climate change on rainfall characteristics at catchment scale requires rigorous research attention. Resource-poor semi-arid regions that already face water resource management problems are likely to be impacted more by climate change (Andersson *et al.*, 2011). The Rossby Center Regional Climate Change (RCA3) (Samuelsson *et al.*, 2011; Jones *et al.*, 2004; Kjellstrom *et al.*, 2005) model was used to simulate climate change projections under 3 scenarios coupled to a hydrological model HBV (Lindstrom *et al.*, 1997) to determine impacts on the Pungwe River Basin in Mozambique and Zimbabwe up to 2050 (Andersson *et al.*, 2011). Whilst surface air temperatures are expected to warm by up to 2°C, annual rainfall was projected to decline by about 10%. The study also projected a delay of the onset of the rainy season by about one month and a corresponding reduction in the length of the growing season. River flows were projected to decline as well as increased inter-annual variability of dry season streamflow.

Luvuvhu River rises in the Soutpansberg Mountains and empties into the Limpopo River on South Africa's border with Mozambique and Zimbabwe. Luvuvhu River is dammed to form the Albasini Dam upstream of the Nandoni Dam. Albasini Dam supplies part of irrigation demands to major commercial farms within the catchment while Nandoni Dam mainly supplies a large portion of domestic water supply. It also supports activities such as recreation and fishing. Thus, climate change would adversely impact on these water users. It is therefore crucial to study the impact of climate change on these water resource systems and develop practical adaptation strategies to minimise the impacts. Adaptive responses that reduce vulnerability to current as well as future climate variability and change are critical in the context of South Africa's urgent socio-economic developmental needs and threatened ecosystem services (Ziervogel *et al.*, 2014).

The study also considered the historical rainfall variability and how climate change will impact on rainfall characteristics in the Luvuvhu River Catchment. Intense precipitation feedbacks between the terrestrial ecosystem and the overlying climate, through analysis of land surface variables and hydro-meteorological parameters in the satellite era from 1979-2014 was also studied. Rainfall variability during that time has been significant and is largely related to the position of the Northwest cloud band on the edge of the Kalahari. The cloud band is sensitive to remote ocean monsoons and the El Niño – Southern Oscillation and provides half of southern Africa's rainfall. A key question to be addressed is whether intense precipitation will become heavier in the Luvuvhu River Catchment in a warmer future climate. Numerical models of our future climate require information on how the atmosphere couples with the land surface processes and vegetation. This gap needs to be filled, to improve the reliability of predictive models and to better manage the land. The study examined how variations in the climatic characteristics like rainfall and temperature impact on the water resources in the Luvuvhu River Catchment.

Climate change and variability are likely to affect efforts targeted at satisfying the increasing domestic demand and generating income to purchase food for the people, achieve poverty reduction and sustainable development strategies. Climate change is associated with increasing temperatures and alteration in the rainfall patterns resulting in changes in streamflow patterns, increased frequency and severity of climate extremes linked to frequent floods and droughts with severe impacts on soil, water and the plant environment affecting crop production and by extension human health and nutrition. In attempts to protect themselves from these adverse effects of climate change and variability, the affected communities confronted with problems of drought, poor yields, floods, amongst others, have never stopped trying to devise adaptation methods to mitigate impacts related to climate change.

Little effort has been made to identify and document strategies used by the affected communities in coping with the impacts of climate change to evaluate the effectiveness of these coping mechanisms. Although farmers in the Limpopo Basin are aware of climate change, few seem to take steps to adjust their farming activities (Gbetibouo, 2009). However, in the Vhembe District, which is within the Luvuvhu River Catchment, many commercial and small scale farmers are beginning to use seasonal forecast information to manage climatic risk (Mpandeli, 2014). The farmers use the information to prepare a seasonal calendar for agricultural activities, make informed decisions for farm planning management and decision making, and, as a tool to manage risk due to the variable environment in which they operate. Other coping and climate change adaptation strategies including crop diversification, early planting, planting crops that require less water, and changing farming practices are used. A study by Mpandeli (2013) recommended that farmers should be encouraged and enabled to use crop diversification and drought-resistant cultivars as some of the climate-risk management strategies. However, the study further noted that this requires further research. Thus, further studies and research on identifying and improving adaptation options for coping with climate change are essential. It is envisaged that this study will also aid in improving existing adaptation options for long term use.

Knowledge of existing adaptation options would form the basis upon which practical methods can be identified and developed to protect the communities from adverse effects of climate change and hence reduce their vulnerability through the integration of the indigenous knowledge and new techniques. Events associated with climate change, in most cases, take people by surprise as they are usually caught unaware. There are no systems put in place to predict changes that come with climate change. The purpose of this study was to partly address this problem by way of modelling alterations in the hydrological system changes associated with climate change and to enable preparedness through early warning and development of adaptation options. A hydrological modelling system that provides future climate change scenarios and predicts the impacts on water resource availability for agriculture and municipal/domestic use is, thus, essential as it will aid in the generation of long term climate change adaptation options.

1.2 OBJECTIVES OF THE STUDY

The purpose of the study is to investigate the impact of future climate change scenarios on water availability for agricultural and municipal/domestic water uses and develop practical adaptation options for vulnerable communities in Luvuvhu River Catchment. The specific objectives are:

1. To predict the effect of future climate change scenarios on water resource availability for agricultural production and municipal/domestic water uses in the catchment.
2. To identify and assess adaptation measures for climate change used by communities in the catchment.
3. To develop practical adaptation options for future climate change scenarios in consultation with key stakeholders.

1.3 THE STUDY AREA

1.3.1 Location

The Luvuvhu River Catchment is situated between the longitudes 29°49´46.16´´E and 31°23’32.02”E and latitudes 22°17’33.57”S and 23°17’57.31”S in the Northern Region of the Limpopo Province of South Africa, otherwise known as Vhembe District Municipality (VDM). It covers an area of approximately 5941 km^2 (Figure 1.1).

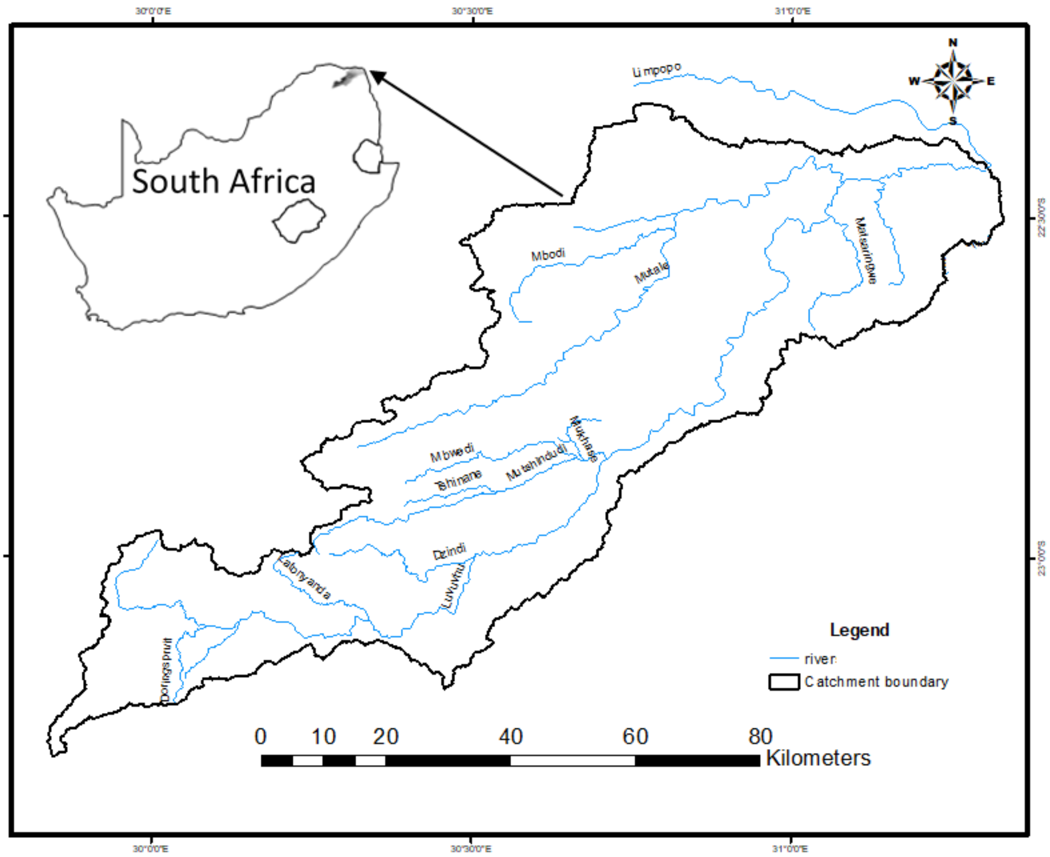

Figure 1.1: A map of the Luvuvhu River Catchment

1.3.2 Climate

The Luvuvhu River Catchment is characterised by hot and wet summers and cold and dry winters. The rainfall received in the area during the summer season averages 450 mm per annum to more than 1200 mm in the mountainous area. It is important to note, however, that some parts of the catchment like Entabeni around the Soutpansberg area receive up to 2000 mm of rainfall per annum. The average daily temperature is 28°C. Thus, some areas of the catchment with very low rainfall and high temperature can be described as semi-arid to arid.

1.3.3 Topography

The predominant topographical feature in the Luvuvhu River Catchment is the Soutpansberg Mountain range. Its highest points and steepest slopes are situated in the upper part of the Luvuvhu River Catchment (Figure 1.2). This has a profound effect on the hydrology of the rest of the catchment with significantly higher rainfall because of topographic influence.

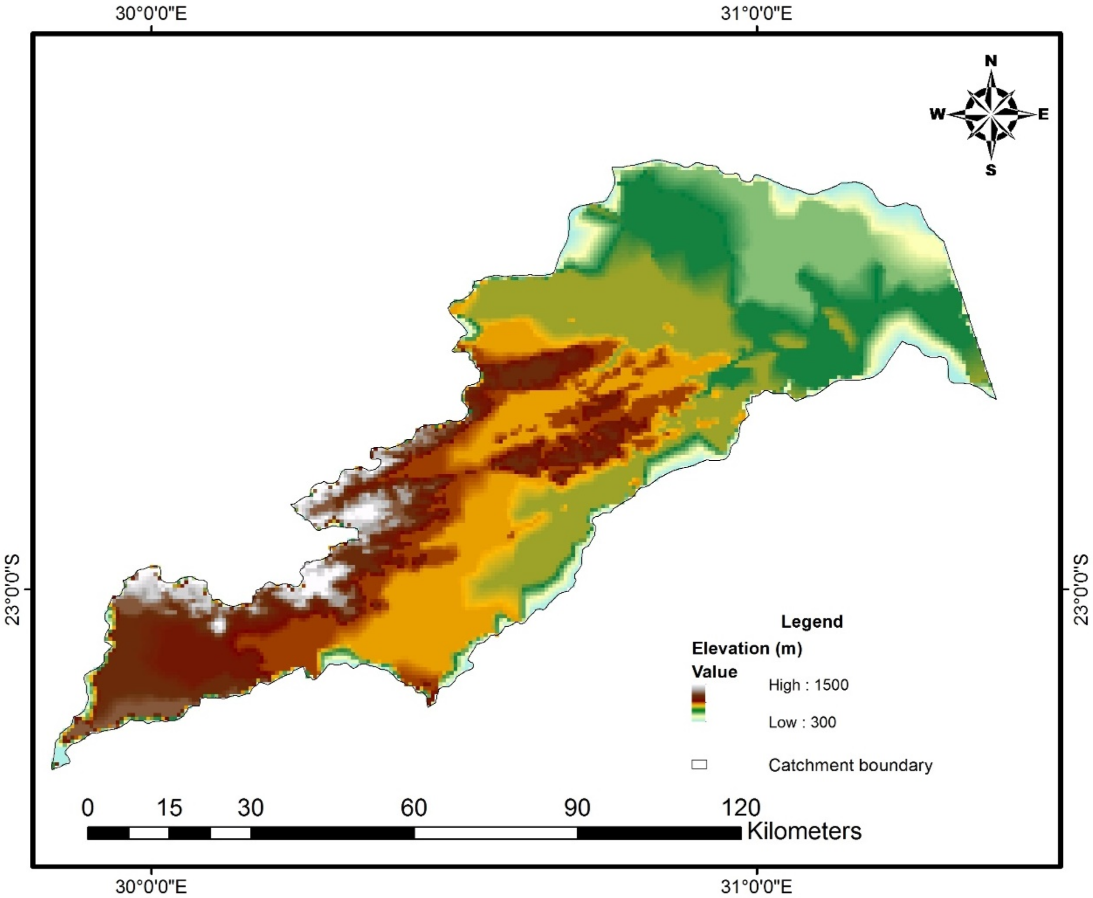

Figure 1.2: Topography of the Luvuvhu River Catchment

1.3.4 Hydrology

The study area is drained by the Luvuvhu River and its tributaries (Doringspruit, Latonyanda, Dzindi, Mutshundudi, Mutale, Mbwedi and Tshinane) (Figure 1.1). When the river reaches Kruger National Park (KNP) it becomes a tributary of the Limpopo River, which extends to Mozambique and ultimately reaches the Indian Ocean.

1.3.5 Geology

The geology is varied and complex and consists mainly of sedimentary rocks in the north and metamorphic and igneous rocks in the south. High-quality coal deposits are found near Tshikondeni and in the northern part of the KNP. Except for sandy aquifers in the Limpopo River Valley, the formation is of relatively low water-bearing capacity (DWAF, 2004).

1.3.6 Vegetation and land use

Land use activities in the Luvuvhu River Catchment include forestry and agriculture. Forestry plantations cover the upper reaches of the Luvuvhu and Latonyanda Rivers, decreasing towards Albasini Dam. Land cover in the southern highlands of the Luvuvhu River Catchment is dominated by exotic tree plantations of pines and eucalyptus, with some remnant and fragmented patches of indigenous forest. Subsistence farming is about a third of the total agricultural component. Riparian vegetation consists of dense stands of large trees, shrubs and reeds (South African River Health Programme, 1999). The riparian vegetation consists of dry acacia woodland species. Riparian vegetation in large areas has been removed to accommodate orchards. Alien vegetation such as Eucalyptus, poplars and Mauritius thorn has invaded the riparian zone (Butt *et al.*, 1994).

The local community farm on the steep slopes adjacent to the upper reaches of the Dzindi River. Some grazing occurs as well as cutting of trees in the riparian zone. Subsistence farming is the dominant land use in the upper reaches of the Mutshindudi and Mbwedi rivers with plantations covering some 17% total sub-catchment area (Butt *et al.,* 1994). Subsistence farming is the dominant form of agriculture in the Mutale catchment. Large-scale citrus, mango, banana, and vegetable farms are common in the nearby Albasini foothills.

1.4 CAPACITY BUILDING AND COMPETENCY DEVELOPMENT

Climate and hydrological modelling require competencies in dealing with large datasets, manipulating and visualisation of simulations including programming skills. This part of the project required training of staff and postgraduate students to enhance their capacity to utilise computer software used in generating the climate change scenarios. A 5-day workshop was held during the week of 4-8 June 2018 at the University of Venda. It was facilitated by an expert, Mrs Patience Mulovhedzi from the South African Weather Service (SAWS).

The students who were directly involved in the WRC study were Ms Shudufhadzo Mukwevho and Mr Tisang Ncube. The facilitator was willing to accommodate additional 6 postgraduate students who were undertaking climate change related studies within the School of Environmental Sciences to promote skills and knowledge transfer. The training was focused on programming in FORTRAN, and visualising simulations in the Grid Analysis and Display System (GrADS) whilst operating in a LINUX environment. These are modelling environments for generating and visualising climate change scenarios data. The details of the students who were directly involved in the WRC study and their progress are included in Table 1.1.

Table 1.1: Details and progress of Masters students

Student	Gender	Race	Degree	Financial Year	Date of first registration	Title of study	Progress
Mukwevho S.G.	Female	African (Black)	Masters	2018/2019-2019/2020	May 2018	Modelling impacts of climate change on hydrology of Luvuvhu River Catchment, Limpopo Province South Africa	Interpretation and discussion of model results
Ncube T.M.	Male	African (Black)	Masters	2017/2018-2018/2019	March 2017	Rainfall variability and change in South Africa (1976-2065)	Graduated cum laude in September 2019.

1.5 STRUCTURE OF THE REPORT

This report consists of 5 chapters. Chapter 1 provides the “Introduction” and it covers the background, objectives of the study, description of the study area, capacity building and competency development and report structure. Chapter 2 covers literature review, methods, results and discussion linked to climate variability and change in Luvuvhu River Catchment. Literature review, methods, results and discussion associated with hydrologic analysis for climate impact modelling are in Chapter 3. Chapter 4 is focused on the development of a climate change adaptation plans for municipal/domestic and agricultural water sectors within the study area.

CHAPTER 2: CLIMATE CHANGE AND VARIABILITY IN THE LUVUVHU RIVER CATCHMENT

2.1 INTRODUCTION

This chapter aims to analyse the historical climate record to understand the present-day climate and its variability and forcing mechanisms. The chapter also presents results from a modelling study of climate change projections over South Africa under high and low mitigation emission scenarios into the far future.

2.2 LITERATURE REVIEW

2.2.1 Climate change in the Limpopo Province

Climate variability and change are likely to affect efforts targeted at satisfying the increasing domestic demand (due to population growth) and generating income to purchase food for the people, achieve poverty reduction and sustainable development strategies. Climate change is associated with increasing air temperatures and alteration of rainfall patterns resulting to changes in streamflow patterns, increased frequency and severity of climate extremes. These are linked to frequent floods and droughts with severe impacts on soil, water and the plant environment affecting crop production and by extension human health and nutrition.

Interannual rainfall variability over southern Africa is higher due to extreme events such that the longer-term trend is not significant statistically (Chikoore, 2016). This variability is largely related to the position of the cloud band on the edge of the Kalahari. The cloud band is sensitive to remote ocean monsoons and the El Niño – Southern Oscillation (ENSO) and provides half of southern Africa's rainfall (Hart et al., 2013). A key question that remains is whether intense precipitation will become heavier in the Luvuvhu River Catchment in a warmer future climate. Numerical models of our future climate require information on how the atmosphere couples with land surface processes and vegetation. This gap needs to be filled, to improve the reliability of predictive models and to better manage the land. The study examines further how variations in the climatic characteristics such as rainfall and temperature impact on the water resources in the Luvuvhu River Catchment.

2.2.2 Greenhouse gas emission scenarios

The main greenhouse gases that absorb terrestrial radiation warming the planet are carbon dioxide, methane and nitrous oxide. The future concentrations of greenhouse gases are unknown. However, there are possible scenarios that define alternative images of how the future might unfold which are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. The scenarios are based on an extensive assessment of driving forces (IPCC, 2007) linked to human population growth, energy production and technological developments.

Representative Concentration Pathways (RCPs) are meant to provide information on all components of radiative forcing that are used as inputs in climate modelling and atmospheric chemistry modelling and they cover a period of up to 2100 (Wayne, 2013). There are four RCPs named according to radiative forcing target level for 2100 developed by Van Vuuren et al. (2011) that have been recently used across the scientific community. The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents (Van Vuuren *et al.*, 2011). These are RCP 2.6, RCP 4.5, RCP6 and RCP 8.5 (Figure 2.1). RCPs for low mitigation result in high baseline greenhouse gas concentrations (RCP8.5) and medium to low mitigation (RCP4.5) (Van Vuuren *et al.,* 2011) have been frequently used to determine the likely future climate. More recently, there are new Shared Socioeconomic Pathways (SSPs, Riahi *et al.*, 2016) which are a set of five narratives that are set to gradually replace RCPs.

RCP 8.5 was developed using the MESSAGE model and the Integrated Assessment Framework by the International Institute for Applied Systems Analysis (IIASA), Austria. It is characterised by increasing greenhouse gas emissions over time, representative of scenarios that lead to high greenhouse gas concentration levels (Riahi *et al.,* 2007). It combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading to high energy demand and Greenhouse gas emissions. Its main purpose is to serve as an input to the CMIP5. The RCP6 was developed by the AIM modelling team at the National Institute for Environmental Studies (NIES) in Japan (Fujino *et al*., 2006). It is a stabilisation scenario in which total radiative forcing is stabilised shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions (Hijioka *et al.*, 2008).

The RCP 2.6 was developed by Integrated Model to Assess the Global Environment (IMAGE) modelling team of the PBL Netherlands Environmental Assessment Agency. The emission pathway is representative of scenarios in the literature that lead to very low greenhouse gas concentration levels. Wise *et al*. (2009) described the scenario as peak-and-decline. This is because its radiative forcing level first reaches a value of around 3.1 W/m^2 by mid-century and returns to 2.6 W/m^2 by 2100. To reach such radiative forcing levels, greenhouse gas emissions are reduced substantially, over time (Van Vuuren *et al.*, 2007). This study is however limited to the recent fifth assessment report's RCP 4.5 and RCP 8.5 emission scenarios.

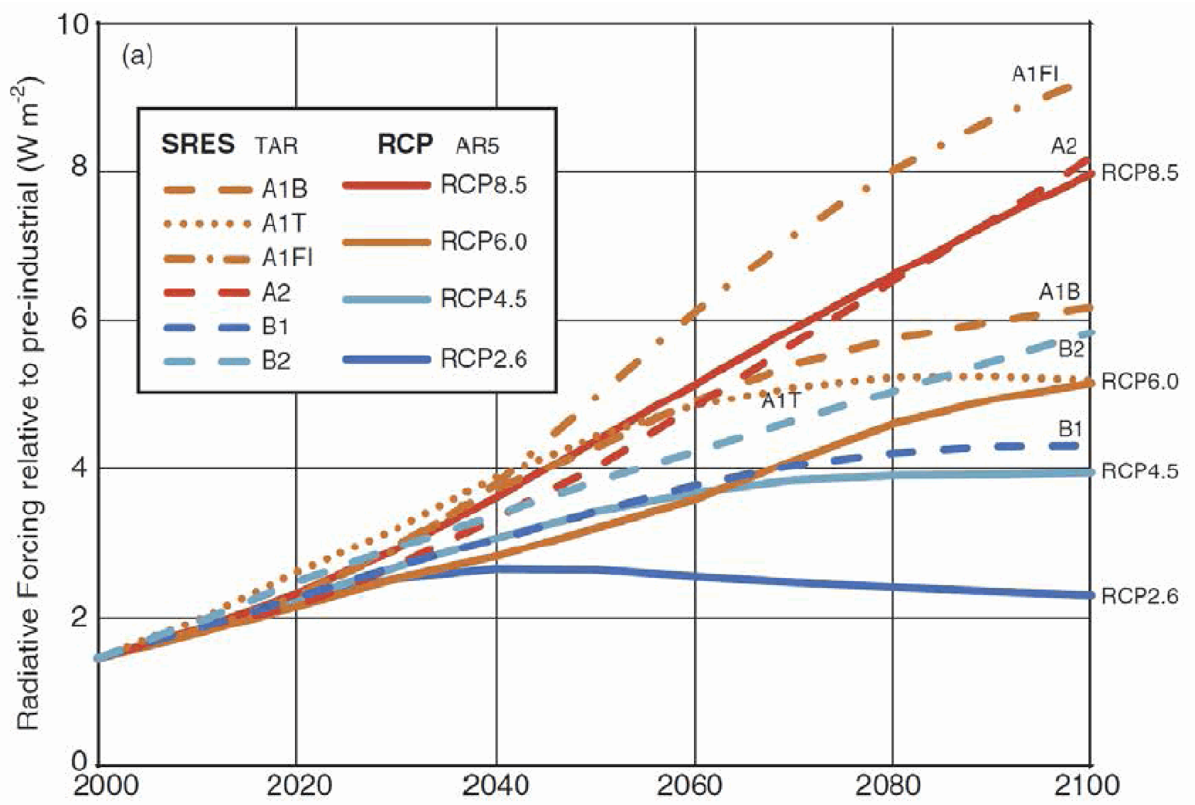

Figure 2.1: Projections of radiative forcing under different emission scenarios (Source: IPCC 2013).

2.2.3 Climate models used for climate change projections

Dynamic climate models have become the primary tools for the projection of future climate change, at both global and regional scales. These models are governed by laws of physics applied to the earth system (Engelbrecht *et al.,* 2011). The IPCC Assessment Report Four (AR4) which projects future global climate change, is based on Coupled Global Climate Models (CGCMs). Kimura and Kitoh (2007) alluded that these models simulate the coupled ocean, atmosphere and land-surface processes. However, more detailed simulations are needed for regional climate-change impact studies and to drive application models, for example, hydrological models applied over small catchments (Praskievicz and Chang, 2009) such as Luvuvhu River Catchment. Dynamic RCMs are used to obtain such detailed projections. These models are applied at high-resolution over selected areas of interest and may be forced at their lateral boundaries or in the far-field by the output of a CGCM (Davies *et al*., 2005).

The use of climate change projection models is increasingly developed to inform climate-change adaptation studies. Most of these climate change projection models are also criticised as not being verifiable, the argument being that it is only possible to verify the reliability of the projections several decades into the future (Engelbrecht *et al.,* 2011). Projections of future climate change may be enhanced through the application and verification of the models used for climate projections over multiple time- and spatial scales (Davies *et al*., 2005). These more recent models are sufficiently versatile to be applied across the range of time scales relevant to short-range weather, seasonal forecasting and the projection of future climate change (Engelbrecht *et al.,* 2011). They can be applied at spatial scales ranging from global simulations at resolutions of 100-200 km, to the micro-scale at resolutions as high as 1 km (Janjic *et al.,* 2001).

Global and regional climate models have also been identified for simulation of future rainfall in the Luvuvhu River Catchment up to 2100 including those from the Coordinated Downscaling Experiment (CORDEX) and the Conformal Cubic Atmospheric Model (CCAM). Since GCMs have a coarse resolution and cannot resolve complex topography (Andersson *et al*., 2011) such as the eastern escarpment and the Soutpansberg Mountain range, GCM simulations are regionalised using dynamical downscaling with the aid of mesoscale RCMs. A significant proportion of the rainfall received in the Luvuvhu River Catchment drains from the slopes of the Soutpansberg, which itself provides forcing for orographic rainfall.

The CORDEX is a World Climate Research Program (WCRP) backed framework to produce ensembles of regional climate projections for all continents globally (Giorgi *et al.,* 2009). CORDEX brings together regional-scale climate projections produced using both statistical and dynamical techniques. It aims to provide a framework to evaluate and benchmark model performance as well as producing projections for use in impact and adaptation studies. The climate projection framework within CORDEX is based on the set of GCM simulations that supported the IPCC Fifth Assessment Report (Crichton, 2013). CORDEX is organised similarly to the Coupled Model Inter-comparison Project phase 5 (CMIP5) for global model simulations, with predefined regions, grids, experimental protocols, output variables, and output format facilitating easier analysis of possible future regional climate changes, not only by the scientific community but also by end-user communities at regional and local levels (Nikulin *et al.*, 2015). CORDEX has common experimental designs that are advantageous in model evaluations, constructing multi-model ensembles and uncertainty assessments (Kim *et al.*, 2014).

Previous research studies (e.g. Tadross *et al.,* 2006; Paeth *et al.,* 2011; Nkulin *et al.,* 2015) have used CORDEX to simulate future climates over Africa, which is particularly vulnerable to climate change and has a low adaptive capacity. For example, water supply and food security are of critical importance in Africa. Nikulin *et al.* (2015) simulated results of the CORDEX-Africa project by evaluating an ensemble of 10 RCM simulations, covering the entire African continent and driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis [ERA-Interim (ERAINT)]. The performance of the individual RCMs and their ensemble average was documented in detail at a range of time scales.

The Conformal-Cubic Atmospheric Model (CCAM), a variable-resolution global atmospheric model was developed by the Commonwealth Scientific and Industrial Research Organization (McGregor JL and Dix MR, 2008). The model plays a crucial role in solving hydrostatic primitive equations using a semi-implicit semi-Lagrangian solution procedure and includes a comprehensive set of physical parameters. CCAM may be applied at the quasi-uniform resolution, or in stretched-grid mode to obtain high resolution over an area of interest (Engelbrecht *et al.,* 2011). For the high-resolution simulations on stretched grids, a digital filter technique may be employed to preserve the large-scale patterns of an earlier performed coarse-resolution CCAM simulation (Thatcher and McGregor, 2009).

The CCAM and Division of Atmospheric Research Limited-Area Model of the CSIRO, have been applied in South Africa for the past 10 years to simulate present-day climate and future climate change (Engelbrecht *et al.,* 2011). The CCAM was forced by bias-corrected sea-surface temperatures from individual host models with additional forcing from carbon dioxide, ozone and sulphate according to the A2 scenario (Engelbrecht *et al.*, 2015). CCAM has been shown to provide satisfactory simulations of annual rainfall and temperature distributions, as well as of the intra-annual cycle in rainfall and circulation over the region (Engelbrecht *et al*., 2009). It has also been shown that the model can provide a realistic representation of observed daily climate statistics such as extreme rainfall events over Southern Africa (Potgieter, 2009).

Notably few researchers performed a set of climate projections over South Africa, southern or tropical Africa using CCAM (e.g. Engelbrecht *et al*., 2011; Engelbrecht *et al*., 2015), to illustrate the capability of the model to function as a flexible downscaling tool at the climate-change time scale. Engelbrecht *et al*. (2011) performed a downscaling procedure involving applying CCAM in stretched-grid mode over Southern and tropical Africa, to obtain simulations of approximately 60 km resolution (Figure 2.2). In the process, the resolution decreased to about 400 km in the far-field. Hence, all simulations were performed on the Sun Hybrid System of the Centre for High-Performance Computing (CHPC) in South Africa.

The CCAM, on average austral summer of DJF simulated that, the average position of the Inter-Tropical Convergence Zone and associated rainfall in a zonal band stretched from Angola over Zambia and into Mozambique (Engelbrecht *et al.,* 2011). The CCAM simulated the average position of the Inter Tropical Convergence Zone and associated rainfall over southern Africa during the austral summer in a zonal band stretched from Angola over Zambia and into Mozambique (Engelbrecht *et al.,* 2011). Other aspects such as the west-east gradient in rainfall distribution over South Africa, and the relatively dry conditions that occur in a zonal band stretching from Botswana to the Limpopo River Basin of South Africa and Zimbabwe, are also well captured in the model simulation. The model simulated a wet bias in representing the average daily summer rainfall totals over most of southern Africa in future climate (Engelbrecht *et al.,* 2015).

More details of CCAM's ability to simulate not only the mean climatology but also the intra-annual cycle of rainfall, the intra-annual cycle in circulation and daily circulation statistics over southern Africa are detailed in Engelbrecht (2005), Engelbrecht *et al*. (2009) and Potgieter (2009). Engelbrecht *et al*. (2011) projected changes in summer rainfall over southern Africa, which is projected to become generally drier thus with a relatively strong signal of drying projected for Zimbabwe, Zambia and Angola. The central interior of South Africa is projected to become somewhat wetter, despite the general drying signal projected for most parts of Southern Africa. This describes that, on a subcontinental scale, the CCAM projection signals are consistent with those of the majority of CGCM projections described in AR4 of the IPCC.

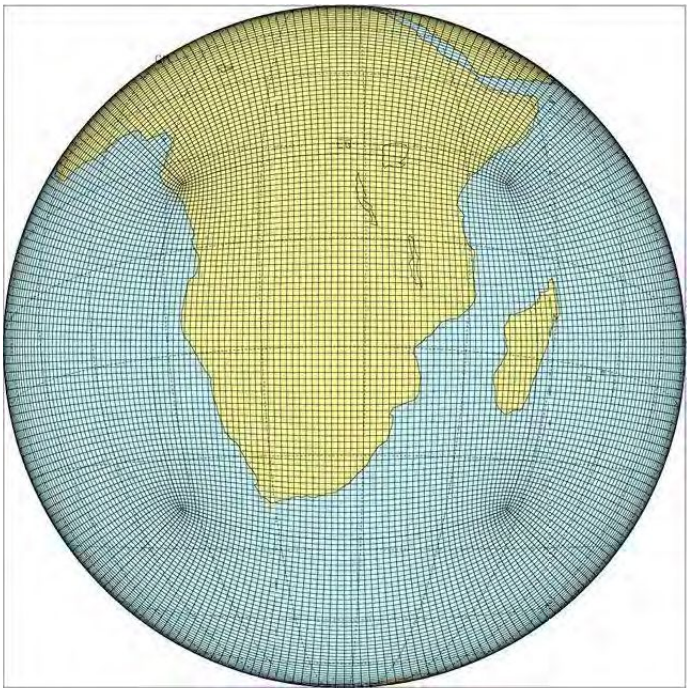

Figure 2.2: C64 stretched conformal-cubic grid over Southern Africa and tropical Africa (Source: Engelbrecht *et al.*, 2011)

2.2.4 Uncertainties in climate change model

Climate model evaluation is a fundamental step in estimating the uncertainty in future climate projections (Kim and Lee, 2003). Different issues related to modelling impacts of climate change on hydrology, namely sources of uncertainty arise in models. Wilby *et al*., (2006) explained that there are four different aspects of uncertainty in climate change impact assessment in hydrology and water resources. The choice of GCMs is the first source of uncertainty. The second is associated with transferring large-scale climatology to regional-scale climatology appropriate for hydrological and water resource impact assessment, namely downscaling processes. The third is related to the parameters and structures of hydrological models used for impact assessment. The fourth source of uncertainty stems from water resource impact models employed for this study.

In climate change impact studies, Chiew *et al.* (2003) developed an approach using synthetic climate change scenarios, in which the historical average temperature and precipitation are changed by fixed amounts at inter-annual, seasonal, or monthly scales. Gillingham *et al*. (2015) support that this uncertainty approach is associated with GCMs and tolerates for sensitivity analysis of change in a hydrological variable.

Gillingham *et al*. (2015) found that the extent of changes in climatic variables is not necessarily realistic consequences of increased atmospheric greenhouse gas concentrations. This problem can be avoided by not selecting them arbitrarily, but instead by basing these on some other data, such as anomalies in the historical record or the range of changes predicted by climate models for the region (Wood *et al.*, 2004). When changes are applied to raw historical climate data, the range of variability in the scenario remains unchanged (Chiew *et al*., 2003). This is problematic because climate change is likely to alter change and variability in precipitation. A refined method known as daily scaling was developed and supported to overcome the problem (Chiew *et al.*, 2003; Wood *et al*., 2004; Wilby *et al.,* 2006). Change factors are applied to ranked historical precipitation data and they are not constant across all years, seasons, or months, but are dependent on the relative magnitude of the event (Chiew *et al.*, 2003).

An alternative approach to climate change scenario generation begins with one or more greenhouse gas (GHG) emissions scenarios, usually from the IPCC Special Report on Emissions Scenarios (Chiew *et al.*, 2003). These scenarios are used to drive GCMs, which rely on large-scale simulations of the coupled ocean-atmosphere system to predict the response of the climate to the projected increase in GHG concentrations (Chiew *et al.*, 2003; Wilby *et al.,* 2006). This is because the outputs from these models are at too large a scale to be useful for most hydrological applications. Instead, Wilby *et al.* (2006) explained that they must be downscaled using either a regional climate model (RCM). This will help to simulate local topographic and other influences on future climate change projections.

Studies indicate that the greatest source of uncertainty in the climate impact modelling chain is the GCM (for example, Wilby *et al*., 2006; Graham *et al*., 2007). GCMs vary widely in their projections, particularly for precipitation. This is because they all model atmospheric conditions and feedbacks differently. The choice of emission scenario is less important for the near-term because most scenarios show very similar levels of emissions through the 2050s and it takes time for the atmosphere to respond (Wilby and Harris, 2006). In basins where summer is the low flow period, the uncertainty in GCM-derived river flows is greatest in summer (Wilby *et al*., 2006), suggesting that changing precipitation and temperature patterns will alter seasonal water balance components in different ways.

Another source of uncertainty is downscaling methods. Wood *et al*. (2004) compared three statistical downscaling methods, using the Variable Infiltration Capacity macroscale hydrological model. The most accurate method was bias correction and spatial disaggregation. Dibike and Coulibaly (2005) used output from a GCM to compare two downscaling methods, regression analysis and a stochastic weather generator.

2.3 METHODOLOGY

2.3.1 Observed and reanalysis data

Rainfall patterns and responses to climate change were studied using station data, satellite remote sensed estimates and model reanalyses. Surface and upper air meteorological observations were obtained from the South African Weather Service including gridded satellite and reanalysis datasets from the archives of global climate centres such as the National Centres for Environmental Prediction (NCEP) and the University of East Anglia's Climate Research Unit (CRU). The use of satellite-based data was explored to augment the observed data which at times are associated with uncertainties owing to such factors as changes in gauge locations. There are incidences of gauges being washed away during floods leading to a lack of requisite data for some periods. Missing data/gaps in data is a typical characteristic of observed data particularly in sub-Saharan Africa.

The NOAA/UMD outgoing longwave radiation (OLR) data were obtained and the annual cycle. OLR may be used as a proxy for convection such that low OLR values indicate periods of deep convection and high rainfall (Chikoore, 2016). The Inter-annual variability of rainfall in the Luvuvhu River Catchment was also analysed using gridded rainfall data from the Global Precipitation Climatology Project (GPCP). The GPCP data are a merger of rain gauge observations with satellite estimates from polar-orbiting and geostationary meteorological satellites (Huffman *et al.*, 2009). The GPCP data are also analysed via Wavelet Analysis to determine dominant cycles in the data and when they occur.

Several historical climate datasets were acquired from global data portals including the KNMI Climate Explorer (https://climexp.knmi.nl/start.cgi), the National Centres for Environmental Prediction (NCEP), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the PotsDam Institute for Climate Impact Research (http://www.pik-potsdam.de/~mmalte/rcps/). Their detailed summary is provided in Table 2.1.

Table 2.1: Data requirements and collection

Data	Level	Source	Period	Resolution	Format	Purpose
Rainfall	Surface	a) Climate Research Unit (CRU) b) South African Weather Service (Station)	1987-2016	Monthly; Stations	Point; Text	Inter-annual rainfall variability; Rainfall characteristics
Outgoing Longwave Radiation (OLR)	200 mb	National Centres for Environmental Prediction (NCEP) Reanalysis II	1987-2016	Pentad; 2.5°x2.5°	Gridded; NetCDF	Variability of convection; active and break periods, wet and dry spells, onset and cessation
Sea Level Pressure (SLP)	Surface	NCEP Reanalysis II	1987-2016	Monthly; 2.5°x2.5°	Gridded; NetCDF	Surface pressure features
Geopotential Heights	850 mb 500 mb 200 mb	NCEP Reanalysis II	1987-2016	Monthly; 2.5°x2.5°	Gridded; NetCDF	Typical pressure and circulation patterns associated with particularly wet and dry spells
Circulation, zonal (u), meridional (v) and vertical velocities (w) and the wind vector	Surface, 850 mb, 500 mb, 200 mb	NCEP Reanalysis II	1987-2016	Monthly; 2.5°x2.5°	Gridded; NetCDF	Surface and upper airflow patterns, uplift and subsidence
Southern Oscillation Index (SOI)	Surface	NCEP Reanalysis II	1987-2016	Monthly; 2.5°x2.5°	Gridded; NetCDF	Influence of the El Nino phenomenon on rainfall anomalies
Indian Ocean Dipole Mode Index (IODM)	Surface	Japan Agency for Marine Earth Science and Technology (JAMSTEC)	1987-2016	Monthly; 5°x5°	Gridded; NetCDF	Influence of the Indian Ocean Dipole on seasonal rainfall anomalies
Divergence field	Surface, 500 mb and 200 mb	NCEP Reanalysis II	1987-2016	Monthly; 2.5°x2.5°	Gridded; NetCDF	Areas of convergence and divergence, uplift and subsidence
Potential Evapotranspiration (PET)	Surface	NCEP Reanalysis II	1987-2016	Monthly; 2.5°x2.5°	Gridded; NetCDF	Variability of the surface water balance
Radiative forcing; Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5	Boundary layer	Potsdam Institute for Climate Impact Research	2000-2100	Annual emissions; global	ASCII	Simulate the future rainfall scenarios under RCP4.5 and RCP8.5

2.3.2 Time series analysis

The analyses focused on the austral summer season from October-March which may be further subdivided into the early summer (October-December), the main rainy season (December-February) and the late summer (January-March). The atmosphere over South Africa is extra-tropical and may be conditionally unstable during the early summer while being tropical and convectively unstable during the late summer (DAbreton and Lindesay, 1993; DAbreton and Tyson, 1994; Dyson *et al.*, 2015). This created the need to study the two seasons distinctively.

Time series of historical (1960-2016) climate data were analysed for seasonal cycles, and variability of onset and cessation seasonal cycles using percentiles. Cycles longer than the annual cycle in the data are analysed using wavelet analysis using the Morlet wavelet. Long-term trends and correlations with large-scale climate signals (e.g. ENSO, IOD) were also analysed.
The analysis of the regional circulation was made to study the large-scale impacts of rainfall variability including geopotential height anomalies at various levels via composite analysis. Middle-level vertical velocity (omega) was analysed for uplift and subsidence whilst OLR anomalies indicate areas of enhanced or suppressed convection. Moisture flux and divergence fields, and humidity anomaly structure for seasons with high and low rainfall were also analysed.

2.3.3 Climate models selected for the study

The global climate models used in this study were obtained from the Coupled Model Inter-comparison Project Phase 5 (CMIP5), listed in Table 2.2 whilst the regional models were obtained from the Coordinated Regional Downscaling Experiment (CORDEX) and are listed in Table 2.3. The regional climate models (~50 km resolution) were nested differently within the global models and, the data was re-gridded to 0.5° x 0.5° (longitude, latitude) to improve the resolution on a localized scale. The projections are considered for both RCP4.5 which is a high mitigation scenario and RCP8.5 a medium to low mitigation scenario. In this study, the far future (2036-2065) changes in rainfall are expressed as percentages whilst the temperature changes are in °C and calculated relative to the baseline period (1976-2005).

Table 2.2: Selected driving Global Circulation Models (GCMs) of different resolutions

MODEL NAME (GCMs)	INSTITUTE/COUNTRY	RESOLUTION	LITERATURE
MIROC5	CCCMa (Canada)	1.4°x1.4°	Watanabe *et al.* (2011)
CNRM-CM5	CNRM-CERFACS(France)	1.4°x1.4°	Voldoire *et al.* (2013)
MPI-ESM-LR	MPI-M(Germany)	1.9°x1.9°	Ilyina *et al.* (2013)
HadGEM2-ES	Hadley Centre (UK)	1.8°x1.2°	Collins *et al.* (2011)

Table 2.3: Selected Regional Climate Models (RCMs) of 0.4°x0.4° resolutions

RCM NAME	INSTITUTION	REFERENCES
REMO2009 (v1)	Helmholtz-Zentrum Geesthacht, Climate Service Centre, Max Planck Institute for Meteorology (MPI-CSC)	Jacob *et al.* (2012)
RCA4 (v1)	Swedish Meteorological and Hydrological Institute (SMHI)	Samuelsson *et al.* (2011)
CCLM4-8-17 (v1)	Climate Limited-area Modelling Community (CLM-Community, CLMcom)	Panitz *et al.* (2014)

2.3.4 Conformal Cubic Atmospheric Model (CCAM)

The study had proposed to use General Circulation Models (GCMs) from CORDEX for simulating climate change scenarios under the RCP8.5 (high baseline concentrations) and RCP4.5 (medium-low mitigation) climate change scenarios. Deliberations with the WRC Project Reference Group at one of its meetings indicated it was better to use CCAM climate projections developed by Council for Scientific and Industrial Research (CSIR) which are readily available for the whole of southern Africa. This was because CCAM projections have an 8 km resolution as opposed to regional models forced by the CORDEX which have a coarse resolution of around 50 km, which are not ideal for small catchments such as the Luvuvhu River Catchment. Thus, downscaled and bias-corrected CCAM projections were used to drive the SWAT hydrological model in the Luvuvhu Catchment which is detailed in Chapter 3. The main reason for this was the size of the Luvuvhu River Catchment and the resolution of CORDEX models. It is acknowledged here that the projections from an ensemble of CORDEX models would produce better results compared to simulations from a single model, but for application to the SWAT model, the CCAM was more practical.

2.4 RESULTS AND DISCUSSIONS

2.4.1 Historical trends

The Limpopo Province in South Africa is characterised by strong climate change and global warming signals from observations and climate models. Maximum temperatures have risen by more than 2°C since 2000 above the 1981-2010 long term mean (Figure 2.3). In a study by Engelbrecht *et al.* (2015), it was found that surface air temperatures over the African continent had risen at a rate more than double the global average rate.

