ADVANCING WATER AND INCOME SECURITY IN THE UNIQUE MAPUTALAND COASTAL PLAIN:

A STRATEGIC DECISION SUPPORT TOOL TO EXPLORE LAND USE IMPACTS UNDER A CHANGING CLIMATE

Report to the
Water Research Commission

by

Susan Janse van Rensburg[1], Ross Blamey[2], James Blignaut[3], Paul Gordijn[1] Nokwanda Gule[1], Seifu Kebede[4], Bruce Kelbe[5], Mkholo Maseko[1], Sulinkhundla Maseko[3], Siphiwe Mfeka[1], Nosihle Mkhize[1], Thobeka Nsibande[4], Marc Pienaar[1], Chris Reason[2], Michele Toucher[1]

[1] South African Environmental Observation Network (SAEON)
[2] University of Cape Town (UCT)
[3] ASSET
[4] University of KwaZulu-Natal (UKZN)
[5] HR&TScc

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Water Research Commission
Bloukrans Building, Lynnwood Bridge Office Park
4 Daventry Street
Lynnwood Manor
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EXECUTIVE SUMMARY

BACKGROUND

Water security is a fundamental prerequisite to foster economic development and alleviate poverty in South Africa (Blignaut and Van Heerden, 2009). Threats to water security include economic activities and land use and land cover (LULC) changes that have harmful, often cascading, impacts on the integrity of ecosystems and their associated water resources (Mutanga et al., 2024) as well as climate change (Engelbrecht et al., 2024). More frequent extreme climate events, such as flooding, heat waves and prolonged droughts, will increase due to climate change (Lee et al., 2021). Climate models generally agree that Southern Africa will become warmer and drier, but projections for precipitation in the eastern areas within this region are inconsistent (Engelbrecht et al., 2024). Of concern is that the demand for water already exceeds supply in several regions within the country. Water scarcity limits economic activity and communities' adaptation potential, precisely when action is required to accelerate climate change adaptation. However, fine spatial scale climate projections that inform adaptation to future climate risks at the scale that decision-makers need are fraught with uncertainty (Engelbrecht et al., 2024).

Integrated resource assessments across land use, economic, and water strategies, in conjunction with the enhancement of knowledge about climate change and associated risks, enable conditions for developing adaptation strategies (Howells et al., 2013, Eriksen et al., 2021). Adaptation success is more likely when it ensures context-relevant and appropriate actions that are developed in conjunction with affected communities (Pörtner et al., 2023). Participatory approaches can lead to more positive outcomes, to empower personal agency through the improvement of awareness of climate change risks while exploring ways to improve the net well-being of the area, with the result of a reduction in vulnerability (Van Rooyen, 2006, Howells et al., 2013).

Within the uMhlabuyalingana Local Municipality (ULM) (Figure I), situated in the northern Maputaland Coastal Plain (MCP), KwaZulu-Natal (KZN), households experience high levels of unemployment and poverty, while also confronted with ecosystem degradation and a decline in water security (Patrick, 2021). This is particularly evident within the rainfall dependant quaternary catchment W70A, which constitutes a large area within the ULM (Figure I). Typified by the absence of rivers importing water into the area (Figure I), since 2001, a decline in the water level of Lake Sibaya, South Africa's largest freshwater lake, reflect the dynamics of the interlinked groundwater aquifer within this catchment.

Climate and particular land uses have been put forward as drivers of water table decline, to the point where there is currently no allocable water within the system to support population growth without the removal of significant areas of commercial plantation forestry (Johnson, 2021). However, commercial plantation forestry, the dominant land use sector within quaternary catchment W70A, is considered an important economic activity for the region, despite their negative impact on the water resource (Bate et al., 2016, Smithers et al., 2017). Sustainable alternatives that provide net benefits, both economically and ecologically, are needed to enhance water security and adaptation potential in the face of an uncertain climate future for the ULM, within quaternary catchment W70A. The ULM and Quaternary catchment W70A fall within the larger Usutu to Mhlathuze (UM) drainage region, designated as primary catchment "W" by the Department of Water Affairs and Sanitation (DWS) (Figure 1 1).

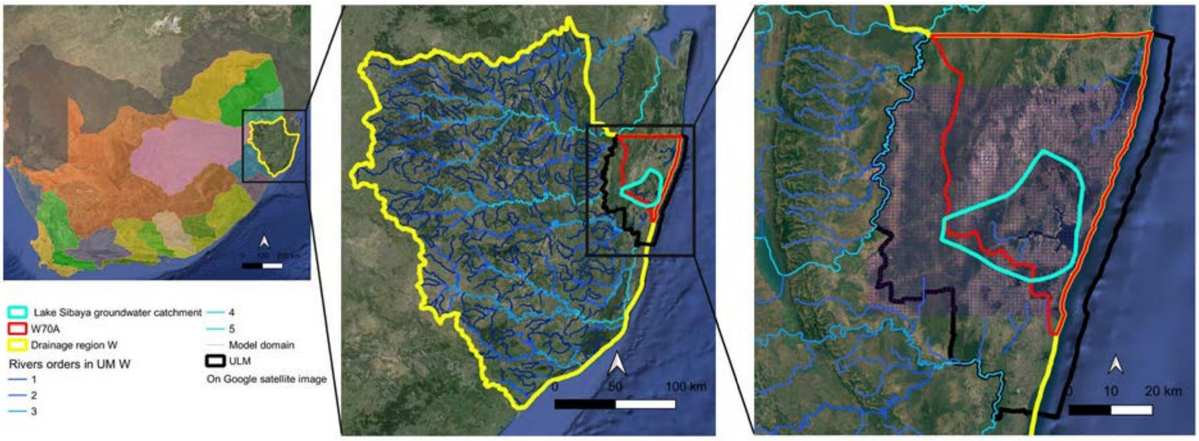

Figure I Location of the ULM (black boundary) and quaternary catchment W70A within the UM catchment area (yellow boundary), extent of the hydrological modelling domain (grid) incorporating most of quaternary catchment W70A (red boundary) and the estimated (Kelbe, 2020) Lake Sibaya groundwater catchment area (light blue). Note the absence of rivers within quaternary catchment W70A

This project was rooted in the lived challenges identified through participatory engagements with traditional councils (TCs) that represent community areas adjacent to Lake Sibaya. Driven by a societal need to improve water and economic security, a multi-scaled, integrated approach was used to assess the potential impacts of alternative land uses defined by the TCs, under different climate future storylines. It attempted to integrate hydrological, climatological, and economic models to provide decision support to land custodians. Furthermore, it sought to understand the current sources of employment, income, and livelihoods within these areas, along with the future land use preferences of the community. Using this baseline, the study could then use modelling to explore these dynamics under alternative future scenarios.

The aims of the project were:

1. The development of a system-wide resource economics model with appropriately scaled and integrated climatological, land cover and hydrological components of the region as a decision support tool to explore the net effects of plausible future trajectories for quaternary catchment W70A with Lake Sibaya's groundwater catchment as the primary response variable;
2. To deliver a significantly new understanding of the regional climate processes for the northern part of KZN and how these might change under climate change;
3. To determine the relative impact of different vegetation units and climate on the hydrological response of the Lake Sibaya groundwater catchment;
4. Identify current as well as plausible future scenarios of climate and land use;
5. To estimate the net economy-wide impacts and consequences of several plausible trajectories of climate and compatible LULC change for the catchment W70A region; and
6. Use co-generative approaches to ensure context relevant and plausible development alternatives that reflect the aspirations of local communities within the MCP, and in doing so advance multiway knowledge transfer and decisions support.

STUDY AREA DESCRIPTION

The study area falls within the Indian Ocean Coastal Belt Biome (IOCBB) (Dayaram et al., 2019). Significant land uses include protected areas, commercial plantation forestry, natural resource areas outside of protected areas (indigenous forests, wetlands, and grasslands), settlements, and cultivation. All areas outside of the protected area network fall under the Ingonyama Trust Board (ITB) and are thus managed through traditional structures.

The UM catchment area (Figure I) provided the appropriate scale to assess climate processes for the study. The hydrological modelling domain (Figure I) included both the internal and external drainage boundaries associated with Lake Sibaya's estimated groundwater catchment area (Kelbe, 2020), which was the focus for assessing hydrological responses (Figure I and Figure II). The hydrological modelling domain thus included the potential impact of surrounding areas on the focal groundwater catchment. The external boundaries of the model domain (Figure II were defined by the ocean to the far east, the Pongola River in the west, the Mkuze River to the south, and the Maputo River and Kosi Bay to the north. The hydrological model domain thus incorporated the majority of quaternary catchment W70A and extended to the western edge of the ULM. The three community areas within the estimated Lake Sibaya groundwater catchment area that were included in the study were Mbila/Zikhali to the south, Mabasa to the west and Tembe to the north (Figure II)

The Lake Sibaya groundwater catchment (Figure II), which depends on local rainfall for recharge, serves as a proxy for the coastal areas within quaternary catchment W70A. It forms part of the alluvial Zululand Coastal Plain groundwater Strategic Water Source Area (SWSA) (Le Maitre et al., 2018), considered to be among the largest unconsolidated aquifers in the country.

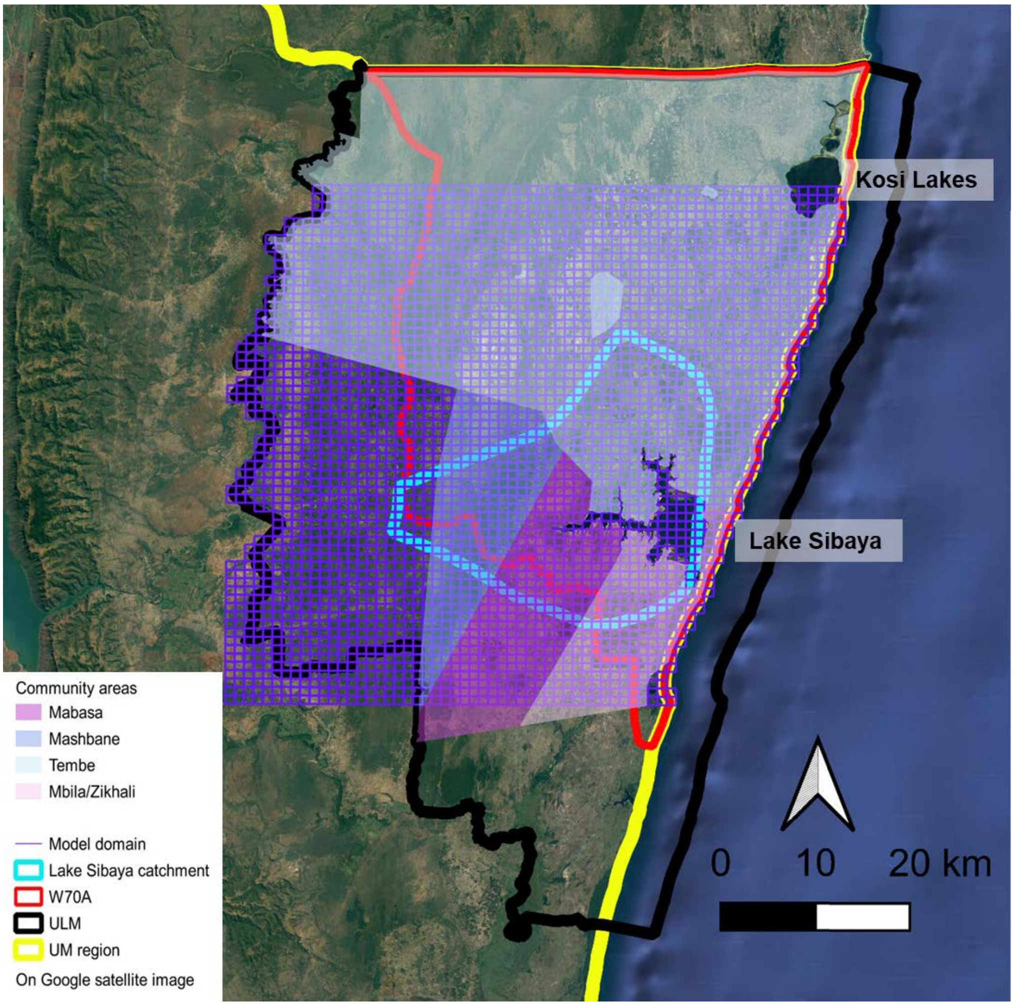

Figure II Location of community areas and the estimated (Kelbe, 2020) Lake Sibaya groundwater catchment area, in relation to the hydrological model domain (grid) and quaternary catchment W70A