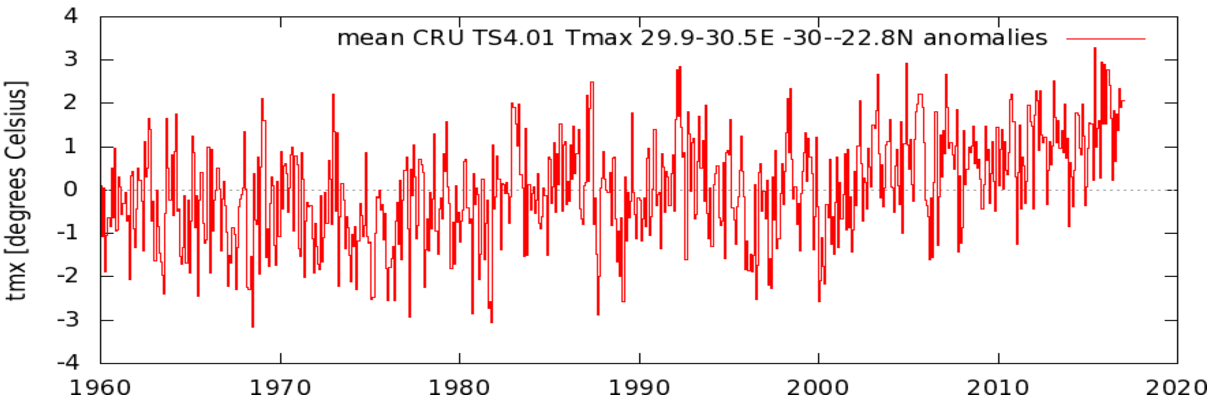

Figure 2.3: Climatic Research Unit (CRU) surface maximum air temperature anomalies (1960-2017)

Five of the hottest years since records began have occurred since 2014, with 2016 being the hottest on record (Figure 2.4). The temperature trend is also accompanied by increased frequency of heatwaves especially during drought years in the catchment. These very high temperatures have serious implications for increased evaporation from open water and exposed soils with even dire consequences for human health.

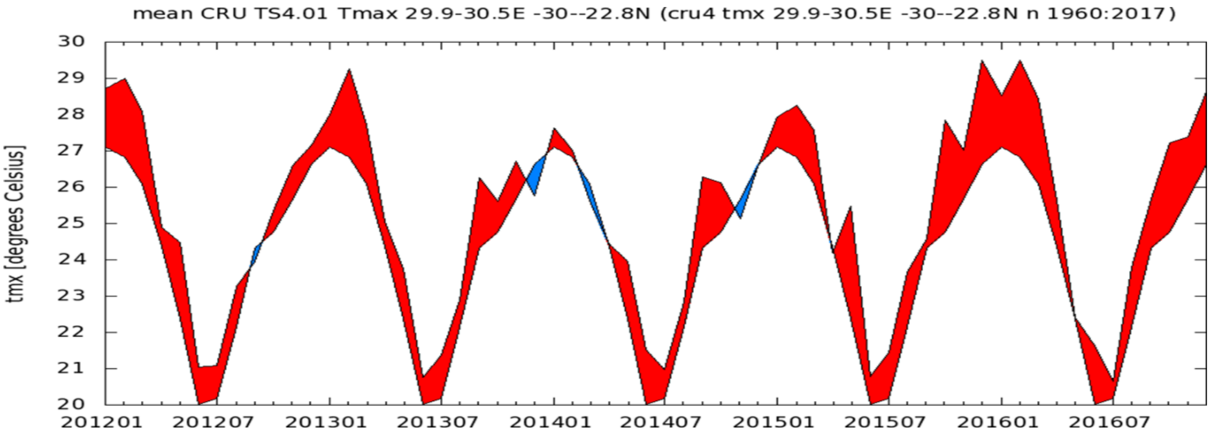

Figure 2.4: Departures of CRU maximum temperatures from the annual cycle

The Luvuvhu River Catchment exhibits a high degree of spatial and temporal rainfall variability. Complex orographic effects due to the Soutpansberg Mountain Range also add to this variability. The mean annual cycle of rainfall peaks during January (Figure 2.5) but the drier (drought) years have an earlier peak in December (2.5% percentile) whereas the wetter years (97.5% percentile) have a later peak in February. The February peak is likely to be due to flood events caused by tropical cyclone landfalls from the southwest Indian Ocean.

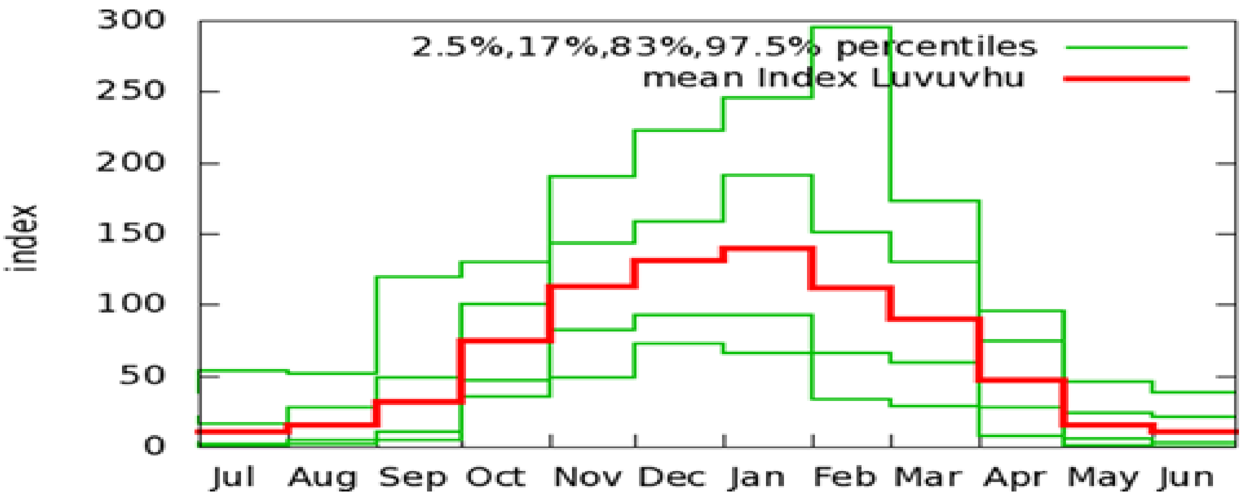

Figure 2.5: Annual cycles of rainfall in the Luvuvhu River Catchment (mean is shown in red)

Rainfall trends are affected by the increase in extreme events in the catchment. By far the wettest period remains the 1999/2000 rainfall season which was dominated by the landfall of tropical cyclone Eline in February 2000 (Figure 2.6), which is detailed in Reason and Keibel (2004). Other landfalls have occurred since then and affected the catchment. These include tropical cyclone Dando which flooded the lower Luvuvhu River Catchment during February 2012 (Chikoore *et al.*, 2015) during a drought season (Figure 2.6). A tropical continental low brought heavy rainfalls during 2013 (Figure 2.6) whilst there was a recent threat from tropical cyclone Dineo which had a track just north of the Limpopo River (Moses and Ramotonto, 2018). The recent tropical cyclone Idai (March 2019) which affected Mozambique, Zimbabwe and Malawi became the most intense cyclone in the Southern Hemisphere since the record began. The 2014/15 and 2015/16 drought seasons were some of the worst to have affected the catchment (Figure 2.7).

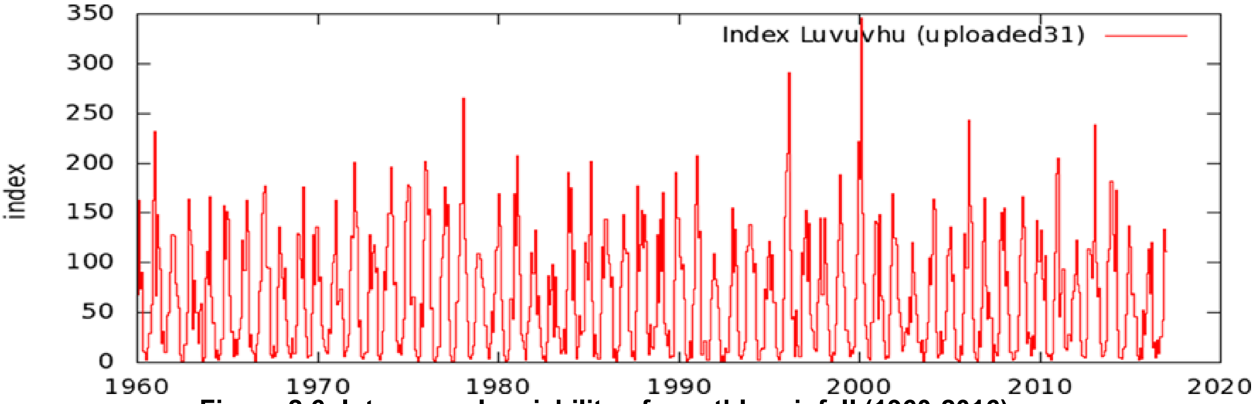

Figure 2.6: Interannual variability of monthly rainfall (1960-2016)

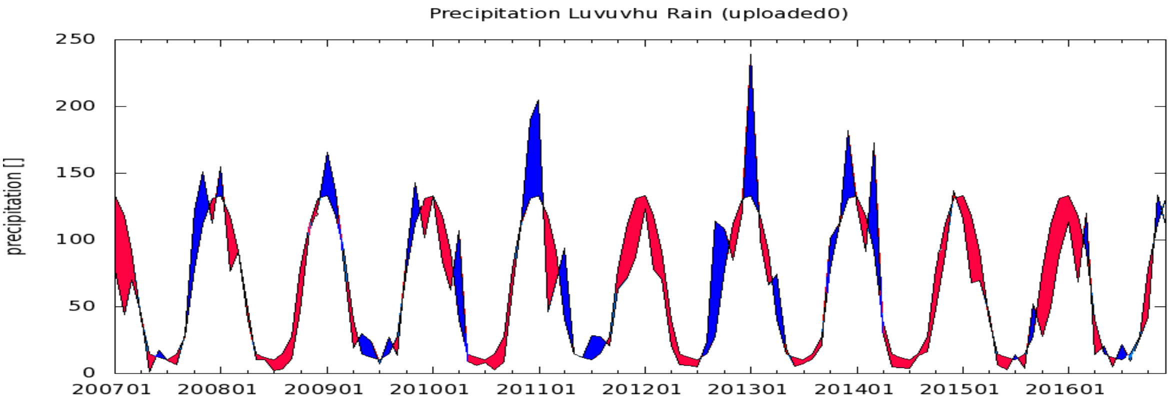

Figure 2.7: Departures from the mean annual cycle of rainfall (2007-2016). Red means below average and blue means above-average rainfall

An analysis of cycles in the data shows three dominant cycles occurring at 3-5 years, 10-11 years and 18-20 years (Figure 2.8), which are all linked to remote influences from ENSO, the Sunspot cycle and an 18-year oscillation in sea surface temperatures (SSTs) southwest of the subcontinent. The high-frequency 3-5-year oscillation has become more dominant since about 1995 as it is also in the wavelet cone of influence (Figure 2.8).

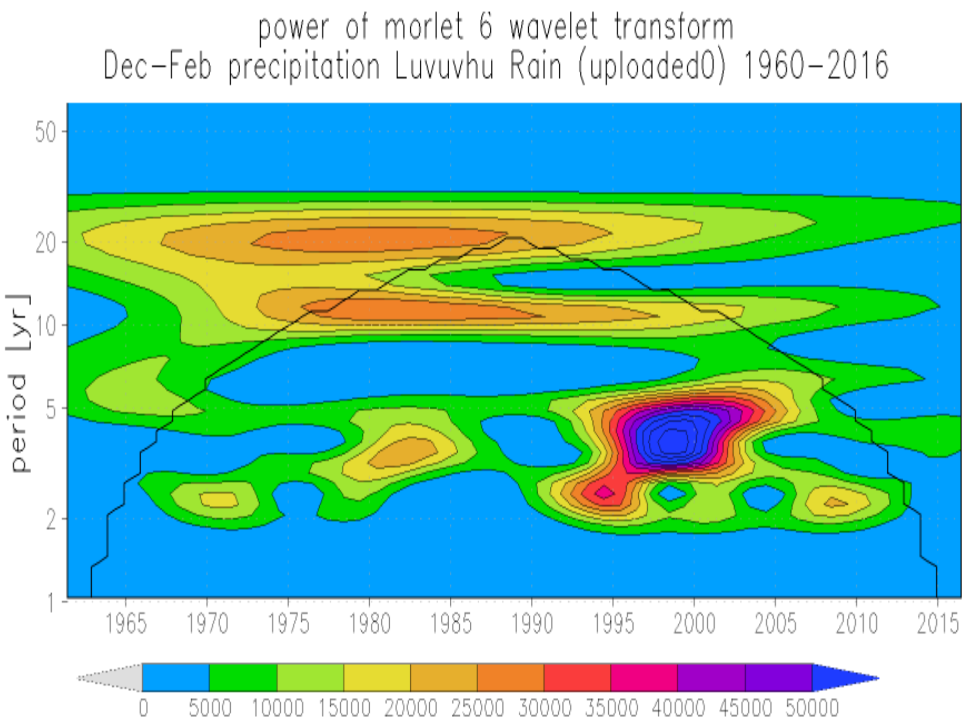

Figure 2.8: Morlet wavelet analysis of Luvuvhu rainfall (1960-2016)

Drought events in the catchment are consistently related to El Nino events in the equatorial Pacific Ocean with a correlation of 0.48 (Figure 2.9). Usman and Reason (2004) defined a drought corridor in southern Africa over the latitudes 20-25°S that corresponds to the geographical area of the Luvuvhu River catchment. The El Nino phenomenon is also used as the main predictor for seasonal rainfall in southern Africa with a probability of below normal of over 80% during a strong El Nino (Figure 2.10). The recent (2015/16) and most intense El Nino on record also resulted in one of the most severe and hottest droughts in the catchment. Global warming and climate change are compounding the effect of El Nino.

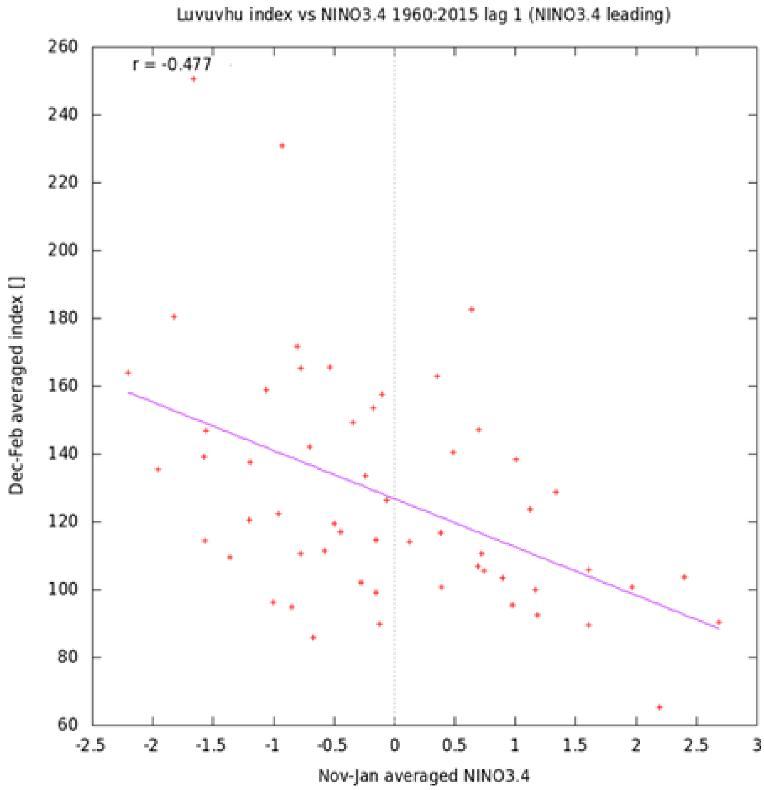

Figure 2.9: Correlation between rainfall in the Luvuvhu River catchment with Nino3.4 leading

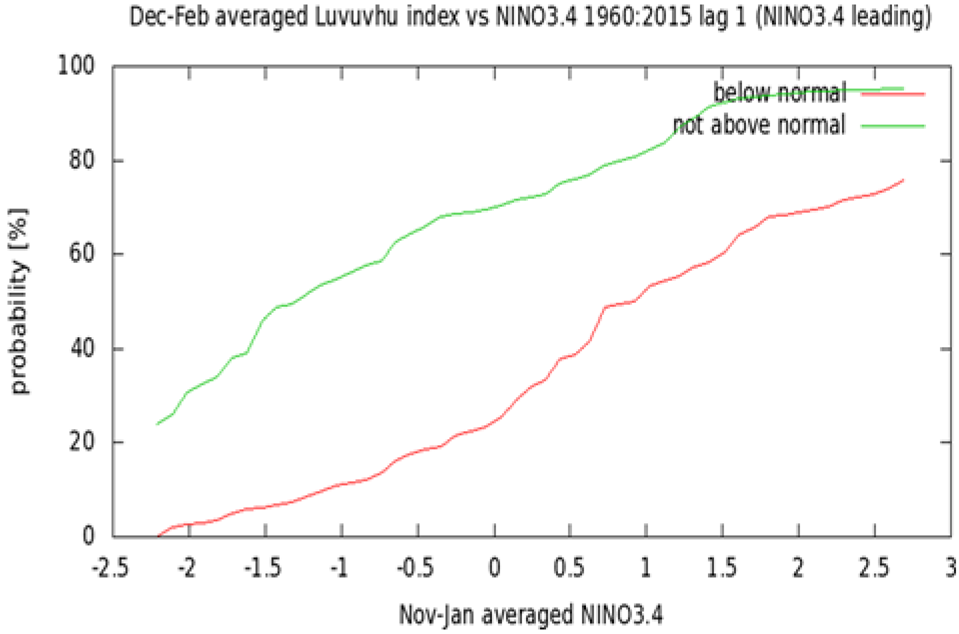

Figure 2.10: Probability of "below normal" and "not above normal" rainfall based on a Nino3.4 index

Characteristics of the rainy season over the Luvuvhu River Catchment are also changing in response to climate change. Changes to the annual cycle of rainfall have been observed with a shift or delay in the onset of the summer rainfall season and, therefore, a prolonged dry season. November rainfall has been declining particularly since the year 2000 (Figure 2.11) resulting in a prolonged dry season with a corresponding lengthening of the fire season. The frequency of mid-season dry spells has been increasing whilst intense precipitation has become more intense consistent with thermodynamic arguments.

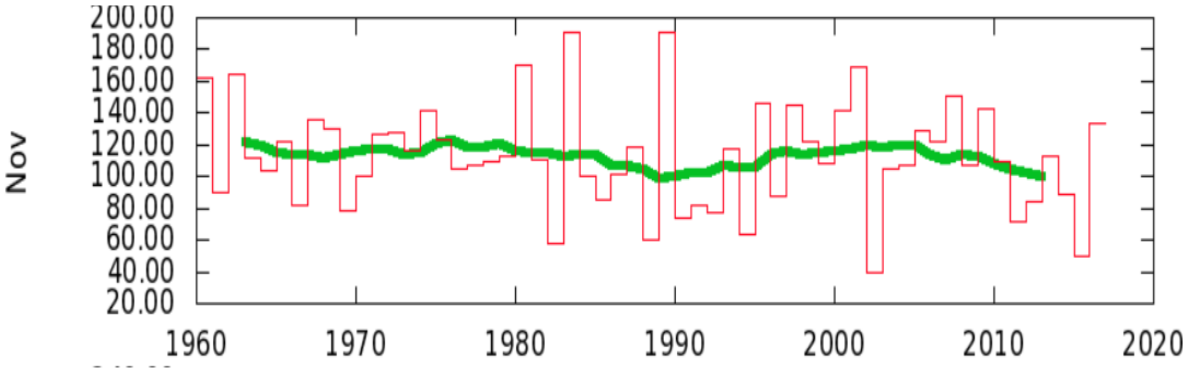

Figure 2.11: Trends of November monthly rainfall in the Luvuvhu River Catchment (1960-2017)

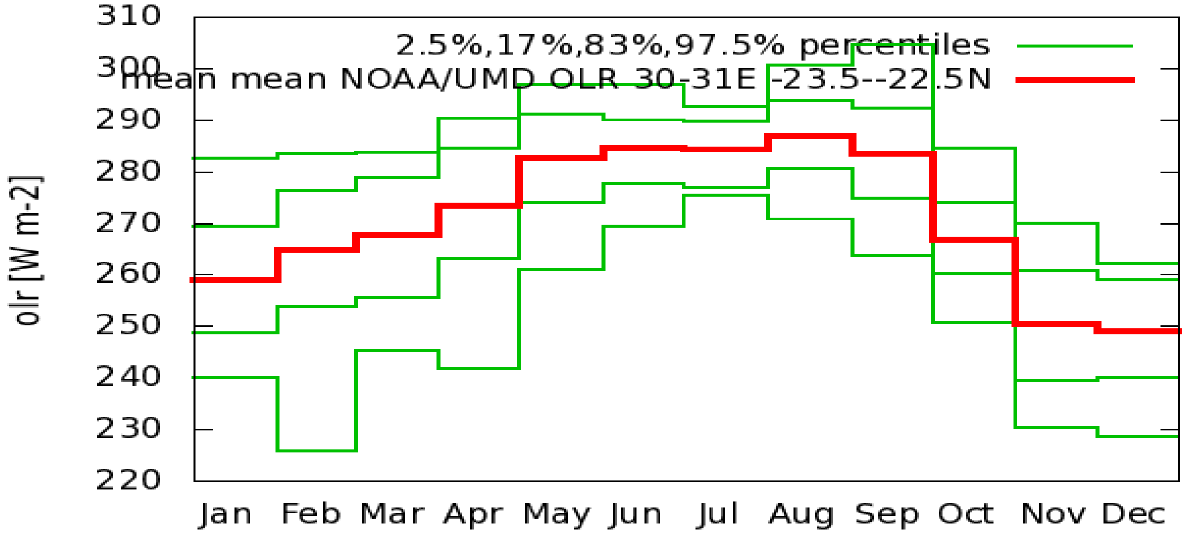

Figure 2. 12: Annual cycles of outgoing longwave radiation over the Luvuvhu River Catchment (Wm^{-2}). The mean is shown in red whilst the green cycles represent 2.5%, 17%, 83% and 97.5% percentiles

As the climate of the Luvuvhu River Catchment is affected by large scale drivers that lie outside the lateral boundaries of the study area, the circulation variables (sea level pressure, geopotential heights, wind vectors, moisture flux transport and the divergence field) were obtained from the NCEP Reanalysis II (Kanamitsu *et al.*, 2002) and were analysed for a domain that includes the surrounding oceans and the deep tropics (for example, Figures 2.13 and 2.14). The mean summer pattern shown here is significantly altered, for example by the occurrence of an El Nino event in the eastern equatorial Pacific.

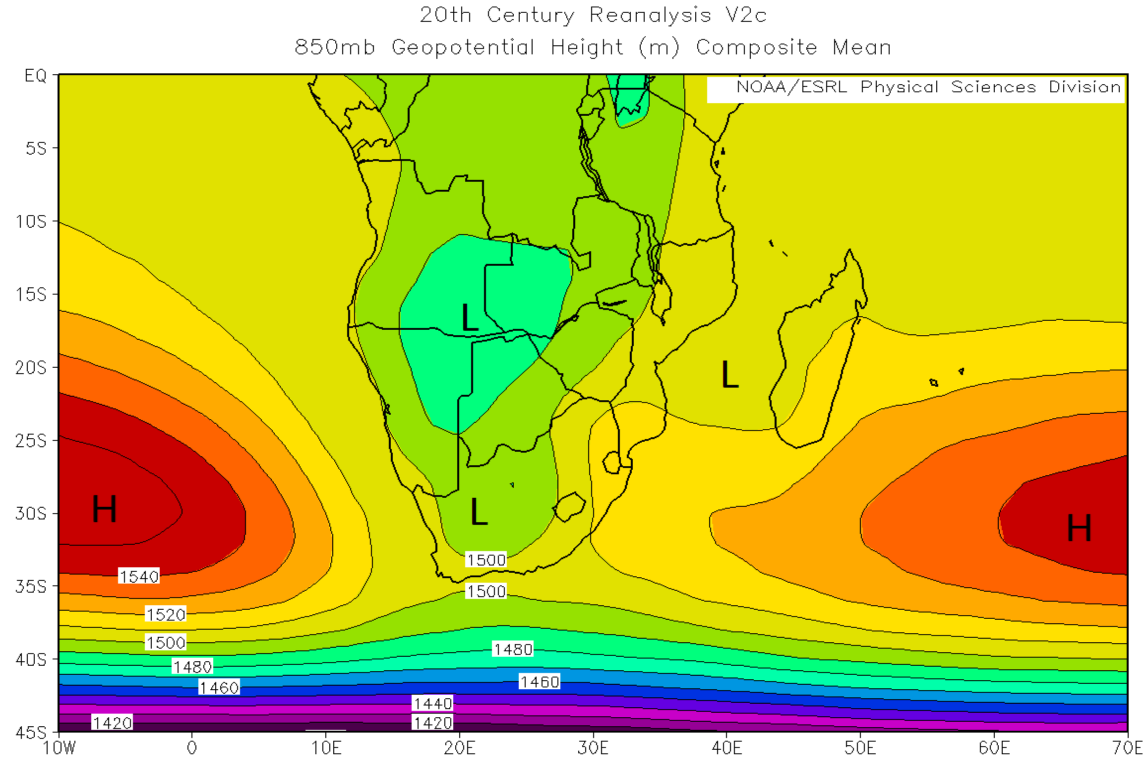

Figure 2.13: Mean summer geopotential height at 850 mb characterising the dominant controls of the low-level circulation over the subcontinent and the adjacent oceans

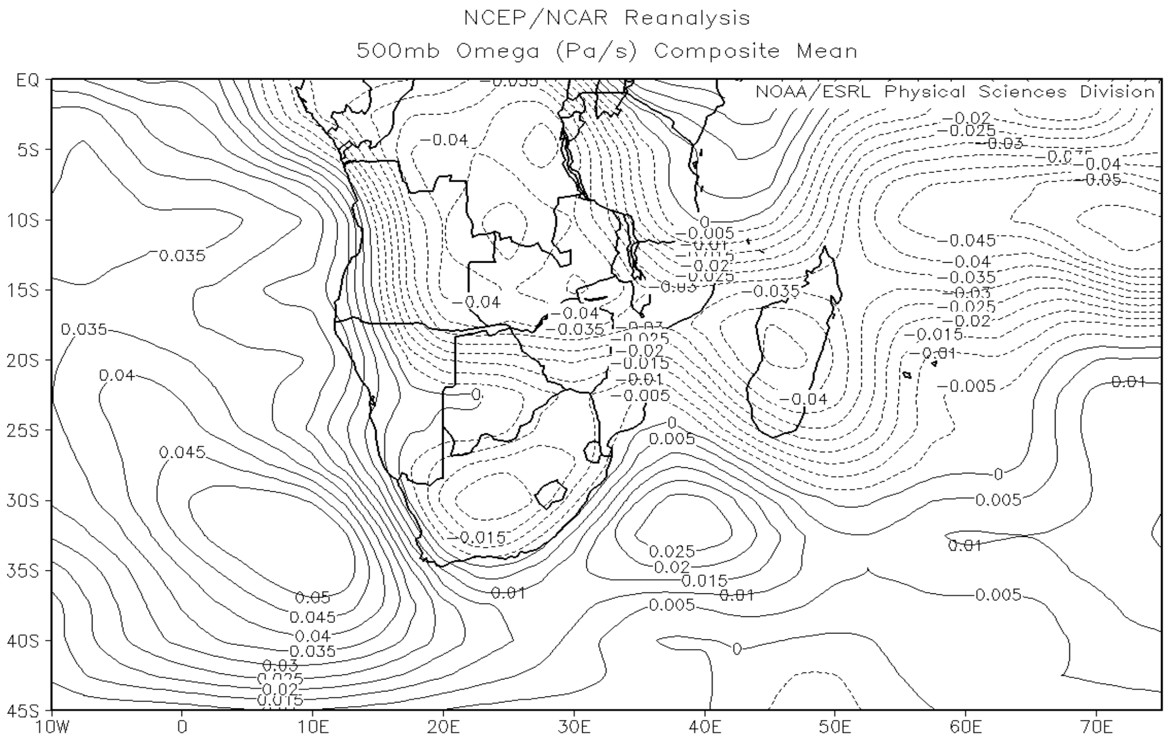

Figure 2.14: Mean summer vertical velocity (omega) over southern African and the adjacent oceans. Negative omega values are associated with uplift, convection, cloud formation and rainfall

The influences of the Pacific and Indian Oceans on the rainfall of the catchment were also tested through analysis of Nino3.4 SST anomalies (Figure 2.15) and the Indian Ocean Dipole Mode (DMI;

Figure 2.16) and cross-correlation with GPCP rainfall data. The correlation of GPCP rainfall across the region with SST anomalies in the Nino 3.4 region of the equatorial Pacific is shown in Figure 2.17. The study area in the Limpopo Province is in an area of significant El Nino impact in South Africa. The climate change signal is also significant in this region.

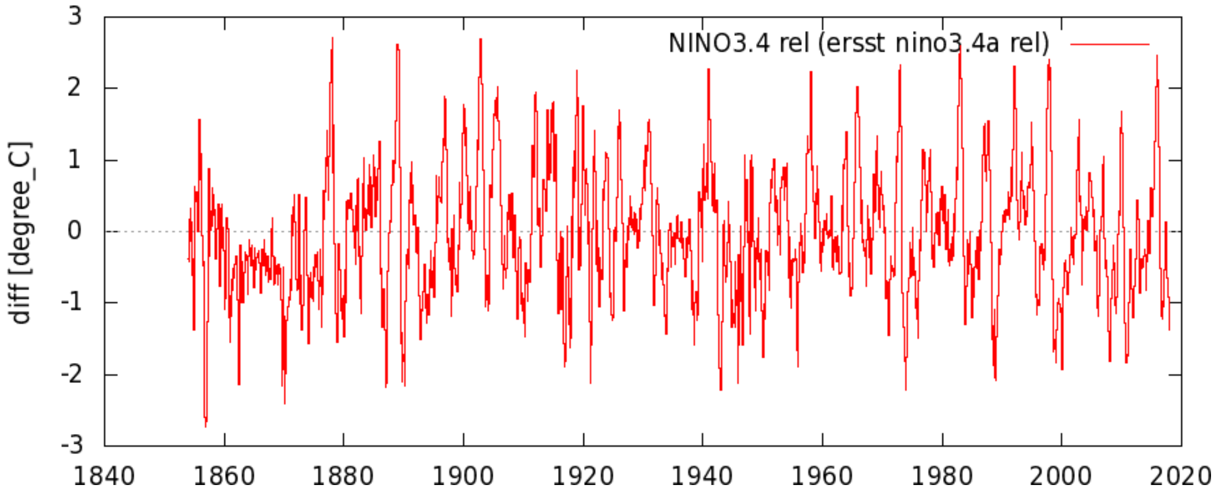

Figure 2.15: Pacific Nino 3.4 SST anomalies over the eastern equatorial Pacific Ocean

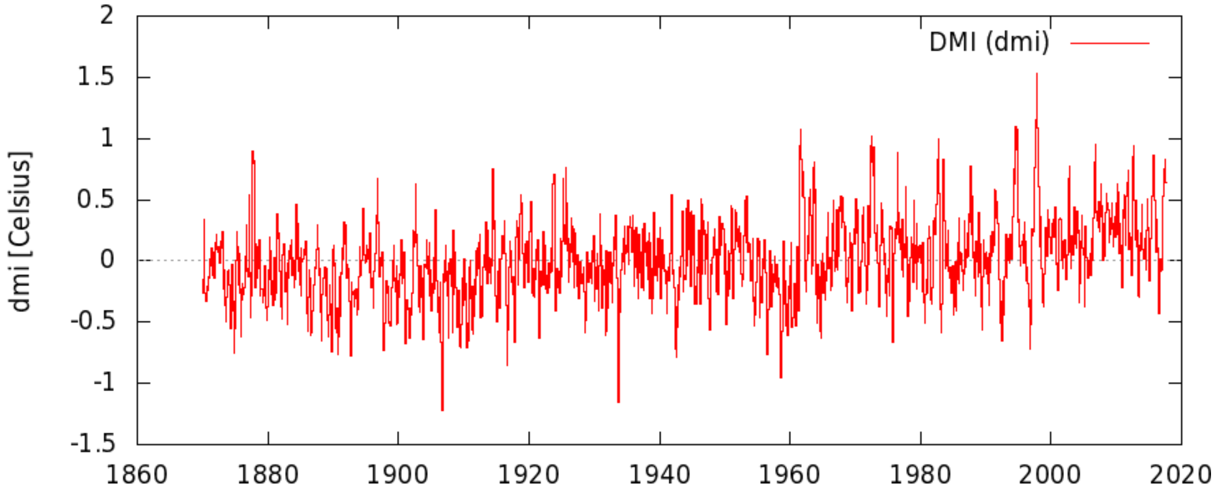

Figure 2.16: Indian Ocean Dipole mode (DMI) over the tropical Indian Ocean from 1870 to present (°C). A positive DMI is mostly associated with drought in the catchment

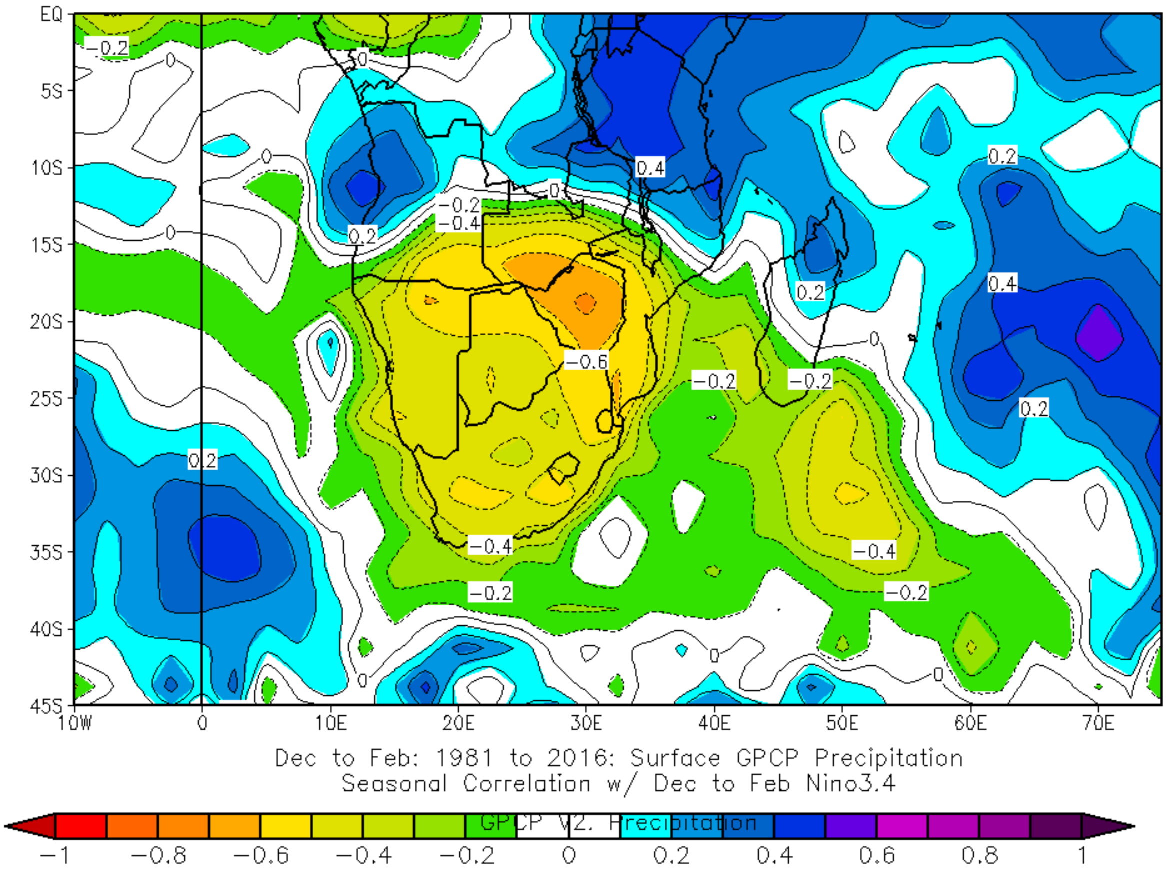

Figure 2.17: Correlation of GPCP precipitation with Nino3.4 SSTs. The shaded areas are significant at 90% or more

2.4.2 Future climate change projections

At long timescales, the change in rainfall patterns in the Luvuvhu River Catchment in the near and far future were modelled based on RCP4.5 and RCP8.5. The RCP 8.5 represents a future with high emissions of greenhouse gases (low mitigation) whilst RCP4.5 is consistent with intermediate emissions. The global average emissions of CO_2 data from pre-industrial times and projections to 2100 were obtained from the PotsDam Institute for Climate Change Impact Research (Figure 2.18).

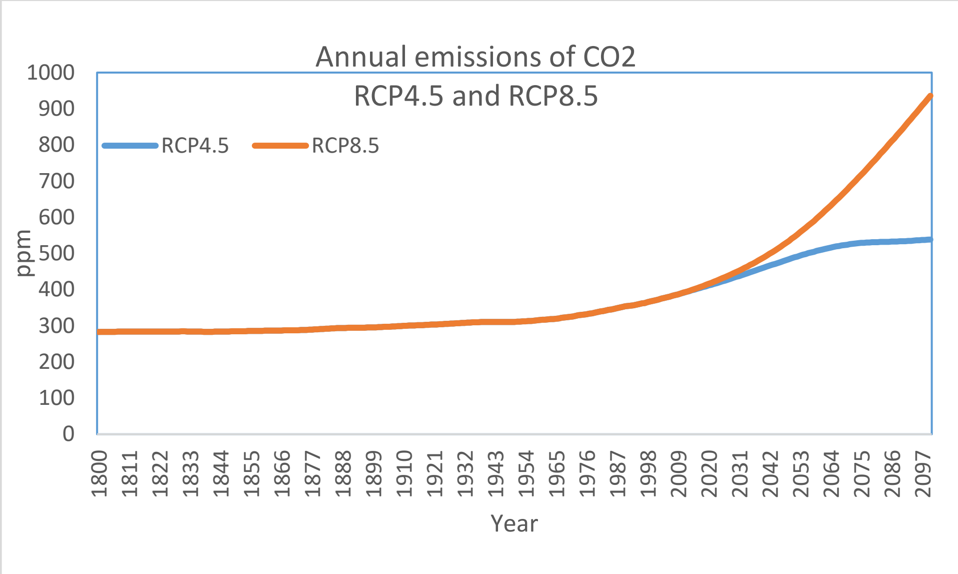

Figure 2.18: Global annual average concentrations of CO_2 from 1800 to present with projections to 2100 (in ppm)

Mean annual temperature change – far future

Significant temperature increases are projected for the far future with values ranging from 2°C to 2.5°C over the central interior and at most 1.5°C for the coastal areas under RCP4.5 (Figure 2.19). REMO2009 nested within MPI, projected consistently lower temperature than other models as was also the case for the near future projections. RCP8.5 projected pockets of intense heating (3°C-4.5°C) at most over western "arid" parts of South Africa including neighbouring deserts (Figure 2.20). Several studies (e.g. Engelbrecht *et al.*, 2015) have projected surfaces to heat up at a faster rate than the rest of the globe over these western parts of southern Africa, linked to the intensified subsidence of dry compressed hot air. The combination of increased temperatures associated with heatwaves and dry spells, subsequently resulting in high-fire danger days (Engelbrecht *et al.*, 2015). This also suggests enhanced evaporation rates, losses of soil moisture and challenges of water supply in the future. High ambient temperatures can directly impact human health through heat-related diseases (Garland *et al.*, 2015; Wright *et al.*, 2015).

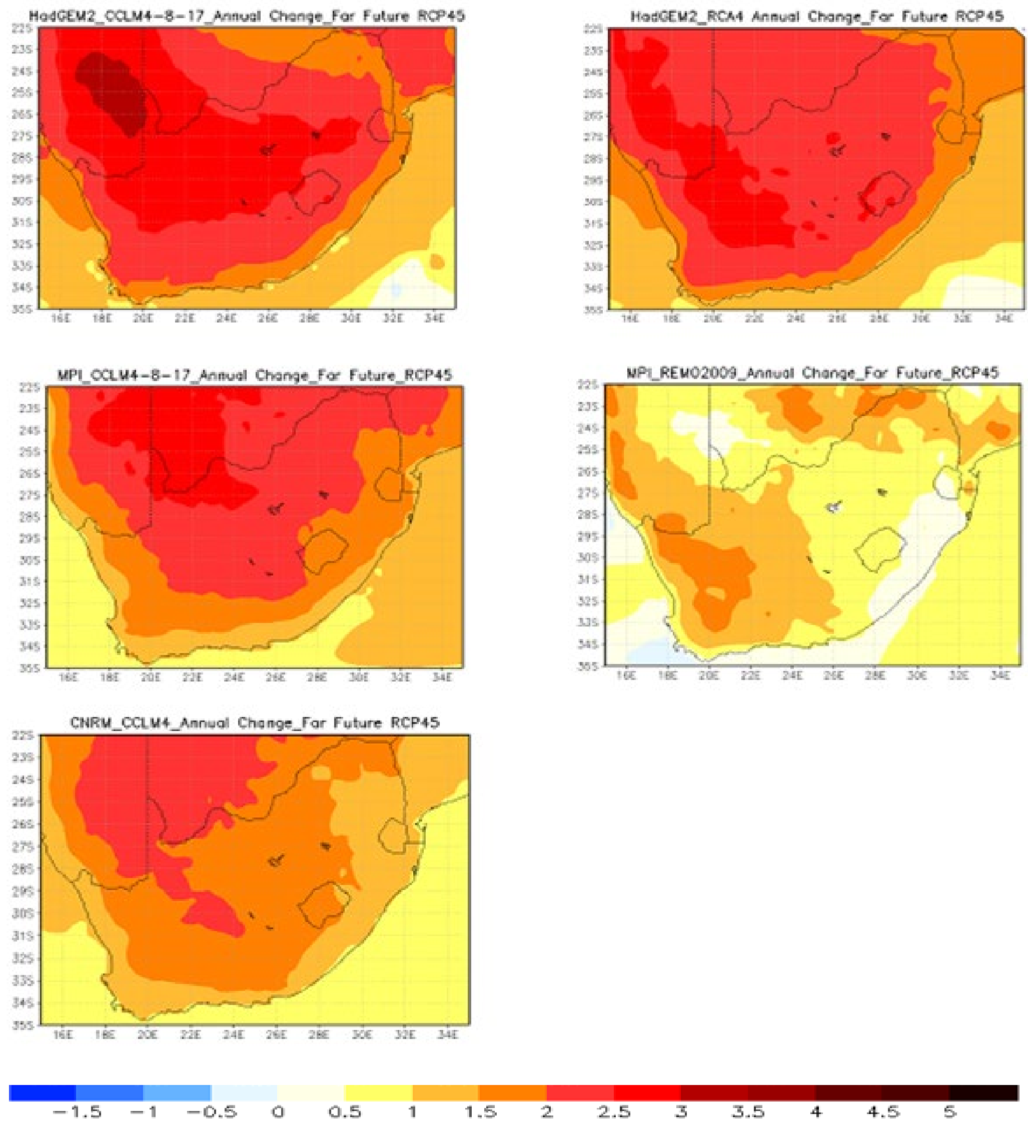

Figure 2.19: Annual mean temperature change (°C) projection, for Far-Future (2036-2065), relative to present climate, under conditions of (a) RCP4.5

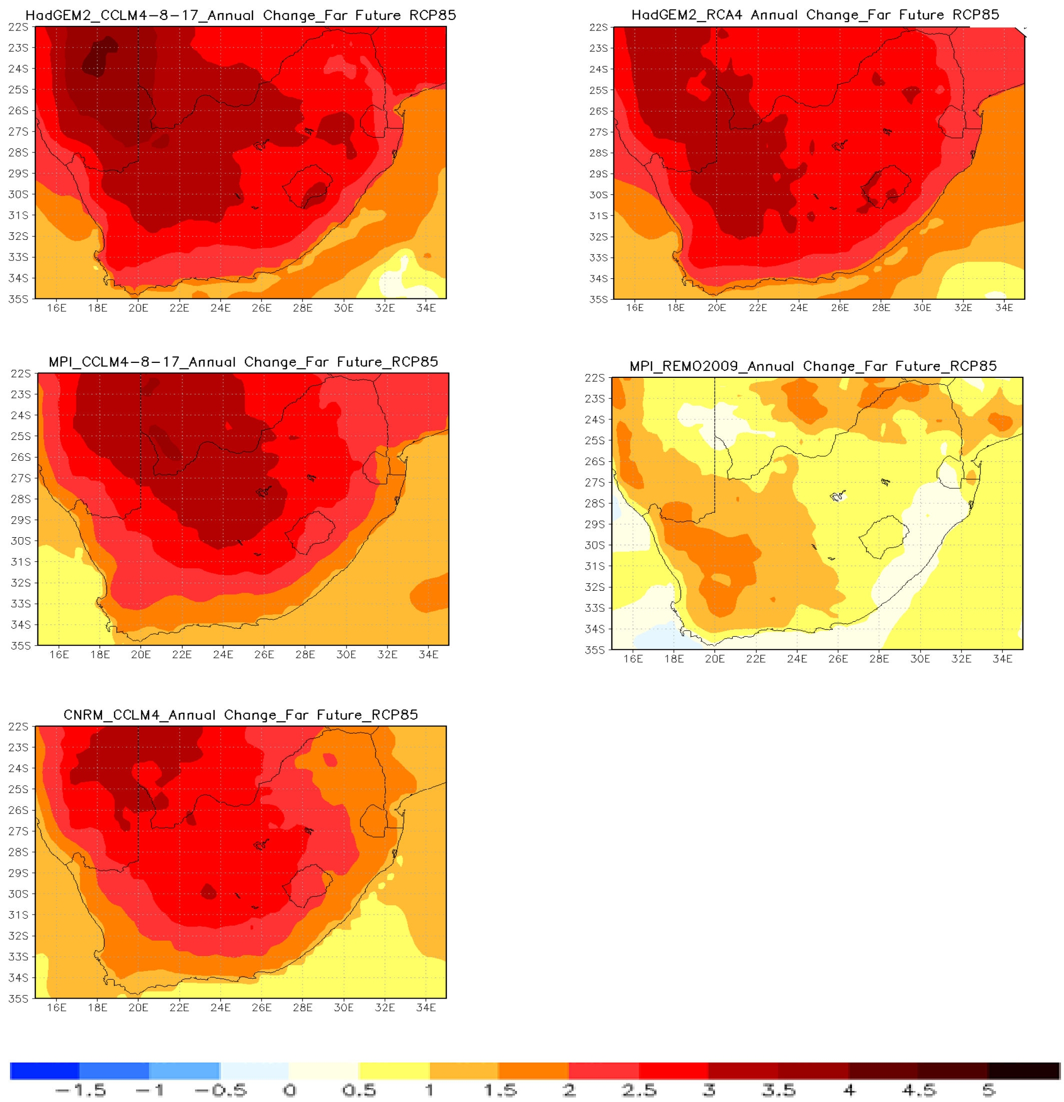

Figure 2.20: Annual mean temperature change (°C) projection, for Far-Future (2036-2065), relative to present climate, under conditions of RCP8.5

Mean DJF rainfall change-far future

The models projected mixed signals of drying and wetting over South Africa (Figure 2.21). However, the different model configurations are all consistent with rainfall decreases over Limpopo. CCLM4-8-17 nested within HAdGEM2 and CNRM and REMO2009 forced on MPI projected slightly increased values (above 5%) over the central interior under RCP4.5 than RCA4 nested within HadGEM2. Areas that are projected to experience increases in rainfall are almost similar to those in the near-future climate (not shown). However, a tongue of extremely decreasing values (-25%) over the eastern parts of the country along the south of Mozambique, tend to be consistently projected by RCMs forced by MPI and CCLM4-8-17 nested on CNRM under RCP8.5 scenario. With regards to the Luvuvhu River Catchment, most of the models under both scenarios, consistently project extreme drying over (-15%), possibly due to the shifting of tropical cyclones (Malherbe *et al.*, 2013) and strengthening of subtropical highs (Engelbrecht *et al.*, 2015). Also, wetting signals over the interior Highveld and southeast coast are projected by most of the models (Figure 2.22), consistent with Engelbrecht *et al.* (2015). As with most climate projections, the rainfall signal is much less robust than the temperature projections.

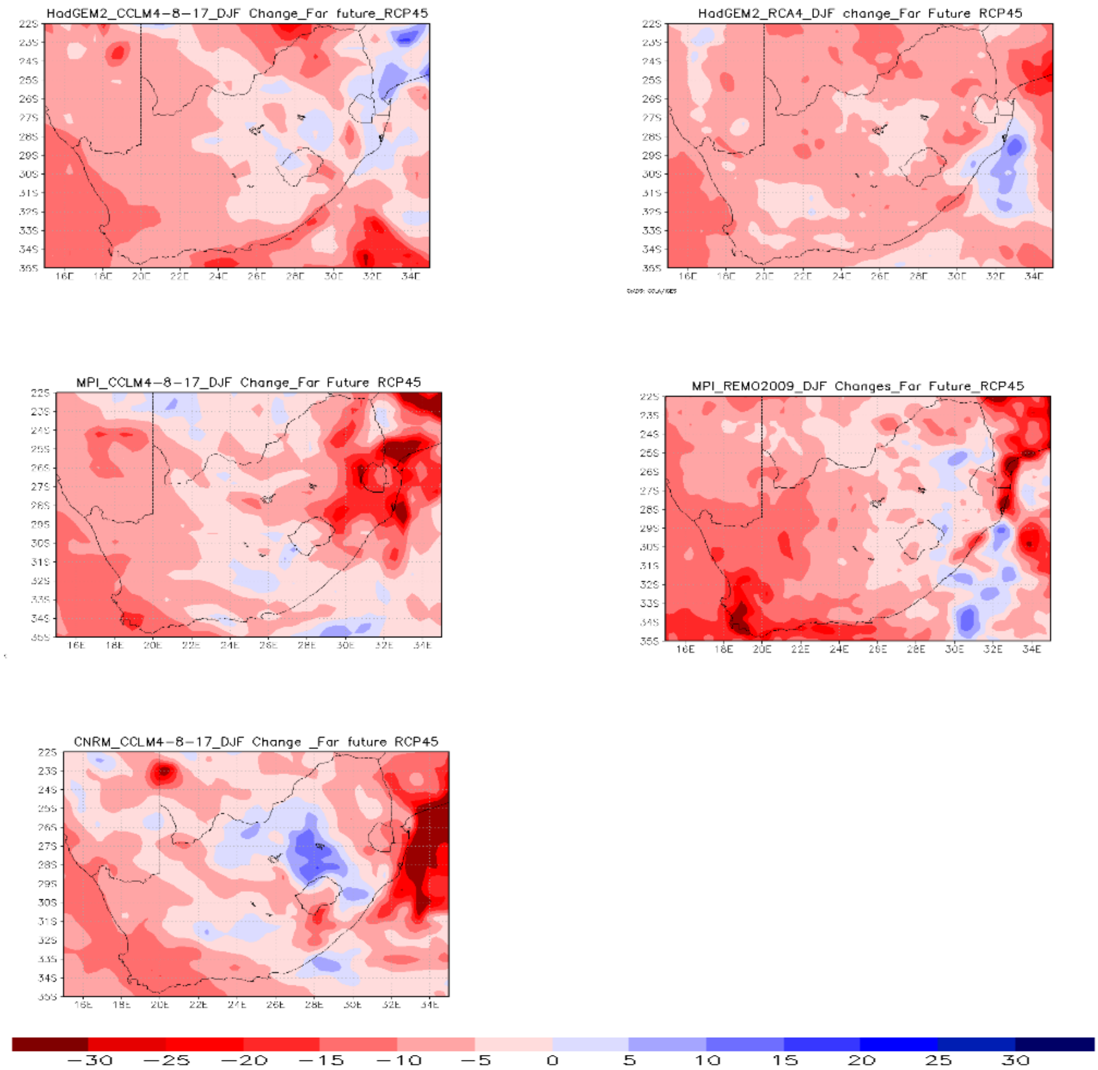

Figure 2.21: DJF mean rainfall change (%) projection, for Far-Future (2036-2065), relative to present climate, under conditions of RCP4.5

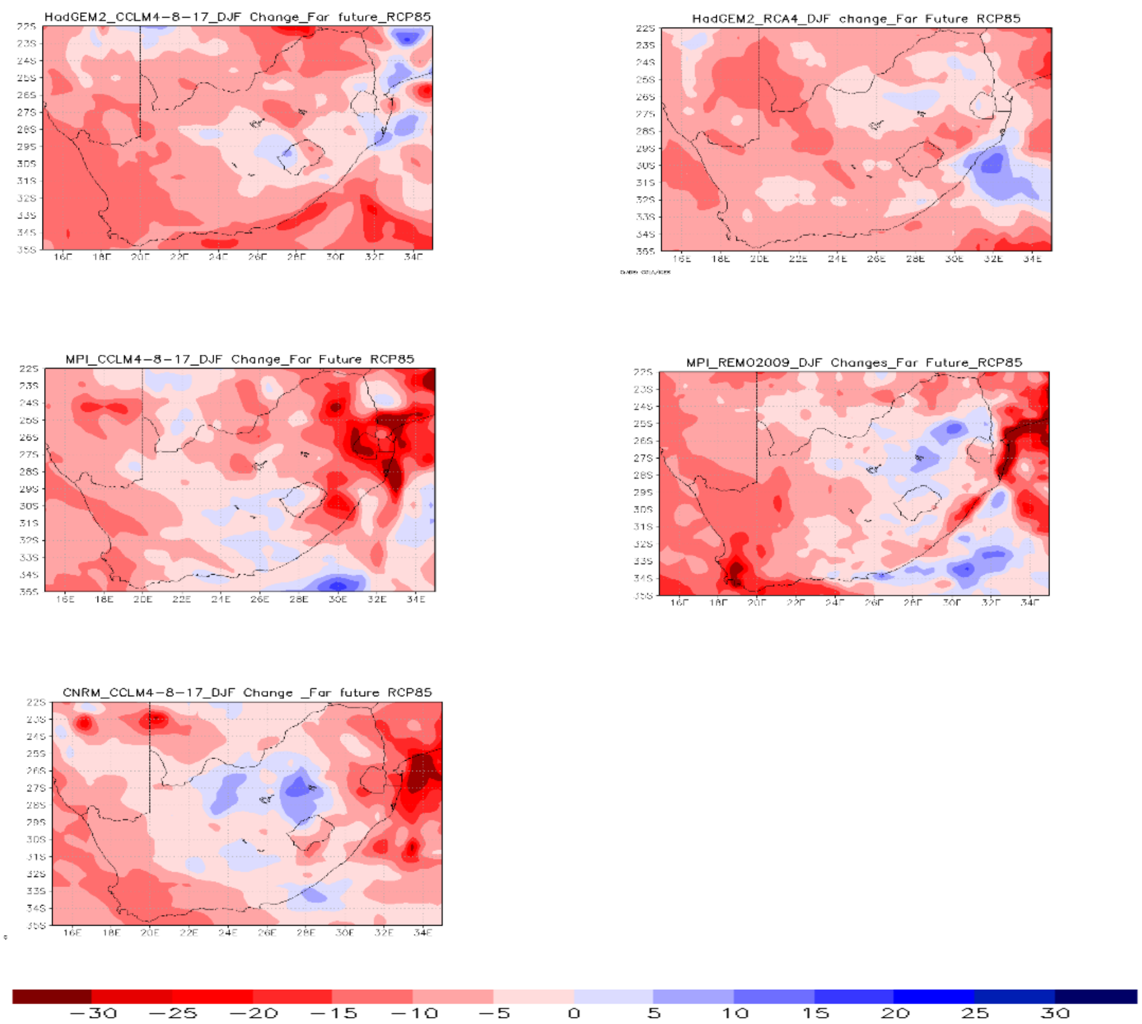

Figure 2.22: DJF mean rainfall change (%) projection, for Far-Future (2036-2065), relative to present climate, under conditions of RCP85

2.4.3 CCAM projections

High-resolution climate change projections under the low mitigation (A2) scenario over southern Africa were obtained from the Conformal Cubic Atmospheric Model (CCAM) runs at 8 km resolution. Downscaled, bias-corrected and SWAT compatible simulations from 1961-2099 were made available through Professor Francois Engelbrecht who is acknowledged here. GCM simulations of the Coupled Model Inter-comparison Project Phase 3 (CMIP3) were downscaled and bias-corrected and were used to force the CCAM projections (Engelbrecht *et al.*, 2015). The model simulations for rainfall and temperature were verified against observations for the period 1961-2010 and climate change anomalies were calculated using present-day climate. Projections of further temperature rises of between 3-5°C were also forecast under low mitigation for subtropical regions including South Africa's Limpopo Province (Figure 2.23).

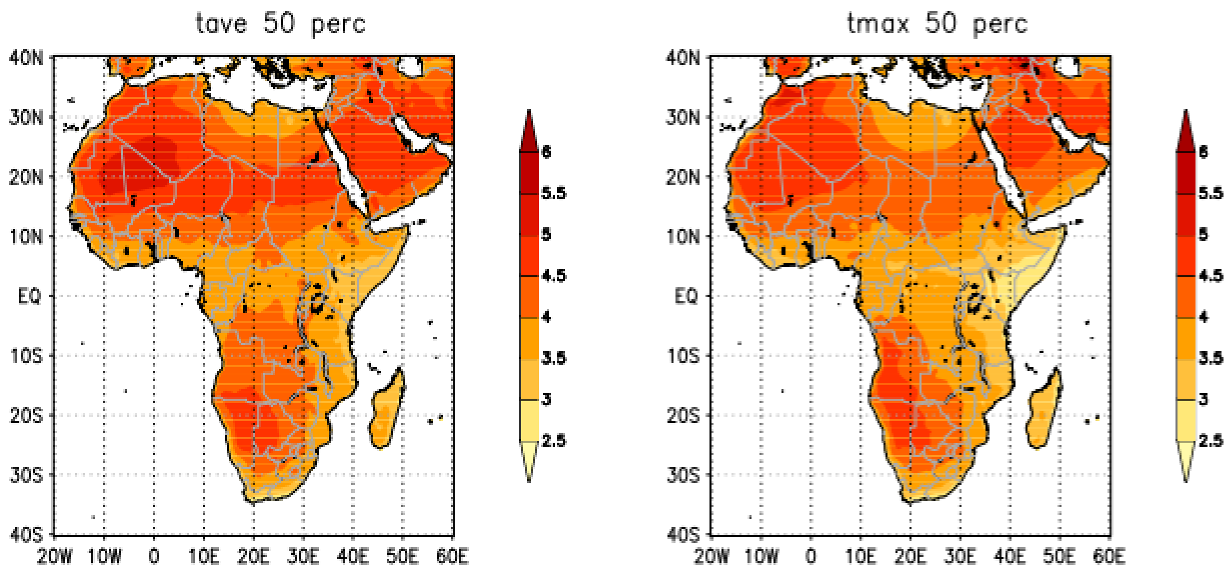

Figure 2.23: CCAM changes in average (left panel) and maximum temperature projections (50th percentile) for 2071-2100 under low mitigation (Source: Engelbrecht *et al.*, 2015)

Heatwave days were also forecast to increase significantly across the Limpopo with large decreases in rainfall (Figure 2.24). The rainfall decreases due to climate change are greatest over the Limpopo in South Africa which may have implications for the surface water balance and water resources of the Luvuvhu catchment. Another study that also used CCAM projections by Garland *et al.* (2015) projected an increase in the number of hot days with increasing risk for human health.

Under low mitigation, rainfall (50th percentile) is projected to decline drastically across western and central southern Africa including South Africa's Limpopo (Figure 2.24). The projected decline in rainfall is consistent with the increased frequency of drought as determined by a Keetch-Bryam drought index (Figure 2.25). The shift in rainfall season has resulted in a prolonged dry season which also implies an extended fire season. The frequency of forest fires was also projected to increase over much of the region, under low mitigation (Figure 2.25).

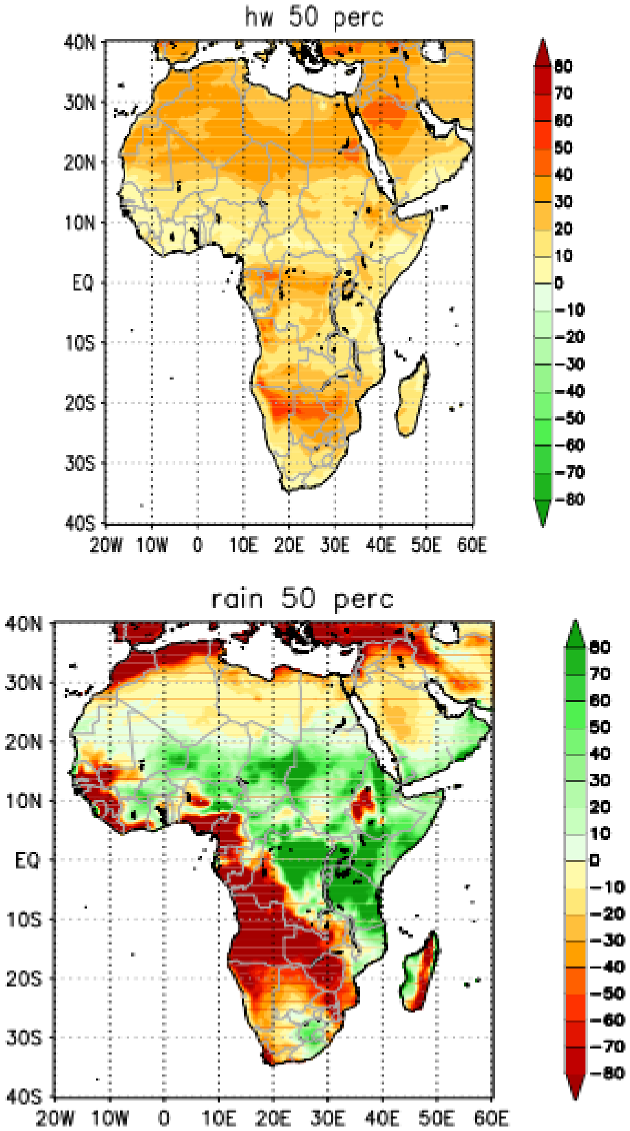

Figure 2.24: CCAM changes in heatwave days (left panel) and rainfall projections (50th percentile) for 2071-2100 under low mitigation (Source: Engelbrecht *et al.*, 2015)

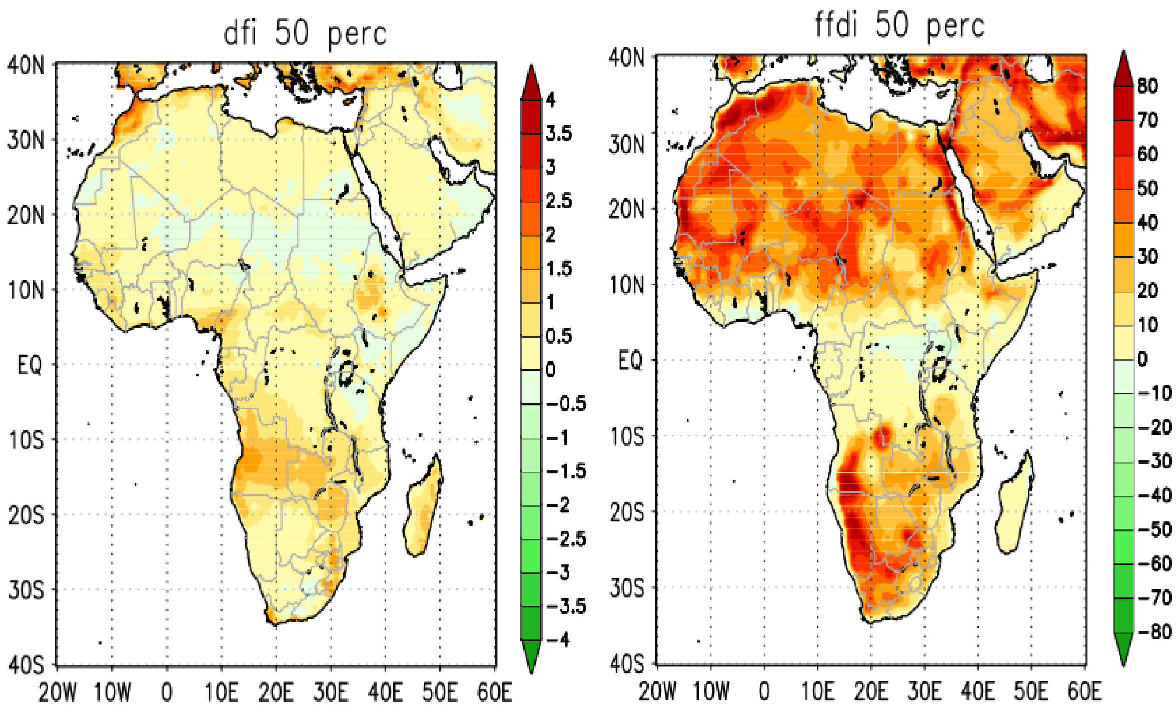

Figure 2.25: CCAM changes and Keetch-Bryam drought index (left panel) and forest fire danger index (50th percentile) for 2071-2100 under low mitigation (Source: Engelbrecht *et al.*, 2015)

For simplification, the average daily temperature for each month of the year for both near and far future projections for selected temperature and precipitation virtual stations (Figure 2.26) representing upstream, midstream and downstream of the Luvuvhu River Catchment were plotted (Figures 2.27 to 2.31). The results generally showed an increase in temperature in the far future in the study area. However, station t-230305 showed a decrease in temperature from near to the far future projections which may be due to local climate variations within the vicinity of this station.

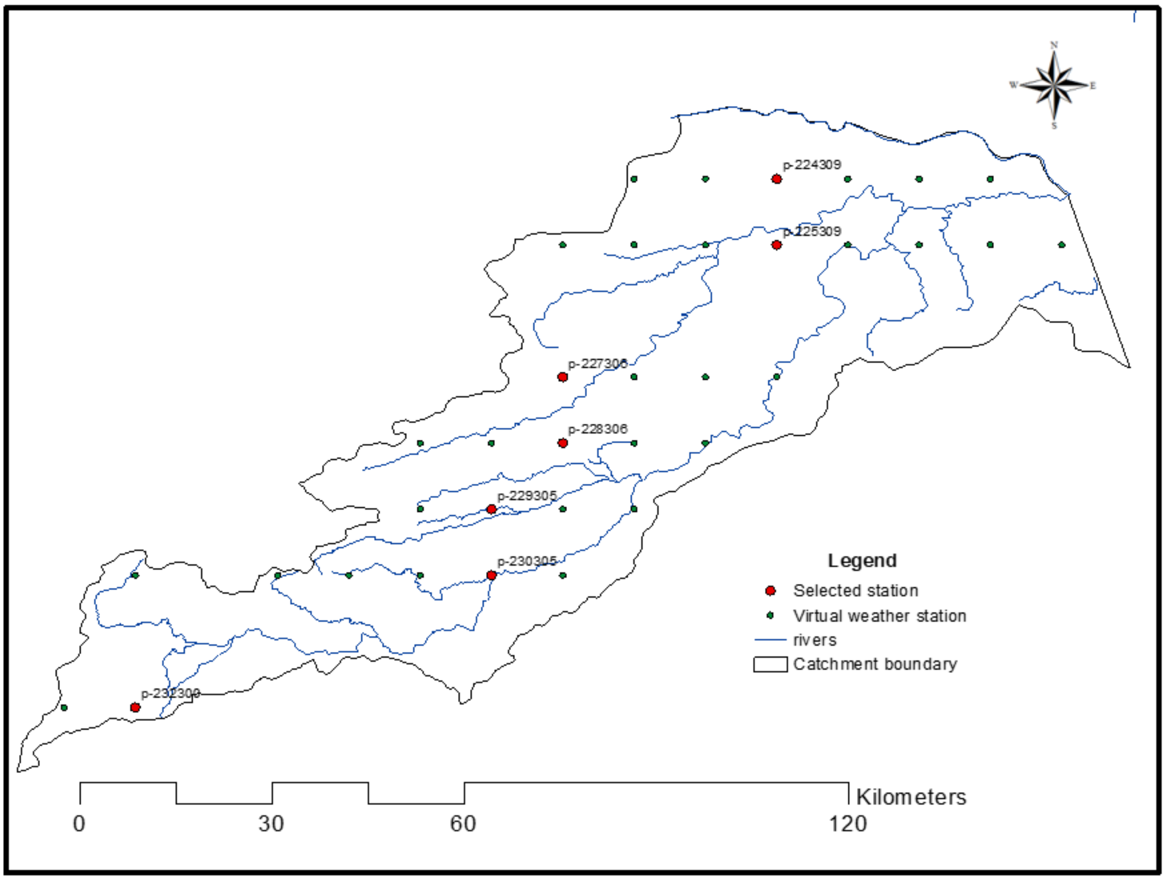

Figure 2.26: CCAM virtual stations used in the study

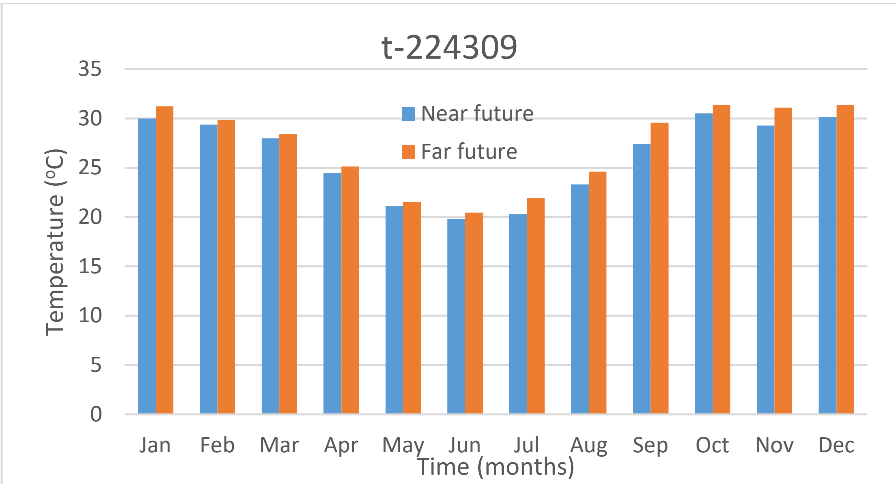

Figure 2.27: Projected monthly average daily temperature for t-224309

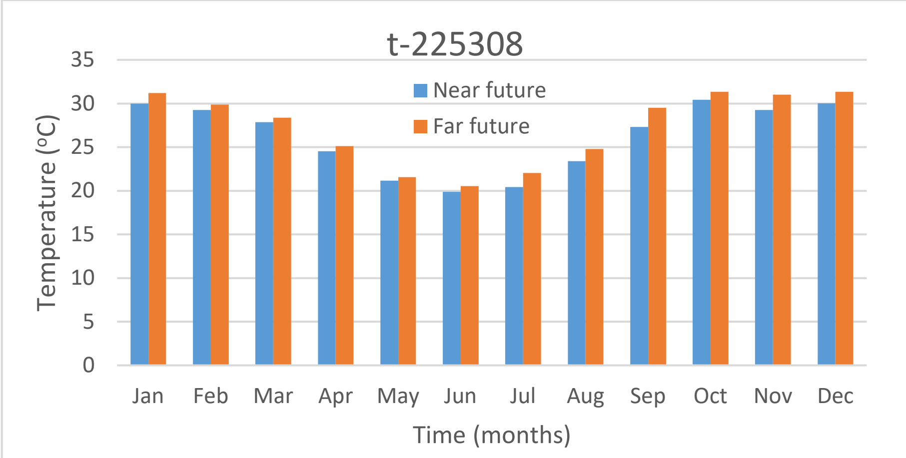

Figure 2.28: Projected monthly average daily temperature for t-2253308

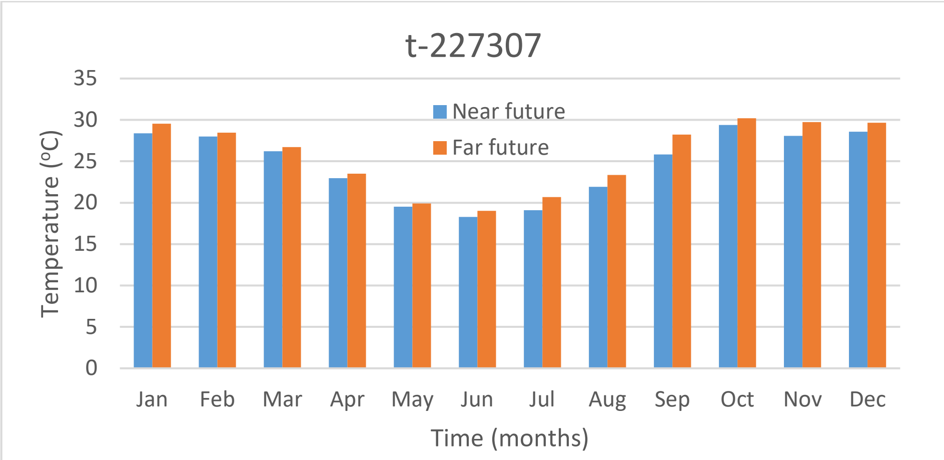

Figure 2.29: Projected monthly average daily temperature for t-227307

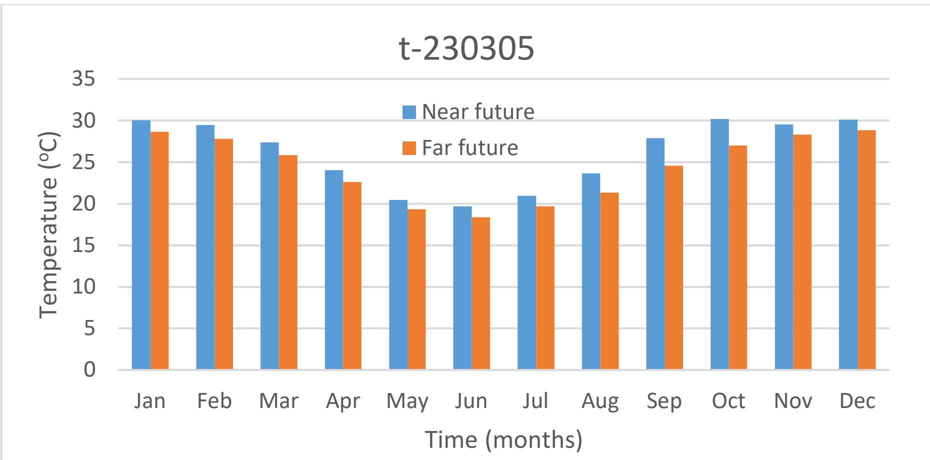

Figure 2.30: Projected monthly average daily temperature for t-230305

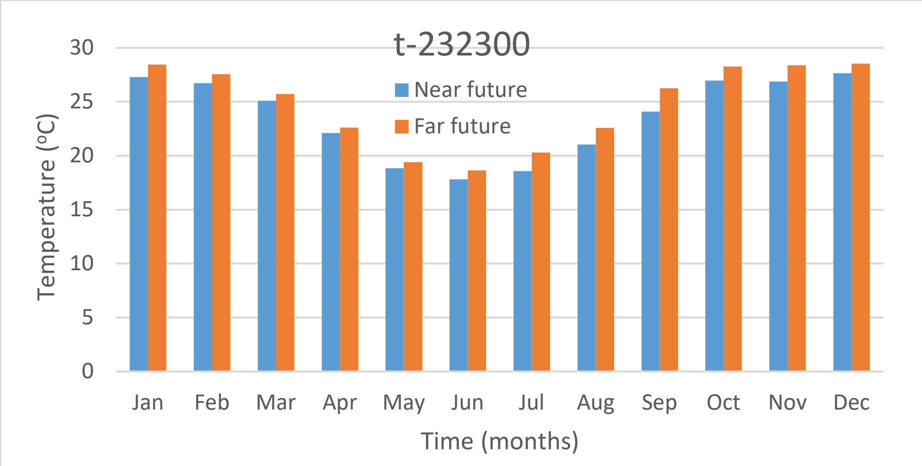

Figure 2.31: Projected monthly average daily temperature for t-2323300

Rainfall behaviour in the Luvuvhu River Catchment varied from upstream to downstream (Figures 2.32-2.36). For most of the stations, it was projected that rainfall will dominantly decrease in most of the months in the future. However, an increase in rainfall was projected for station p-232300 in the far future projections. This may be due to the location of the station which is adjacent to the Soutspanberg mountain range suggesting the likelihood of the effect of orography on future rainfall. All stations indicated that relatively high average monthly rainfall occurs in the rainfall months of November-February while the dry seasons (April to September) have relatively low average monthly rainfall. The average minimum and maximum temperatures also indicated a relatively warmer summer and cooler winter months. These indicate that virtual stations captured the rainfall and temperature behaviour of the Luvuvhu River Catchment.

If average rainfall for the near future was higher than that for the far future, rainfall was considered to be decreasing. An increase in rainfall was considered if the near future rainfall for a particular month was lower than that of the far future. Both increase and decrease in future rainfall were dominant for stations p-232300, p-230305, p-224309 and p-225308 while p-229305 showed a dominant decrease in future rainfall (Figures 2.32-2.36). Concerning the rainfall season, the months of October, December and January had a dominant increase in rainfall while November, February and March had a dominant decrease in rainfall for all stations (Table 2.4). The results indicate variable behaviour in the future where both extreme events (drought and floods) will prevail.

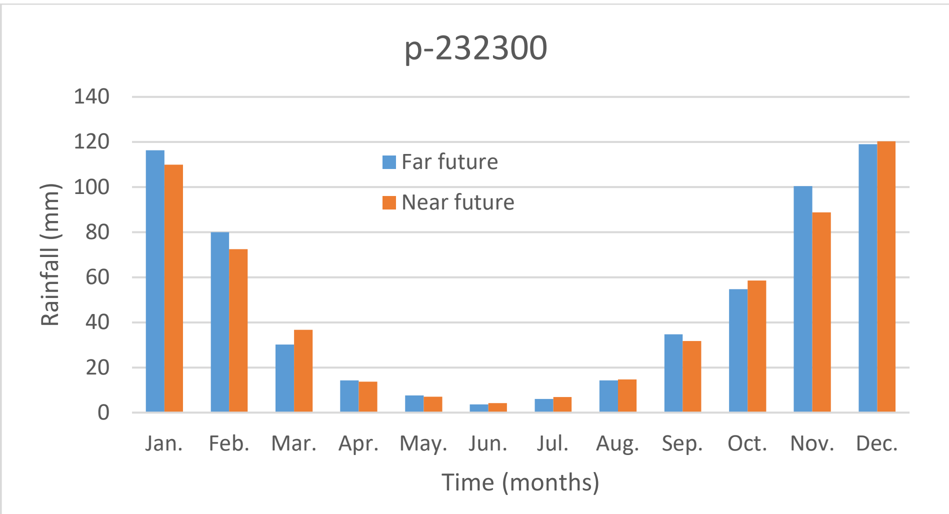

Figure 2.32: Projected monthly average monthly rainfall for p-232300

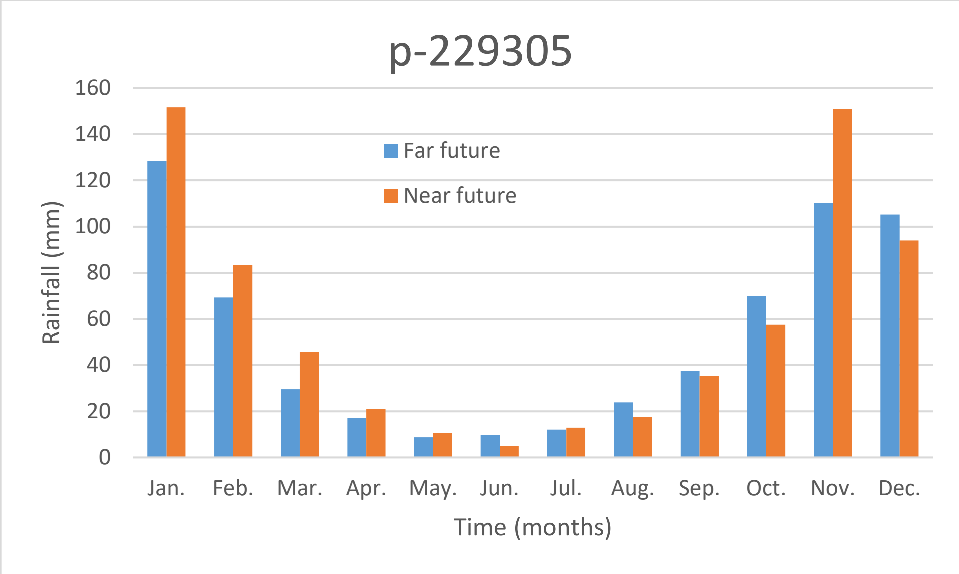

Figure 2.33: Projected monthly average monthly rainfall for p-229305

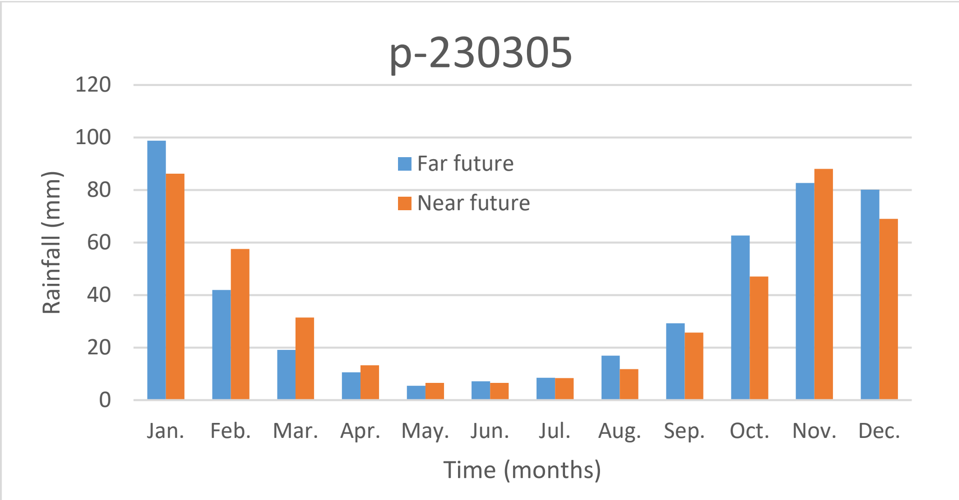

Figure 2.34: Projected monthly average monthly rainfall for p-230305

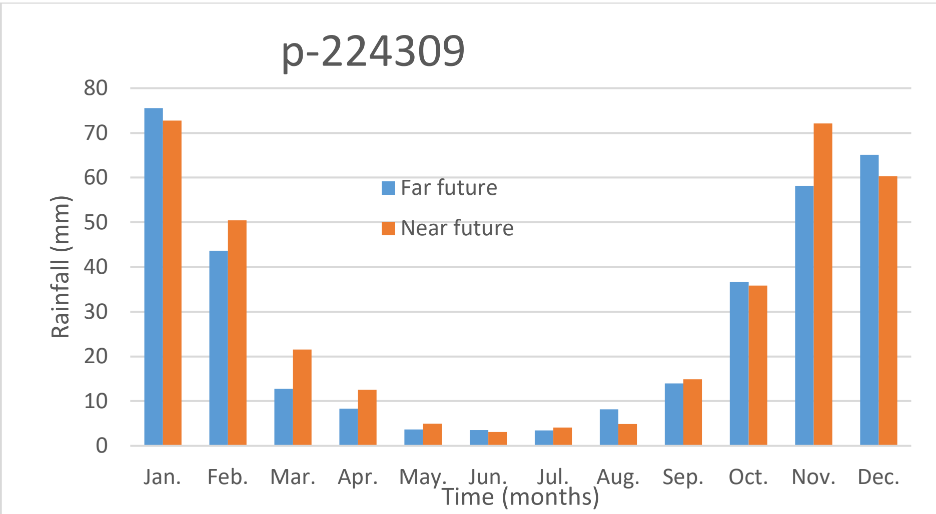

Figure 2.35: Projected monthly average monthly rainfall for p-224309

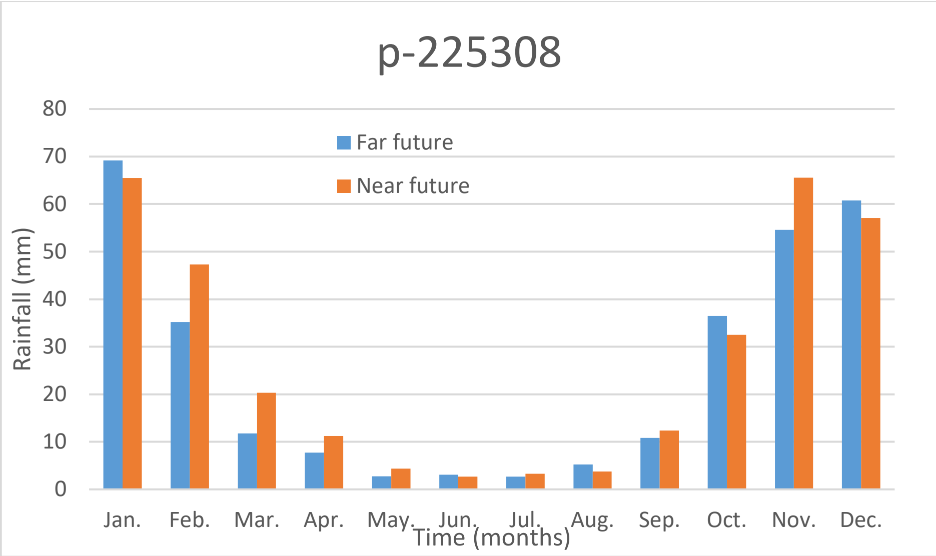

Figure 2.36: Projected monthly average monthly rainfall for p-225308

Table 2.4: Future rainfall changes in the rainfall season

Month	p-232300 (Upstream)	p-229305 (Upstream)	p-230305 (Midstream)	p-224309 (Downstream)	p-225308 (Downstream)
Oct	Decrease	Increase	Increase	Increase	Increase
Nov	Increase	Decrease	Decrease	Decrease	Decrease
Dec	Decrease	Increase	Increase	Increase	Increase
Jan	Increase	Decrease	Increase	Increase	Increase
Feb	Increase	Decrease	Decrease	Decrease	Decrease
Mar	Decrease	Decrease	Decrease	Decrease	Decrease

Detailed analysis of the statistics showed that the average number of precipitation days (PCPD) will decrease in the far future (Table 2.5 to 2.8). The average monthly precipitation (PCP_MM) for station p-228306 will also decrease in the far future. This is further confirmation of what the trend has shown for the historical records. A decrease in rainfall will have negative consequences for most vulnerable communities who rely on rainfed crops.

Table 2.5: Near future projected rainfall statistics for p-232300

	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD
Jan.	80.4	8.3	51.0294	0.652	0.9117	28.57
Feb.	72.48	5.5119	7.0908	0.5937	0.8648	24.12
Mar.	36.74	3.2455	10.0819	0.4543	0.7862	22.27
Apr.	13.76	1.0821	6.8169	0.3127	0.679	15.8
May.	6.98	0.5328	7.1083	0.2599	0.5893	12.73
Jun.	4.15	0.3164	4.5419	0.2386	0.5323	10.69
Jul.	6.95	0.4516	3.5986	0.2888	0.5926	13.44
Aug.	14.71	0.9211	4.842	0.3625	0.6533	16.58
Sep.	31.78	3.1808	14.7706	0.3981	0.6946	17.74
Oct.	58.6	4.8329	6.6556	0.4843	0.7983	22.67
Nov.	88.82	7.0294	5.5572	0.5568	0.8721	25.6
Dec.	120.25	8.7623	5.1999	0.6694	0.8995	28.08

Key

PCP_MM = average monthly precipitation [mm]
PCPSTD = standard deviation
PCPSKW = skew coefficient
PR_W1 = probability of a wet day following a dry day
PR_W2 = probability of a wet day following a wet day
PCPD = average number of days of precipitation in month

Table 2.6: Far Future projected rainfall statistics for p-232300

	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD
Jan.	116.31	7.8326	5.5907	0.6234	0.9132	28.43
Feb.	80	5.9941	6.448	0.5963	0.8742	24.63
Mar.	30.14	2.1184	7.6881	0.4588	0.7822	22.5
Apr.	14.28	1.3466	12.1517	0.3483	0.6527	15.93
May.	7.62	0.534	3.6192	0.2643	0.5938	12.97
Jun.	3.71	0.2645	3.4524	0.2401	0.5265	10.7
Jul.	6.07	0.3894	3.3106	0.3006	0.5711	13.37
Aug.	14.28	0.7338	2.356	0.3666	0.6881	17.63
Sep.	34.77	3.557	12.2002	0.42	0.6982	18.33
Oct.	54.69	4.6756	7.479	0.5108	0.7954	23.3
Nov.	100.38	8.2259	5.2058	0.5211	0.8734	25.27
Dec.	119.06	8.4637	4.9899	0.6542	0.8858	27.43

Table 2.7: Near future projected rainfall statistics for p-228306

	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD
Jan.	82.6	5.238	4.403	0.6433	0.8487	26.25
Feb.	65.4	5.1748	6.0973	0.5635	0.8421	23.22
Mar.	32.2	2.2668	5.5729	0.4177	0.7295	20.03
Apr.	15.51	1.3179	5.5992	0.3083	0.6449	14.86
May.	6.62	0.5139	4.7666	0.2489	0.5805	12.25
Jun.	6.09	0.4868	4.2485	0.2394	0.5664	11.08
Jul.	8.33	0.5838	3.8651	0.2776	0.628	13.89
Aug.	11.72	0.7411	3.2878	0.331	0.63	15.39
Sep.	22.88	2.0539	9.7107	0.3259	0.6928	16.28
Oct.	43.14	3.7535	7.0644	0.3851	0.7086	18.31
Nov.	86.16	7.1621	6.3695	0.5721	0.8205	23.83
Dec.	70.1	4.7277	5.1799	0.6169	0.8306	25.42

Table 2.8: Far future projected rainfall statistics for p-228306

	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD
Jan.	69.18	6.945	7.8796	0.5481	0.813	24.07
Feb.	35.19	3.7349	6.2333	0.4579	0.7443	19.17
Mar.	11.78	1.8767	23.8144	0.3522	0.6191	15.67
Apr.	7.7	0.8331	10.0748	0.2643	0.5936	12.47
May.	2.74	0.2284	6.3995	0.2065	0.514	9.53
Jun.	3.07	0.264	5.6476	0.242	0.5146	10.3
Jul.	2.68	0.1898	6.016	0.271	0.5159	11.57
Aug.	5.23	0.3212	4.4936	0.3578	0.6599	16.47
Sep.	10.82	1.968	19.1605	0.3165	0.5842	13.47
Oct.	36.46	4.2385	7.0924	0.3561	0.7022	17.8
Nov.	54.56	5.2627	5.8432	0.4096	0.7997	20.97
Dec.	60.75	5.8959	6.2164	0.4656	0.7889	22.27

2.5 SUMMARY

This chapter has detailed the present-day climate of the Luvuvhu River Catchment and the various forcing mechanisms on several time scales. Multi-model projections in the study area have also been made under low and high mitigation scenarios. The main signal in this study which is consistent with several modelling studies for southern Africa is that of rapid warming which is higher than the global average. Over the northeast of South Africa where the Luvuvhu catchment is located, the temperatures are projected to be more than 2°C by the year 2076. Rainfall is also projected to decline significantly posing major implications for water supply, commercial and smallholder agriculture and rural livelihoods.