The area falls within the tropical to subtropical climate transition zone and is considered to be a climate-sensitive region, strongly influenced by regional oceanic and remote forcing (Mpungose et al., 2022). There is a significant gradient in the mean annual precipitation (MAP) from east (wet) to west (dry) (Pitman and Hutchison, 1975; Weitz and Demlie, 2015). Paleo evidence indicates that Maputaland is susceptible to extreme variations in precipitation (Neumann et al., 2008, Stager et al., 2013, Botha, 2015, Humphries et al., 2019). Furthermore, the sandy nature of the area makes it particularly vulnerable to the consequences of climate change given the nature of geomorphological processes that may emerge under increasing aridity, such as wind erosion leading to dune blowouts in the coastal dune cordon that currently separates the sea from the land (Botha, 2015).

Terrestrial (Moll, 1980, Van Wyk and Smith, 2001) and aquatic diversity is high, with numerous wetlands and wetland types (Kramer, 2003, Grundling et al., 2013a, Grundling, 2014, Gabriel et al., 2018, Van Deventer et al., 2021). Peatlands, (wetlands containing accumulated deposits of organic matter), are locally common on the MCP, and account for 60% of all South Africa's peat resources (Grundling et al., 2016). With the exception of some wetland types, soils are sandy and nutrient poor (Atkinson and Barichievy, 2014).

The region is predominantly rural, with high levels of unemployment, limited economic opportunities, poor infrastructure development and low literacy levels (Fairer-Wessels, 2017). Natural resource use, dryland and wetland cultivation and livestock grazing are important activities that contribute to livelihoods within the study area. Commercial plantation forestry and ecotourism/conservation are also two important sector-based activities within the area. The extent of commercial forestry plantations within the ULM doubled between 1986 and 2019, to over 40 000 ha, which coincided with a decline in wetlands and open fresh water resources (Ramjeawon et al., 2020).

INTEGRATED MODELLING FRAMEWORK

To inform land use choices, this project aimed to use an integrated approach to assess the potential impacts of LULC change and climate change on the future well-being within the ULM. To achieve this, it was necessary to integrate hydrological, climatological, and economic aspects. However, the spatial and temporal scales among these elements are generally misaligned, hence a multi-scale approach was adopted.

Decision support tools can be broadly categorised as (i) "dynamic", in which scenarios can be interactively tested through models, and (ii) "informational", in which there is a focus on the provision of relevant facts and data without the involvement complex modelling. The aim was to provide a dynamic decisions support tool with the potential to be interactive to facilitate "least regret" choices.

An 'up-front integration' approach was used to develop a conceptual model that outlined how components would link together to inform the decision support system. This was subsequently fleshed out to explore and clarify scaling issues, data requirements and data flows to understand the current conditions (Figure III). Thereafter a range of future scenarios were simulated (Figure IV), incorporating relevant data produced from the Status Quo (SQ) past to present scenario. Iterative learning, data refining and workflow requirements were required throughout the project as needs became more specific and where issues arose. Likewise, assumptions, and perceptions about what was possible had to be regularly adjusted. Limitations also became more apparent as the study delved into details and examined provisional results.

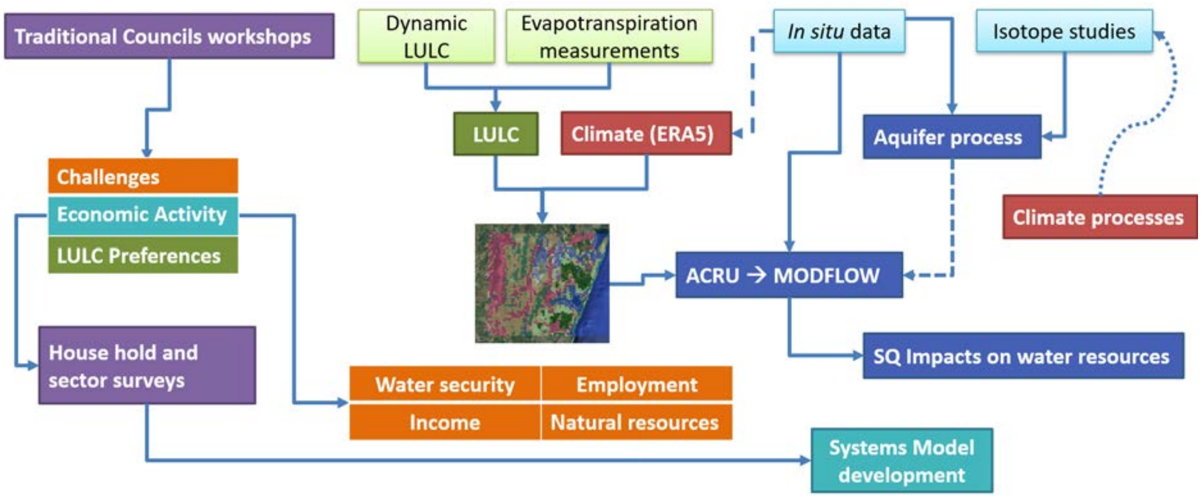

Figure III Summary of the conceptual integration framework, illustrating linkages and data flows required to understand the past to current dynamics (SQ)