CHAPTER 3: HYDROLOGIC ANALYSIS FOR CLIMATE IMPACT MODELLING

3.1 INTRODUCTION

This chapter is focused on hydrological modelling for assessment of the impacts of climate change on water resources availability for agriculture and domestic/municipal water uses. The hydrological modelling was based on Soil Water Assessment Tool (SWAT) in the Luvuvhu River Catchment. The meteorological data used in the setup of the SWAT model was from the CCAM projections. Streamflow was projected for the near future (2021-2050) and the far future scenarios (2051-2080).

3.2 HYDROLOGIC ANALYSIS

The hydrologic analysis provides a useful method for describing the physical features of the earth's surface. One can model the flow of water and perform quantitative analysis on a Digital Elevation Model (DEM) data. Hydrologic analysis can extract the information about where water comes from and where it is going to on any cell of a raster data. It can be used in many applications ranging from identification of the flood extent, the position of pollution source in a river, streamflow forecasts, etc. Lately, hydrologic analysis has been simplified using hydrologic models, which are either physically-based or theoretical (Beven *et al*., 1987). These types of hydrologic models are mainly used for research purposes to gain a better understanding of the hydrologic phenomena operating in a catchment and of how changes in the catchment may affect these phenomena. The computational aspects of hydrologic phenomena are generally defined by the laws of continuity, energy and momentum. As such these models are seldom used to generate synthetic data. All other types of models, varying from deterministic forms, using much information about the physical processes involved, to "black box" forms, where physical processes are not involved, are used for operational purposes to generate synthetic sequences of hydrologic data for facility design or use in forecasting.

In the current study, the projected climate data on temperatures and rainfall was fed into a calibrated SWAT model to simulate the future flows based on the predicted climate scenarios. The data were prepared in a format that suits the SWAT model input data requirement. Historical data on rainfall, temperatures (Max. and Min.), relative humidity, solar radiation and wind speed acquired from various rainfall stations located in the catchment or its vicinity were assessed to establish their status in terms of the period of data availability and status of the data. This enabled choice of the period for model simulation, calibration and validation. Other input data for the SWAT model set up were the DEM, soil information, land cover data, and drainage network. The process involved in SWAT data input, set up, calibration, validation and simulation of streamflow are illustrated below based on the ArcSWAT version (ArcSWAT 2012.10.24). This involves selecting the installed ArcSWAT extension, Watershed Delineation, definition of hydrologic response units (HRUs), editing of SWAT databases, definition of weather data, application of default input files, model set up and run. The simulation results can then be displayed using graphical tools embedded within the interface (Figure 3.1).

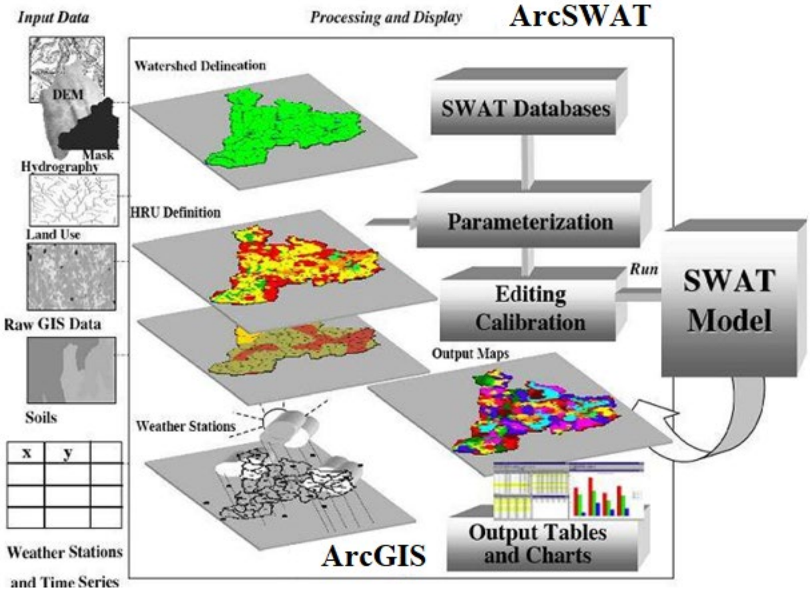

Figure 3.1: ArcSWAT Interface illustrating processes in SWAT simulation of flow (modified from Di Luzio et al., 2002)

3.2.1 The SWAT model

The SWAT model is a process-based, continuous physically-based distributed parameter river basin model developed to simulate water, sediment and pollutant yields to assist water resources managers to predict and assess the impact of land use management on water, sediment yield, and diffuse pollution for large ungauged catchments with different soil types, land use and management (Levesque *et al.*, 2008; Neitsch *et al.*, 2005). During model setup, the catchment is divided into sub-basins based on topography and drainage pattern and into hydrologic response units (HRU) based on unique combinations of soil and land use. The model is embedded into an ArcGIS 10.5 interface making it able to handle large data sets in varied geographic scales. Components of the SWAT model include hydrology, climate, nutrient recycling, crop growth, sediment movement, agricultural management, and pesticide dynamics. The model has been used worldwide for a variety of applications with notable success (Ndomba and Birhanu, 2008), and found to be excellent for hydrological modelling and water resource management (Vilaysane *et al.*, 2015) for reasons that include its computational efficiency and flexibility on input data requirements (Stehr *et al.*, 2008).

SWAT has gained international acceptance as a robust interdisciplinary watershed modeling tool as evidenced by international SWAT conferences, hundreds of SWAT related papers presented at numerous scientific meetings, and many articles published in peer-reviewed journals. The model can be used in a variety of catchment areas ranging from a few hectares to thousands of square kilometers and performs long term simulations. Model predictions are spatially distributed thereby providing spatial information regarding upstream sources of modeled quantities (Andualem and Yonas, 2008). The model can simulate streamflow to a high level of spatial detail through watershed division into sub-basins (Santhi *et al.*, 2006). Gassman *et al.* (2007) present a detailed review, including historical development and applications of the SWAT model. The SWAT model was selected because it is a continuous time, spatially distributed model capable of linking hydrological processes to crop growth and agricultural management practices and has successfully been applied in a variety of scales and environmental conditions (Rouholahnejad *et al.*, 2014). The SWAT model has been, in various ways, used to study the effect of land cover dynamics on catchment hydrology (Odira *et al.*, 2010; Tadele and

Förch (2007) and impact of climate change on the hydrologic response (Githui *et al.*, 2008). The model has been used to predict the impact of water availability in irrigated agriculture based on estimated runoff from various land use scenarios built into the model (Technical Brief 2, 2007) in the upper Malalprabha catchment, India. The impact of climate change on water resource components has been performed by Faramarzi *et al.* (2013) at the continental scale, using sub-basin as a hydrologic unit, through feeding of the future climate data (based on selected GCMs) into calibrated SWAT model. The study emphasised the role its results would play in further analysis of adaptation strategies.

3.2.2 Hydrologic analysis for climate impact modelling

Soil and Water Assessment Tool (SWAT) was used to evaluate the impacts of a climate scenario based on CCAM projections on streamflows in the Luvuvhu River Catchment for 2021-2050 and 2071-2100, using 1979-2014 as the reference period. SWAT model has been applied, with notable success, in climate change modelling studies focused on climate change impact on water resources (Githui *et al.*, 2008; Obuobie and Bernd, 2008). SWAT delineates Hydrological Response Units (HRU) which assists in the management of water resources within a catchment. The model, though data-intensive, is fairly comprehensive taking into account most of the parameters that influence the catchment hydrologic response including land use changes, soils, topography and climate. SWAT has gained international acceptance as a robust interdisciplinary watershed modeling tool and has been used for a wide range of applications for reasons that include its computational efficiency and flexibility on input data requirements (Stehr *et al.*, 2008). Figure 3.2 shows the link between climate variable transfer from global to catchment scale and hydrological modelling.

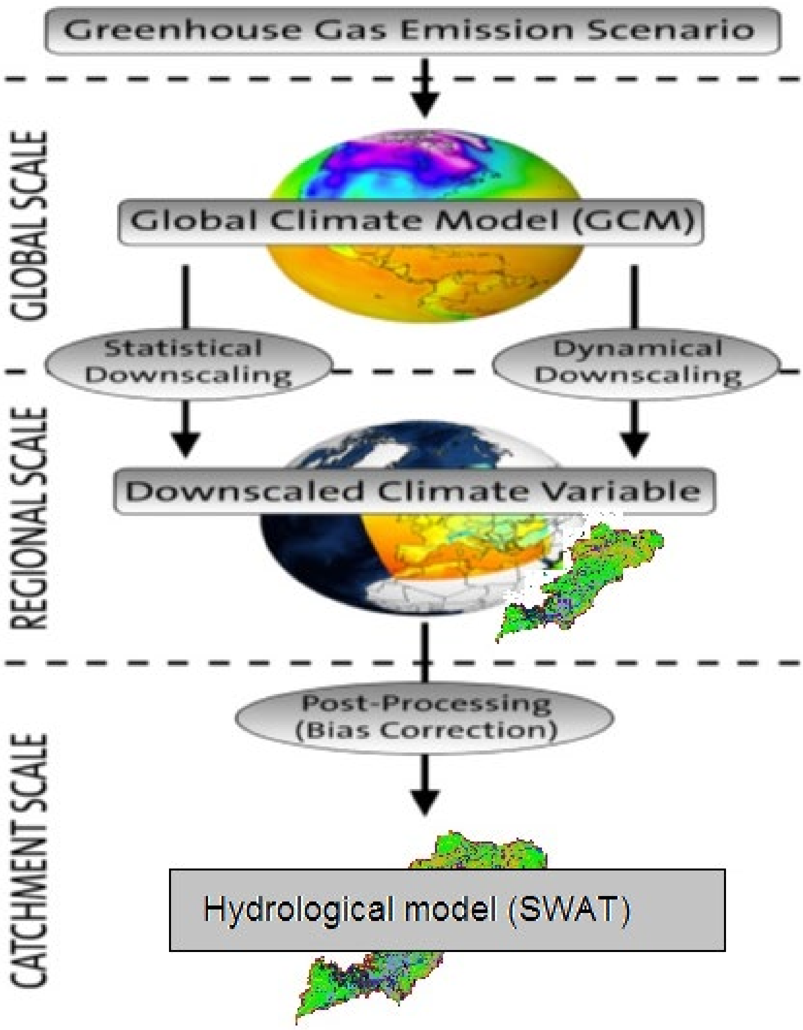

Figure 3.2: Scheme of the climate variable transfer from global to catchment scale (Adopted from Teutschbein, 2013)

3.3 DATA COLLECTION

The data collection was comprehensive with meteorological, hydrological, land cover and soils data forming part of the key data requirements. Statistical techniques and trends analyses aided the identification of relationships within and between data sets. The table below summarises data requirements and collection for this project (Table 3.1).

Table 3.1: Data requirements and collection

Data group	Data type	Data category	Data source	Purpose
1. Remote sensing data	- Satellite imageries	Secondary data	WEB/RCMRD/ Purchase from some institutions	Climate projections
	- Topographical maps (including contour lines)	Secondary data	Geo-Spatial center/DRDLR	Input for SWAT Model
	- Land survey (Land use and Land cover data)	Secondary data	DRDLR / DEA	Input for SWAT Model
2. Meteorological data	- Rainfall	Secondary data	SAWS/ ARC-ISCW/CSIR	Inter-annual rainfall variability; Rainfall characteristics
	- Temperature	Secondary data	SAWS/ ARC-ISCW/ CSIR	Climate characteristics
	- Humidity	Secondary data	SAWS/ ARC-ISCW/ CSIR	Input for SWAT Model
	- Radiation	Secondary data	SAWS/ ARC-ISCW/ CSIR	Input for SWAT Model
	- Wind	Secondary data	SAWS/ ARC-ISCW/ CSIR	Input for SWAT Model
	- Sunshine	Secondary data	SAWS/ ARC-ISCW/ CSIR	Input for SWAT Model
3. Hydrological data	- Streamflow	Secondary data	DWS	Input for SWAT Model and prediction of future streamflow for Luvuvhu River Catchment
	- Surface runoff	Secondary data	To be estimated using SWAT	To predict future runoff for Luvuvhu River Catchment
	Evaporation	Secondary data	DWS	
4. Soil data	- Soil texture	Secondary data	ARC-ISCW	Input for SWAT Model
	- Soil type	Secondary data	ARC-ISCW	Input for SWAT Model
	- Soil profiles	Secondary data	ARC-ISCW	Input for SWAT Model
	- Hydraulic conductivity	Secondary data	ARC-ISCW	Input for SWAT Model

3.3.1 Streamflow

The study area is drained by the Luvuvhu River and its tributaries (Doringspruit, Lotoyanda, Dzindi, Mutshundudi, Mutale, Mbwedi and Tshinane). Streamflow data for the main river and its tributaries were obtained from the Department of Water and Sanitation (DWS). The data varied in terms of duration and quality. Some stations have several missing data while others had representable records. Figure 3.3 shows the location of streamflow gauging stations acquired for the study. It is important to note that not all the stations meet the requirements for consideration in the study due to irreparable gaps.

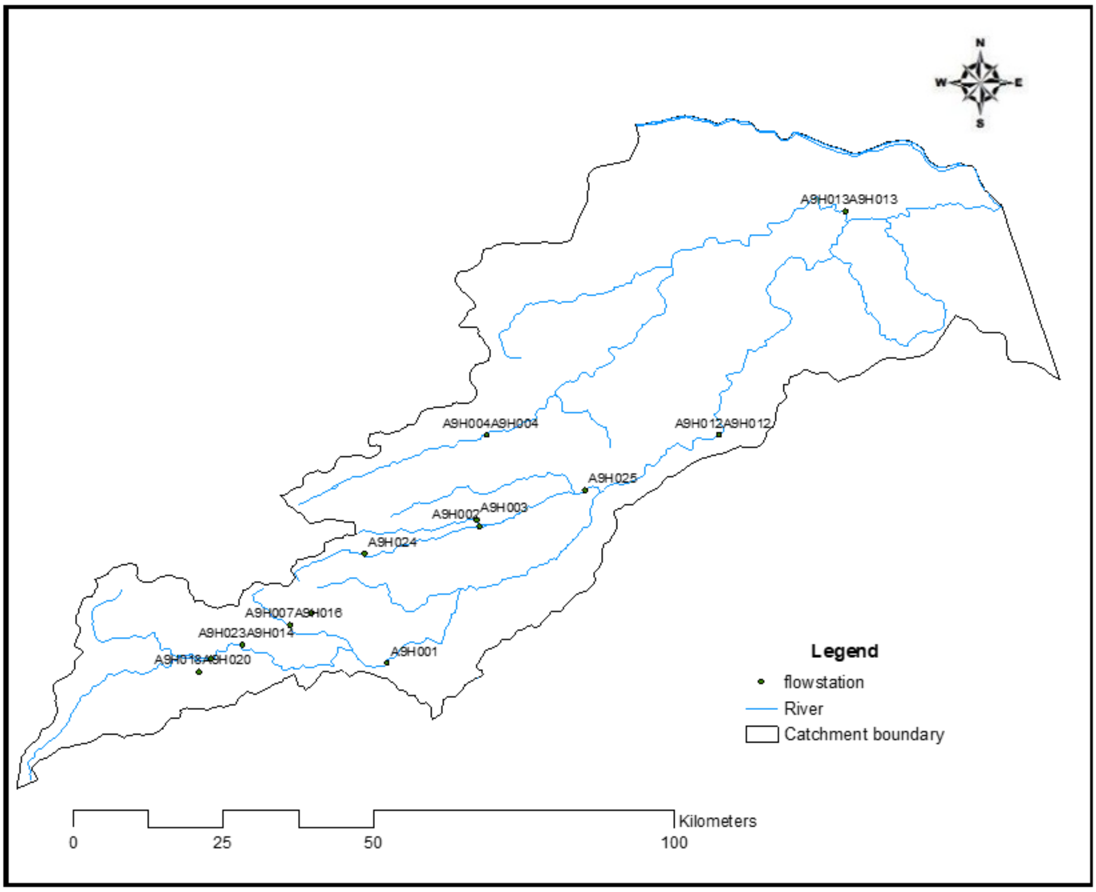

Figure 3.3: Location of streamflow gauging stations in the Luvuvhu River Catchment

3.3.2 Evaporation

Evaporation data was obtained from the DWS. A total of three stations, i.e. Goedehoop (A9E002), Levubu settlement (A9E001) and Nandoni (A9E004) located near big reservoirs were selected and are shown in Figure 3.4. The reason for selecting the above stations was that they had data that covers both seasonal and long-term changes. Estimated evaporation data in a study by Nendauni (2011) were adopted and extended in the current project. These include data for stations Goedehoop (A9E002) and Levubu settlement (A9E001). Evaporation data were estimated for those stations that have temperature data using the Hargreaves Method (Hargreaves and Samani, 1985).

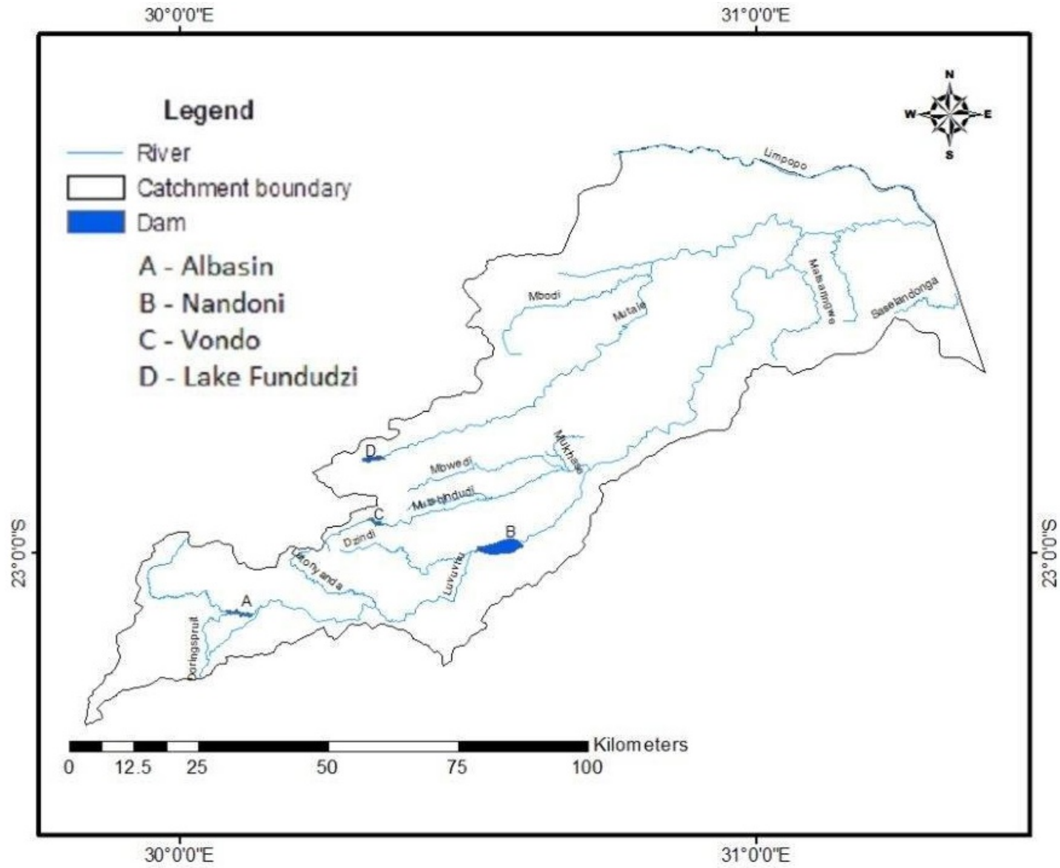

Figure 3.4: Location of evaporation gauging stations within Luvuvhu River Catchment

3.3.3 Land cover

Land cover maps prepared by the Department of Environmental Affairs (DEA) cover maps were obtained. These represent the land cover of the years 1990 and 2012. Moreover, remotely sensed data such as Landsat and Spot images were obtained from different agencies. For example, the United States Geological Society (USGS) and the South African National Spatial Agency (SANSA). It is important to note that already in the Luvuvhu River Catchment, the land cover changes have been mapped by Griscom *et al*. (2010) for environmental modelling purposes including the extinction of biodiversity, particularly in the lower reaches of the catchment including the Kruger National Park. Significant changes were reported in the above study and their impacts on hydrology were highlighted. Figure 3.5 shows the land cover in the Luvuvhu River Catchment for the year 2012.

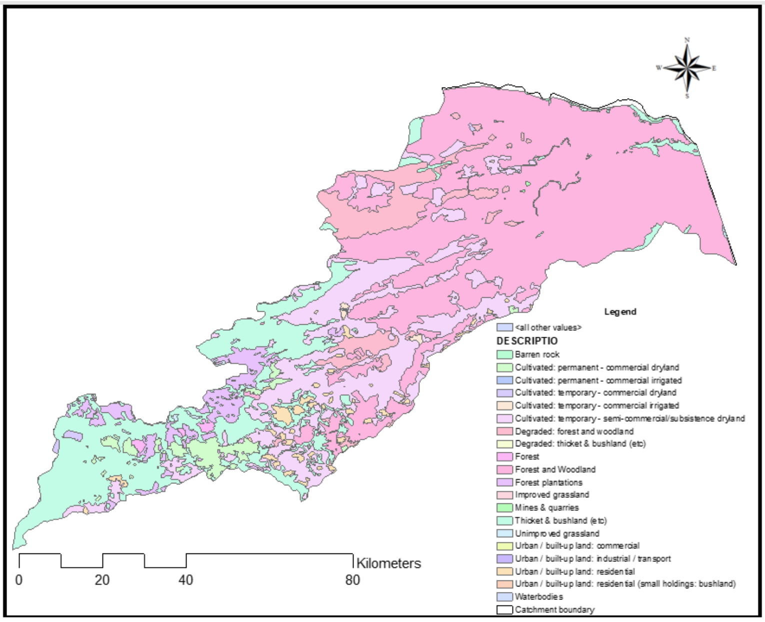

Figure 3.5: Land cover of the Luvuvhu River Catchment for the year 2012 (Source: DEA, 2015)

3.3.4 Soil

Course scale, 1:1 000 000, soil's data, in digital format was acquired from the Global Environment Facility Soil Organic Carbon database (URL: http://www.isric.org). This dataset was an upgraded version developed by national experts from the global Soil and Terrain database. The data were reclassified into the major hydrological soil groups of the catchment with the help of FAO/UNESCO revised manual for soil maps of the world based on their drainage characteristics. In addition, a course scale map for soils was acquired from the ARC's land types map (ARC-ISCW, 2006) (Figure 3.6). It shows the soil texture of the Luvuvhu River Catchment.

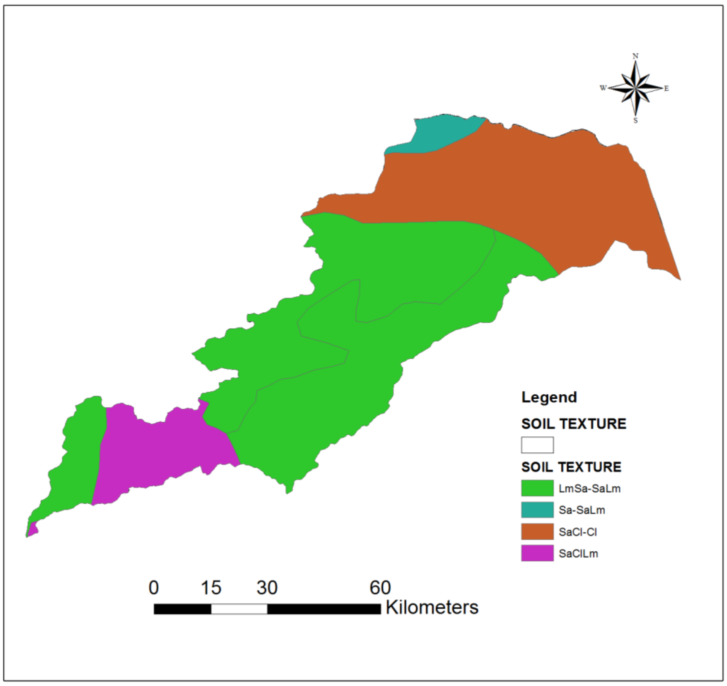

Figure 3.6: Soil map for Luvuvhu River catchment (Source: ARC-ISCW, 2006)

3.4 SETUP OF THE SWAT MODEL

The setup of the SWAT model required that the data collected be pre-processed before it can be uploaded into the model. The following datasets were prepared for the Luvuvhu River Catchment as they were inputs required for SWAT used in this study.

- SWAT virtual stations (rainfall, humidity, temperature).
- CCAM projections from the CSIR (rainfall, humidity, temperature).
- Digital Elevation Model (DEM).
- A series of land-use maps derived from hard copies obtained from ARC-ISCW.
- 36 years of daily rainfall data of the seven rain gauge stations from South African Weather Service and SWAT database.
- Daily discharge data of three gauging stations covering the period January 2002 to December 2014.
- Daily maximum and minimum temperature data for the basin for the period 1979-2014, obtained from the South African Weather Service and SWAT database.
- A land type map 1:250 000 scale with the physical soil layer properties (including texture, bulk density, available water capacity, saturated conductivity) were collected from ARC's Institute of Soil, Climate and Water from 2230 and 2330 land type maps for Messina and Tzaneen, respectively.

3.4.1 Digital elevation model

The DEM (Figure 3.7) was downloaded from the Consultative Group for International Agricultural Research-Consortium for Spatial Information website. For this study, the Shuttle Radar Terrain Model was the source of the Digital Elevation Model. DEM was used to generate the delineated Luvuvhu Catchment (Figure 3.7) for hydrological modelling. The latter was further delineated into sub-basins. In total, 25 sub-basins were delineated for the Luvuvhu River Catchment as shown in Figure 3.8.

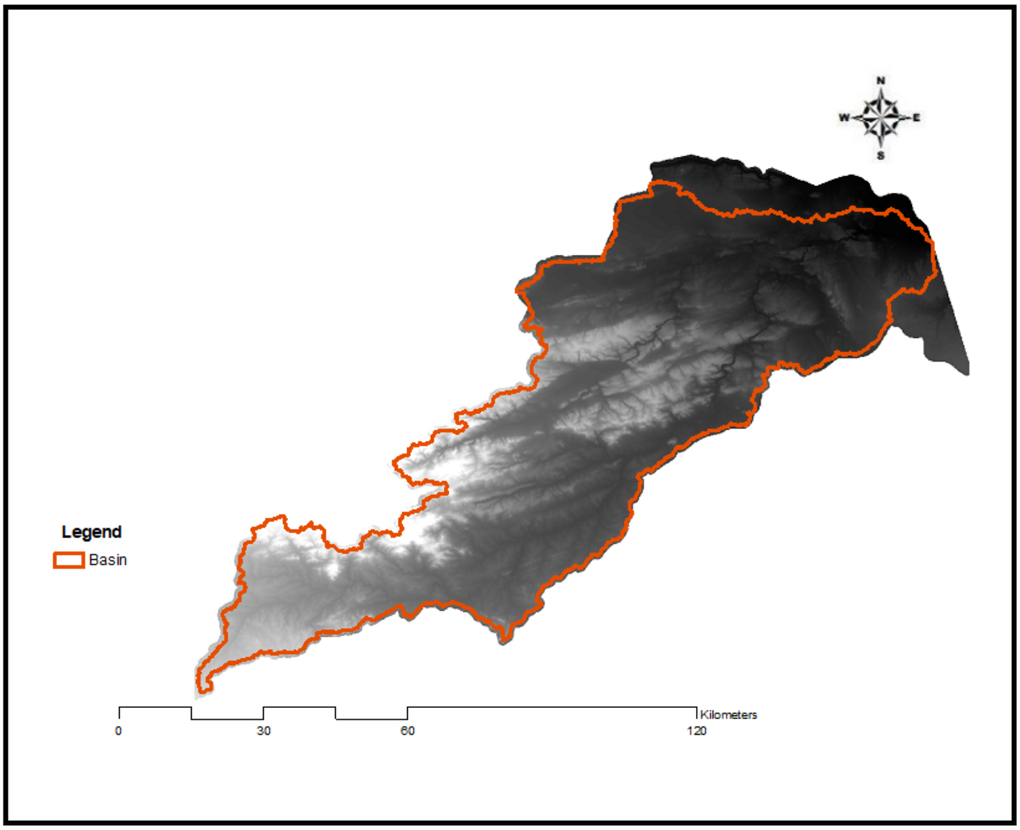

Figure 3.7: Digital Elevation Model and the delineated Luvuvhu River Catchment

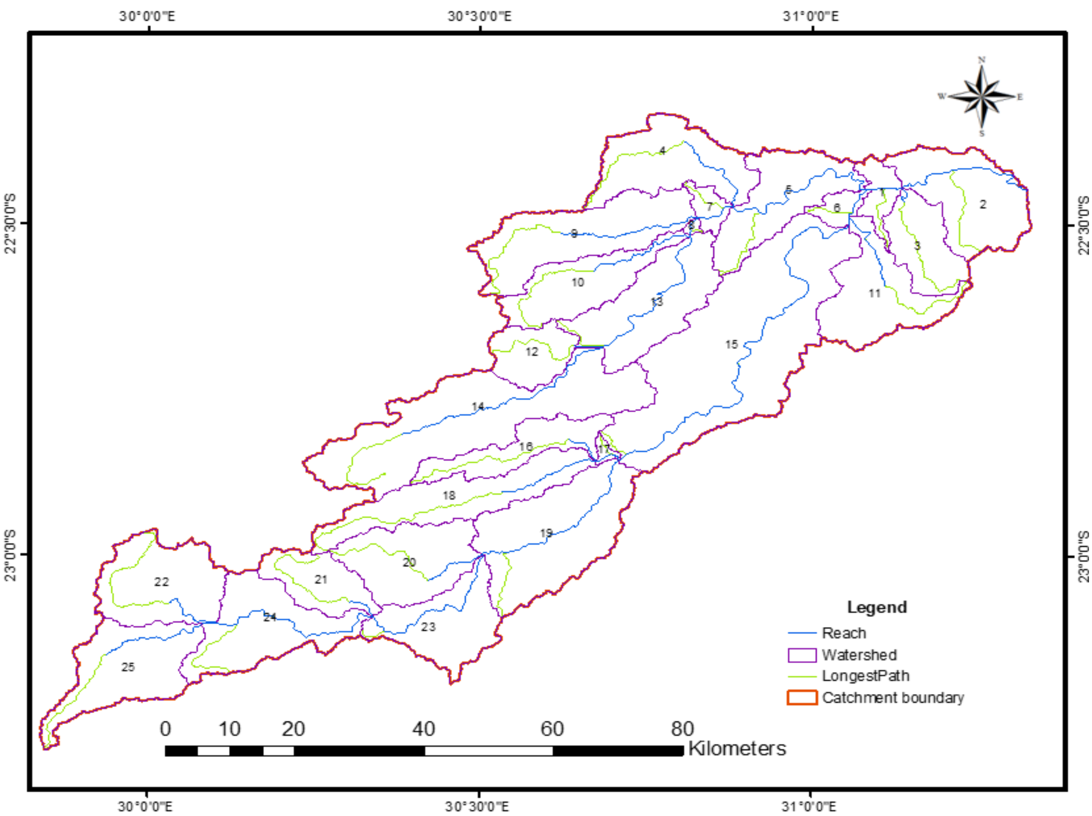

Figure 3.8: Sub-basins delineated within the Luvuvhu River Catchment

3.4.2 Soil

The SWAT database inbuilt within the ArcSWAT model only contains soil types for the United States. Thus, it was necessary to build a soil database of the Luvuvhu River Catchment from existing land types maps from 2230 (Messina) and 2330 (Tzaneen) at scales of 1: 250 000. Soil maps were rectified and mosaicked, such that the study area was extracted by sub-setting it from the full map. Boundaries of different soil textures were digitised and various polygons were assigned to represent different soil categories which formed a land type map for the study area as shown in Figure 3.9. Figure 3.10 indicates an example of soil component and layers parameters that were manual input into ArcSWAT based on information from the land types. The estimated soil properties which include texture, bulk density, hydraulic conductivity, available water content (AWC) and hydrologic soil group at different depths for each land use class are in Table 3.2.

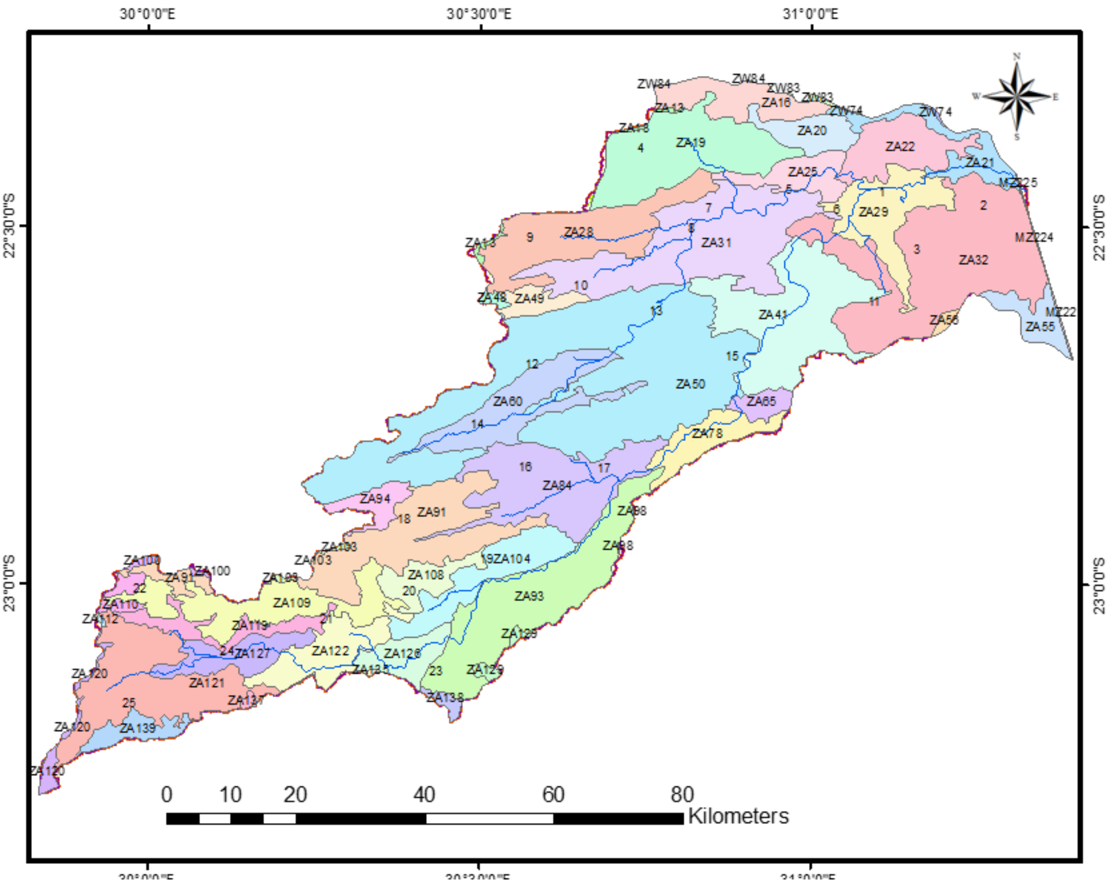

Figure 3.9: Land type map for the Luvuvhu River Catchment (land type classes are described in Table 3.2)

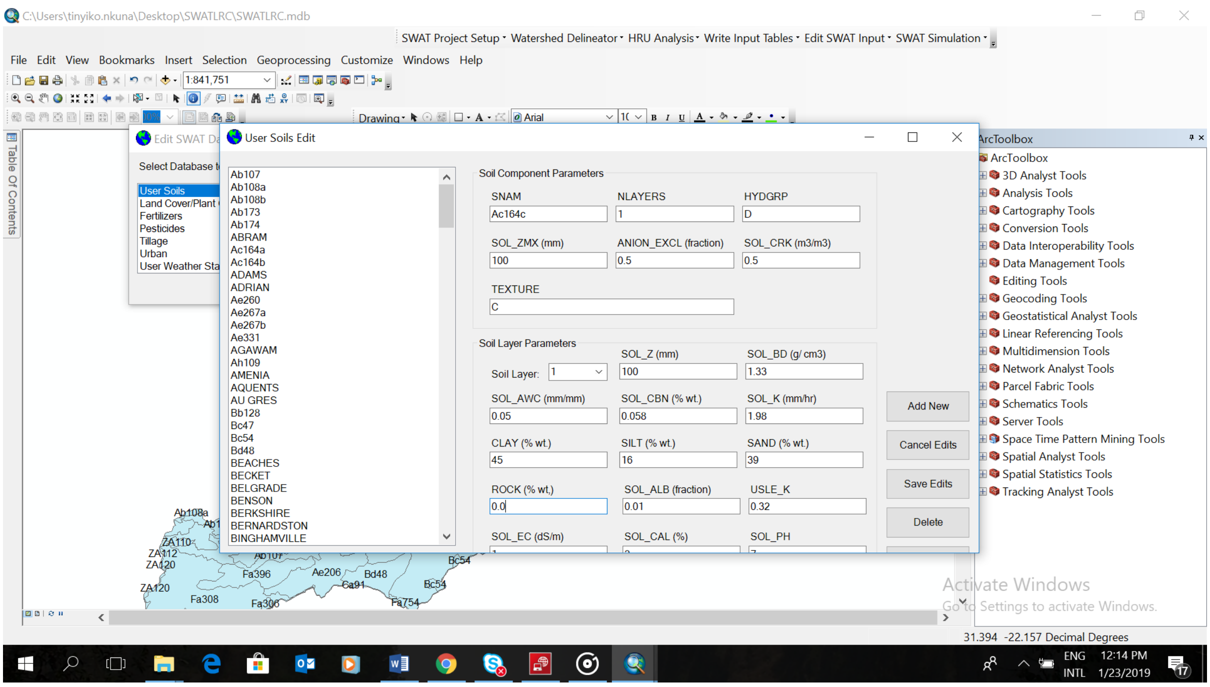

Figure 3.10: An example of soil component and layers parameters that were manually input into ArcSWAT

Table 3.2: Estimated soil properties for different land types

Item no	**Land type**	**Approx. Texture**				**Soil properties**							
		Depth (mm)	Ave. % clay (given)	% silt	% sand	Texture	Bulk density (g/cm^3)	K_s (mm/h)	AWC (cm/cm)	ROCK %	C	Texture	HYD GRP
1	AC164a	500	8	4	88	S	1.51	30.0	0.02	0.0	0.05	Loamy sand	A
2	AC164b	300	34	36	30	C-L	0.97	1.90	0.11	0.0	0.05	Clay loam	B
3	FC485a	800	34	36	30	C-L	0.97	1.5	0.11	5	0.05	Clay loam	C
4	AB108a	1016	33	22	45	S-C-L	1.31	0.97	0.15	3	0.05	Loam	B
5	Ib440	389	15.0	83.0	2.0	S-L	1.59	1.88	0.22	5.0	0.05	Silt loam	D
6	Bb128	518	15	2	83	S-L	1.63	35.72	0.05	0.0	0.058	Sandy loam	A
7	Ab173	807	36	19	45	S-C	1.53	1.86	0.12	0.0	0.058	Clay loam	B
8	Ab108b	1016	33	22	45	S-L	1.55	2.63	0.11	3.0	0.058	Sandy loam	B
9	ZA110	300	19	29	52	L	1.37	1.90	0.16	0.0	0.05	Loam	B
10	ZA112	300	9	8	83	L-S	1.49	29.0	0.01	0.0	0.05	Loamy fine sand	A
11	Ab107	763	32	23	45	S-C-L	1.56	2.98	0.12	1.7	0.058	Clay loam	C
12	ZA120	300	15	18	67	S-L	1.48	31.0	0.06	0.0	0.05	Sandy loam	A
13	Fa308	443	17.0	3	80	S-L	1.64	27.66	0.06	0.0	0.05	Sandy loam	A
14	Ae260	981	30	25	45	S-C-L	1.57	3.64	0.12	0.1	0.05	Clay loam	B
15	Bd48	580	14	3	83	S-L	1.63	39.12	0.05	0.9	0.05	Sandy loam	A
16	Fa331	738	20	2	78	S-L	1.64	5.83	0.06	1.7	0.05	Sandy clay loam	A
17	BC54	300	19	15	66	S-L	1.47	32.0	0.05	0.0	0.05	Sandy loam	A
18	AE267a	600	11	20	69	S-L	1.2	15.8	0.05	0.0	0.05	Sandy loam	A
19	Ca91	568	18	30	52	S-L	1.62	13.31	0.11	0.0	0.058	Loam	B
20	Fa306	183	15.0	83	2.0	S-L	1.59	1.88	0.22	0.0	0.05	Silt loam	C
21	FA754	300	12	19	69	S-L	1.18	11.6	0.09	0.0	0.05	Sandy loam	A
22	AB174	300	19	15	66	S-L	1.47	8.0	0.05	0.0	0.05	Sandy loam	A
23	FB359	475	28	29	43	L	1.31	0.5	0.15	0.0	0.05	Clay loam	D
42	EA206b	300	14	18	68	S-L	1.17	15.0	0.10	2.0	0.05	Sandy loam	
25	AE267b	600	15	18	67	S-L	1.48	8.0	0.06	0.0	0.05	Sandy loam	A
47	IA113b	300	23	33	44	L	1.31	1.93	0.12	0.0	0.05	Loam	B
2	FC485b	800	28	52	20	S-L	1.37	1.0	0.16	0.0	0.05	Silt clay loam	D
28	FC728	1200	28	52	20	S-L	1.37	1.0	0.16	0.0	0.05	Silt clay loam	D
29	AE331	300	15	18	67	S-L	1.48	20.0	0.06	0.0	0.05	Sandy loam	A
30	IB316	400	28	29	43	L	1.31	1.0	0.15	0.0	0.05	Clay loam	B
31	FB498	900	19	29	53	L	1.37	5.2	0.16	0.0	0.05	Loam	B
32	FC487	300	19	29	53	L	1.37	5.2	0.16	0.0	0.05	Loam	B
33	BC47	850	19	15	66	S-L	1.47	7.0	0.05	0.0	0.05	Sandy loam	A
34	FB497	500	19	29	52	L	1.37	2.3	0.16	0.0	0.05	Loam	B
35	AH109	300	6	5	89	S	1.51	35.0	0.07	3.0	0.05	Fine sand	A
36	IB441	300	28	29	43	L	1.31	2.95	0.15	0.0	0.05	Clay loam	B

Item no	**Land type**	**Approx. Texture**				**Soil properties**							
		Depth (mm)	Ave. % clay (given)	% silt	% sand	Texture	Bulk density (g/cm^3)	K_s (mm/h)	AWC (cm/cm)	ROCK %	C	Texture	HYD GRP
37	AC164c	1000	45	16	39	C	1.33	1.98	0.07	0.0	0.05	Clay	D
38	EA161	500	31	35	34	C-L	1.29	5.0	0.13	0.0	0.05	Clay loam	B
39	BA60	850	19	15	66	S-L	1.47	7.0	0.05	0.0	0.05	Sandy loam	A
40	CA93	300	15	18	65	S-L	1.48	8.0	0.06	0.0	0.05	Sandy loam	A
41	BD56	450	14	18	68	S-L	1.51	28.0	0.07	0.0	0.05	Sandy loam	A
26	EA206a	1058	14	18	68	S-L	1.17	28.0	0.10	2.0	0.05	Sandy loam	A
43	Ab179	1058	25	30	45	L	1.59	6.01	0.12	11.0	0.058	Loam	B
44	FB496	1000	12	19	69	S-L	1.18	29.1	0.09	0.0	0.05	Sandy loam	A
45	FA756	720	19	29	52	L	1.37	3.0	0.16	11	0.05	Loam	B
46	AE328	900	15	18	67	L	1.48	25.0	0.06	8.0	0.05	Sandy loam	A
26	IA113a	800	23	33	44	L	1.31	3.0	0.12	0.0	0.05	Loam	B
48	ZW83	300	28	29	43	L	1.31	1.4	0.15	0.0	0.05	Clay loam	C
49	ZW84	300	28	29	43	L	1.31	1.4	0.15	0.0	0.05	Clay loam	C

3.4.3 Land use/cover

In total, 13 land uses were classified based on the land cover classes (Figure 3.11). It is important to note that the classification process was simplified using the existing SWAT codes. The description of the codes and percentages of areas covered by each land use class are in Table 3.3.