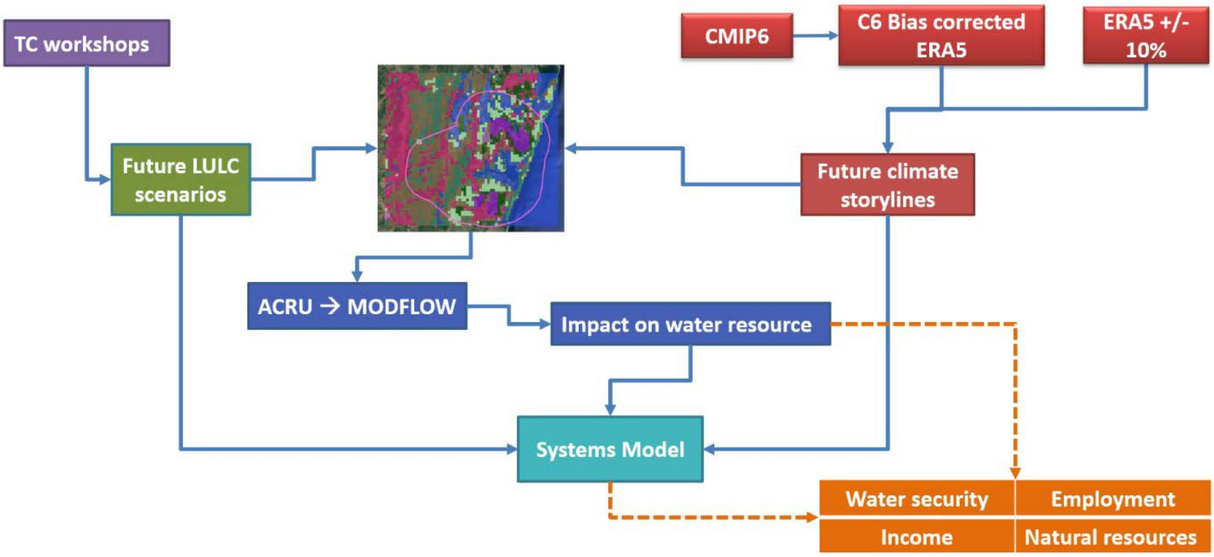

Figure IV Summary of linkages and data flows for future scenarios

There is a well-recognised gap between climate change science and reliable and usable climate information appropriately packaged for local scale decisions support (Hewitt et al., 2020, Rodrigues and Shepherd, 2022). Careful messaging is thus imperative in discussions of "possible" future climate scenarios with local communities. Storyline approaches are increasingly being used as a way of exploring climate futures as a way of handling uncertainties (Shepherd et al., 2018, Young et al., 2021, Hurk et al., 2023). A simple storyline approach, using "what if" scenarios, was thus used within this project, rather than reference to future projections, which could be misconstrued as accurate realities.

LAND USE LAND COVER CHANGE, CURRENT ECONOMIC AGENTS AND PLAUSIBLE FUTURE LAND USE SCENARIOS

People and land uses are fundamentally connected. Economic development and population growth drive land use change (Foley et al., 2005). Some of these economically driven land uses impact on the water resource (Bate et al., 2016). To ensure environmentally and economically sustainable development, these impacts must be understood in order to inform integrated water resource management, land use planning, and adaptation strategies (Bailey et al., 2016, Pörtner et al., 2023). Understanding how past to current changes in land use have impacted a system provides a baseline from which to assess the future outcomes of possible alternative choices made now. The choices should also be assessed in relation to how likely they are to improve or worsen the current challenges faced in a region, under different future climate scenarios. Land cover changes may also influence these dynamics.

Commercial plantation forestry land use negatively impacts the water resources in MCP (Kienzle and Schulze, 1992, Weitz and Demlie, 2014, Smithers et al., 2017, Nsubuga et al., 2019, Ramjeawon et al., 2020, Johnson, 2021). However, previous studies have not accounted for the impact of actual dynamic changes in LULC over time, but rather used simple switches between the percentage of grassland to commercial plantation forestry more generally (Weitz, 2016, Kelbe, 2020). In addition, bush encroachment, which is a feature of many landscapes within South Africa (O'Connor et al., 2014) has not been accounted for in these hydrological studies. Bush encroachment is a major concern that was highlighted in several community engagements within the study area. This project intended to use a more spatiotemporally representative LULC change data series, using available South African National Land Cover (SANLC) data, from the past to present, as input data for hydrological models. However, a cursory inspection of the SANLC images revealed changes in woody vegetation contrary to documented provincial and national trends (O'Connor et al., 2014). So, the development of a revised LULC change time series became an additional objective of this project.

The level of detail required for the surface water hydrological model (the ACRU Agrohydrological model, Schulze (1995)) was coarse (1 km x 1 km), with each pixel based on the dominant land cover. Using the SANLC maps from 1990, 2014, 2018, and 2020, the range of LULC classes available from these classifications was aggregated into eight categories that could be hydrologically distinguished with confidence. The SANLC imagery was then systematically verified against available historic air and landscape photos using a parsimonious systematic visual assessment. The results indicated a in decrease grassland and wetlands, and an increases in commercial plantation forestry area, consistent with results from Ramjeawon et al. (2020),. Several instances were identified where wetland areas, as per the National Biodiversity Assessment 2018 wetland layer (Van Deventer et al., 2019), have been converted to commercial plantation forestry.

The alternative future LULC scenarios and the challenges that the outcomes of these should be measured against, were determined through engagements with the TCs. The main challenges common across all TCs were distilled as; (i) water security, (ii) unemployment, (iii) economic status and (iv) natural resource (ecosystem) degradation (integrity) (see Figure III and Figure IV).

The TC workshops identified cultivation, commercial plantation forestry, conservation/ecotourism, natural resource use and livestock farming as major current land uses and livelihood sources for the area. Future preferences included a range of land-based and non-land-based suggestions (commercialisation and marketing). To assess the relative hydrological impacts of these, the LULC suggestions were simplified into a set of "single land use change" scenarios, encompassing both common and novel suggestions while addressing a specific concern (bush encroachment). The baseline SQ scenarios, (holding LULC consistent at 2020 levels under the future climates), were prioritised to test data flows as this is what alternatives would be assessed against. A "No Commercial Plantation Forestry" scenario was also included. Notably, no one suggested increasing commercial plantation forestry. The scenarios selected to simulate to the year 2050 included:

0. **Status Quo (SQ):** no change in the 2020 Land Cover to 2050;
1. **No Forestry (NF):** 1957 to 2050 simulation with all commercial plantation forestry changed to grassland;
2. **Bush Encroachment (BE):** 2020 LULC with a 50% loss of grassland being converted to thicket;
3. **Dryland Crop (DC):** 2020 LULC with 50% of the commercial forestry block (CFB) converted to Dryland Crop;
4. **Irrigated Crop (IC):** 2020 LULC with 50% of the CFB converted to Irrigated Crop;
5. **Agroforestry**: 2020 LULC with 50% of the CFB converted to agroforestry proxy;
6. **Dryland Macadamia (DMac):** 2020 LULC with 50% of the CFB converted to Dryland Macadamia;
7. **Irrigated Macadamia (IMac):** 2020 LULC with 50% of the CFB converted to Irrigated Macadamia;
8. **Dryland Marula (DMar):** 2020 LULC with 50% of the CFB converted to Dryland Marula; and
9. **Irrigated Marula (IMar)**: 2020 LULC with 50% of the CFB converted to Irrigated Marula;