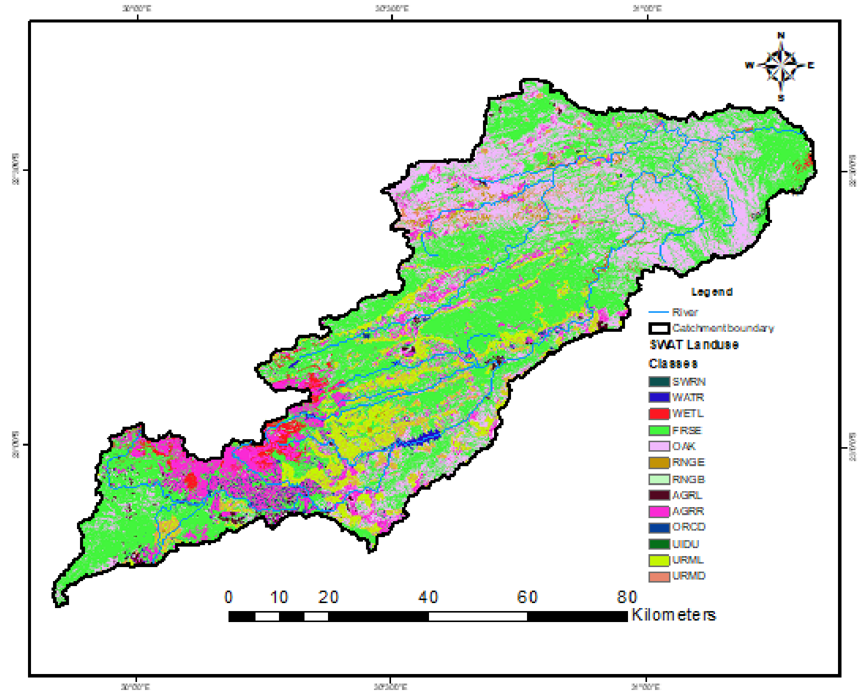

Figure 3.11: Land use/cover classes

Table 3.3: Description of land use/cover classes for the study area

Land cover	SWAT CODE	Area (%)
Barren land (rock/sand/clay)	SWRN	0.01
Water	WATR	0.54
Wetlands	WETL	1.68
Forests	FRSE	47.46
Trees	OAK	28
Grassland/herbaceous	RNGE	1.58
Range shrubland	RNGB	0.15
Generic (agriculture)	AGRL	0.75
Crops	AGRR	9.58
Orchards	ORCD	0.78
Urban industrial	UIDU	0.06
Urban medium density	URML	7.25
Residential	URMD	2.16

3.5 SUB-DIVISIONS OF THE MODEL INTO HYDROLOGICAL RESPONSE UNITS (HRUs)

Based on the combination of land use, soil types, and slope data, the model was subdivided into small areas known as hydrological response units (HRUs). A minimum threshold of 10% was used to eliminate minor land uses, soils, and slopes in each sub-basin to facilitate processing and to limit the number of HRUs in each sub-basin. This resulted in 244 HRU's for the 25 sub-basins. Figure 3.12 shows the slope and land use combined map while the delineated sub-basins of the Luvuvhu River Catchment are in Figure 3.8.

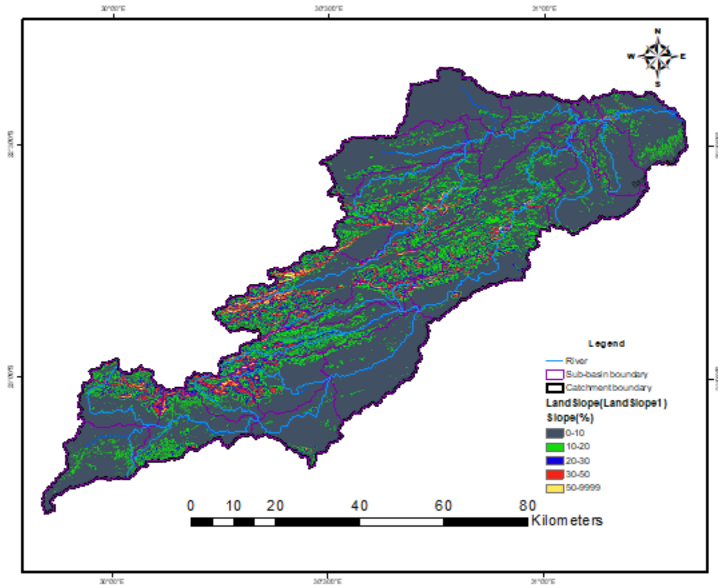

Figure 3.12: Slope and land use combined map

3.6 MODEL SETUP, CALIBRATION AND VALIDATION

The DEM, soils and land cover data which were in GIS format were used to setup the model. This was done in the ArcGIS 10.5's ArcMap using the ArcSWAT added as an extension. All the spatial datasets used in the study were projected to UTM 35 south and WGS84 datum. This was to satisfy the requirement of ArcSWAT of using the same projection to avoid mismatch of datasets during processing. The step-by-step procedure for setting up the model was adopted from Jayakrishnan *et al.* (2005) and Durães *et al.* (2011). However, some modifications were considered to successfully run the model. For example, the datasets used in the model were user-defined, unlike the latter study which made use of default datasets for the United States. Figure 3.13 indicates the processes followed in setting up and running the SWAT model.

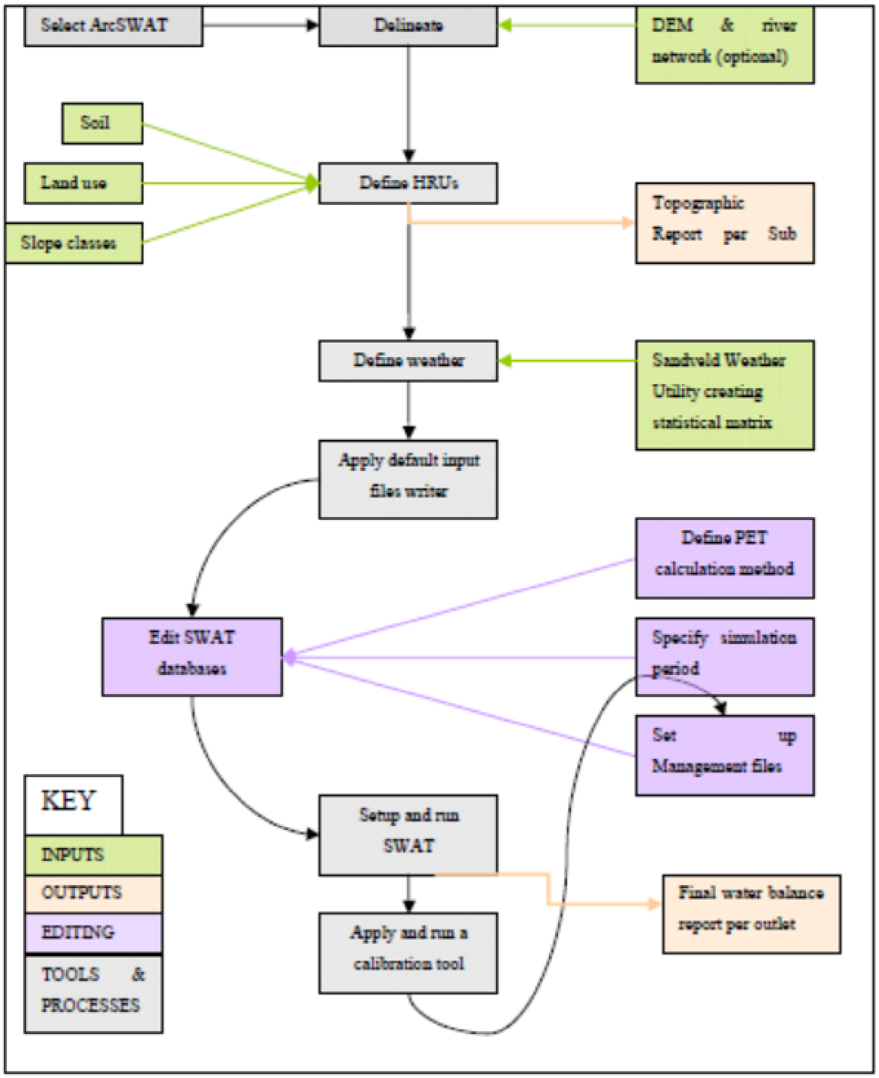

Figure 3.13: Workflow diagram for setup and run ArcSWAT (Lewane, 2009)

Figure 3.14 shows the hydrological cycle of the study area after running the model for the whole catchment using historical data for the period 1979-2014. This helps to identify model problems in the initial stages of the modelling process. For example, if the input/output to the catchment is greater/less than what is observed. Thus, alerting the modeller of the possibility of modifying model parameters to an acceptable range as shown in Table 3.4. Multi-site calibration was adopted to deal with the spatial heterogeneity of the catchment. Twelve parameters were selected for streamflow calibration. These were adjusted at the same time at a specified calibration location. Examples of three calibrated and validated sub-basins are provided. Both calibration and validation periods (Table 3.5) varied from one location to the other. This was since the streamflow records were not consistent. The model performance parameters used in this study included Nash Sutcliffe Efficiency (NSE), percent bias (PBIAS) and R^2 (Table 3.6). Evaluation of the performance of the model based on the criteria in Table 3.7 generally shows acceptable to very good model performance indicating that the model is suitable for projecting future streamflows.

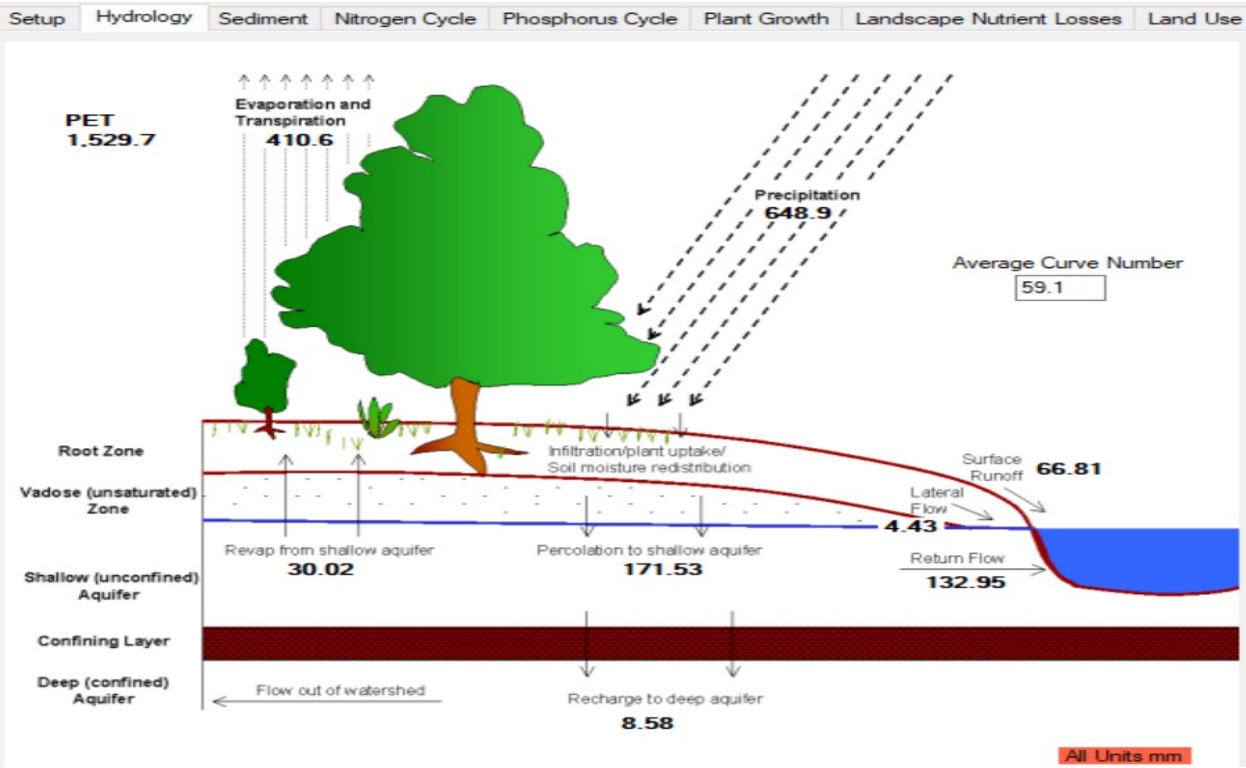

Figure 3.14: Hydrological cycle of the study area based on historical data

Table 3.4: SWAT model parameters

Parameter	Description	Minimum	Maximum	Calibrated value
r_ALPHA_BF.gw	Baseflow alpha factor (day)	0.499	1.50	0.88
r_CN2.mgt	Initial SCS (soil Conservation Service) runoff curve no. for moisture condition II	-0.018	0.35	0.03
r_GW_DELAY.gw	Groundwater delay time (day)	-17.20	24.31	1.34
r_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	-2388.60	200.31	1683.14
r_GW_REVAP.gw	Groundwater “revap” coefficient	0.09	0.23	0.14
r_CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	54.61	163.91	148.36
r_ESCO.hru	Soil Evaporation compensation factor	-0.12	0.63	0.21
r_ALPHA_BNK.rte	Baseflow alpha factor for bank storage	0.13	0.71	0.59
r_SOL_K.sol	Saturated hydraulic conductivity	-137.61	154.22	6.75
r_SOL_AWC.sol	Available water capacity of the soil layer	0.48	1.453	0.93
r_SURLAG.bsn	Surface runoff lag coefficient (day)	-0.85	15.722	3.12
r_REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” to occur (mm)	153.64	461.36	429.42

Table 3.5: Calibration and validation periods

Station name	Station no	SWAT delineated Sub-catchments no.	Calibration period	Validation period
Mutshundudi	A9H025	18	2001-2006	2007-2010
Mhinga	A9H012	15	2001-2006	2007-2010
Weltevreden	A9H005	24	2004-2007	2008-2010

Table 3.6: SWAT model performance

Station name and number	SWAT delineated sub-catchment no.	Calibration period			Validation period		
		NSE	R^2	PBIAS	NSE	R^2	PBIAS
Mutshundudi(A9H025)	18	0.63	0.76	23.00	0.53	0.80	13.00
Mhinga (A9H012)	15	0.72	0.69	18.00	0.51	0.68	12.00
Weltevreden (A9H005)	24	0.55	0.82	-10.00	0.44	0.73	-14.00

Table 3.7: Criteria for evaluating performance measures

Performance Measure	Criteria
R^2	0.65-0.7 Good[a] 0.75-0.85 Very good[a]
NSE	0.8-0.9 Very Good[b] 0.65-0.75 Good[a] > 0.5 Acceptable
PBIAS	± 25% Acceptable[c]

[a]Yan *et al.* (2014); [b]Shamsudin and Hassim (2002); Moriasi *et al.* (2007)

Figures 3.15 and 3.16 indicate good graphical fits of simulated and observed streamflow, though some of the peak streamflow events were underestimated. It is important to note that the model predicted the peak flood event for the year 2000 in sub-basin 15 despite having no observed streamflow for that period (Figure 3.15). This also shows that the model can predict future streamflow.

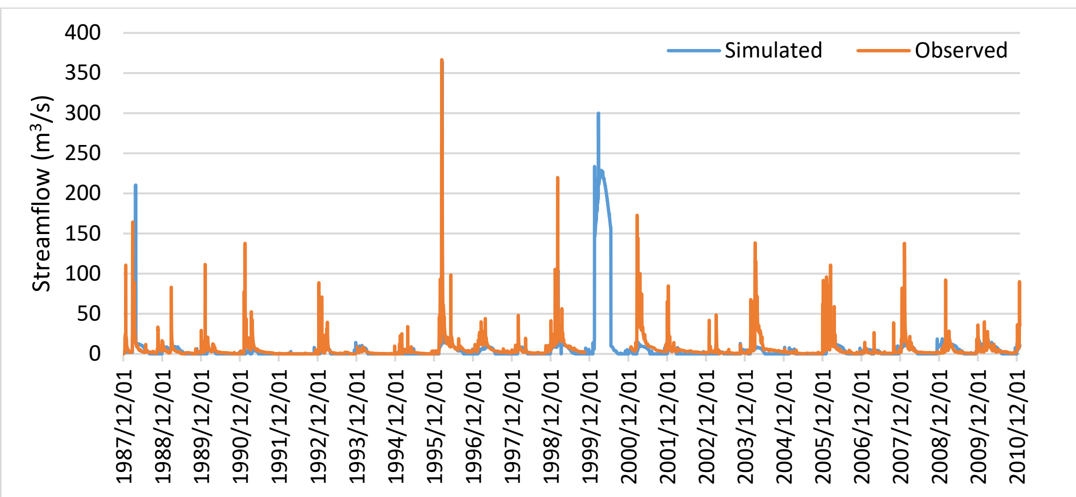

Figure 3.15: Observed and simulated streamflow for sub-basin 15

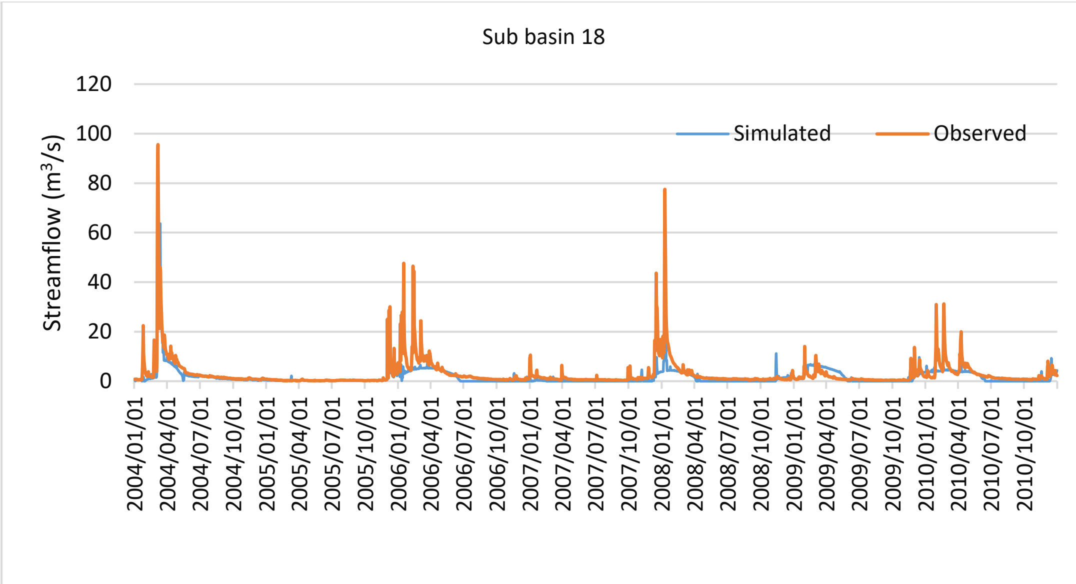

Figure 3.16: Observed and simulated streamflow for sub-basin 18

3.7 SIMULATED RESULTS FOR FUTURE SCENARIOS AND IMPLICATIONS ON WATER RESOURCES AVAILABILITY

Figures 3.17 to 3.19 indicate comparisons of maximum monthly historic and simulated streamflows for sub-basins 24, 18 and 15 for the near future (2021-2050) and far future (2051-2080) scenarios. Sub-basin 24 is in the upstream of the catchment where some stations showed an increase in rainfall in the future. This though did not signal an increase in the streamflow amounts. This may be attributed to the fact that temperature generally increases in the study area contributing to an increase in evaporation. On the other hand, sub-basin 18 and 15 represented both mid and downstream, respectively. They both showed a continuous decrease in the streamflow amounts in the near and far future. This suggests that there will be pressure on the available water for different uses in the Luvuvhu River Catchment.

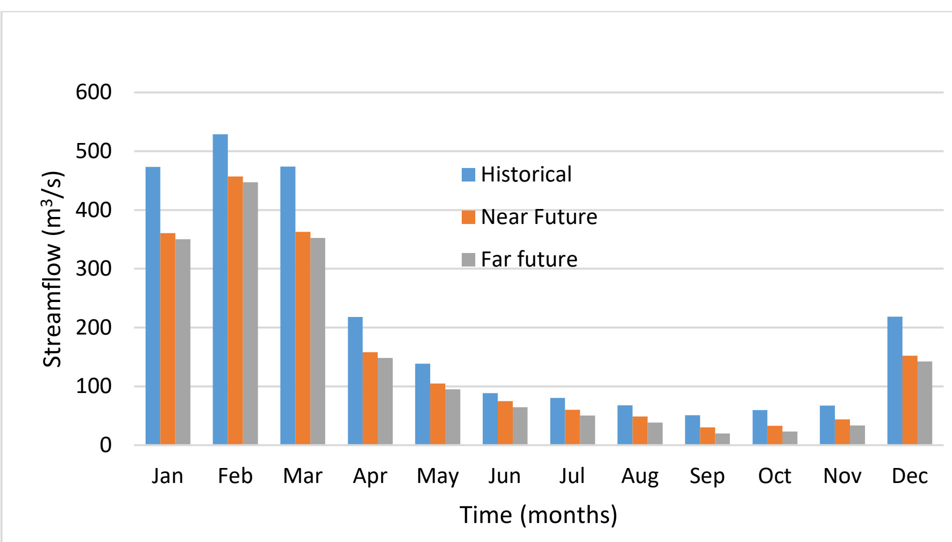

Figure 3.17: Near and far future in comparison with historical streamflow for sub-basin 24

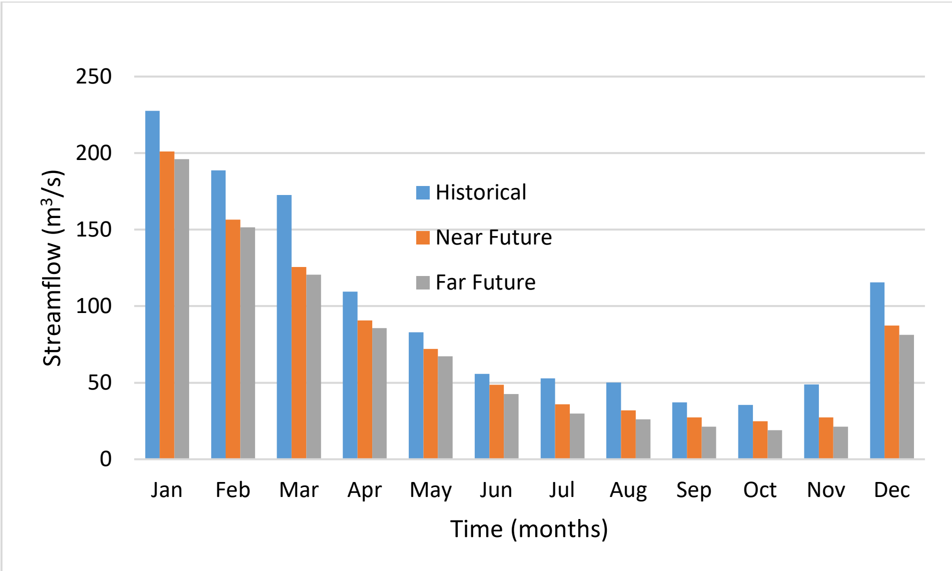

Figure 3.18: Near and far future in comparison with historical streamflow for sub-basin 18

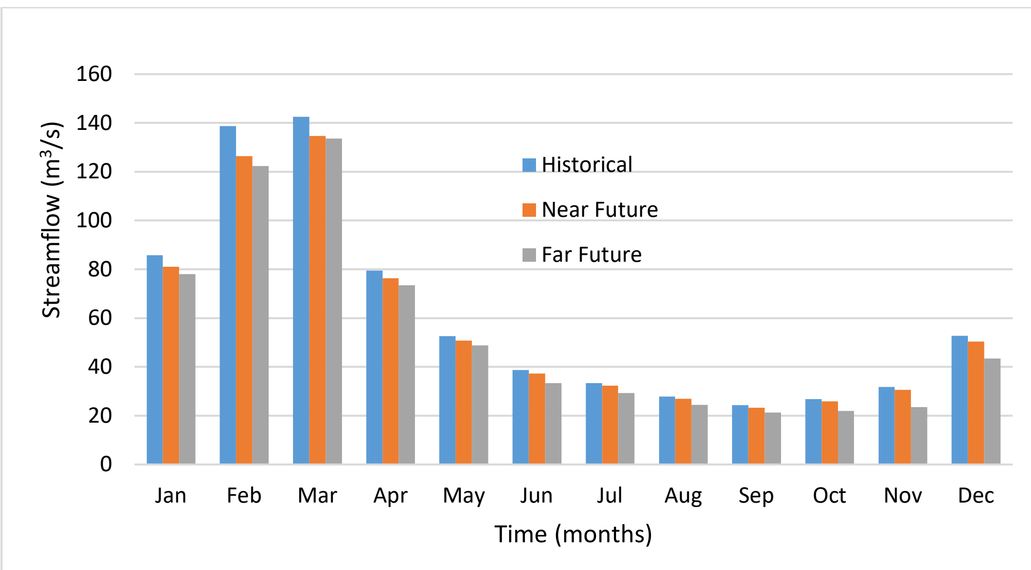

Figure 3.19: Near and far future in comparison with historical streamflow for sub-basin 15

3.8 IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES AVAILABILITY AND IMPLICATIONS ON WATER REQUIREMENTS FOR IRRIGATION AND MUNICIPAL/DOMESTIC USE

3.8.1 Impacts of climate change on projected inflows into selected dams

The sub-catchments that drain water into Albasini and Nandoni Dams (Figures 3.20 and 3.21) were delineated in ArcGIS to enable estimations of near and far future inflows into the dams. Meteorological data from CCAM virtual stations and model estimated evaporation (based on the temperature, humidity, wind and the radiation) were used as inputs. Albasini and Nandoni Dams are in the most upstream area of Luvuvhu River Catchment (Figure 3.22) which receives relatively high rainfall as compared to the rest of the catchment. Entabeni Bos station which records some of the highest rainfall events in South Africa is located within this area. This makes the upstream of Luvuvhu River Catchment a strategic water resource area for both domestic and agricultural water supply in the catchment. Land use data was based on the 2014 land cover map (Figures 3.23 and 3.24). Since Nandoni Dam is located downstream of Albasini Dam, the outlet of Albasini Dam was considered as an inflow point into the Nandoni Dam sub-catchment. The downstream flow releases from Albasini Dam were, therefore, included as input into the SWAT model for estimating inflows into Nandoni Dam.

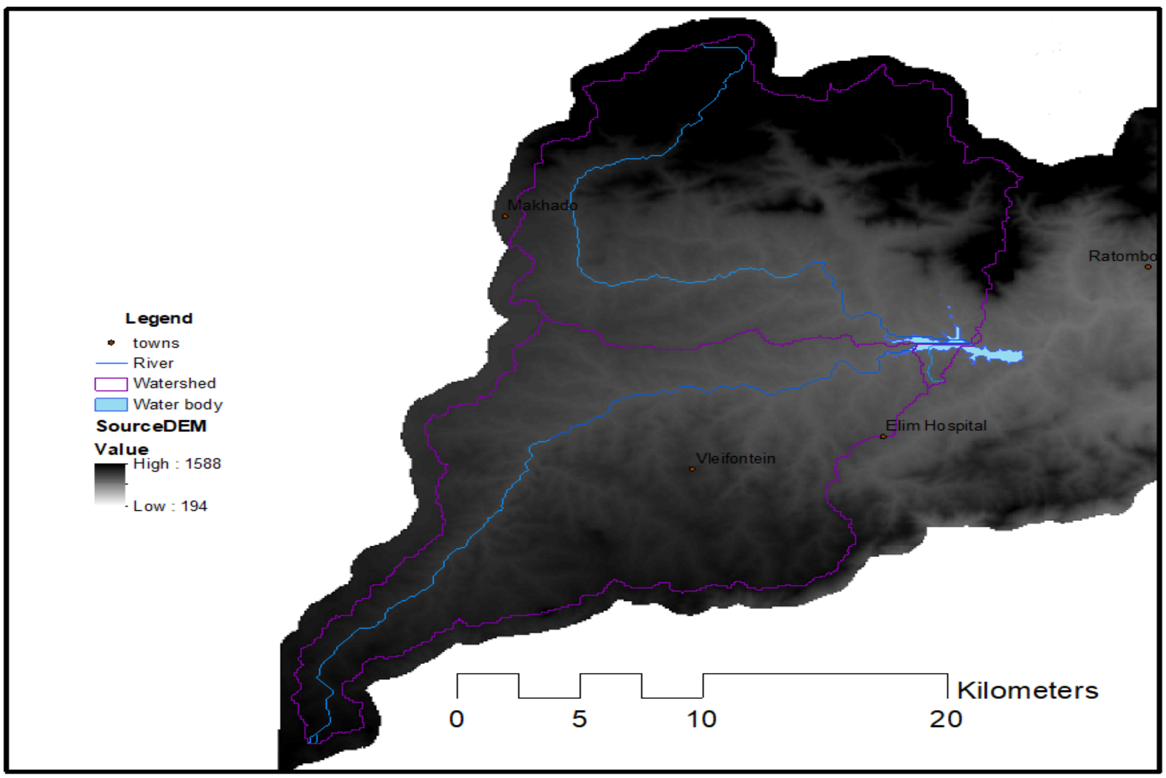

Figure 3.20: Albasini Dam sub-catchment

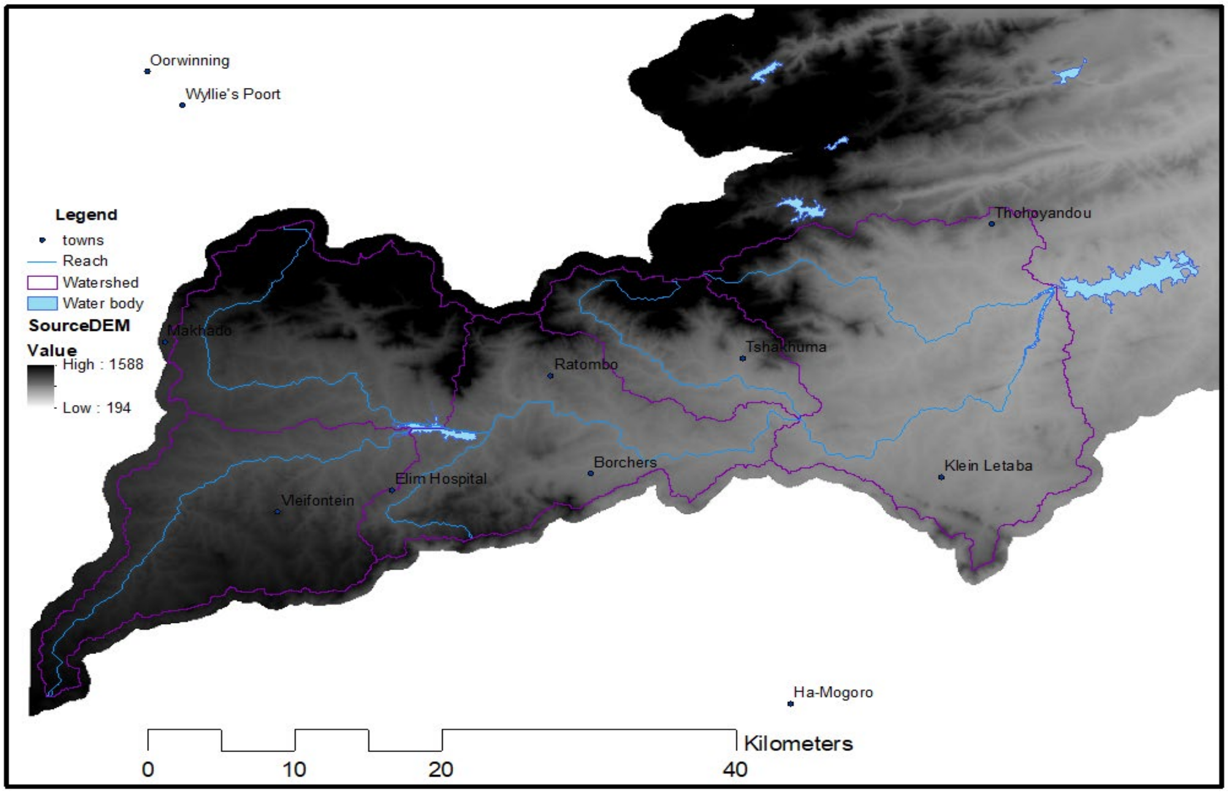

Figure 3.21: Nandoni Dam sub-catchment

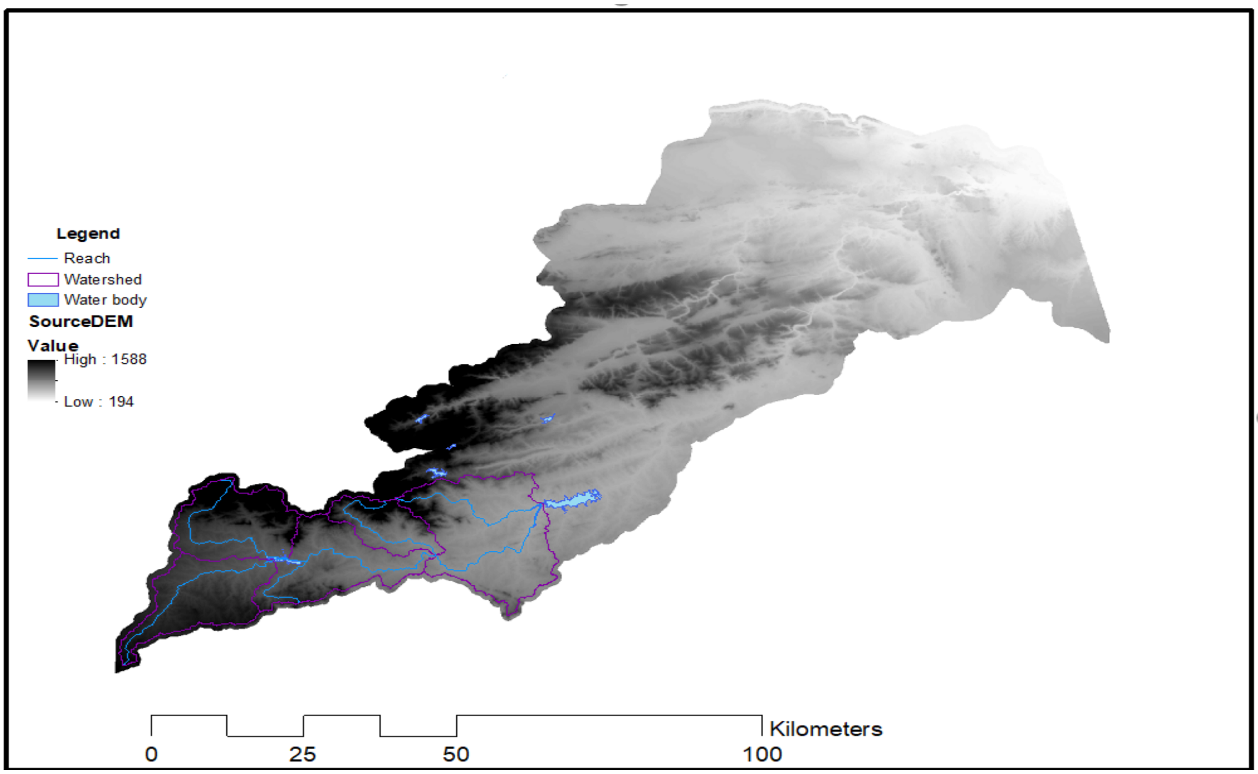

Figure 3.22: Albasini and Nandoni Dam sub-catchments within Luvuvhu River Catchment

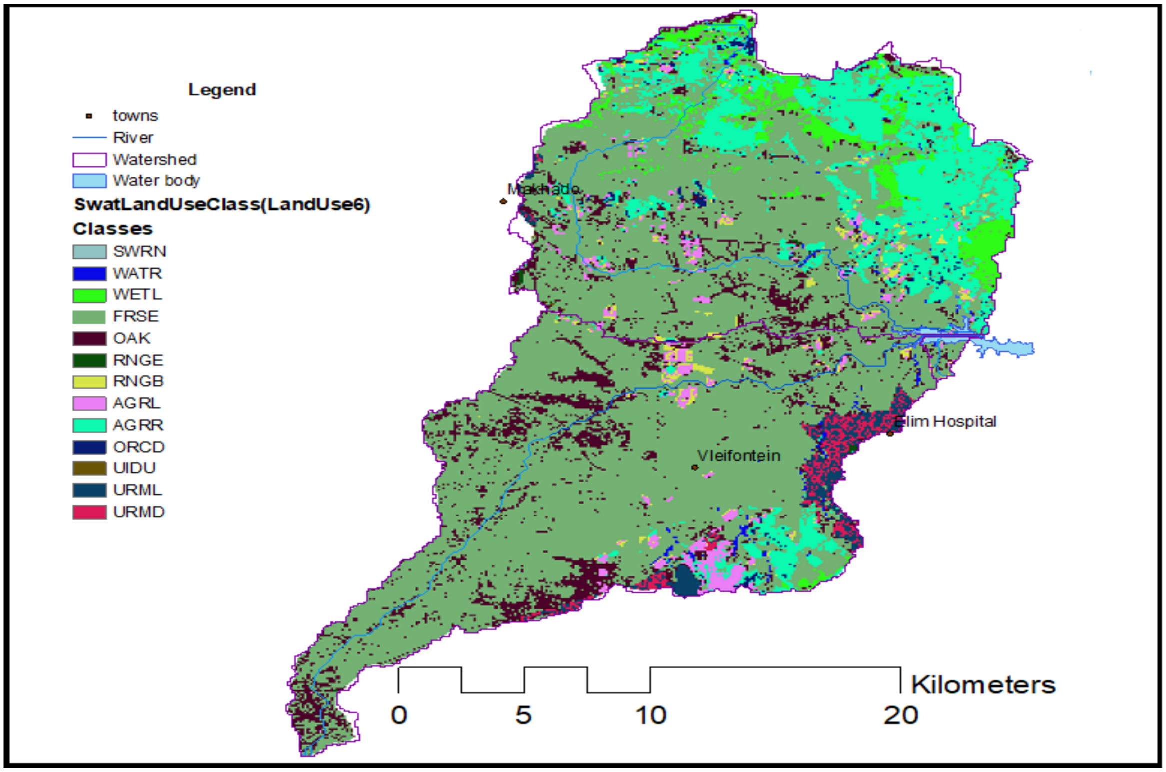

Figure 3.23: Land use cover for Albasini sub-catchment

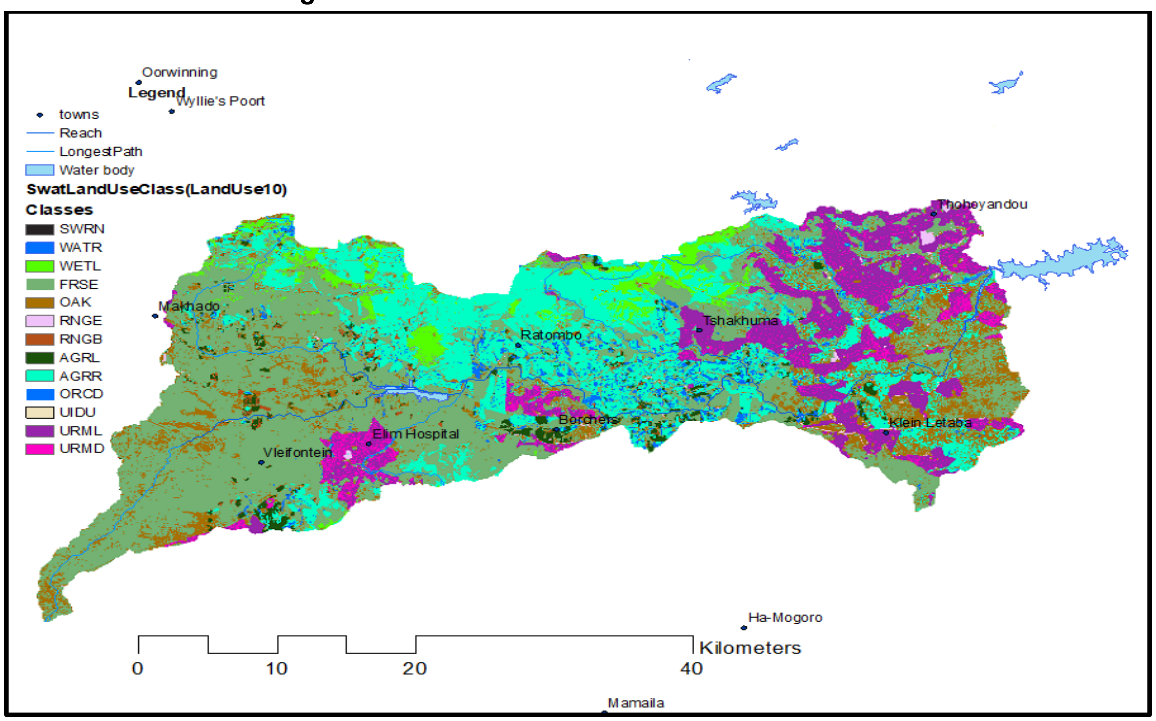

Figure 3.24: Land use cover for Nandoni sub-catchment

Annual cumulative monthly inflows for Albasini and Nandoni Dams were computed from monthly inflows for April of the previous year to March of the current year for the periods April 2021 to March 2050 (near future) and April 2051 to March 2080 (far future). A year was considered to be the period from April of the previous year to March of the current year to obtain the total inflows into the dam on the decision date (1 April of the current year) for reservoir operation (water allocation purposes). For example, the year 2021/22 represents the period of April 2021 to March 2022. The decision date is the date in which an operating rule curve is used to allocate water for various uses for a period of one year (starting from a decision date) (Ndiritu *et al.*, 2017). A decision on the volume of water to be allocated in most developed surface water systems including (Albasini and Nandoni Dams) is done based on operating rule curves. Operating rule curves show the volume of water to be allocated for given reservoir storage. For surface water systems, the decision date of 1 April is associated with the end of the rainy season when most of the rainfall has been received. The annual cumulative inflows, therefore, indicate the volume of water that will supplement available dam water storage at the end of the rainfall season.

Regression analysis was conducted using the Data Analysis tool of Microsoft Excel to determine trends for near and far future cumulative annual inflows and their significance. The significance of each of the trends was tested at a significance level (α) of 0.05. A trend was considered significant if the computed p-value is less than α (0.05), otherwise, it was not significant. The annual cumulative inflows for the near future for Albasini and Nandoni Dams have increasing linear trends while those of the far future have decreasing trends (Figures 3.25 to 3.28). Table 2.4, as noted in sub-section 2.4.3, indicated a dominant decrease in rainfall in the months of November, February and March in the far future. This together with an expected increase in temperature in the far future are likely to be the cause of inflow trends. The trends for cumulative inflows for near future had p-values of 0.217 and 0.213 for Albasini and Nandoni Dams, respectively (Figures 3.25 and 3.26). Trends for far future cumulative inflows had p-values of 0.112 and 0.105 for Albasini and Nandoni Dams, respectively (Figures 3.27 and 3.28). The p-values were greater than the significance level (α) of 0.05 indicating that the trends for cumulative inflows for the near and far futures were not statistically significant. This is likely to be influenced by year-to-year variations in inflows.