REGIONAL CLIMATE PROCESSES AND PLAUSIBLE FUTURE CLIMATE SCENARIOS

The region of Northern KZN, and the southern extremities of Mozambique is a highly biodiverse and sensitive area which acts as a transition zone in south-eastern Africa between tropical and subtropical weather patterns and whose climate is not well understood. It is an area highly prone to drought as well as to occasional devastating floods which are the result of extreme rainfall events. While extreme rainfall events can cause loss of life and significant damage, they also help lessen the severity of droughts in the region. Results here from the climate analysis from 1980 to 2019 found that extreme rainfall events are more likely to take place in the late summer months (Jan-Mar) compared to the early summer months (Oct-Dec). This is due to the large-scale environment favouring the development of large convective systems during the late summer. The analysis of past extreme events (1980-2019) demonstrated that in the post 2000 period to 2019 there were fewer extreme events then in the past, particularly in the early summer months.

As with most parts of the summer rainfall region in Southern Africa, rainfall variability in northern KZN is strongly associated with the El Niño-Southern Oscillation (ENSO). With La Niña (El Niño) generally being wet (dry) over the region. There are exceptions to this (i.e. not all El Niños are dry), with recent studies demonstrating the role of regional circulation features that enhance or dampen the ENSO impact over Southern Africa. How these dynamics will change under future climate are important to resolve.

Looking to future climate conditions, the Coupled Model Intercomparison Project (CMIP6) model which output simulates future climate indicates that the summer months are projected to become slightly wetter in future, but there is considerable uncertainty with this given the model spread. There is a more consistent message of future drying during the early summer months, where a large portion of the models projecting a general drying for the Southern Africa region during the mid-21st century during this period. An even more robust signal that has emerged from all models is the considerable increase in temperatures towards the end of the century. The full model ensemble suggests that temperatures could rise by 2°C or more (with some models suggesting an 8°C increase) by the end of the 21st century. These warmer temperatures, coupled with decreases in early summer rainfall could have a significant negative impact on agricultural production during the start of the summer and is a concern for food and water security as well as human health.

It is noted that biases and uncertainties are persistent in the CMIP6 models that are found in the previous CMIP experiments. An example of which is that the models appear to capture the seasonal cycle reasonably well for the region, but they do produce too much rainfall (a common problem for Southern Africa). The next generation of high-resolution climate projection models will add more details to the resolution of climate processes which will help to address some of the shortcomings presented in this research.

A take away from this study is that the lack of observations in the study region in the past somewhat restricts any robust analysis into past climate variability. It is also for this reason that long-term satellite or model derived products are used as a substitute in the analysis of recent historical climate. However, the limitations of using such products are apparent in this study where they do not necessarily accurately represent the daily or seasonal climate of the region (based on the limited observation data that are available). This gap in observation data highlights the need to install and maintain observation instruments in the region, as is undertaken currently by the National Research Foundation (NRF)-South African Environmental Observation Network (SAEON) and Expanded Freshwater and Terrestrial Observation Network (EFTEON), which will be a huge benefit to research in decades to come NRF-SAEON.

APPROACH TO ADVANCING HYDROLOGICAL STUDIES

Radical intervention is considered essential to secure the decline in groundwater resources within the ULM (Johnson, 2021). However, undertaking disruptive interventions necessitates a comprehensive understanding of the various components of the system to furnish defensible information that justifies interventions. Consequently, the reliability of hydrological outcomes should be as robust as possible. This project aimed to address some limitations evident in previous hydrological studies.

The Study used a multi-pronged approach, drawing on isotopic and numerical modelling methodologies, complemented by extensive *in situ* data gathering, which included previously unmeasured parameters, to address various persistent challenges and limitations identified in previous studies.

Advances undertaken within this study to enhance the credibility of outcomes included:

- The use of isotopes to explore the relationship between rainfall and groundwater recharge, investigate aquifer characteristics and improve on the conceptual model flow paths, assess the isotopic water balance; and explore the use of isotope studies to assess tree water source partitioning.
- The use of a spatially compatible gridded loosely coupled ACRU-MODFLOW modelling approach. Recharge simulated for each grid by the ACRU model was used as an input to the MODFLOW model. Rainfall and lake potential reference evaporation from the ACRU model were used for simulating of the lake water balance in MODFLOW.
- The Incorporation of actual dynamic LULC change impacts on the water resource for past to current simulations. The matched ACRU-MODFLOW gridded approach allowed for the incorporation of dynamic vegetation change into the ACRU model to account for a more representative spatiotemporal LULC change.
- The dynamic LULC change assessment was conducted across the entire model domain, in contrast to other studies that limited their "change" simulations to the Lake Sibaya groundwater catchment area (Smithers et al., 2017, Kelbe, 2020).
- A rainfall gradient from east (wetter) to west (drier) exists over the study area (Pitman and Hutchison, 1975, Weitz and Demlie, 2015). Previous studies have not captured this gradient adequately. Within this study the spatial variability of the rainfall across the study area was captured using an internally consistent gridded rainfall product.
- *In situ* measurements included targeted variables recommended in prior studies, chosen for their feasibility and significant potential to reduce uncertainties and enhance the representation of the groundwater system. NRF-SAEON Eddy Covariance, surface-renewal systems and the NRF-SAEON weather station array where used to enhance crop coefficients used in the study. Periodic streamflow measurements were undertaken and groundwater level data from additional wells were incorporated were extending time-series measurements.
- A revised water level record for Lake Sibaya, based on multiple sources of information, was produced to address inconsistencies noted in previous studies (Meyer and Godfrey, 2003, Smithers et al., 2017). This was supported by two infield survey campaigns conducted jointly by DWS and NRF-SAEON to survey all lake level gauging stations and boreholes within the area in relation to a consistent elevation benchmark.