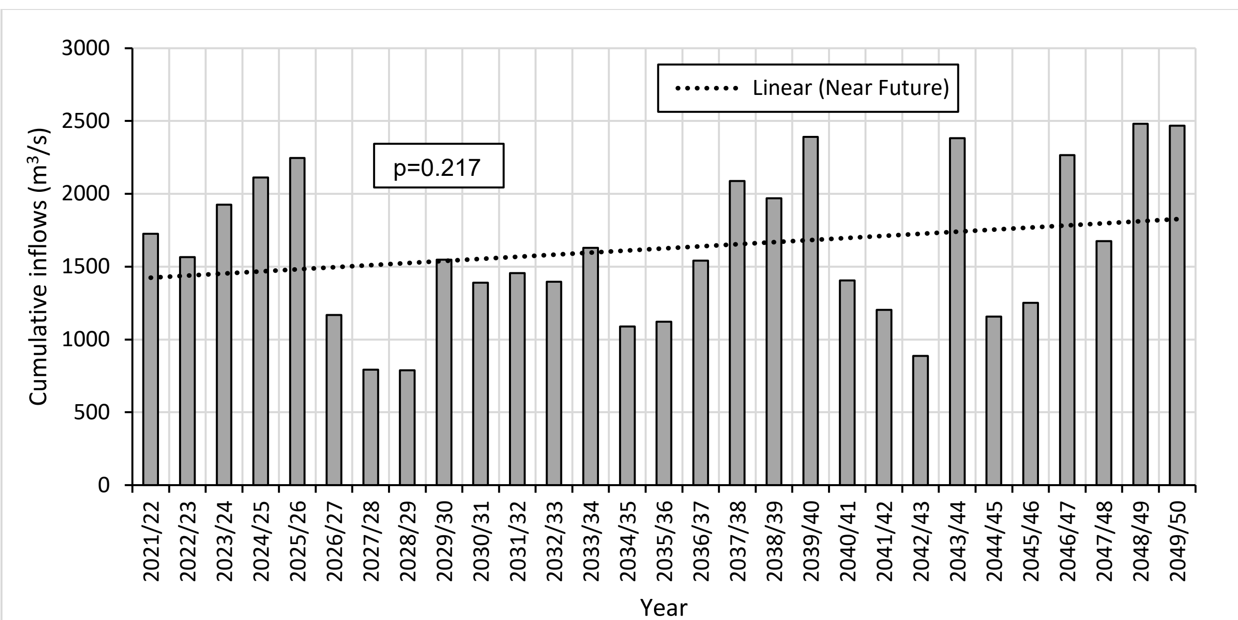

Figure 3.25: Annual cumulative inflows into Albasini Dam for the near future

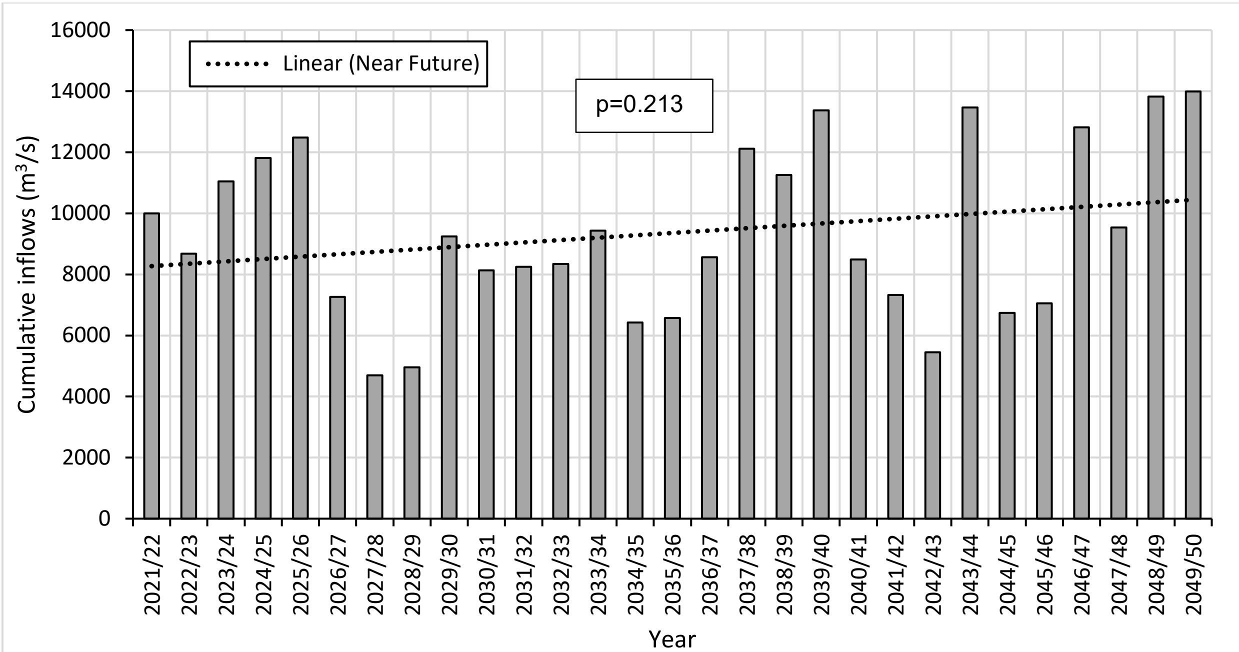

Figure 3.26: Annual cumulative inflows into Nandoni Dam for the near future

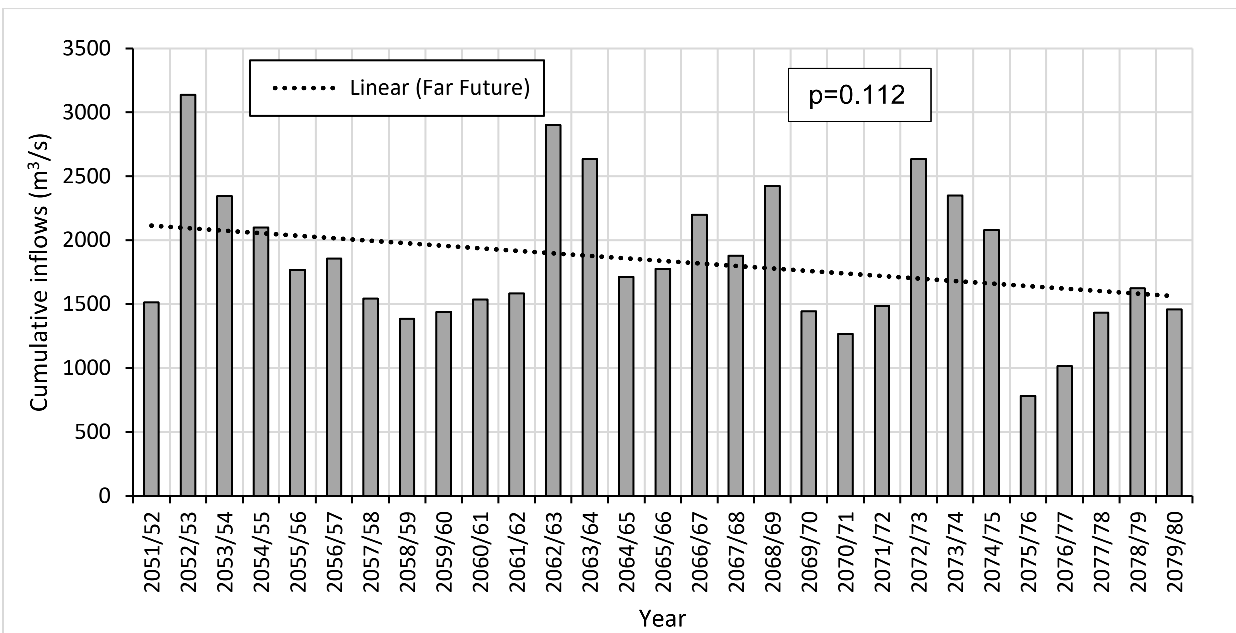

Figure 3.27: Annual cumulative inflows into Albasini Dam for the far future

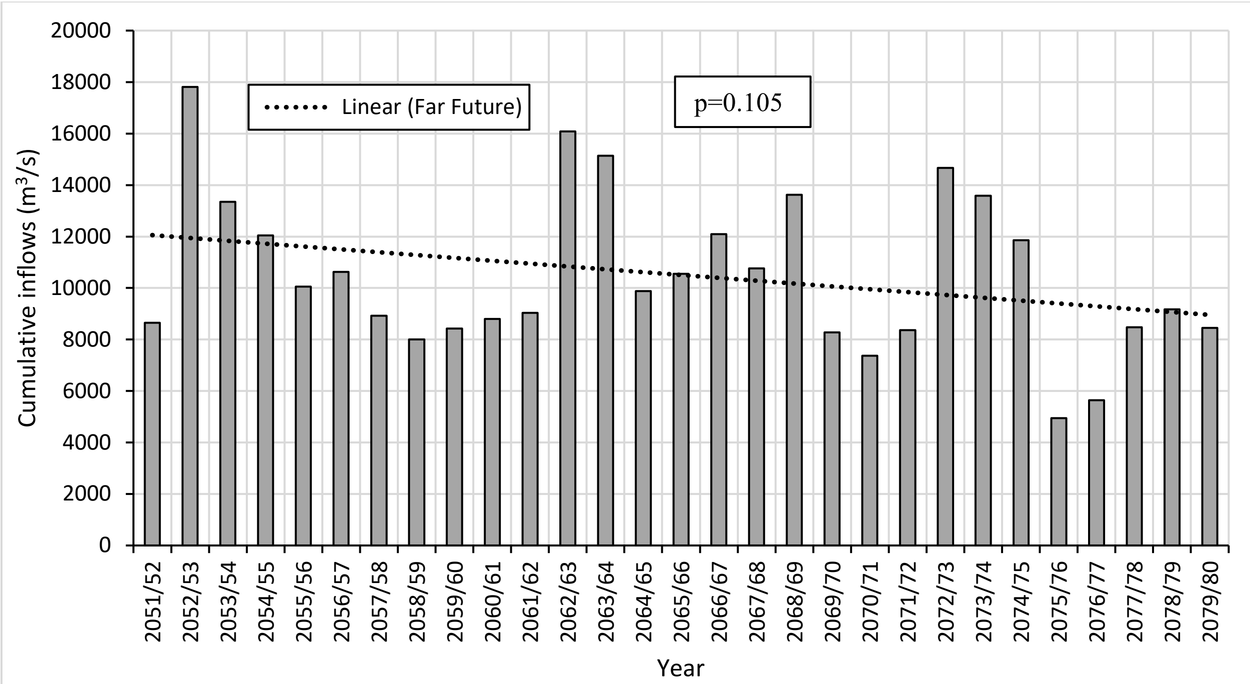

Figure 3.28: Annual cumulative inflows into Nandoni Dam for the far future

The cumulative inflows into Nandoni Dam for near and far future scenarios are higher than those of Albasini Dam (Figures 3.25 to 3.28). This is expected due to a relatively large sub-catchment area (1320 km^2) of Nandoni Dam and inflow contributions from main tributaries of Luvuvhu River including Latonyanda and Dzindi Rivers (see the rivers in Figure 3.4). The area contributing runoff to Albasini Dam is 500 km^2. The upstream of Latonyanda River is in a high rainfall area that receives a mean annual rainfall of 1287 mm. The expected runoff contribution to Nandoni Dam is, therefore, higher compared to that of Albasini Dam. Odiyo *et al.* (2015) indicated that the Latonyanda River downstream of Albasini Dam contributed mean and maximum daily flow for the period 1970 to 2008 of 0.91 and 49 m^3/s, respectively. The releases from Albasini Dam also become inflows into Nandoni Dam as explained earlier.

It is expected that an increase or decrease in cumulative inflows into the dam will have an impact on available water in the dam and will hence influence the decision on the volume of water to be allocated for domestic and agricultural water use in each year. This analysis has therefore assisted in determining how the changes in inflows into the dam will affect water availability and allocation in the near and far futures (i.e. impact of different climate change scenarios on water available for allocation). Though the cumulative inflows for near-future scenarios have increasing trends, their year-to-year variations as shown by fluctuating bars (Figures 3.25 to 3.28) indicate that there will be variability in inflows into the dams which will affect water resources availability and allocation. The far future scenario with decreasing trends will also be worsened by the year-to-year variations of cumulative inflows.

3.8.2 Projected future water requirements for irrigation

The study had proposed to estimate irrigation water requirements under changing climate conditions using SAPWAT4. SAPWAT4 requires information on irrigation system (type, design application, efficiency, distribution uniformity and wetted area), soils (type, effective depth, salinity and irrigation water salinity) and farm characteristics (field size, irrigated area and crop area) for crop setup and estimation of irrigation water requirements. SAPWAT4's requirement for information on farm characteristics indicates that it is more suitable for estimating irrigation water requirements at a farm/field scale. It is, therefore, not applicable to catchment scale studies. Crop water requirements for selected crops within Luvuvhu River Catchment were estimated based on reference crop evapotranspiration, duration of different growth stages and estimated reference evapotranspiration (Equation 3.1).

$$ET_{crop} = K_c \times ET_o \tag{3.1}$$

where ET_{crop} = the water requirement of a given crop in mm/day, K_c = the crop factor and ET_o = the reference crop evapotranspiration in mm/day. Reference evapotranspiration was estimated based on the Hargreaves equation (Hargreaves and Samani, 1985):

$$ET_o = 0.0023 R_a TD^{0.5}(T_a + 17.8) \tag{3.2}$$

where R_a is extraterrestrial radiation (mm/day), TD is the difference between the daily maximum and minimum temperatures, T_a is the mean daily temperature and R_a was computed as:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega s \sin(\phi)\sin(\delta) + \cos(\phi)\cos\delta \sin(\omega s)] \tag{3.3}$$

where G_{sc} is the solar constant, *dr* is the inverse relative distance Earth-Sun, ωs is the sunset hour angle], ϕ is the latitude and δ is the solar declination. Equations for calculating these variables are found in Allen *et al.* (1998).

Estimated ET_o were divided by a pan coefficient of 0.7 to convert them into evaporation to enable comparison with observed pan evaporation. This could only be done for CCAM temperature stations (t-232300, t-232305 and t-229306) which were within the vicinity of pan evaporation stations. Data from the temperature stations includes both historic and projected CCAM future temperatures for the period 1961/01/01 to 2099/12/31. Evaporation data for stations A9E002 and A9E004 were compared with evaporation estimated based on the Hargreaves equation. The data periods used corresponded to the period when pan evaporation data was available (Table 3.8). The distribution of the stations is in Figure 3.29. Data for stations A9E001 and A9E003 were excluded as they were not reliable due to large gaps and replicated daily values for each month, respectively.

Table 3.8: Evaporation and temperature stations

Evaporation station	Observed data period	Estimated temperature station
A9E002	1961/01/01 to 2019/09/01	t-232300
A9E004	2009/11/30 to 2019/07/01	t-230305
A9E004	2009/11/30 to 2019/07/01	t-229306

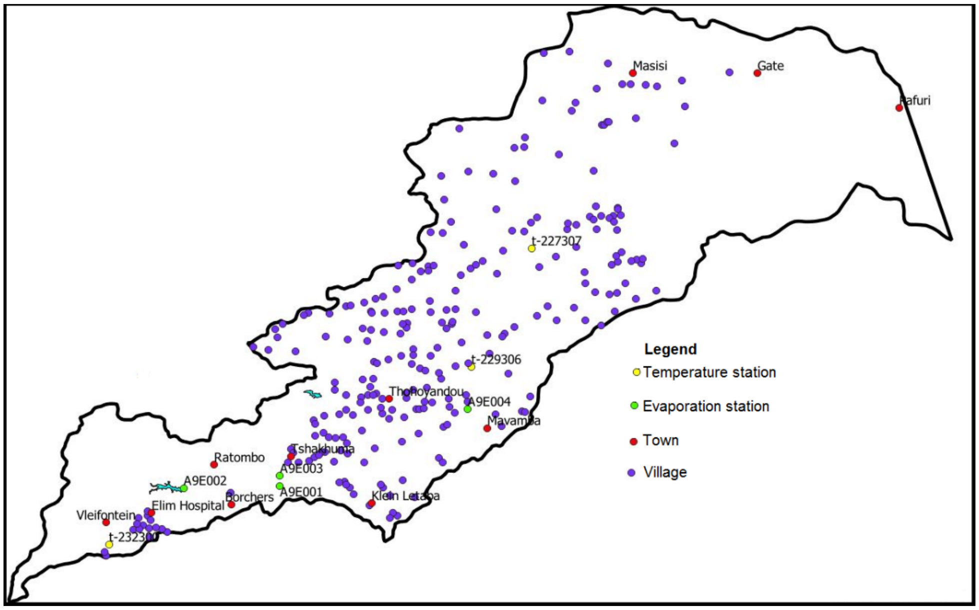

Figure 3.29: Distribution of stations

Comparisons of observed and estimated evaporation indicate similar behaviour (pattern) though evaporation was overestimated in some of the periods (Figures 3.30-3.32). The results presented are for 3 years to show a clear view of the comparison between observed and estimated values.

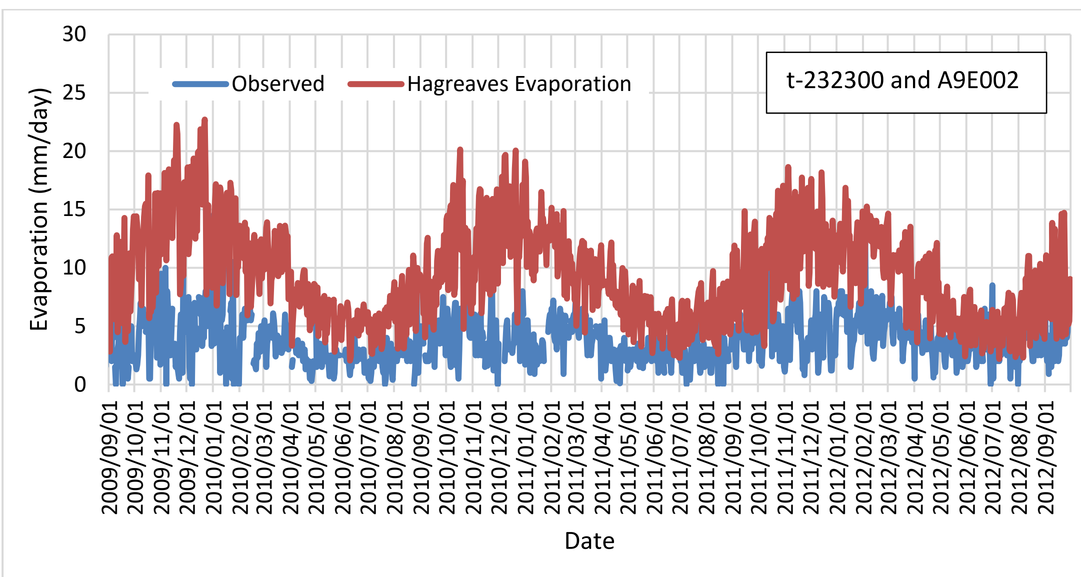

Figure 3.30: Observed (A9E002) and estimated (t-232300) evaporation

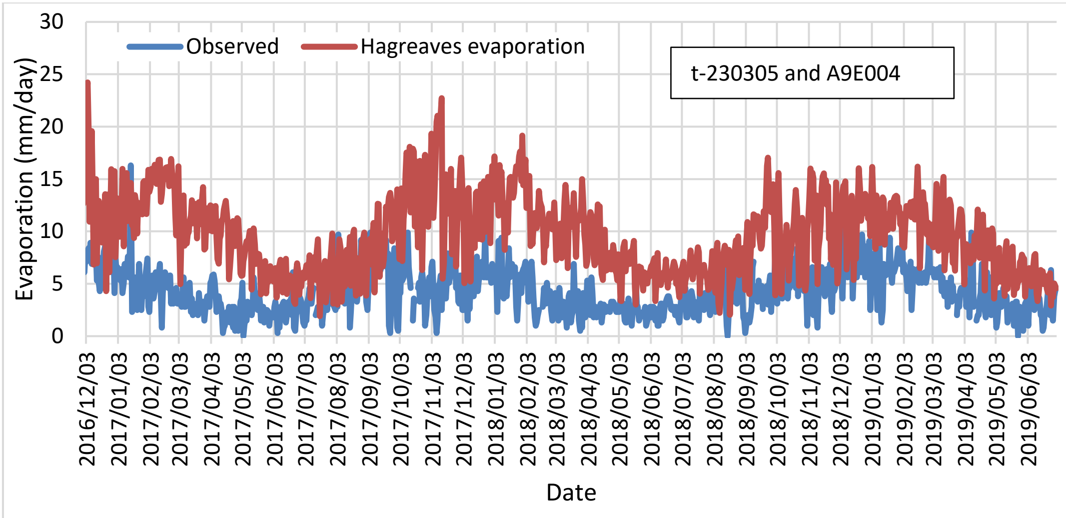

Figure 3.31: Observed (A9E004) and estimated (t-230305) evaporation

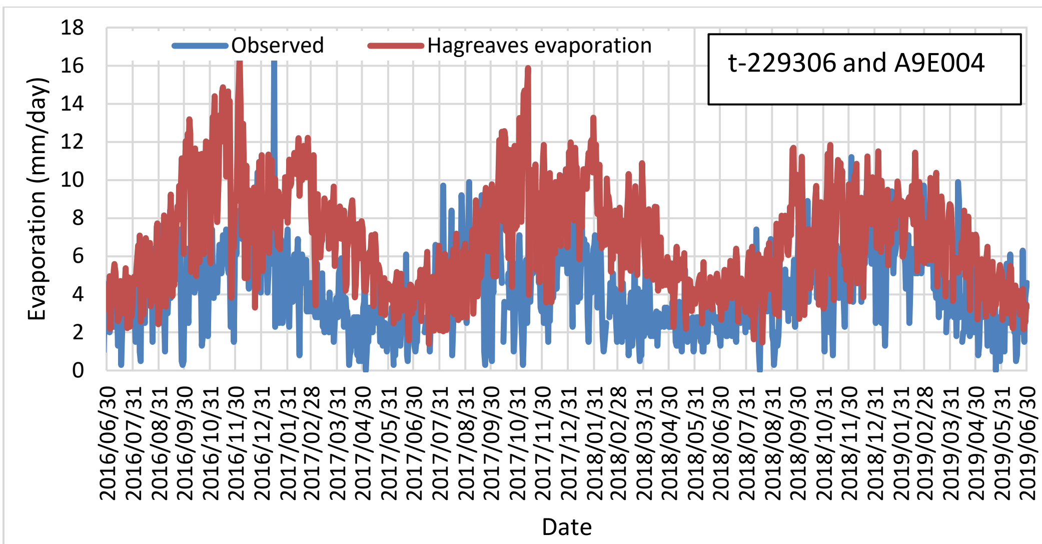

Figure 3.32: Observed (A9E004) and estimated (t-229306) evaporation

Commercial and subsistence (small scale) farming of diverse crops are common within the Luvuvhu River Catchment. Some of the common crops include mangoes, avocadoes, guavas, macadamia nuts, tomatoes and bananas. Department of Rural Development and Land Reform (2016) has identified crops that were prioritised for inclusion in the Vhembe District Municipality Agri-Park programme. The programme is aimed at eradication of rural poverty as part of the 2011 Green Paper on Land Reform policy review and reformulation process. The crops were prioritised based on biophysical (climatic, soil and resilience to weed, pest and disease and adaptability to adverse conditions); transport, market access and demand; strategy, payback and profitability; human, physical and financial capital, linkages and processing opportunities, job creation (direct on-farm job creation), local development, global competitiveness and trade, political and institutional issues; social issues, and food security and sustainability factors. Table 3.9 indicates the descriptions of prioritised, common and crops with more potential for development in Luvuvhu River Catchment.

This study estimated future water requirements for selected crops within the Luvuvhu River Catchment under changing climatic conditions. Temperature data from CCAM stations t-232300, t-232305, t-229306 and t-2207307 were used in the estimation of historic (2010-2019) and projected future evapotranspiration (2020-2099). Evapotranspiration data was required for the estimation of crop water requirements. The selection of the stations was done such that the estimations covered areas in the upstream, midstream and towards the downstream of the Luvuvhu River Catchment. The crop coefficients (K_c) and the duration of different growth stages used in the estimations are in Table 3.10.

Table 3.9: Prioritised, common and crops with more potential for development

Crop	Reason for selection	Description	Planting date/season
Tomatoes	Prioritised	Seasonal, sensitive to very low and very high temperatures (Department of Rural Development and Land Reform, 2016) At temperatures below 12ºC and above 35ºC, flowers are often shed. This leads to poor fruit set, and the quality of the fruit produced under such conditions may be detrimentally affected (Stevens *et al*., 2012)	September
Maize	Common (staple food)	The minimum temperature for germination is 10ºC. The critical temperature harming yield is approximately 32ºC.	October 15 (Schulze and Walker, 2007)
Avocadoes	Prioritised	Cool subtropical conditions with a mean daily temperature of 20 to 24ºC (Department of Rural Development and Land Reform, 2016)	Early spring
Baby vegetables (carrots)	Prioritised	Can be grown throughout the year, endure a considerable amount of heat (Department of Rural Development and Land Reform, 2016)	Throughout the year
Macadamia nuts	Prioritised	Macadamia flourish between 16 and 25°C and nut quality is superior when grown at an altitude of 600 m or lower (Mogala, 2014)	
Mango	Prioritised	Mango trees will grow and produce well in areas with very high temperatures (45°C). However, when the maximum temperature exceeds 46°C vegetative growth ceases, especially if it is accompanied by low humidity. Certain cultivars are less tolerant to high temperatures and low humidity, and the fruit will show symptoms of sunburn (NDA, 2000)	August to September (NDA, 2000)
Pigeon pea	Prioritised	Pigeon peas grow well under temperatures of between 18 and 35°C. Pigeon peas are drought tolerant but are frost intolerant legume crops. Under dry areas with less than 600 mm annual rainfall, pigeon peas produce seeds abundantly owing to the crop maturing early and the incidence of pest damage being low (DAFF, 2009)	Planting starts from October to December
Bananas	Feasible and common	optimum mean monthly temperatures for bananas are 25-28°C, with a range of 20-35°C (Schulze and Maharaj, 2007)	Summer planting (December/January) has been identified as the optimum in most areas (Stevens *et al*., 2012)
Tea	More potential for development	Average temperatures below 12 to 13°C and above 30°C delay the development of the shoots to be plucked. The ideal mean annual temperature is thought to lie between 18 and 20°C (DAFF, 2016)	In general, planting is completed by end-May/ June in draughty areas and by September to early November in other places (DAFF, 2016)

Table 3.10: Crop coefficients and duration of crop growth stages

Crop	K_c initial	K_c mid	K_c end	Duration of crop growth stages					Planting period
				Initial	Development	Mid	Late	Total	
Tomato	0.60	1.152	0.70-0.90	35	45	70	30	180	
Maize, Field (grain) (field corn)	1.20	0.3511 (harvest after complete field drying)	2 .00	20	35	40	30	125	15 Oct-16 Feb
Banana	0.50	1.10	1.00	120	90	120	60	390	1 Dec-24 Dec*

*refers to Dec of the following year

Figures 3.33 to 3.35 indicate the crop water requirements for three selected crops (banana, maize and tomato) for the three 10-year periods (2010-2019, 2050-2059 and 2090-2099). These have been used as examples to indicate the crop water requirements under changing climatic conditions. There is a general increase in crop water requirements in the periods 2010-2019, 2050-2059 and 2090-2099. This is related to the expected increase in future temperatures which will increase crop evapotranspiration. Luvuvhu River Catchment is expected to have increased temperatures in the future as explained in Chapter 2 of this report.

The crop water requirements for banana (Figure 3.33) increased due to an increase in K_c to a value of 1.10 at the mid growth stage. They decreased from April to August though K_c was still high (1.10). This decrease can be associated with the drop in temperature since this period is part of the winter season characterised by low temperatures. The gradual increase in water requirements for the period of September to December can also be linked to a temperature increase during the summer season. For maize, relatively high water requirements (Figure 3.34) were at the mid and late growth stages (9 December to 16 February, $K_c = 2$). Crop water requirements for tomato were higher for the mid growth stage (06 October to 19 November) as compared to the rest of the stages (see Figure 3.35) due to an increased crop coefficient of 1.152 (Table 3.10).

Comparisons of average crop water requirements for the three 10-year periods (2010-2019, 2050-2059 and 2090-2099) consistently indicate an increase in irrigation requirements for near and far futures (Figures 3.36 to 3.38). The differences in average crop water requirements ranged from 1.70 to 6.62, 0.76 to 4.88 and 1.38 to 5.01 mm/day for maize, banana and tomato, respectively (Table 3.11). Maize which is a staple food for most of the communities in Luvuvhu River Catchment had the highest range of changes in crop water requirements. The highest average crop water requirements were in the months Jan, Oct and Nov for maize, banana and tomato, respectively.

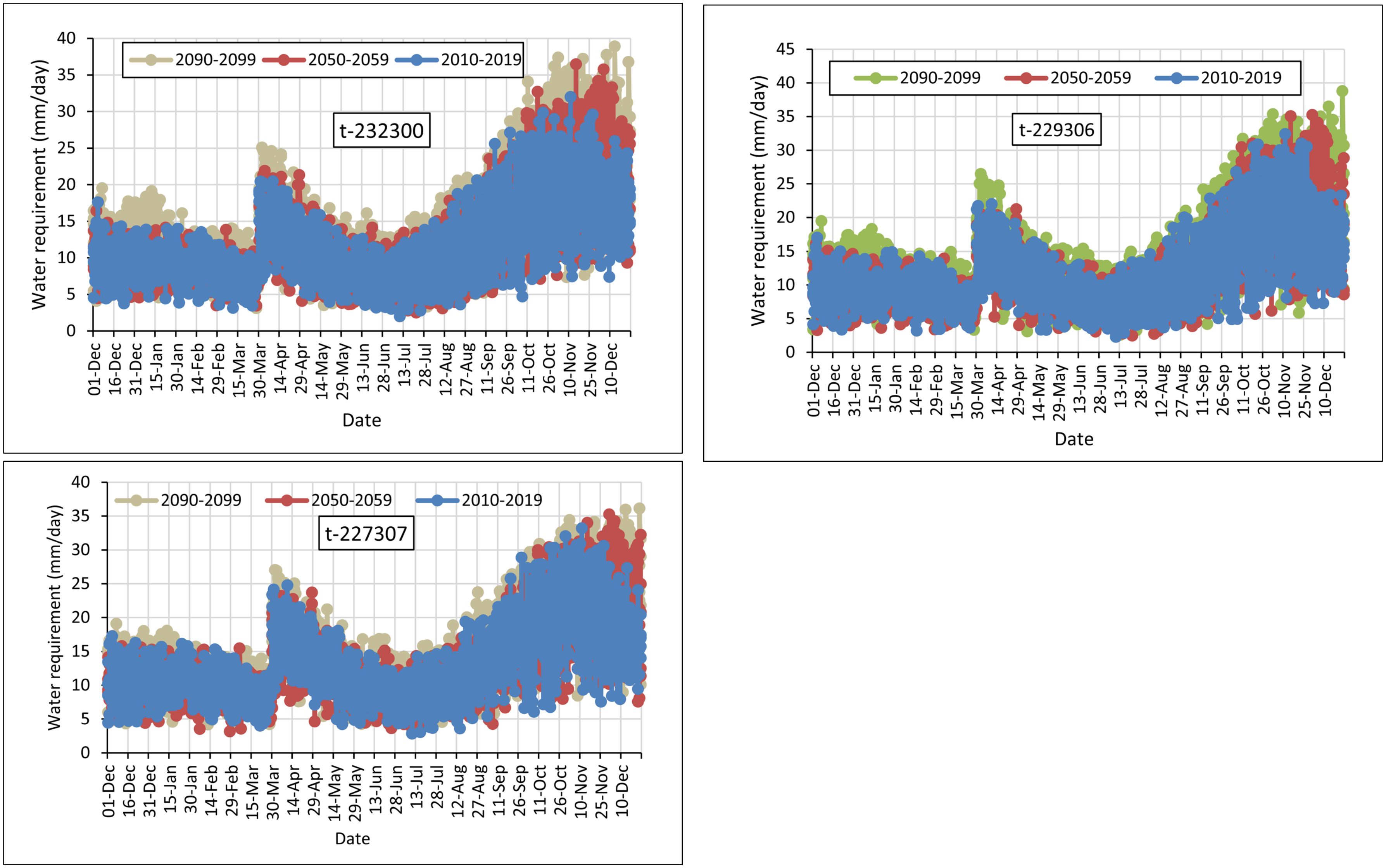

Figure 3.33: Estimated water requirements for banana

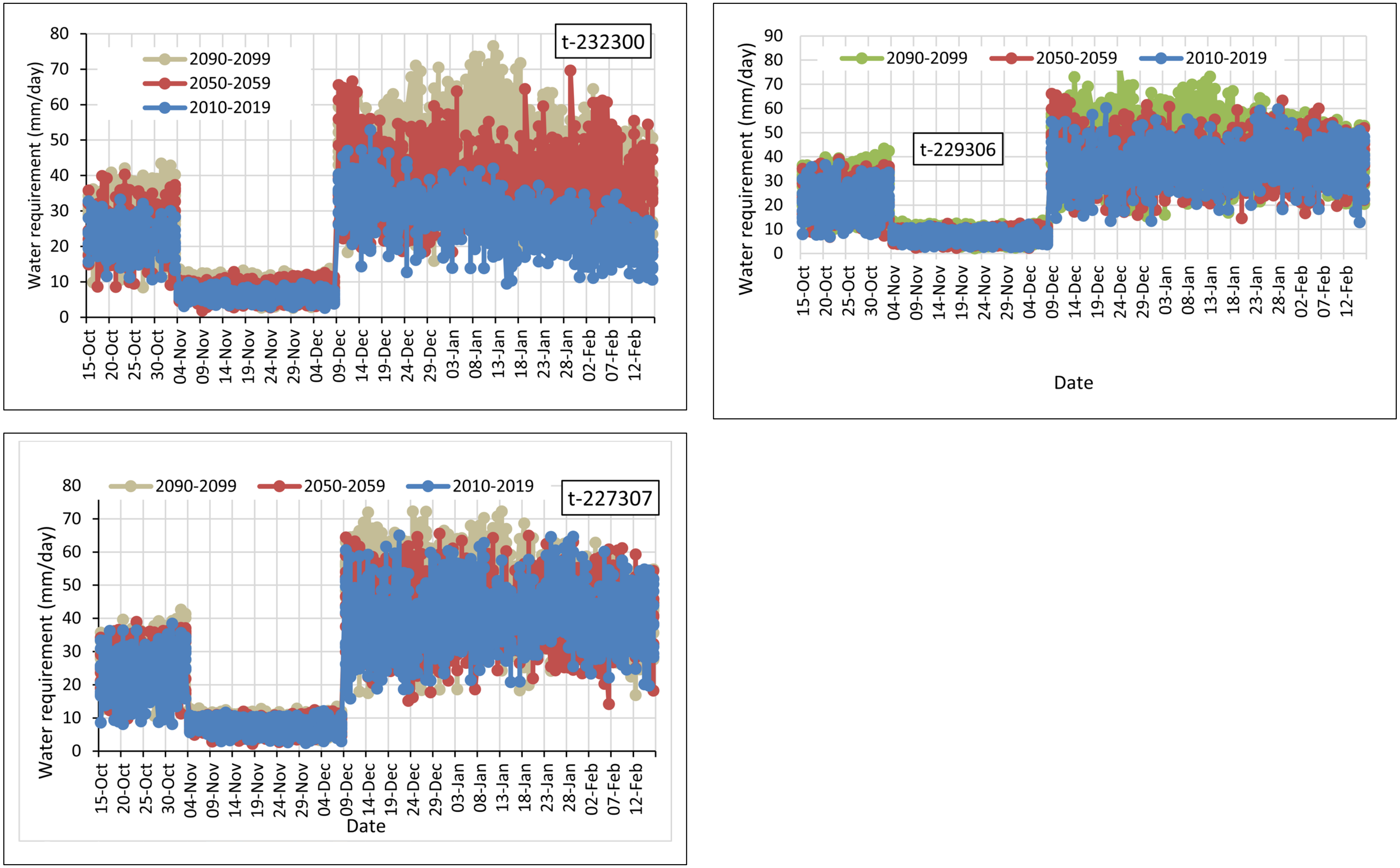

Figure 3.34: Estimated water requirements for maize

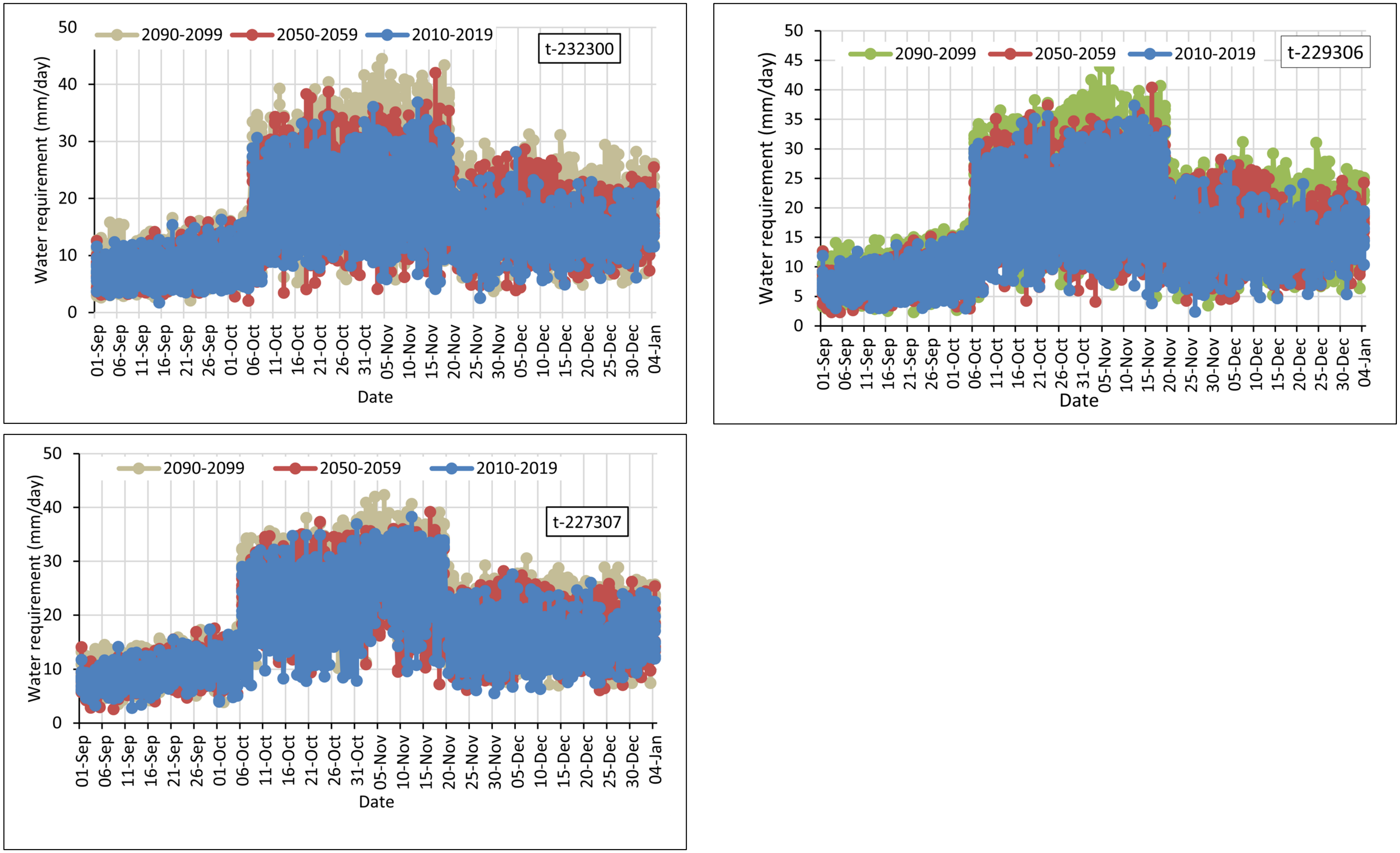

Figure 3.35: Estimated water requirements for tomato

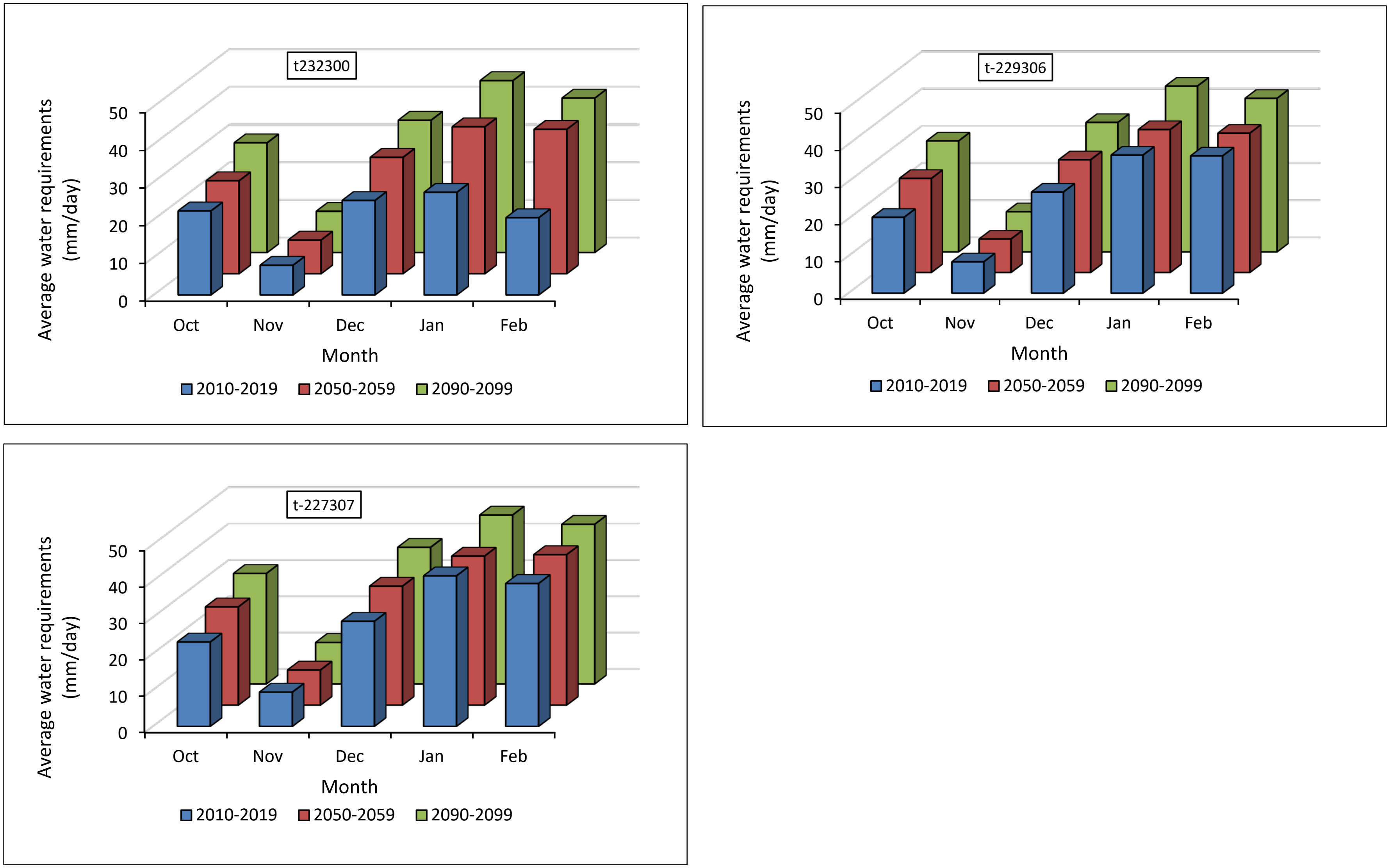

Figure 3.36: Average crop water requirements for maize

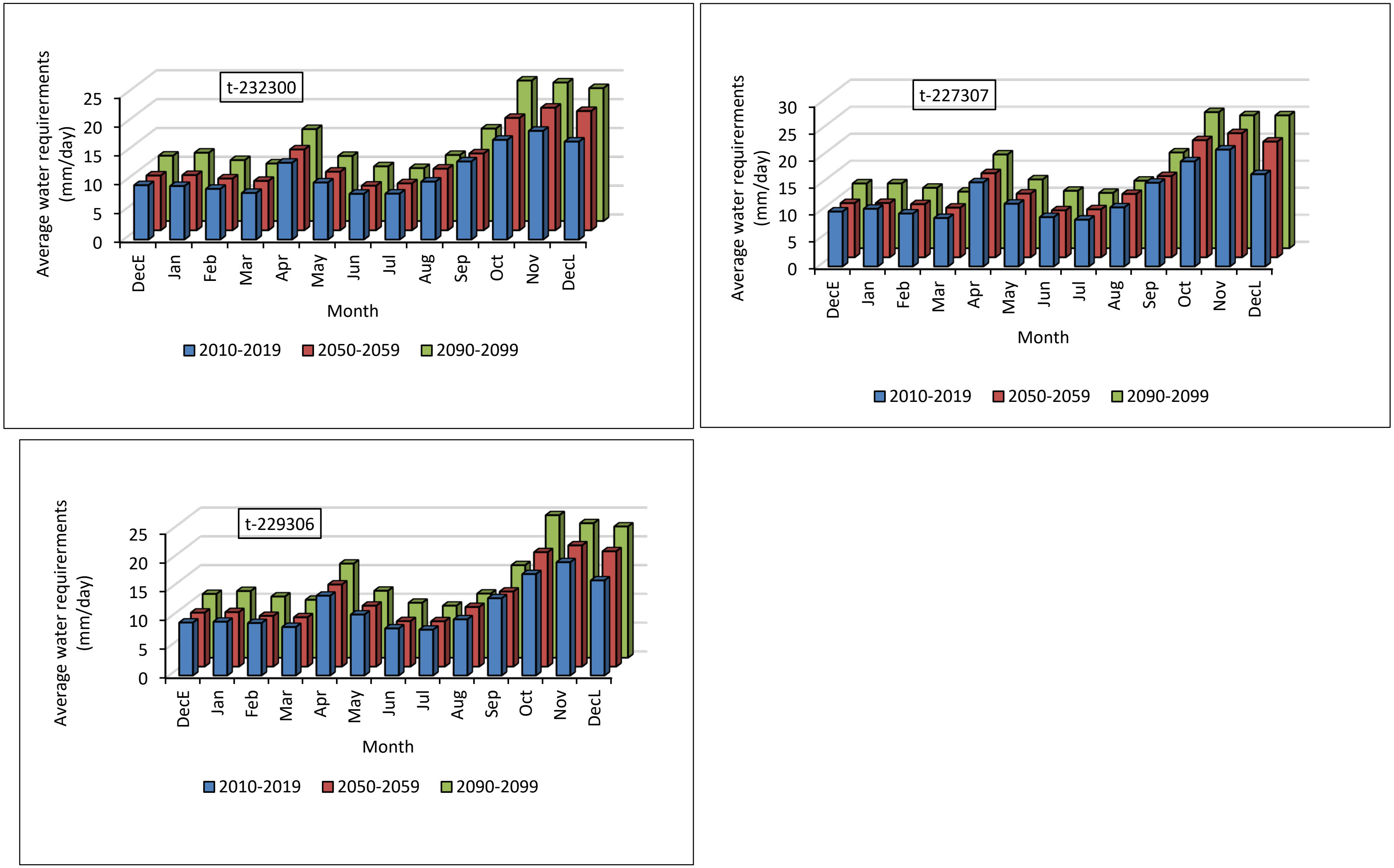

Figure 3.37: Average crop water requirements for banana

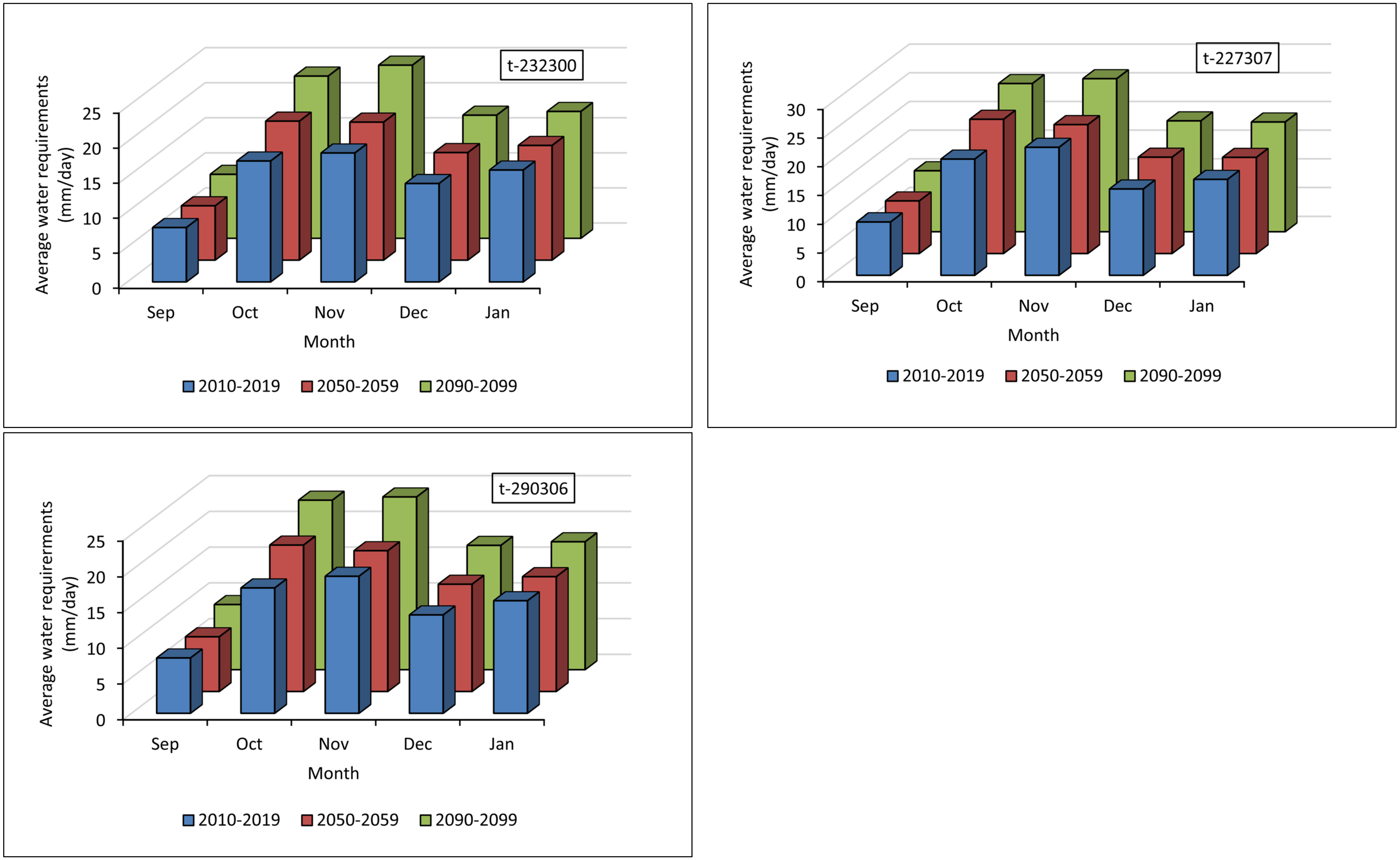

Figure 3.38: Average crop water requirements for tomato

Table 3.11: Differences in average crop water requirements based on temperature data from different stations