These approaches were used to advance confidence in the attribution of impacts on the water resource to specific drivers; climate and different LULC types, which is of key importance in informing adaptation strategies. Results are presented in the relevant sections that follow.

ISOTOPE HYDROLOGICAL STUDY

Stable isotopes of water (^{18}O and ^{2}H) were used to explore the relationship between rainfall and groundwater recharge; the interconnection between open water bodies and adjacent aquifers, and to investigate the interconnection between aquifers and thereby improve existing conceptual models upon which groundwater models have been based.

Stable isotopes of the water molecule are proven tracers of water movement in the hydrological cycle. This is because each water body, rainfall event, storm, or flood event, etc., is imprinted with its unique isotope signature (composition). This property does not change as the water moves through the aquifers, allowing the linkage of groundwater bodies to their recharge sources and mechanisms thereof. The isotope composition changes when there is a phase change, such as during the evaporation of open water bodies. This leaves open water bodies with an enriched (richer in heavy water isotopes) isotopic composition compared to non-evaporated water bodies. Consequently, connections between open water bodies (wetlands, lakes) and adjacent water bodies can be traced.

Data on the water bodies, groundwater and daily rain water were collected to meet the study objectives. *In situ* data and sample collections were achieved through five sampling campaigns to gather water samples over different seasons. The trips took place in September 2021 (Spring), October 2021 (Summer), April 2022 (autumn), May 2022 (early winter), and August 2022 (later winter/early spring). The Palmex collector allowed for virtually evaporation-free rain sampling for subsequent water stable isotope analysis. A total of 157 samples were collected from groundwater, surface water, lake, and rainfall sources for this study over the two years (2021/22). This included sampling and data from the nested boreholes all recording groundwater levels over the period 2019 to 2024.

The data revealed some key hydrological processes that contribute to the improvement of the conceptual model.

- Groundwater recharge takes place after the rain water has undergone open water evaporation, probably in wetlands, temporary ponds, and temporary floodplains. The ponding effect implicates that recharge principally is focused and takes place from such water bodies.
- There is a strong correlation between the rainfall amount and its ^{18}O. A comparison of this with the groundwater isotope signals revealed that the minimum rainfall amount that is required to achieve recharge in the aquifer is roughly 30 mm/day.
- Results demonstrated that the amount weighted average isotopic composition of the rainfall waters is relatively more enriched than the initial isotopic composition of the initial water that recharge the aquifer water. Furthermore, there is a strong similarity between the isotopic composition of the groundwater (revealed from the intersection between local evaporation line (LEL) and Local Meteoric Water Line (LMWL)) and the isotopic composition of the heavy rain storms, such as the April 2021 storm, further revealing that groundwater recharge takes place from heavy rainfall events. The contribution to groundwater recharge in the small rain event months of October, November, and December was minimal.
- There appear to be several groundwater flow systems feeding the lake. The first one originates from west of the lake. There is also flow from the north as well as from the south western arm region (i.e. all around the edges of the lake from the north, west and southwest). These flow patterns are widely inferred in previous conceptual models. There also seems to be flow which originates from the northeast dune area of Lake Sibaya, (Mabibi side), previously not inferred. Regarding the south-eastern edge of the lake, the shallow flows that originate from the dune cordon appear to be sensitive to changes in rainfall and the direction of the flow may change depending on the filling and emptying of the shallow dune cordon aquifer, possibly related to

the south basin lake level, and rainfall conditions. Outflow is evident in the eastern edge of the south basin just south of Banda Banda Bay.

- Heavy rains appear to be the principal source of groundwater recharge. The future of Lake Sibaya's hydrology is tied to this regional climate. However, LULC change will have impacts too, both through water use associated with the LULC as well as potential transformation of wetland and open water bodies which allow for the temporal accumulation of rainwater in ponds preceding recharge.
- The relatively dilute chemistry of Lake Sibaya reveals leakage from the lake to adjacent aquifers, most likely in an easterly direction through the dune cordon towards the sea.
- The first preliminary water balance calculated from the isotope balance equation reveals that the lake water balance is dominated by groundwater inflow and evaporation. The isotope-based water balance estimation for Lake Sibaya can be used as an additional constraint to improve the numerical groundwater flow model developed for the region.

Groundwater discharge out of the lake to adjacent aquifers was revealed from the isotope study, primarily through the dune cordon between the lake and the sea. The other possible groundwater discharge process that need investigation, which could be revealed with isotopes, is the discharge through evapotranspiration (ET). Isotope based investigations of tree water use is a new frontier in tree water use studies. The challenge with the use of isotopes for tree water use studies is obtaining representative samples of xylem water and its source waters (soil water). Xylem water is challenging to extract and soil water is difficult to extract without causing fractionation. With these limitations in mind, the soil water, xylem water, rain and groundwater isotope data revealed that during summer months, *Eucalyptus grandis* and *Dichrostachys cinerea* appear to be using groundwater, whereas results from the winter mons were inconclusive. Better sampling design, sample extraction, and laboratory analytical methods are needed to better understand groundwater discharge processes via ET.

MODELLING RECHARGE USING THE ACRU MODEL

The physical-conceptual ACRU agrohydrological model, which is sensitive to LULC change and climate change, was used to simulate the recharge across the hydrological model domain (Figure II). The ACRU model was configured in a 1 km x 1 km grid. This was a novel configuration and only possible as the deep percolation was the sole output used from the model. The configuring of the model as a grid allowed a spatial compatibility with the MODFLOW groundwater model. Recharge output from the ACRU model for each grid (3 394 grids) was used as input to the MODFLOW model.

Rainfall is the primary driver of the hydrological cycle in the ACRU model. The model requires daily rainfall as well as daily minimum and maximum temperature as input. The lack of observed climate data (both quantity and quality) within the model domain (Figure II) meant that alternative climate data sources were needed. The decision taken was to use the gridded ERA5 rainfall and temperature products for the historical climate period from 1959 to 2020. Daily A-pan equivalent reference evaporation was estimated using the Hargreaves and Samani (1985) daily A-pan equation. As the project aimed to evaluate land use choices into the future, future climate storylines were required. The future climate storylines were drawn from the CMIP6 suite of models, however, only those with daily rainfall and temperature could be considered which narrowed the range of differences in the scenarios. A wet storyline and a dry storyline were selected based on the summer (October-March) being the wettest or driest respectively in the mid-century. The overestimation of rainfall in the CMIP6 and coarse grid scale, meant that a bias correction had to be applied to the CMIP6 data. Using this methodology, a continuous recharge time series for the period 1959 to 2050 was supplied to the MODFLOW modelling team for a wet and dry future storyline.