Crop	Month	t-232300	t-229306	t-227307
Maize	Oct	4.43	4.54	3.35
	Nov	2.01	1.81	1.72
	Dec	4.20	4.49	4.83
	Jan	6.62	6.14	5.47
	Feb	2.65	3.83	2.51
Banana	Dec	1.83	1.70	1.94
	Jan	2.27	2.12	1.95
	Feb	1.59	1.83	1.34
	Mar	1.40	1.50	1.27
	Apr	1,91	2.08	1.79
	May	1.12	1.05	0.94
	Jun	1.74	1.65	1.93
	Jul	1.03	1.17	1.35
	Aug	0.77	0.79	0.76
	Sep	2.70	3.03	2.69
	Oct	4.86	4.88	3.51
	Nov	2.76	2.31	1.62
	Dec	2.34	2.76	3.18
Tomato	Sep	1.38	1.46	1.46
	Oct	3.32	3.23	2.43
	Nov	5.01	4.47	4.21
	Dec	2.22	2.38	2.54
	Jan	1.73	1.83	2.37

3.8.3 Projected future water requirements for domestic/municipal water use

Information on projected future water requirements for some of the regional water supply schemes within Luvuvhu River Catchment was obtained from all towns' reconciliation strategies for northern region reports from the DWS through the link www6.dwa.gov.za/DocPortal/. Table 3.12 indicates the details of the villages/areas supplied, water sources and remarks for expected population growths and demands, livelihood and water availability status. This information is crucial when assessing the impact of climate change on water requirements for domestic/municipal use. Figures 3.39 and 3.40 indicate an increase in future water requirements with time for both low and high population growth scenarios for most of the regional schemes associated with population increase and/or planned improvement in water services. However, Makuya and Lambani regional water supply schemes will not have a significant increase in water requirements in the future, they are still under threat since they were already in deficit in the year 2011 as indicated in Table 3.12. Makuya regional water supply scheme does not have sufficient water to cater for the future domestic needs (Table 3.12).

Table 3.12: Some of the regional water supply schemes within the Luvuvhu River Catchment

Regional water supply scheme	Quaternary catchment	Villages/Areas supplied	Water source(s)	Remark
Tshakhuma	A91D and A91E	Rembander, Khwekhwe, Tshakuma, Tsianda, Khodesa, Ha-Mutsha and Khwekhwe	Tshakuma WTW and a number of boreholes	Decreasing population over next 20 years, extremely poor, high unemployment and a history of social neglect, demand expected to increase due to planned improvement in level of services, will be in deficit in relation to water availability from 2016.
Damani	A92	Matangari A & B, Tshiombo, Mianzwi, Mbahela, Muhotoni, Mutshenzheni, Tshivhilwi, Mbulu, Khubvi, Tshirengani, Damani, Tswingoni, Muhuyu, Thenzheni, Tshipako, Tshirunzini, Tshinyete, Thondoni D, Mukula, Tshidimbini, Vondwe, Makhuvha, Tshitereke, Matatshe, Mavunde, Vhudzholi, Makhumbe, Matenzhe, Tshamabera, Tikiline, Tshamabere, Masakani, Mafhefhera, Diambete, Mashishi, Tshitavha C, Tshitavha B, Luungani, Tswera, Mahunguvhni, Tshitavha, Mutshenzheni, Tshivhangani, Luvhimbi, Shadani, Maholoni, Muthambi and Makonde	Damani Dam	Increasing population over the next 20 years, predominantly rural in nature, not in deficit in 2011.
Lambani	A91	Maduluni, Pfukoni, Sathane, Nzanwe, Madandila, Mahangala, Lulongwe, Luemneni, Gunda, Thondoni D, Thondoni C, Thondoni B and Thondoni A	Xikundu Weir (20% of total allocation (33%) for Lambani and Tshifudi)	Decreasing population over the next 20 years, planned improvement in water services will increase demand, was in deficit in 2011.
Makuya	A91D, A91H, A91J and A92B	Tshamdisa, Fandani, Mutshikilini, Domboni, Ngewnani A, Dotha, Gondeni, Maholoni, Mutandani, Guyuni West, Guyuni East, Musunda and Ha-Willie.	Local aquifer	Population projected to increase until 2020 and decrease from 2020-2030, low level of water supply, with a large portion (69%) of the population being serviced at or below the RDP level, was in deficit in 2011 and did not have sufficient water to cater for the future domestic needs.
Tshifudi	A91H	Muvomoni, Duvhuledza, Mpandoni, Ha-Begwa, Lukalo, Matoroni, Tshikopane, Masiwane, Tshaulu B, Tshaulu A, Gonela, Buluni, Manzemba, Khambela, Gaba, Phaswana, Tshifudi A, Tshidzini B, Tshidzini A, Musenga and Vhufumba.	Xikundu Weir (80% of total allocation (33%) for Lambani and Tshifudi)	Increase in population over the next 20 years, mostly rural, was in deficit in 2011.
Valdezia	A91	E Ribyeni, Valdezia, Amancini, Maboko, Saundi, Juda, Ndhekeni, Maphophe, Mashau-Tondoni, Nghatsani, Nkuna, Mogwena A and Mogwena B	Nandoni Dam and a number of boreholes	Increase in population over the next 20 years, predominantly rural in nature, was in deficit in 2011
Vondo South	A91	Manavhela, Tshino, Vuwani, Hanani, Ha Davhana A, Ha Davhana B, Tshivhangani, Tshitungulwane, Tshivhulana, Tshimbupfe A, Tshimbupfe B, Tshirululuni and Tshilata.	Nandoni Dam and a number of boreholes	Increase in population over the next 20 years, predominantly rural, cluster will be in deficit after 2021.

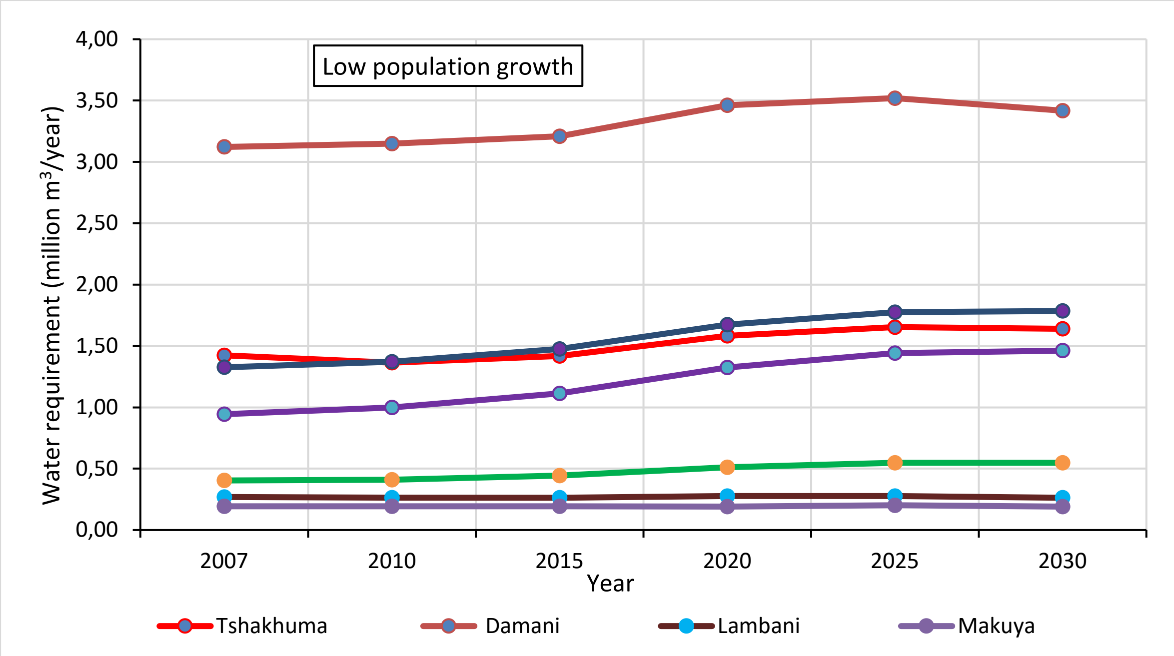

Figure 3.39: Projected water requirements for the low growth scenario

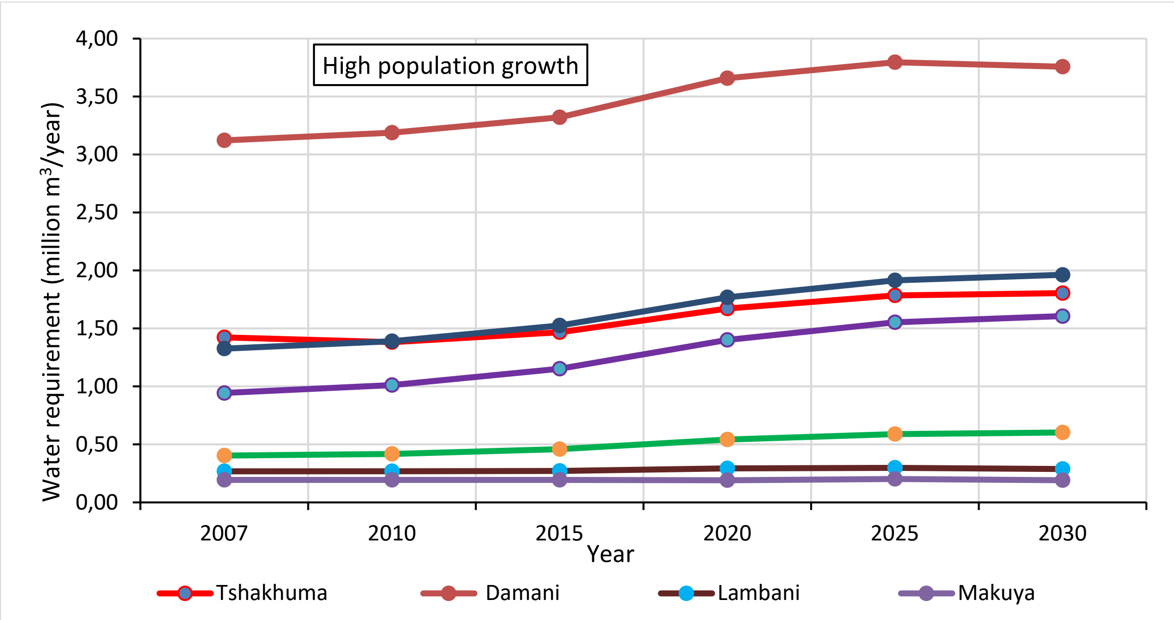

Figure 3.40: Projected water requirements for the high growth scenario

3.8.4 Implications of future water resource availability on water requirements for irrigation and municipal/domestic uses

The results of this study have indicated a consistent increase in crop water requirements for near and far futures for selected crops (maize, banana and tomato). The total irrigation water requirements for individual farms will be far much higher than the estimated crop water requirements depending on the area under irrigation within the farms. The consistent increase in irrigation water requirements in the future will put pressure on available water resources from Albasini Dam. Thus, Albasini Dam which is mainly used for supplying irrigation water to major commercial farms upstream of the catchment faces a risk of not being able to meet the irrigation water requirements particularly in the far future, which is characterised by decreasing cumulative inflows trends and variability. The decrease in rainfall in the future is expected to highly reduce crop productivity in rainfed agriculture as the irrigation water requirements increase. As indicated in subsection 3.8.2, maize which is a staple food for most of the communities in Luvuvhu River Catchment had the highest range of changes in crop water requirements. This indicates that food security will be threatened if the irrigation water requirements will not be met.

The results in sub-section 3.8.3 indicate increases in projected domestic water requirements up to 2030 for both low and high population growth scenarios for most of the regional schemes associated with population increase and/or planned improvement in water services (Figures 3.39 and 3.40). Nandoni Dam supplies water to other regional water supply schemes which are not within the Luvuvhu River Catchment. Water from Nandoni Dam is planned to supplement the Giyani regional water supply scheme as an effort to meet future water demands. The DWS based this decision on the fact that water supply from Nsami Dam near Giyani, Limpopo Province was under severe pressure to accommodate ever-increasing water demands in the area (Nurizon Consulting, 2014). Nandoni Dam is also used to supplement Matoks bulk water supply scheme to supply water to 87 200 people from 15 villages (Department of National Treasury, 2013). The water requirements for the areas within these regional schemes are also expected to increase in the future due to similar reasons (population increase and/or planned improvement in water services). This is expected to put severe pressure on the Nandoni Dam system resulting to further water supply deficit. Some of the schemes that depend on Nandoni Dam are already facing water deficit. For example, Valdezia regional water supply scheme was already in deficit in the year 2011 while Vondo South was expected to be in deficit by the year 2021 (Table 3.12).

It is important to note that the volume of water available for allocation in the study area will be affected by the existing dam water storage (water already available in the dam), reduced capacity of the dam due to sedimentation, evaporation losses from the dam and the changes in downstream (ecological) water requirements. Reservoir sedimentation is of serious concern in South Africa as it results in an average annual loss of 130 million m^3 of storage capacity in the country (Basson *et al.*, 2003). Almost 25% of reservoirs in South Africa have lost between 10 to 30% of their original storage with an average annual storage capacity loss to sedimentation of 0.4% (Msadala *et al.*, 2010). The loss in reservoir storage due to sedimentation is expected to increase in the Luvuvhu River Catchment in the future due to increased urbanisation, deforestation and farming activities that enhance soil erosion. Nkuna (2012) indicated major land use changes in the Luvuvhu River Catchment which include an increase in agricultural areas and a decrease in the natural forests to ensure food security due to the increasing population. These changes are expected to increase sedimentation which will reduce Albasini and Nandoni reservoir' storages and yields. A study done by Ndiritu *et al.* (2018) indicated that sedimentation reduced short-term yield for the Nahoon Dam in the Eastern Cape, South Africa up to 34% and this effect depends on the target draft (water demands) and the expected assurance of supply.

3.9 SUMMARY

The hydrological model used in the study simulated behaviour of streamflow in the Luvuvhu River Catchment. Other hydrological parameters were also simulated for the same area including infiltration and evapotranspiration. Generally, there will be an increase in temperature and a decrease in rainfall for both the near and far future. Streamflow forecasts show a decrease in rare but intense flood events.

The cumulative inflows for near-future scenario had non-significant increasing trends, though there was a year-to-year variations (variability) in inflows into the dams which will affect water resources availability and allocation. The far future scenario with non-significant decreasing trends will also be worsened by the year-to-year variations of cumulative inflows. The consistent increase in irrigation water requirements in the future will put pressure on available water resources from Albasini Dam, particularly for major commercial farms upstream of the catchment. The decrease in rainfall in the far future will highly reduce crop productivity in rainfed agriculture which will be exacerbated by increased irrigation water requirements. Food security will, therefore, be threatened if the irrigation water requirements will not be met.

Domestic water requirements for the future are expected to increase due to population increase and/or planned improvement in water services. Nandoni Dam is planned to supplement the Giyani regional water supply scheme and it will also supplement water to Matoks bulk water supply scheme which are not in the Luvuhvu River Catchment. These are expected to put severe pressure on the Nandoni Dam system resulting to a water supply deficit. Decreasing cumulative inflows in the far future and which will be compounded by year-to-year variability in cumulative inflows will also impact on water resources available for allocation to domestic users.

Water available for allocation in the study area will also be affected by the reduced capacity of the dams due to sedimentation, evaporation losses from the dam and downstream (ecological) water requirements. Land use changes in the Luvuvhu River Catchment are also likely to increase sedimentation into the reservoirs. The footprint for water consumption by individual entities should be updated regularly to abate the impacts of climate change on water resources in the Luvuvhu River catchment.

CHAPTER 4: DEVELOPMENT OF CLIMATE CHANGE ADAPTATION PLAN

4.1 INTRODUCTION

This chapter is focused on the development of climate change adaptation plan. It includes a review of existing climate change adaptation strategies, the identification of stakeholders, stakeholder workshops and the climate change adaptation plan.

4.2 EXISTNG CLIMATE CHANGE ADAPTATION OPTIONS

Existing climate change adaptation options have been reviewed to establish if they can be improved and/or integrated into climate change adaptation plan to be developed in this study. South Africa has developed a number of strategies aimed at responding to climate change impacts. National climate change response White Paper sets out South Africa's climate change response strategy aimed at achieving the national climate change response objective in a manner consistent with the outlined principles and approach (DEA, 2010a). It is structured around strategic priorities on risk reduction and management; mitigation actions with significant outcomes; sectoral responses; policy and regulatory alignment; informed decision making and planning; integrated planning; technology research, development and innovation; facilitated behaviour change; behaviour change through choice and resource mobilisation.

Some of the water sector adaptation strategies described in the National Climate Change Response Green Paper of 2010 (DEA, 2010b) include continuing to develop and maintain good water management systems, accelerating the development and/or capacity of effective and accountable catchment management agencies, investing in monitoring capabilities across a range of disciplines, accelerating the finalisation and implementation of cost-effective water and water-use pricing, optimising the re-use of wastewater, increasing investments in wastewater treatment capacity, increasing investments in maintenance and renewals to minimise system losses in infrastructure networks, developing and implementing a household rainwater harvesting incentive programme, exploring desalination opportunities, vigorously enforcing compliance with water quality standards and, developing and rolling out more effective support mechanisms to ensure that safe drinking water is available to all.

The Long-Term Adaptation Scenarios Flagship Research Programme (DEA, 2013) was developed in response to the South African National Climate Change Response White Paper by developing national and sub-national adaptation scenarios for South Africa. DEA (2013) noted that adaptation response strategies for the water sector could be usefully identified at distinct governance levels (national, sub-national or system and sub-catchment or municipal scales). It also emphasised that research and focused monitoring would be valuable for supporting the development of tools, approaches and case studies for which water planning may consider long-term climate change; understanding the way in which climate-driven changes in water resources availability or demand may constrain or enable different development pathways in different parts of South Africa, particularly for agricultural production and energy generation; and exploring the implications of long-term hydrological change on the ecological reserve.

Schulze (2011) reported that a strategy for adaptation to climate change specific to the South African water-related sector is required to provide an in-depth understanding of the ramifications of projected climate change and for the development of a dynamic, water-related adaptation response strategy to climate change. The latter study developed a practical approach to adaptation to climate change in the water-related sectors which include national, regional and bulk water suppliers, water user associations/irrigation boards, municipalities, disaster risk management, rainfed agriculture, including livestock activities, irrigated agriculture, the insurance industry, road transport sector, hydro-electric power industry, poor rural communities, informal urban communities, individual households, aquatic and terrestrial ecosystems. Some of the strategies for poor rural communities include storage and reticulation (small reservoir for surface water), borehole drilling, rainwater harvesting, early warning systems, amongst others.

South African national adaptation strategy (DEA, 2016b) outlined vulnerabilities and proposed adaptation responses in nine sectors: disaster risk reduction and management; human settlements; water; agriculture, forestry and fisheries; biodiversity and ecosystems; health; mining; energy; and transport and public infrastructure. These sectors are vulnerable to climate change impacts and play important roles in South Africa's economy. With respect to the water sector, broad strategies related to water governance, water infrastructure development, operation and maintenance, and water management were identified.

DEA (2016a) described climate change adaptation responses for rural areas including benefits from careful ecological management (for example, management and restoration of wetlands and river corridors can limit water runoff, provide grazing fodder, and increase potable water), increase adaptive capacity due to farm support in the form of subsidies and provision of equipment and use of traditional knowledge and farming techniques.

Limpopo Province climate change adaptation strategy (DEA, 2015) provides key risks related to climate change and a list of potential response options for each of these risks. Climate response strategies for the province include creating a Climate Smart Agriculture programme to help develop or promote the use of specific seed or plant varieties in specific locations, enhancing conservation agriculture, initiating a dedicated climate change adaptation programme for cattle ranching/livestock rearing in the province, funding and implementing comprehensive climate change awareness programme. Strategies for water supply include establishing cross-sectoral and inter-departmental governance framework to help integrate and mainstream climate change adaptation into all water-related operations, ensuring that proposed water-related infrastructure projects explicitly integrate climate change resilience into their planning and design stages, raising performance and efficiency of water service delivery for domestic use, with aggressive quantitative targets and strengthening existing Catchment Management efforts.

Vhembe District Municipality's climate change vulnerability assessment and response plan (VDM, 2016) was developed through the Local Government Climate Change Support initiative. Developed response plan for the water sector included minimising the impacts of less water available to dilute wastewater discharge and irrigation return flows, managing the quantity of water available for irrigation and drinking and reducing impacts on human health and ecosystems.

The main challenge with most of the strategies developed in South Africa is that they are not implemented. Ngwenya (2017) commended the South African national adaptation strategy noting that it combines a commitment to build SA's resilience and adaptive capacity with the provision of guidance on the integration of climate change responses into current and future development objectives. However, it was noted that lack of an implementation plan hinders the overall strategy, leaving an information void that will impede citizens from gaining the kind of deep understanding that ought to be characteristic of a comprehensive national adaptation strategy. The Limpopo climate change adaptation strategy and Vhembe District Municipality's climate response plan also lack implementation plans or clear responsibilities and proposed budgets for each intervention.

A study by Mpandeli (2013) recommended that farmers should be encouraged and enabled to use crop diversification and drought-resistant cultivars as some of the climate-risk management strategies. However, the study further noted that this requires further research. Thus, further studies and research on identifying and improving adaptation options for coping with climate change are essential. Mpandeli (2014) identified that farmers in the Vhembe District have always applied different coping and climate change adaptation strategies to increase production during drought periods including adjusting fertilizer inputs, practicing crop diversification, food preservation and adopting destocking during uncertainty periods. The latter study proposed further coping and climate change adaptation strategies including the use of drought-resistant seeds, the use of early maturing crop varieties, practicing of crop diversification system, changing farming practices and the use of seasonal climate forecasting.

Some of the adaptation strategies for farmers within selected municipalities in Limpopo Province identified by Maponya and Mpandeli (2012) include the use of DACOM system for weather monitoring, indigenous knowledge practices, wind directions and clouds to determine rainfall expectation, amongst others.

Forty small-scale farmers at Dzindi smallholder irrigation scheme were interviewed by Chigavazira (2012) to identify their climate adaptation strategies and the role of the state in building the capacity of rural small-scale farmers to adapt to climate change. Identified strategies for reducing the impacts of climate change included early morning or late night irrigation to avoid extreme terrestrial radiation and severe evaporation during the day, high yielding crop varieties, commodity exchange, reducing production space to maximise irrigation and planting drought-resistant crop varieties. The study also identified a lack of support from the government with respect to capacitating and assisting farmers to adapt to climate change.

Climate change adaptation measures for water supply in Limpopo Province developed by LEDET (2016) include:

- Establish a cross-sectoral, inter-departmental governance framework to help integrate and mainstream climate change adaptation into all water-related operations.
- Ensure that proposed water-related infrastructure projects explicitly integrate climate change resilience into their planning and design stages.
- Raise performance and efficiency of water service delivery for domestic use, with aggressive quantitative targets.
- Strengthen existing Catchment Management efforts.

Vhembe District Municipality (VDM) (2016) developed a climate change response plan after identifying key climate change vulnerability indicators in VDM. Sector response plans were in the form of proposed projects prioritised to respond to each of the identified indicators. Tables 4.1 and 4.2 indicate response plans identified for the water and agricultural sectors, respectively.

Table 4.1: Climate change response plan for the water sector in VDM (VDM, 2016)

Project name	Objective	Sub-project activities
Manage decreased water quality in ecosystems	Minimise the impacts of less water available to dilute wastewater discharge and irrigation return flows such as reduced water quality and downstream health risks to aquatic ecosystems.	• Research and improve understanding of climate change impacts on water quality and availability. • Conduct a climate change impact assessment on health risks to aquatic systems. • Strengthen management plans on wastewater treatment, to enable the ability to respond to the declining water reserves. • Adopt and enforce simple, innovative, adaptive engineering approaches and wastewater treatment initiatives that will ease the burden on natural water dilution as water quantities decline. • Identify and implement wastewater monitoring initiatives that will indicate risks to aquatic systems. • Create an awareness on the reuse of wastewater thus minimising negative impacts of wastewater on aquatic systems. • Protect and rehabilitate aquatic systems so that they can provide flow attenuation and ecosystem goods and services that are required to buffer increased pollution.
Manage the quantity of water available for irrigation and drinking	Manage the quantity of water available for irrigation and drinking which could be affected by increasing water temperatures linked to higher ambient temperatures.	• Research and improve understanding of climate change impacts on water quality and availability. • Incorporate projected climate change impacts into the planning of municipal water supply. • Identify and implement innovative water harvesting and savings initiatives to enable adaptation to reduced water for irrigation and drinking water. • Promote knowledge generation, knowledge sharing, stakeholder participation and awareness-raising regarding reduced water availability. • Collect information on indigenous knowledge which has previously been utilised in the past and will contribute towards building resilience. • Plan for projected increases in drought cycles as a result of climate change and introduce appropriate measures to maintain an acceptable assurance of water supply. • Implement watershed management that responds to reduced water availability to optimise yields of clean freshwater and storage capacity in dams.
Manage the increased impacts of floods due to litter blocking the sewer system	Reduce impacts on human health and ecosystems, as increased rainfall intensities, flash floods and regional floods cause litter and wash-off debris that block water and sanitation systems.	• Retrofit and modify existing water and sanitation systems using adaptive engineering approaches to reduce impacts of increased litter and debris. • Conduct an impact assessment of climate change-induced litter and debris. • Build climate change resilient drainage infrastructure that will incorporate increased litter and debris. • Commission a risk-averse approach to water quality protection by imposing stringent controls on water polluting land uses and activities to ensure that the impacts of climate change are not exacerbated. • Incorporate the possibility of extreme water-related climate change events into the planning of the provision of basic services such as water in order to prevent long term disruption of services and pollution of water bodies. • Develop a flooding early warning and response system. • Conduct awareness campaigns on the type of waste materials that should not be flushed to avoid sewer blockage, e.g. diapers (disposable nappies and sanitary towels) and used condoms.

Table 4.2: Climate change response plan for the agricultural sector in VDM (VDM, 2016)

Project name	Objective	Sub-project activities
Adapt to the shift of grain (maize, wheat and barley) production areas	Manage the change in grain production areas	• Research and improve understanding of grain production. • Conduct research on alternative agricultural production that can be implemented. • Promote knowledge generation, knowledge sharing, stakeholder participation and awareness-raising in grain production. • Implement evidence based monitoring initiatives that feed into management systems. • Identify climate resilient land-uses that will support the agricultural industry's efforts to exploit new agricultural opportunities, new areas and new crops thus reducing climate change impacts on current agricultural potential.

4.3 IDENTIFICATION OF STAKEHOLDERS

Sustainable establishment of climate change adaptation strategies requires transdisciplinary approaches that include involvement of stakeholders to become part of the change and find innovative ways to unite their efforts and capacities (Walmser, 2017). Stakeholders' participation is indispensable to incorporate their views for the successful planning and implementation of adaptation measures (Haque, 2016). Within the context of climate change, stakeholders include those who are affected by the indirect and direct consequences of climate change as well as decision-makers on adaptation (IPCC, 2007). Stakeholder involvement has the potential to integrate expert science and locally based knowledge (Rauschmayer and Wittmer, 2006), create a sense of ownership, and ensure sustainable implementation and change (Walmser, 2017). In the current study, such stakeholders include farmers (large and small scale), government departments, municipalities, community leaders, political leaders, amongst others.

This study intended to achieve self-mobilisation (Figure 4.1) level of participation where stakeholders will have a strong sense of ownership of the developed practical climate change adaptation strategies and can independently implement them. This will assist in long term sustainable implementation of the developed practical climate change adaptation strategies. This will also ensure that practical climate change adaptation strategies are developed jointly with communities and other stakeholders. The stakeholder identification and analysis approach (Figure 4.2) developed by Ballejos and Montagna (2008) and adapted by André *et al.* (2012) was adopted for the current study, to ensure the identification of relevant stakeholders and their active participation.

The snowball method was used for stakeholder identification and analysis in the current study. It is a simple but effective method that involves asking the initial group of stakeholders identified by the project team to suggest other stakeholders who are, in turn, asked the same question until no more individuals can be identified (Conde and Lonsdale, 2015). Time and resources, however, limited the number of stakeholders involved in the study. The snowball method has been widely applied in climate change adaptation studies including André *et al.* (2012), Akompab *et al.* (2013), Conde and Lonsdale (2005) and Ampaire (2017). Table 4.3 shows a brief description of stakeholder types adapted from André *et al.* (2012). This was used in achieving stage one of the stakeholder identification and analysis process.

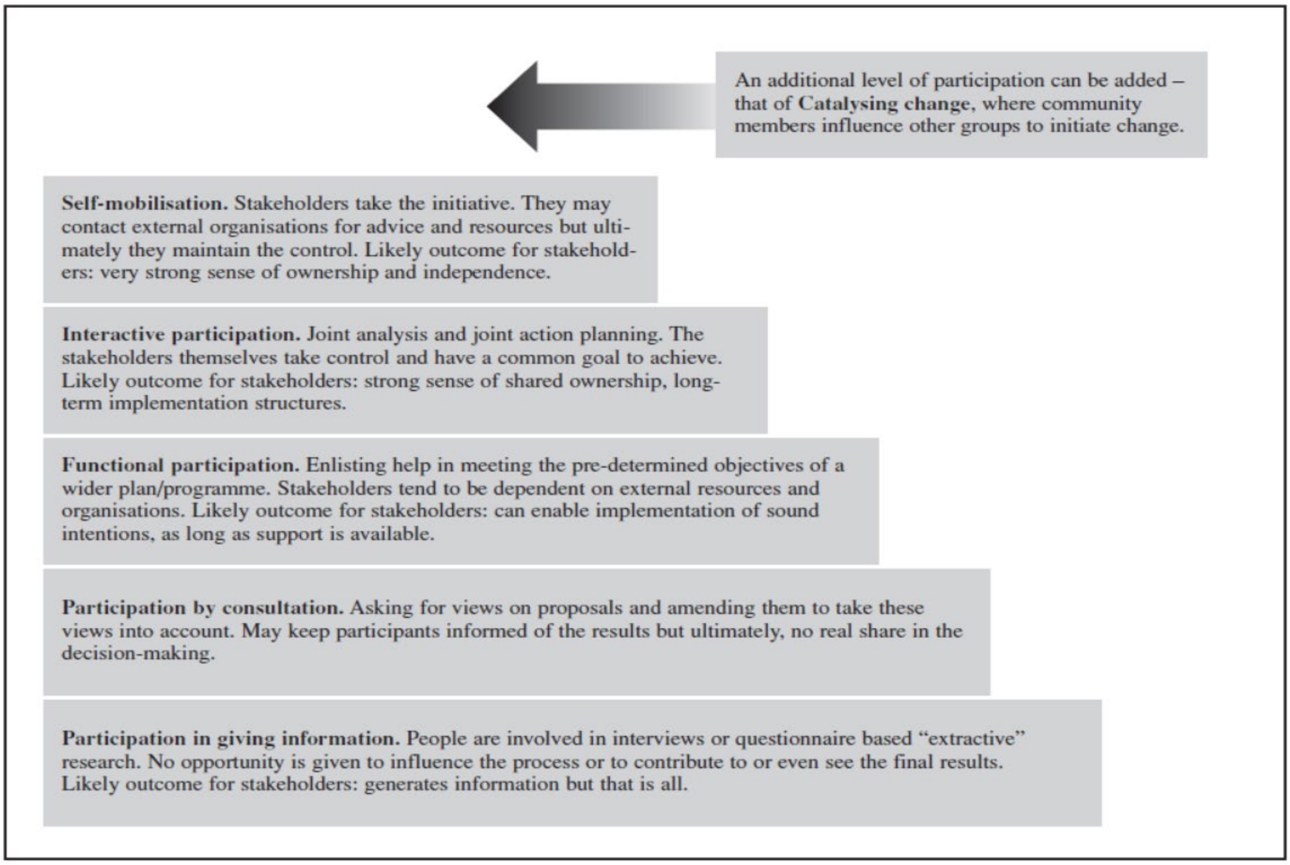

Figure 4.1: Levels of participation (Conde and Lonsdale, 2015)

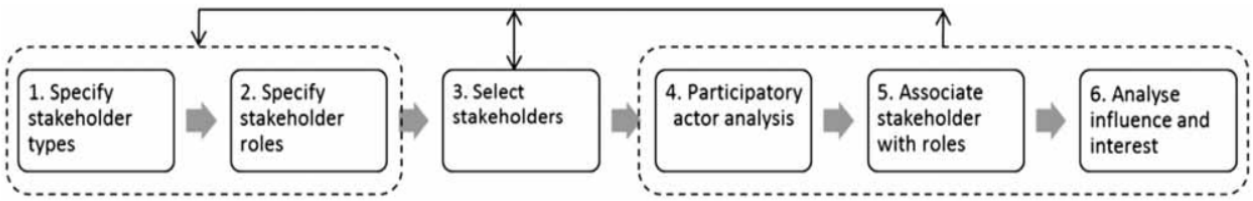

Figure 4.2: Stages for stakeholder identification and analysis (André *et al.*, 2012)

Table 4.3: Stakeholder types and description adapted from André *et al.* (2012)

Stakeholder type	Brief description/role
Functional (F)	Stakeholders who make decisions on, prepare for and/or implement adaptation and those affected by decisions on adaptation actions
Geographical location (G)	Affected stakeholders within the boundaries of the study (Luvuvhu River Catchment)
Knowledge and abilities (K)	Stakeholders assumed to have certain knowledge and skills related to adaptation or expert knowledge on the climate system and climate risks
Hierarchical level (H)	Decision-makers and other types of influential stakeholders who indirectly could facilitate or hinder adaptation

Identified stakeholders and their roles are provided in Table 4.4. Stakeholders from DWS and VDM fall within functional and hierarchical level categories as they are involved in making decisions on current and future water allocation within the study area. The National Water Resource Planning Directorate of

DWS Pretoria in consultation with DWS Polokwane and VDM are responsible for water resources assessment, development of operating rules for efficient water allocation to different water users, and their implementation. Thus, they are responsible for decision making and could facilitate the implementation of practical climate change adaptation strategies. Communities including villages and Levubu Farmers Association will be affected by decisions on adaptation actions as well as the direct impacts of climate change. The Department of Agriculture, Land Reform and Rural Development (DALRRD) works directly with small scale farmers and thus, they know how small scale farmers are likely to adapt to climate change impacts.

Researchers from the CSIR and the South African Weather Services have expert knowledge on the climate systems and climate risks. These stakeholders are members of the project's reference group implying that they have maximum participation and contribution in the study through both stakeholder consultation and reference group meetings.

Table 4.4: Identified stakeholders and their roles and details

Institution	Stakeholder role
Department of Water and Sanitation	F, H
Vhembe District Municipality (VDM)	F, H
Levubu Farmers Association	G, F
Luvuvhu Catchment Management Forum	G, F
Communities within Luvuvhu River Catchment	G, F
Department of Agriculture – Limpopo Province	F, K
Experts in field of study	K

4.4 STAKEHOLDER CONSULTATION WORKSHOPS AND DEVELOPMENT OF CLIMATE CHANGE ADAPTATION PLAN

4.4.1 Stakeholder consultation workshops

A stakeholder workshop (Figure 4.5) was conducted with DWS Thohoyandou VDM on 09 July 2018. The research team members, Dr Chikoore, Mr Nkuna and Dr Makungo gave presentations on climate change projections, hydrological modelling of climate change impacts and climate change adaptation options, respectively. The workshop noted general lack of understanding of climate change impacts on water resources. Through the assistance of Mr Masakona (Water Services Manager, VDM), the research team managed to attend the integrated regional water monitoring committee (IRWMC) meeting which was held on 06 June 2019 in Polokwane. Mr Nkuna and Dr Makungo gave presentations on preliminary results on climate change projections and hydrological modelling of climate change impacts, and climate change adaptation options, respectively. During the meeting, the research team liaised with Mrs Sylvia Tshivhase who oversaw Water Users Associations (WUAs) in Limpopo Province.

Figure 4.3: Stakeholder workshop held in Thohoyandou on 09 July 2018

A stakeholder workshop that was organised with the assistance of Mrs Tshivhase from DWS Polokwane and Mr Masakona from VDM was held on 16 August 2019 at Khoroni Hotel in Thohoyandou (Figure 4.4). Prof. Odiyo (the research leader) opened the workshop, highlighted the importance of stakeholder participation and thanked the stakeholders for the commitment they showed as reflected in good attendance of the workshop. In Prof. Odiyo's opening remarks he emphasised the fact that the impacts of climate change on water resources have become a reality making climate change adaptation of critical importance. He further emphasised that the participation of stakeholders particularly the farmers from Luvuvhu Catchment Management Forum (CMF) who hold indigenous knowledge on changes that have been occurring and whose farming activities are directly impacted on by climate change, particularly frequent droughts with extreme temperatures and occasional floods of high intensity, are important participants when coming up with climate change adaptation plan.

Research team members (Figure 4.5) gave presentations linked to the findings of the study. Prof. Chikoore presented the findings of climate change projections based on 50 km resolution GCMs. Mr Nkuna presented the findings of climate change projections based on an 8 km resolution CCAM which indicated increases in temperatures in the near and far future. The presentations also illustrated the expected impacts of projected decreases in rainfall and streamflows and increase in temperatures on rain fed agriculture, soil moisture availability for crops and water resources availability for domestic and agricultural water uses.

Figure 4.4: Stakeholder workshop participants – 16 August 2019

Figure 4.5: Workshop presentations – 16 August 2019

A stakeholder (small scale farmer) from Mhinga Village indicated that since 2015/16 they have experienced heatwaves and only received little rain in 2017 followed by no rain and heatwaves in 2018. It rained a little at the beginning of 2019 and it is uncertain if the rainfall season of 2019 will be good. This had severely impacted on their rainfed agriculture. The stakeholders noted that the results presented are frightening to the farmers as they show that the conditions of the future will be worse. It was identified that some of the farmers have been tracking the drought years and could identify the severe droughts such as 1963/64, 1982/83, 1992/93, 2005/06 and specified the 2015/16 drought as the most severe. The stakeholders also acknowledged the importance of the knowledge sharing workshop and would appreciate if solutions to deal with the threatening impacts of climate change should be addressed in the workshop. Dr R Makungo gave a brief presentation of the process of developing a climate change adaptation plan which included answering questionnaires (aimed at the establishment of existing and proposed adaptation strategies) and the use of Climate Actions Prioritisation (CLIMACT Prio) tool to prioritise and rank the identified climate adaptation strategies. Attendance registers for all the workshops are provided in Appendix A.

4.4.2 Development of climate change adaptation plan

In the workshop held on 16 August 2019, stakeholders were divided into two groups representing agricultural and domestic water use sectors. Figure 4.6 shows stakeholders working in sub-groups. Each stakeholder filled in their relevant questionnaires to list preferred climate change adaptation strategies. The questionnaires are available in Appendix B. The Multi-Criteria Decision Analysis (MCDA) method within CLIMACT Prio tool Excel Spreadsheet developed by IHS (2016) was used for prioritising the identified climate change adaptation strategies. MCDA is a decision support tool that allows consideration of quantitative and qualitative data in ranking alternative options and provides a systematic procedure for assessing and scoring options against a range of decisions (Werners, 2013). It was found to be suitable for this study because:

- It allows for consideration of stakeholders' preferences in the scoring and weighting of criteria making it suitable for stakeholder engagement (Tröltzsch *et al.*, 2016).
- It includes a full range of social, environmental, technical, economic, and financial criteria
- It incorporates the perspectives of local people who are the most affected, adaptation responses and, therefore, aids in the acceptability of the developed strategies (Haque, 2016).

The procedures followed in MCDA are indicated in Figure 4.7. CLIMACT Prio procedures which include feasibility assessment, selection of adaptation actions, criteria evaluation, scoring of adaptations (impact assessment matrix) and weighting of criteria were followed to prioritise and rank the identified climate change adaptation strategies.

Figure 4.6: Stakeholders working in groups

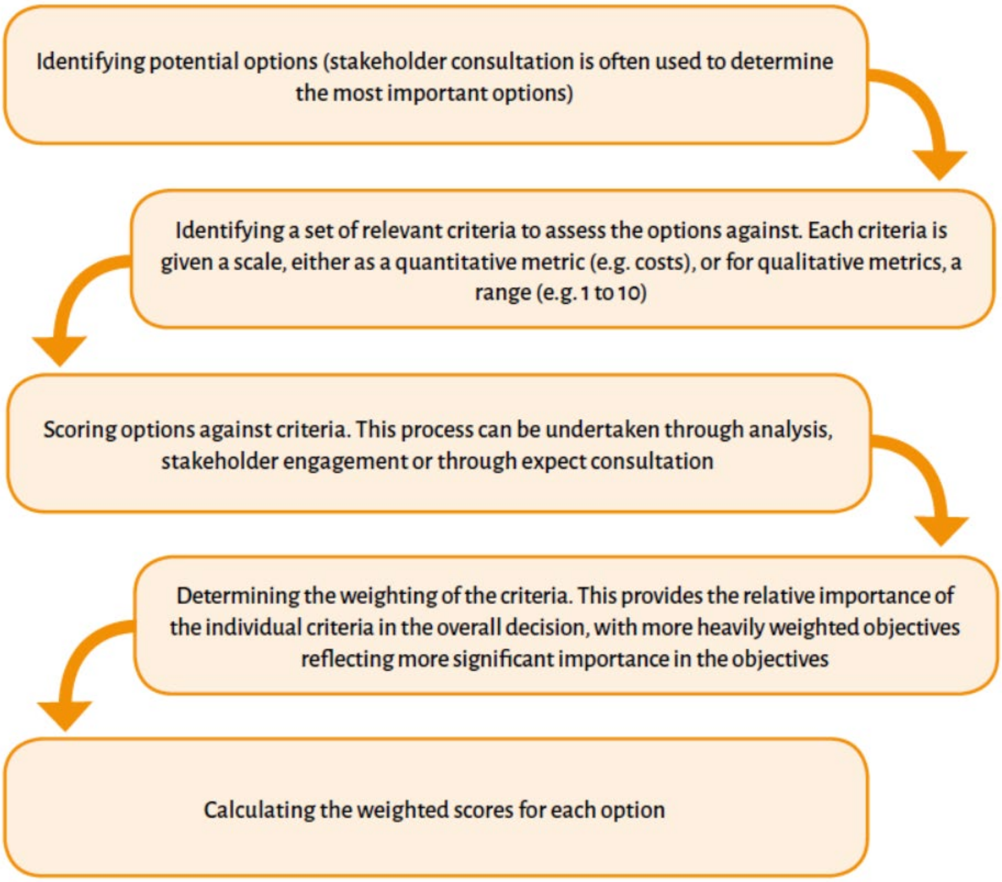

Figure 4.7: Multi-criteria decision analysis criteria (source: Tröltzsch et al., 2016)

Existing climate change adaptation strategies from Mpandeli (2014) and Chigavazira (2012) were also discussed and added to the list of those identified by stakeholders. In the feasibility assessment of adaptation strategies for municipal/domestic (Table 4.5) and agricultural (Table 4.6) water uses, identified strategies were screened by the stakeholders following a pre-defined feasibility and impact criteria (Table 4.7) to identify those that may not be viable to implement and allow shortlisting of those to be taken for further assessment. For each criterion, the strategies were rated as either high, medium, or low which were assigned a numerical score of 3, 2, or 1, respectively, for feasibility ranking in CLIMACT Prio. Though enforcement of by-laws scored high on the feasibility and impact criteria (Table 4.5), the stakeholders excluded it from the shortlist since the farmers were interested in strategies that they can implement.

Table 4.5: Feasibility assessment of adaptation strategies for municipal/domestic water use

Adaptation Actions	Stakeholder Acceptability	Technical Feasibility	Ease of Implementation	Financial feasibility	Mainstreaming Potential	Effectivenes	Multi-sectoral/objective
Drought resilient crops	High	High	Low	Low	Medium	High	High
Afforestation	High	High	Medium	Medium	Medium	High	High
Recycling	High	High	Medium	Medium	Medium	High	Medium
Community awareness	High	High	Medium	Medium	High	High	High
Maintenance of water infrastructure	High	Medium	Medium	Low	Medium	Medium	Medium
Water conservation	High	High	Medium	Medium	Medium	High	High
Reduction of gas emmision	Medium	Medium	Low	Low	Medium	Medium	Medium
Crop rotation	High	Medium	High	High	High	High	High
Law enforcement	Medium	Medium	Low	Low	Medium	Medium	Medium
Removal of Alien plants	High	High	Medium	Medium	Medium	Medium	Medium

Table 4.6: Feasibility assessment of adaptation strategies for agricultural water use

	Feasibility criteria					Impact Criteria	
Adaptation Actions	Stakeholder Acceptability	Technical Feasibility	Ease of Implementation	Financial feasibility	Mainstreaming Potential	Effectivenes	Multi-sectoral/objective
Adjusting fertilisers	High	High	High	High	High	High	High
Practicing crop diversification	High	Low	High	High	High	High	High
Food preservation	High	High	High	High	High	High	Medium
Adopting destocking during uncertainty period	High	High	High	High	Low	Medium	Low
Use of drought resistant seeds	High	High	Low	Low	Low	High	High
Use early maturing crop varieties	High	High	High	Low	Low	High	High
Changing farming practices	High	Low	Low	Low	Medium	High	High
Use of seasonal climate forecasting	High	High	Low	High	Medium	Medium	Low
Planting high yielding crops varieties	High	High	High	High	High	High	High
Reducing production space to maximise irrigation	High	High	High	High	Low	High	High
Commodity exchange	Medium	Medium	Medium	Low	Low	Low	Low
Reduce sand mining	High	Low	High	High	High	High	High
Reduce illegal dumping	Low	High	High	Low	High	High	Low
Reduce deforestation/forest fires	High	High	High	Low	High	High	High
Reduce soil erosion	High	High	High	High	High	High	High
Enforcement of by-laws	High	High	High	High	High	High	High

Table 4.7: Feasibility and impact assessment criteria

	Criteria	High	Medium	Low
Feasibility Criteria	**Stakeholder acceptability:** *Would local residents accept it?*	Majority of residents in area	Limited majority	Low support
	Technical feasibility: *Will necessary design, implementation and maintenance support be available for the option?*	Design available	Resources to develop design, implement and maintain	No available resources to develop, design, implement and maintain
	Ease of implementation: *Can it be implemented at the local government level, or does it depend upon state/provincial or national support?*	Can be implemented without external support	Can implement this with some support	Cannot implement this without external support
	Financial viability: *Is it a financially realistic option? Does the city have funding or potential access to funding to cover the costs?*	Financially realistic with available funding	More limited funding opportunities	Expensive and limited funding opportunities
	Mainstreaming potential: *Could it be integrated with existing local government planning and policy development?*	Yes, easily and fully through many plans and strategies	Yes, partly but with more time and through more limited plans and strategies	Relatively limited potential, would require additional activities
Impact Criteria	**Effectiveness:** *How well would it work on reducing vulnerability (in relation to the other actions)?*	Vulnerability will be reduced to a large extent (in relation to the other actions)	Vulnerability will be reduced to a moderate extent (in relation to the other actions)	Vulnerability will be reduced to a limited extent (in relation to the other actions)
	Multi-sectoral and multiobjective: *Would it address objectives in other sectors?*	Yes, significant cross over with other sectors and objectives	Some cross over with other sectors and objectives	Little cross over with other sectors and limited impact on other objectives

In the feasibility assessment, the adaptation strategies were ranked from highest to lowest based on their total score for all criteria. The top 7 strategies by rank for municipal/domestic (Table 4.8) and agricultural (Table 4.9) water uses were selected for further evaluation based on criteria in Tables 4.5 and 4.6, respectively, for municipal/domestic and agricultural water use sectors.

Table 4.8: Selected adaptation strategies for municipal/domestic water use

Rank	Adaptation action	Type	Sector	Time frame
1	Crop rotation	Non-structural	Agriculture	Short term
2	Community awareness	Non-structural	Disaster management	Short term
3	Water conservation	Structural	Water management	Long term
3	Afforestation	Non-structural	Agriculture	Long term
5	Recycling	Non-structural	Disaster management	Short term
6	Drought resilient crops	Non-structural	Agriculture	Short term
6	Removal of Alien plants	Non-structural	Ecological	Short term

Table 4.9: Selected adaptation strategies for agricultural water use

Rank	Adaptation action	Type	Sector	Time frame
1	Adjusting fertilisers	Non-structural	Agriculture	Short term
1	Planting high yielding crop varieties	Non-structural	Agriculture	Short term
1	Reduce soil erosion	Structural	Agriculture	Short term
5	Food preservation	Non-structural	Agriculture	Short term
6	Reducing production space to maximise irrigation	Non-structural	Agriculture	Short term
6	Practicing crop diversification	Non-structural	Agriculture	Short term
6	Reduce sand mining along river banks	Non-structural	Ecological	Medium term

The evaluation criteria in Tables 4.10 and 4.11 were used to evaluate and prioritise the climate change adaptation options for municipal/domestic and agricultural water use, respectively. The criteria were discussed and verified through group discussions with the various stakeholders in the workshop. The criteria on risk and vulnerability were added based on suggestions from stakeholders within municipal/domestic and agricultural water use groups, respectively. The rest of the criteria was adapted from De Bruin et al. (2009). The categories of criteria and their respective scales were agreed upon by the stakeholders following suggestions in IHS (2016) user manual. A qualitative scale from 1-5 was selected for the study, where 1 indicates the worst performance and 5 indicates the best performance. In terms of cost, 1 indicates a costlier action while 5 indicates a cheaper action. For risk and vulnerability, 1 indicates a most risky/vulnerable action while 5 indicates a less risky/vulnerable action.

Table 4.10: Evaluation criteria for municipal/domestic water use

Criteria	Category of Criteria	Scale	Min/Max
Cost	Economic	1-5	Min
Job creation	Economic	1-5	Max
Public and political acceptability	Social	1-5	Max
Urgency	Feasibility	1-5	Max
Importance	Social	1-5	Max
Vulnerability	Social	1-5	Min
No regret characteristics	Economic	1-5	Min

Table 4.11: Evaluation criteria for agricultural water use

Criteria	Category of Criteria	Units	Min/Max
Importance	**Economic**	"1-5"	Max
Urgency	**Feasibility**	"1-5"	Max
No regret characteristics	**Economic**	"1-5"	Min
Co-benefits	**Environmental**	"1-5"	Max
Effect of mitigation	**Climate**	"1-5"	Max
Public and political	**Social**	"1-5"	Max
Costs	**Economic**	"1-5"	Min
Job creation	**Economic**	"1-5"	Max
Risk	**Feasibility**	"1-5"	Min

Each adaptation action was scored based on the evaluation criteria (impact assessment matrix). The scores were normalised to ensure the selected criterion has a similar scale and interpretation. In Climact Prio, normalisation was done by linear interpolation resulting to a scale of 0-1. Tables 4.12 and 4.13 indicate the results of impact assessment matrix which include evaluation criteria scores for each adaptation option and their normalised values in brackets. Radar graphs indicating normalised scores for each adaptation option for municipal/domestic and agricultural water uses are provided in Figures 4.8 and 4.9. Crop rotation and removal of alien plants were considered to be costlier compared to the rest of the adaptation options for municipal/domestic water use sector (Table 4.12). The costs are associated with the purchase of different type of crops required for crop rotation. Typically, farmers tend to focus on planting one or limited types of crops such as maize or orchard fruit trees. Removal of alien plants is done through the government's Working for Water Programme and it is considered as relatively costly at community level. Removal of alien plants had the lowest score for job creation as the stakeholders noted it is likely to result to limited creation of jobs at community level.

Table 4.12: Impact assessment matrix for municipal/domestic water use sector

	Cost	Job creation	Public and political acceptability	Urgency	Importance	Vulnerability	No regret characteristics
Adaptation option	**Min**	**Max**	**Max**	**Max**	**Max**	**Min**	**Min**
Crop rotation	4 (0.8)	5 (1)	4 (0.8)	5 (1)	5 (1)	5 (1)	5 (1)
Community awareness	5 (1)	4 (0.8)	3 (0.6)	4 (0.8)	4 (0.8)	4 (0.8)	5 (1)
Water conservation	5 (1)	5 (1)	4 (0.8)	4 (0.8)	5 (1)	5 (1)	5 (1)
Afforestation	5 (1)	4 (0.8)	5 (1)	5 (1)	5 (1)	4 (0.8)	5 (1)
Recycling	5 (1)	5 (1)	5 (1)	4 (0.8)	4 (0.8)	5 (1)	5 (1)
Drought resilient crops	5 (1)	3 (0.6)	5 (1)	4 (0.8)	4 (0.8)	5 (1)	5 (1)
Removal of alien plants	4 (0.8)	2 (0.0)	3 (0.6)	4 (0.8)	5 (1)	5 (1)	5 (1)

Community awareness and removal of alien plants (Table 4.12 and Figure 4.8) had low scores on political and public acceptance criterion as stakeholders reported that lack of communication between government, municipality and community structures on running awareness campaigns slow the process of acceptance and implementation of this option. Implementation and effectiveness of climate change adaptation options is dependent on public and political acceptability and there is therefore a need to improve on communication for success of this adaptation option. Public awareness encourages the local population to adapt and be prepared for the likely impacts of climate change and to foster community participation in decision-making (Sinay and Carter, 2020). All adaptation options for municipal/domestic water use sector had high scores (5) for no regret characteristics. Adaptation options with no regret characteristics would yield economic and environmental benefits which exceed its cost if implemented (de Bruin, 2009) and are therefore beneficial and justifiable irrespective of whether climate change occurs, as well as across a range of possible climate futures (Willows *et al.*, 2003; Siedenburg, 2003). This means that all the adaptation options have economic and environmental benefits and are justifiable. Crop rotation and afforestation were regarded as most urgent options when compared to the others as they had high scores. High score on urgency criterion indicates that postponing action may result in higher costs or irreversible damage (de Bruin, 2011).

All climate change adaptation options for agricultural water use sector (Table 4.13 and Figure 4.9) had best performance for importance, urgency, no regret characteristics, co-benefits, effect of mitigation, public and political acceptability and are considered to have cheaper implementation costs, except for the reduction of sand mining along river banks option. Reducing production space to maximise irrigation is the only adaptation option which is less risky. The farmers based this on the fact that reducing production during periods of water shortages aids in maximising irrigation which is associated with increased crop yield. Since all climate change adaptation options scored high on the co-benefits criterion, they are expected to reduce climate change related vulnerability and have other benefits that are not related to climate change as reported by Abramovitz *et al.* (2002). They are also expected to contribute to socio-economic development in any climate change scenario because of their potential to generate co-benefits (Gutman, 2019). For example, crop diversification as a climate change adaptation option reduces the possibilities for crop failure due to extreme weather which improves crop yield (harvest). Other benefits of crop diversification may include increased income for farmers and ensuring food security and improving soil quality.

Table 4.13: Impact assessment matrix for agricultural water use sector

Options/Criteria	Importance	Urgency	No regret characteristics	Co-benefits	Effect of mitigation	Public and political acceptability	Costs	Job creation	Risk
	Max	Max	Min	Max	Max	Max	Min	Max	Min
Adjusting fertilisers	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	3 (0.6)
Planting high yielding crop varieties	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	3 (0.6)
Reduce soil erosion	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	3 (0.6)
Food preservation	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	3 (0.6)
Reducing production space to maximise irrigation	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)
Practicing crop diversification	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	3 (0.6)
Reduce sand mining along river banks	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	5 (1)	3 (0.6)	3 (0.6)	3 (0.6)

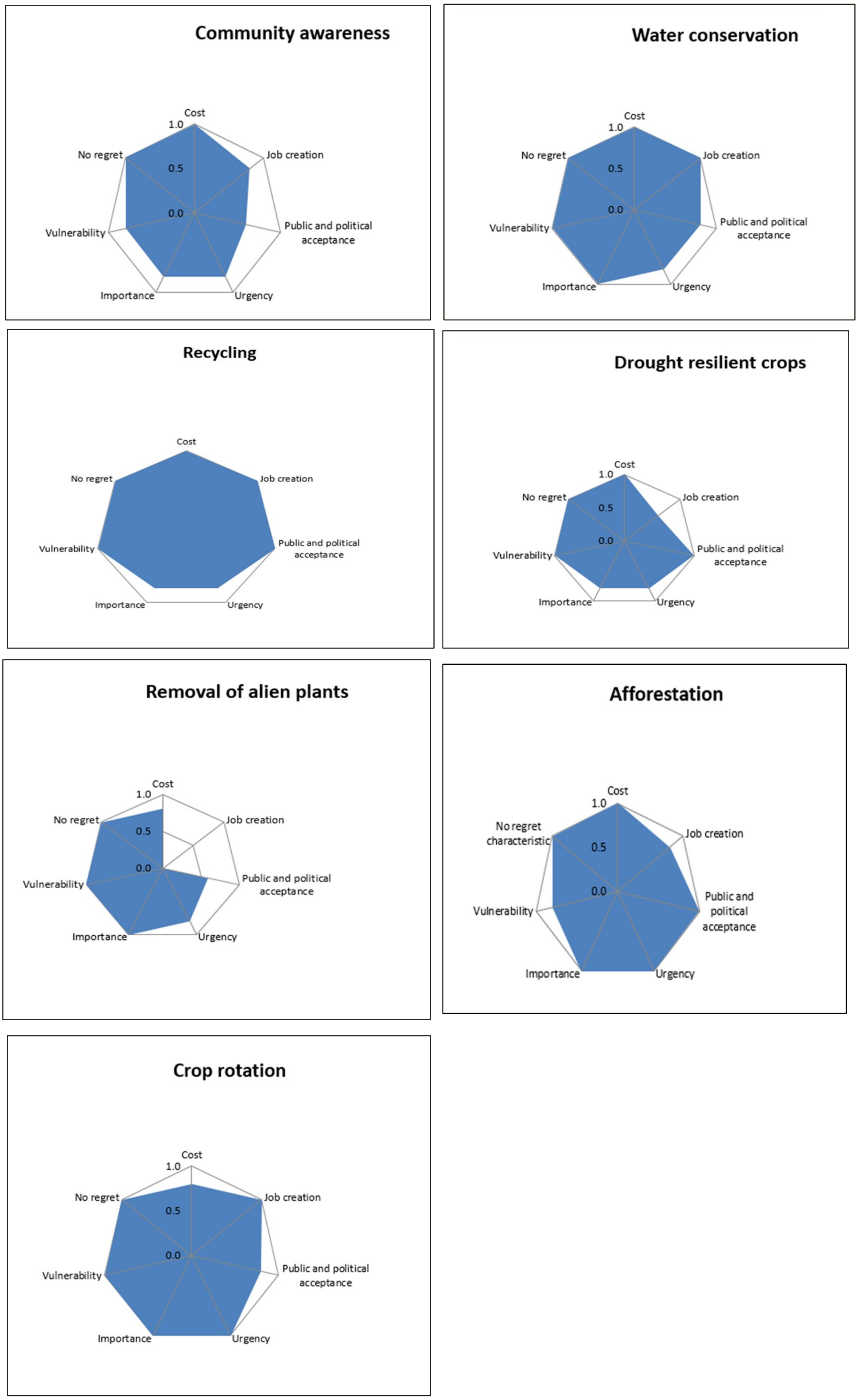

Figure 4.8: Normalised scores for each action for municipal/domestic water use

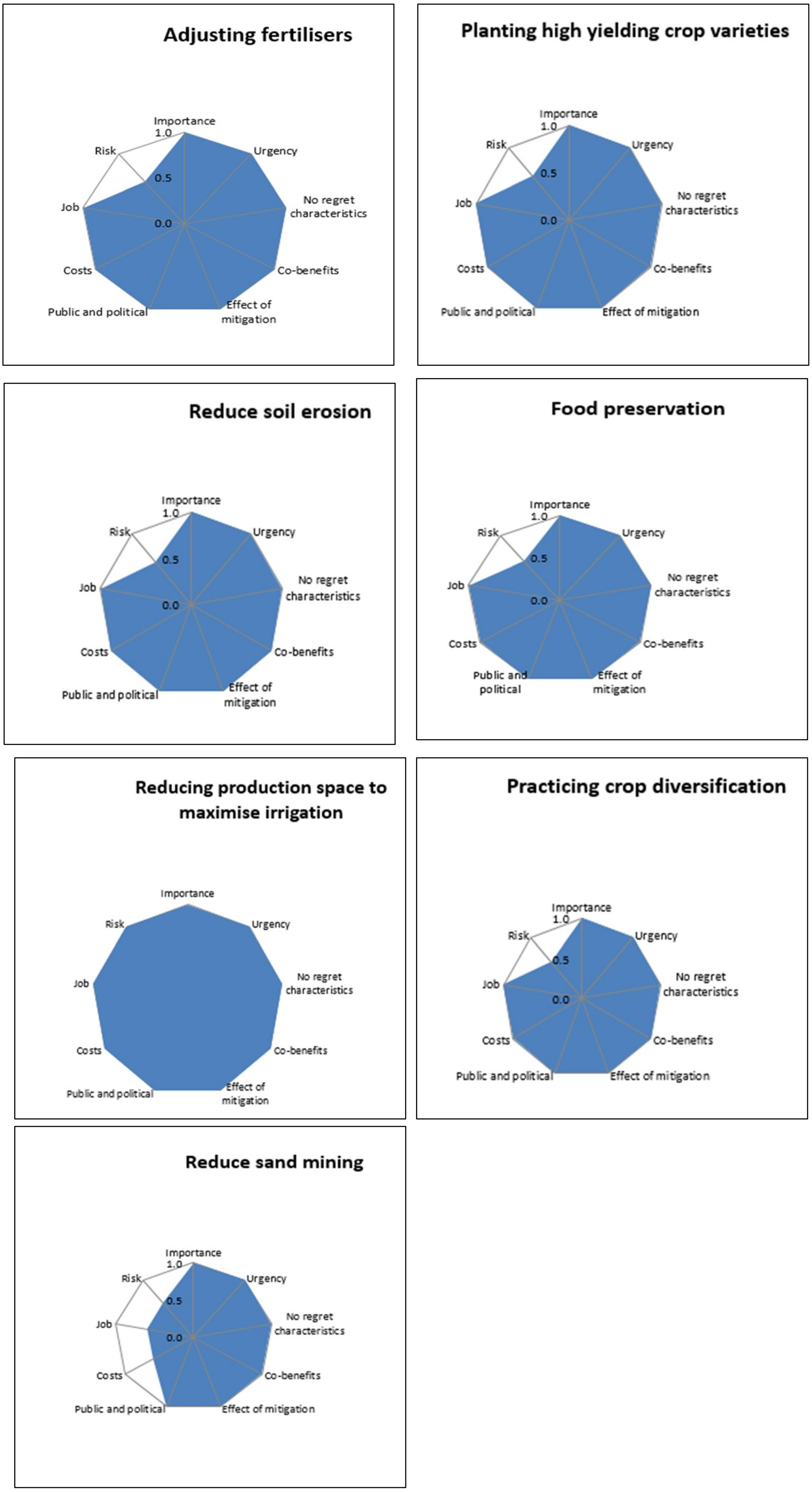

Figure 4.9: Normalised scores for each action for agricultural water use

Groups of stakeholders assigned weights to the criteria to indicate if any should be given a higher or lower weight with respect to others depending on the perceived importance. There were 3 and 2 groups of stakeholders from municipal/domestic and agricultural water use sectors, respectively. The following steps as described in HIS (2016) were followed in the weighting of the criteria:

- The criteria were ranked from the most important to the least important. The most important (first ranked) criterion was rated 1, second most important criterion 2 and so on.
- Weighting preferences were defined verbally and arithmetically based on the scales in Table 4.14.
- CLIMACT Prio was used to calculate the average weights along with the standard deviations.

Table 4.14: Verbal and arithmetic scales of criteria weighting (IHS, 2016)

Verbal scale	Arithmetic scale
Very high	90 - 100
High	70 - 80
Moderate	50 - 60
Low	30 - 40
Very low	10 - 20

The criteria weightings by stakeholders from municipal/domestic and agricultural water use sectors are in Tables 4.15 and 4.16, respectively. The deviation of the weightings from the groups was identified by the standard deviation. The smaller the standard deviation the higher the convergence, implying that criteria with high standard deviations will need further consultations between stakeholders to avoid later conflicts. The standard deviations were generally low indicating high convergence/agreement of the groups' opinions (Tables 4.15 and 4.16). The average weights for agricultural and domestic water use sectors are in Figure 4.10.

Table 4.15: Criteria weighting by groups of stakeholders from municipal/domestic water use sector

	Group 1				Group 2				Group 3						
Criteria	**Rank**	**Verbal scale**	**Arithmetic scale**	**Weights**	**Rank**	**Verbal scale**	**Arithmetic scale**	**Weights**	**Rank**	**Verbal scale**	**Arithmetic scale**	**Weights**	**Average arithmetic Scale**	**Average Weight**	**Standard deviation**
Cost	3	Very High	90	14.3%	2	High	80	13.8%	1	Very High	100	17.5%	90	15.2%	2.0%
Job creation	2	Very High	100	15.9%	3	Very High	100	17.2%	2	High	70	12.3%	90	15.1%	2.6%
Public and political acceptability	6	High	70	11.1%	4	High	70	12.1%	7	High	80	14.0%	73	12.4%	1.5%
Urgency	4	Very High	90	14.3%	1	Very High	90	15.5%	5	High	70	12.3%	83	14.0%	1.6%
Importance	5	Very High	100	15.9%	5	High	70	12.1%	4	High	80	14.0%	83	14.0%	1.9%
Vulnerability	1	Very High	100	15.9%	7	Very High	100	17.2%	3	Very High	100	17.5%	100	16.9%	0.9%
No regret characteristic	7	High	80	12.7%	6	High	70	12.1%	6	High	70	12.3%	73	12.3%	0.3%

Table 4.16: Criteria weighting by groups of stakeholders from agricultural use sector

	Group 1				Group 2						
Criteria	**Rank**	**Verbal scale**	**Arithmetic scale**	**Weights**	**Rank**	**Verbal scale**	**Arithmetic scale**	**Weights**	**Average arithmetic Scale**	**Average Weight**	**Standard deviation**
Importance	2	Very High	90	11.4%	1	High	80	10.7%	85.0	11.0%	0.5%
Urgency	5	Very High	100	12.7%	4	Very High	100	13.3%	100.0	13.0%	0.5%
No regret characteristics	9	High	70	8.9%	7	High	70	9.3%	70.0	9.1%	0.3%
Co-benefits	1	High	80	10.1%	2	High	80	10.7%	80.0	10.4%	0.4%
Effect of mitigation	8	Very High	90	11.4%	5	High	70	9.3%	80.0	10.4%	1.5%
Public and political	7	High	70	8.9%	9	High	80	10.7%	75.0	9.8%	1.3%
Costs	3	Very High	90	11.4%	3	High	70	9.3%	80.0	10.4%	1.5%
Job creation	4	Very High	100	12.7%	6	Very High	100	13.3%	100.0	13.0%	0.5%
Risk	6	Very High	100	12.7%	8	Very High	100	13.3%	100.0	13.0%	0.5%

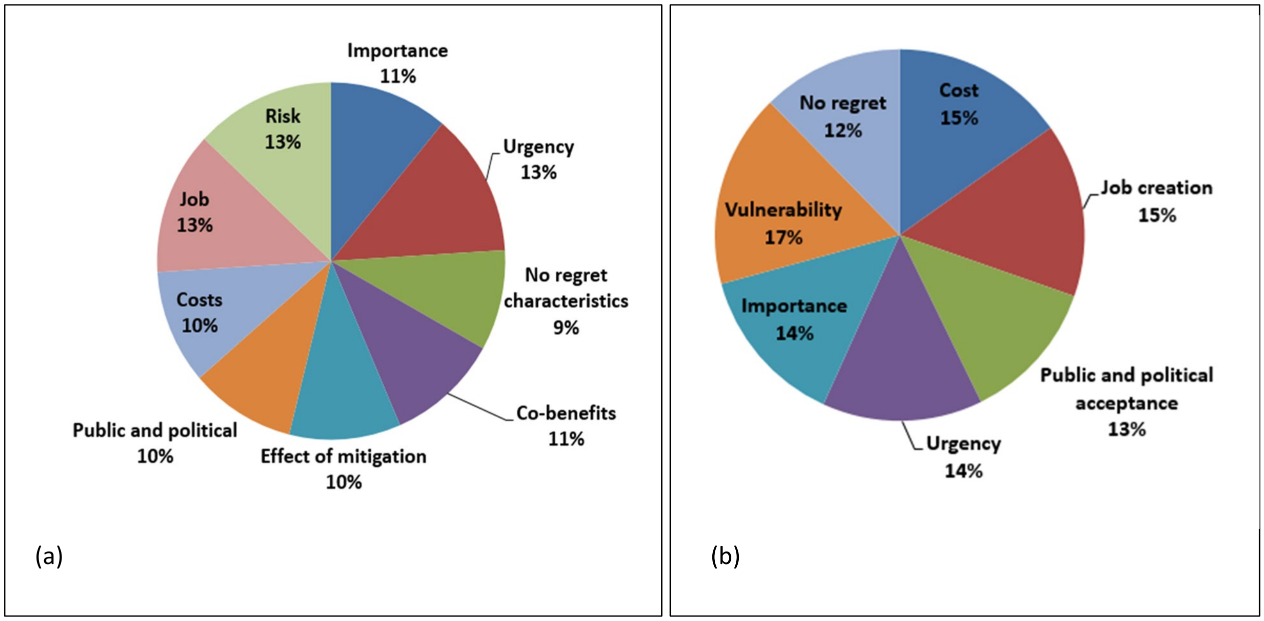

Figure 4.10: Weights assigned to evaluation criteria for (a) municipal/domestic water use and (b) agricultural water use

The scores from impact assessment matrix were combined with the average weights elicited by the stakeholders to automatically estimate the weighted final scores. This calculation results in the final score of each option. The calculation was based on the weighted summation formula while the ranking of adaptation options was determined automatically by the tool. Figures 4.11 and 4.12 indicate the scores and ranking of climate change adaptation options for municipal/domestic and agricultural water use sectors, respectively. Water conservation had the highest score (1) and rank (1) while removal of alien vegetation had the lowest score (0.74) and rank (7) for municipal/domestic water use sector (Figure 4.11). Recycling, afforestation and crop rotation had an equal score of 0.94 and rank of 2. Reducing production space to maximise irrigation had the highest score (1) and rank (1) while reducing sand mining had the lowest score (0.84) and rank (7) for agricultural water use sector (Figure 4.12). The rest of the adaptation options had equal score of 0.95 and rank 2. High score of climate change adaptation options indicate high priority to implement them (Van Ierland et al., 2013). Water conservation and reducing production space to maximise irrigation were therefore climate change adaptation options with highest scores and priority for implementation for both municipal/domestic and agricultural water use sectors, respectively.

Draft climate change adaptation plans for municipal/domestic and agricultural sectors are in Tables 4.17 and 4.18, respectively. Most of the climate change adaptation options for municipal/domestic and agricultural water use sectors had short time frames. Effects of adaptation options with short time scale are felt immediately after implementation (Champalle *et al.*, 2015) and therefore encourage community buy in. The effects of most of the climate change adaptation options in this study will therefore be felt immediately after implementation. This will encourage the communities to further implement and anticipate positive outcomes for adaptation options with medium and long time frames. Water conservation had long term implementation since it requires establishment of partnerships between stakeholders including communities, universities and municipalities which will encourage education and awareness on how this option is beneficial and linked to climate change adaptation. Afforestation will be a long term and low cost adaptation option if the indigenous tree species which are readily available in the study area are planted.

Reducing sand mining also has medium term implementation time frame because it requires enforcement through by laws which have not yet been developed and encouragement of communities to minimise sand mining along river banks. Discussions with farmers indicated that they are already implementing some of the adaptation options such as adjusting fertilisers, planting high yielding crop varieties and reducing soil erosion.

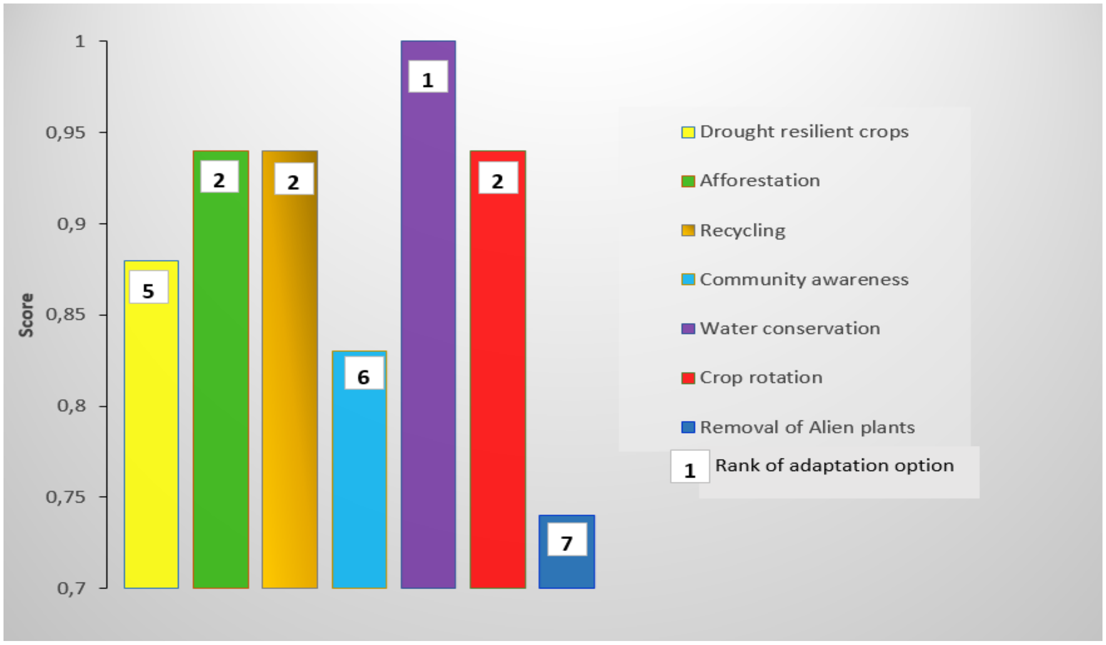

Figure 4.11: Scores of climate change adaptation strategies for domestic water use sector

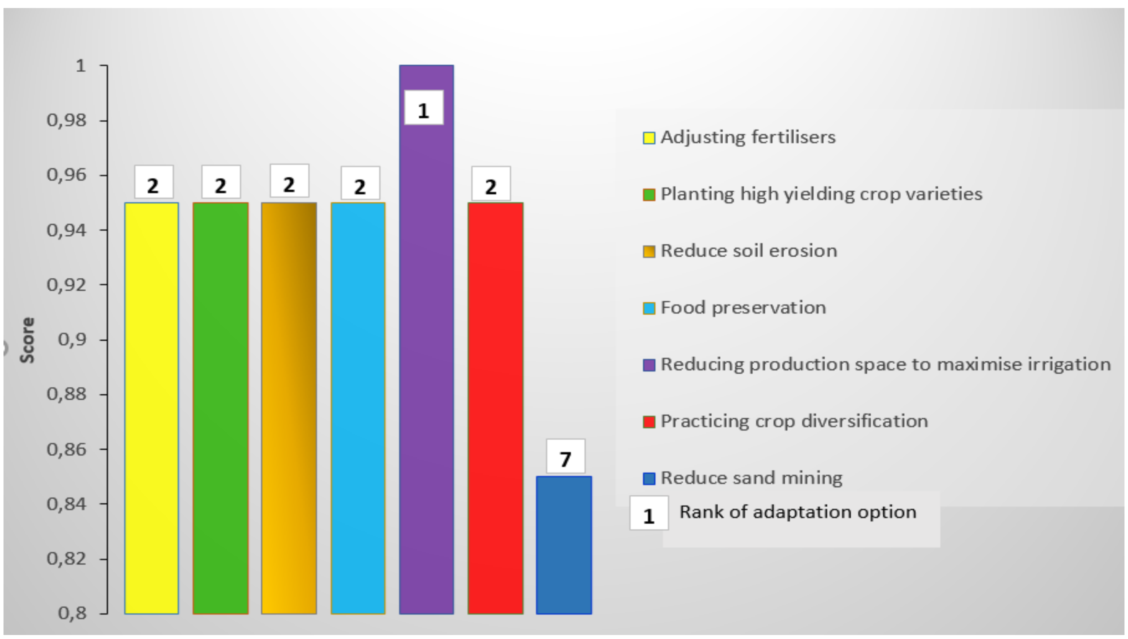

Figure 4.12: Scores of climate change adaptation strategies for agricultural water use sector

Table 4.17: Draft climate change adaptation plan for municipal/domestic water use

Adaptation actions	Explanation/benefit	Institutional responsibility	Time frame			Relative costs	Implementation
			Short term (1-5 years)	Medium term (5-10 years)	Long term (10-20 years)		
Crop rotation	Crop rotation in household gardens aids in saving water that can be used for domestic use	Farmers				Low	Part of water conservation. Can be implemented by communities in short term.
Community awareness	Awareness related to climate change impacts, water saving strategies, smart use of water resources, illegal water connections	VDM and communities				Low	Involvement of government and community structures (CIVIC, Ward Councillors, traditional leaders) is required Thulamela Municipality has a forum constituted of CIVIC, Ward Councillors, traditional leaders and municipality officials which can initiate this. Can be implemented in short term.
Water conservation	No use of hose pipe for car washing or grass and/or vegetables watering; avoiding wastages when collecting and/or using water from standpipes, managing use of water in household gardens, minimising water leaks and transmission losses	VDM and communities				Low	Should be linked to community awareness. Partnerships between stakeholders including communities, universities and municipalities which include education on water issues are required. Can be implemented in long term.
Afforestation	Afforestation depletes and limit flow into rivers.	DALRRD and Department of Environment, Forestry and Fisheries (DEFF)				Low	Willingness to reduce afforestation. Enforcement by government is required. Can be implemented in long term
Recycling	Recycling water within households, materials (plastic/papers) to reduce water pollution	SANCO and communities				Low	Can be implemented by communities in short term. Awareness is required.
Drought resilient crops	Drought resilient crops require less water resulting to reduced need for irrigating household gardens using river or groundwater	DALRRD and DEFF				Low	Part of water conservation. Can be implemented by communities in short term.
Removal of alien plants	Alien plants consume more water and their removal prevents water losses and increase streamflow and inflows into dams. For example, in Mutale River flowing from Thathe Vondo forests, springs at the river source are drying out.	DWS				Medium	Part of water conservation and afforestation. Can be implemented in medium term.

Table 4.18: Draft climate change adaptation plan for agricultural water use

Adaptation actions	Explanation/benefit	Institutional responsibility	Time frame			Relative costs	Implementation
			Short term (1-5 years)	Medium term (5-10 years)	Long term (10-20 years)		
Adjusting fertilisers	Apply fertilisers that also retain soil moisture	DALRRD and CMF	■			Low	Can be implemented by farmers in short term if use of traditional fertilisers which are cheaper and can retain moisture longer as compared to modified fertilisers is encouraged. Government encourages group of farmers to get support for farming initiatives aimed at ensuring community food security and economic development. Modified fertilisers only last for 4 months and work well with drip irrigation.
Planting high yielding crop varieties	Planting certain type of crops (e.g. 3-months maize)	DALRRD and CMF	■			Low	Can be implemented by farmers in short term.
Reduce soil erosion	Structures such as gabions retain soil nutrients and moisture	DALRRD and CMF	■			Low	Can be implemented by farmers in short term.
Food preservation	Building structures or use of traditional herbs to preserve food or use	DALRRD and CMF		■		Low	Can be implemented by farmers in medium term.
Reducing production space to maximise irrigation	More water available for irrigation, reducing losses	DALRRD and CMF		■		Low	Can be implemented by farmers in medium term.
Practicing crop diversification	Crop diversification aids in improved (crop yield) harvest	DALRRD and CMF	■			Low	Can be implemented by farmers in short term.
Reduce sand mining along river banks	Sand mining impacts on quantity and quality of river water available for irrigation	DEFF		■		Medium	It may take longer to develop by laws and convince people to minimise/stop sand mining.

4.5 SUMMARY

The climate change adaptation options and plan for the municipal/domestic and agricultural water uses were developed in consultation with stakeholders. Engagement with stakeholders promoted transfer of research knowledge on impacts of climate change on water resources. It also encouraged active engagement of stakeholders and self-mobilisation level of participation where stakeholders will have strong sense of ownership of the developed practical climate change adaptation options and can independently implement them.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The semi-arid nature and highly variable rainfall distribution within the Luvuvhu River catchment are expected to exacerbate the impact of climate change on water resources availability for agricultural production and municipal/domestic water use. Historical trends analyses indicated that the Luvuvhu River Catchment exhibits a high degree of spatial and temporal rainfall variability. The variability is exacerbated by the complex orographic effects due to the Soutpansberg Mountain Range. Morlet wavelet analysis of Luvuvhu rainfall (1960-2016) indicated that a high-frequency of 3-5-year oscillation linked to remote influences from the El Nino Southern Oscillation (ENSO), a decadal cycle linked to the Sunspot cycle and an 18-year oscillation linked to sea surface temperatures (SSTs) have become more dominant since 1995. This indicates increased frequency of drought events, which have also become more intense due to higher temperatures and enhanced evapotranspiration. Most of the global circulation models (GCMs) under high mitigation and medium to low mitigation scenarios, consistently project extreme drying (decrease in rainfall) over (-15%), possibly due to the expansion and strengthening of subtropical highs and therefore the retreat of rain bearing systems. Significant and robust surface air temperature increases were projected from GCMs for the far future with values ranging from 2°C to 2.5°C in the study area. The combined increase in temperatures and decrease in rainfall will have negative consequences for most vulnerable communities who rely on rain fed crops.

The CCAM models indicated temperature increases of between 3-5°C under low mitigation for subtropical regions including South Africa's Limpopo Province. For most of the stations in the study area, it was projected that rainfall including the average number of precipitation days will dominantly decrease in most of the months in the future. SWAT was used to predict the impacts of climate change on streamflow in the Luvuvhu River Catchment using different scenarios. The results from hydrological modelling indicated continuous decrease in streamflow for the near future (2021-2050) and the far future scenarios (2051-2080). Analysis of impacts of climate change on projected inflows into Albasini and Nandoni Dams indicated increasing linear trends for the near future while those of the far future had decreasing trends which were not statistically significant due to year-to-year variations in inflows.

The results of the study indicated increase in irrigation requirements for near and far futures and increase in future domestic water requirements for both low and high population growth scenarios for most of the regional schemes in the study area. The increase in domestic water requirements combined with the need to supplement water supply schemes which are outside the Luvuvhu River Catchment will put pressure on available water resources from Albasini and Nandoni Dam resulting to water supply deficit. Food security will also be threatened if irrigation water requirements cannot be met due to inadequate rainfall and irrigation water from Albasini Dam. Most of the climate change adaptation options for municipal/domestic and agricultural water use sectors had short time frames indicating that their effects will be felt immediately after implementation. This will encourage the communities to further implement and anticipate positive outcomes for adaptation options with medium and long time frames. Farmers are already implementing some of the adaptation options such as adjusting fertilisers, planting high yielding crop varieties and reducing soil erosion. Water conservation and reducing production space to maximise irrigation were found based on MCDA results as the climate change adaptation options with highest priority for implementation for both municipal/domestic and agricultural water use sectors, respectively.

5.2 RECOMMENDATIONS

A study on impacts of climate change and land use/cover change on hydrology, water resources availability and allocation in the Luvuvhu River Catchment is essential. Such a study should be based on climate change projections at a higher resolution such as 1 km resolution. The newer models from the Coupled Model Inter-comparison Project phase 6 (CMIP6) and the refined greenhouse gas emission scenarios called Shared Socio-economic Pathways (SSPs) are recommended in studies of the future climate.

The effect of sedimentation on storage capacities of the reservoirs in the future should be studied as this will influence water resources availability in the study area. A study on the use of water resources planning and allocation models to predict the impact of climate change on water resources yield and operating rules of Nandoni and Albasini Dams should also be conducted.

Pilot studies to test the effectiveness and improve acceptability of the developed climate change adaptation options are essential to encourage practical implementation. Thus, discussion forums for different stakeholders and awareness campaigns to solicit implementation of the developed practical climate change adaptation options are essential.

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