Due to the bias in the CMIP6 future storylines and the fact that the CMIP6 bias corrected runs were strongly influenced by the ERA5 period to which the corrections were applied, an approach to determining alternative wet and dry future climate scenarios was required. The method used was to select a relatively wet period in the past (1971 to 2000) and a relatively dry period (1991 to 2020), and to these periods apply a 10% increase for the wet future and 10% decrease for the dry future to the ERA5 rainfall data assigned to the hydrological response unit (HRU) grids. To ensure consistency between the temperature and rainfall records, the ERA5 temperature data for the selected periods was used with 1°C added to each daily maximum and minimum temperature record to account for the expected warming.

As the LULC play a significant role in partitioning rainfall into the components of interception, plant and soil water evaporation, infiltration, runoff, and recharge, variables related to the vegetation and water use are required as inputs to the ACRU model. The most sensitive vegetation water use parameter is the crop coefficient (K_c). Given this, *in situ* field-based ET measurements were used to determine specific K_c values for the site where possible.

Once the ACRU model was configured a sensitivity study was undertaken to determine which input variable the recharge was most sensitive to. The finding was that the uncertainty in the recharge output is going to be driven predominantly from the uncertainty that exists in the rainfall records for the area and the sparsity of those rainfall records in a highly spatially variable rainfall region. Comparison of the ERA5 rainfall to observed rainfall revealed that the ERA5 product underestimates annual rainfall by 90 mm, which is an 11% underestimation averaged over the grids for the study area. Based on the sensitivity results this will result in the recharge being underestimated by approximately 30%.

Following this, a validation study was undertaken for the ACRU model. Typically, the ACRU model is confirmed against streamflow, however, for this study, a different approach to the validation of the model output was required. The approach taken was to confirm that the simulated ET was within the range of the expected ET based on available measurements. The pattern of ET over the course of the year mimicked the pattern expected, with lower ET values in the drier winter months and higher ET values in the wetter summer months. Further, as expected with the commercial forestry plantation trees being evergreen while the grass died back in winter, the ET from the commercial forestry plantation trees was far greater than the grass in the winter months, but similar in the summer months.

With confidence in the model established and an understanding of the sources of uncertainty, the recharge for the model domain (Figure II), was simulated under a historical climate (1959 to 2020) accounting for dynamic LULC change across four time slices. The spatial pattern of the recharge for the historical past reflects the rainfall pattern as well as the land uses present in the area. The recharge is highest to the south of Lake Sibaya along the coast, reaching over 400 mm per annum on average. The commercial plantation forestry areas to the north of Lake Sibaya, on average, do not experience recharge from the B-horizon to the groundwater zone. Most of the recharge occurs in the summer months (Oct-Mar), with large areas receiving little to no recharge during the winter months of April to September. Recharge was also simulated under CMIP6Wet (C6Wet), CMIP6Dry (C6Dry), ERA5Wet and ERA5Dry future climate storylines and for the various land use scenarios, which included SQ (land use as at 2020), no forestry, and a 50% change of commercial plantation forestry areas to (i) Bush Encroachment; (ii) Dryland Crop; (iii) Dryland Agroforestry; (iv) Dryland Macadamia; and (v) Dryland Marula. Across all scenarios, the areas that changed from commercial plantation forestry to an alternative land use experienced an increase in recharge, regardless of the climate storyline.

As with all models, the accuracy and quality of the ACRU model simulation is only as good as the input data. In this project there were several concerns and problems related to the input data available. The most significant concern, given the sensitivity of the recharge to this, was the accuracy of the rainfall data. The hydrological model results must be interpreted in this context, they are not a true representation of reality. However, the patterns, trends and relative changes in the results can help in understanding influences in the system and in making decisions.

MODFLOW GROUNDWATER MODEL

An existing MODFLOW groundwater model (Kelbe, 2020) was updated to enhance the model's rigor in order to assess of the relative impacts of climate and LULC change within the model domain (Figure II) on the Lake Sibaya groundwater catchment. Updates included extending of groundwater and streamflow data, as well as the implementation of gridded recharge covering the entire model domain. The gridded recharge, simulated by ACRU, utilised the corrected SANLC maps for four time slices adapted to reflect actual changes in LULC over time within the hydrological domain (Figure II). Furthermore, gridded satellite rainfall and temperature data were used instead of point data.

The past to current simulations performed by the updated model revealed that there was a slight improvement in the representation of the observed Lake Sibaya water level trends when compared to those of the previous model. The revised model was then tested, under the extreme future hydroclimate future storylines. The future simulations revealed issues not apparent in the “past to current” simulations and provided an opportunity to re-evaluate and update the model’s hydraulic properties. The final calibration results from the updated model (2.94 m Residual Mean Square Error – RMSE) were comparable to those of the previous model (2.87 m RMSE). Mylopoulos et al. (2007) achieved similar results (2.8 m RMSE) in their study where they developed and calibrated a multi-layered groundwater model for an area experiencing water resource declines.

Lake Sibaya water levels were utilised for model validation, as in Kelbe (2020). The Lake Sibaya groundwater catchments’ primary sandy aquifer results in a highly interconnected groundwater and lake system (Weitz, 2016, Kelbe, 2020), that enables the use of the Lake Sibaya’s water level to validate the groundwater model, similar to the study by Dogan et al. (2008). The updated model's lake simulation indicated an improved representation of Lake Sibaya's responsiveness to rainfall events and closely mirrored observed values. The lake water balance for both the updated and previous model indicated an overall loss in water volume, which supports the declining lake level trend and aligns with observed data. The now updated Kelbe (2020) model could thus then be used with confidence for future scenario simulations.

RELATIVE IMPACTS OF FUTURE LAND USE-CLIMATE STORYLINES ON HYDROLOGICAL OUTCOMES: IMPLICATIONS FOR THE SYSTEMS MODEL

The hydrological outcomes of climate future storylines and nine LULC scenarios were tested, along with efforts to connect these outcomes to economic impacts.

After configuring the ACRU and MODFLOW models for the past-to-current period, future LULC scenarios were simulated to determine their hydrological impact by 2050 under the future climate storylines. These impacts were assessed in relation to the future SQ simulations for which LULC remained constant at the 2020 LULC configuration.

SQ and all LULC simulations revealed declining trends in the lake level (used as the hydrological system response variable) under the C6Dry and C6Wet future climate storylines. This demonstrated the overriding impact of warmer, extended drier, and slightly wetter future storylines typified by few extreme rainfall events. An equivalent precipitation period to this is the historic period from 1991 to 2020. All

C6Wet scenarios showed a slightly less dramatic decline than the C6Dry scenarios. Removing 50% of commercial plantation forestry and replacing it with “Dryland Crop” or “Dryland Marula” resulted in a more positive effect on lake levels relative to the SQ, especially towards the end of the simulation period, hinting at lag effects. However, these impacts were insufficient within the simulation period to result in lake level recovery to pre-2010 levels.

In stark contrast to the C6 future climate storylines, recovery was consistently observed for all future LULC scenarios, from the current declining trend, under the ERA5Wet future climate storyline. This storyline represents a wetter precipitation period than the 1971 to 2000 period, which was characterised by a higher number of extreme rainfall events then the 1991 to 2020 period.

The No Forestry scenario vividly demonstrated the extent of the impact of plantation forestry on the water table, a crucial point conveyed during community workshops. Had commercial plantation forestry never been introduced (“No Forestry” LULC scenario), current lake levels would be at least 1.5 m higher than they are today despite two decades of low rainfall leading up to 2020, and the 14-year current breach in drought reserve would not have occurred. Water levels remained above 16.6 m AMSL up to 2020. Under the C6Dry climate future storyline, the recent crisis conditions would only have been reached by the mid to late 2040s. A declining trend under the “No Forestry” scenario for both C6 future climate storylines demonstrates the dominant impact of a climate future with few extreme rainfall events. In the ERA5Wet future storyline, the system recovers rapidly to over 19 m AMSL by 2050. In contrast, under the ERA5Wet (best-case) climate future storyline, under SQ conditions (no reduction in forestry), the lake system, which had fallen below 15 m AMSL by 2020, had not recovered above 17.8 m AMSL by 2050, indicating a cumulative and potentially escalating deficit in the water resource. Collectively, these results demonstrate that commercial plantation forestry exacerbated the impact of below-average rainfall in the region. Maintaining the SQ land use in combination with bush encroachment is the worst option under all climate futures.

The two C6 and the ERA5Wet storylines represent extended periods of possible worst- and best-case future climate storylines, where climate signatures would be the predominant influence on the groundwater resource. The climate future storylines are within the range projected by CMIP6 ensembles which range from a -7% decrease in summer rainfall to an increase of +19%. In this study extended periods of time that represent conditions with either a higher or lower frequency of extreme rainfall events were tested. A more probable future is likely to be one with more interspersed extreme wet and dry periods, i.e. not such lengthy extended periods of one or the other. In such cases, land use choices will likely exert a more significant influence on the net outcome.

Attempts were made to establish links between hydrological outcomes and the ULM Lake Sibaya Catchment systems model (ULMCatchMOD) to explore socio-economic consequences. A key integration point that emerged was the assessment of groundwater availability in relation to crop/tree irrigation demand, the deficits of which were factored this into the ULMCatchMod through crop damage function (DF) equations. Unfortunately, due to the complexity and time-consuming nature in setting up hydrological configurations, no way was found to couple the models dynamically in relation to groundwater levels with ensuing feedback on economic activities. Only those LULC scenarios which had been simulated could be incorporated.

NET OUTCOMES OF FUTURE LAND USE-CLIMATE STORYLINES

The effects of climate and LULC change in the MCP have been acknowledged in the past, but their socioeconomic impact has not been analysed before. The objective was to quantify the impact of varying LULC scenarios under three future climate storylines, namely the C6Dry and C6Wet and the ERA5Wet for the ULM within the MCP. A system dynamics model (ULMCatchMOD) was custom-built to simulate the economy and dynamics of the ULM under these scenarios for the period 2024 to 2050.

The hypothetical scenarios included converting 50% of the commercial forestry plantations to either Dryland Crop; Marula or macadamia orchards; an increase in the number of tourists visiting the area (non LULC based); and a loss of grasslands to bush encroachment. The data used was obtained from diverse sources, including surveys (primary data collection), literature, expert opinion, and the climate and hydrological outcomes from within this project.

The ULM economy comprises a diverse range of household economic activities, but they are mostly subsistence in nature and are highly vulnerable to changes in climate and land use. Survey data revealed that tourism, as well as income from crafts, generated significantly more income and employment then commercial eucalyptus forestry plantations at the household level. While the primary food sources for all households was shops, 68.6% of households supplement their food source through subsistence cultivation. Of all households surveyed (217), 38.3% consider themselves water insecure. Climate change awareness is low (49.6%).

Using three economic indicators, namely actual cumulative value (primarily for household economic activities), employment potential, and the net present value (NPV) of net cashflow projections, it was ascertained that by switching 50% of the commercial eucalyptus plantation forestry with, for example, cassava, is likely to result in more favourable outcomes for households. It has been estimated that the relative increase in the NPV of the sectoral cashflows could be between 9% and 33% higher compared to the SQ for the C6Dry and ERA5Wet scenarios respectively, depending on the LULC scenario. However, some scenarios resulted in worse economic outcomes (mixed Dryland Crop) under C6 climate futures. Among the crops, cassava has higher cumulative benefits per hectare compared to maize, groundnuts and vegetables and is more resilient under drier future climate storylines. Similarly, employment is likely to be higher by between 18.47% and 205.12% relative to the SQ scenario. In a much wetter future the model demonstrates several options that would result in net gains relative to the SQ. A 50% loss in grasslands to bush encroachment is likely to reduce livestock productivity in the area, by reducing the cattle population by 13%.

It is evident that the existing LULC distribution was designed to promote economic development, however, the economic status at the household level has remained stagnant. The commercial eucalyptus plantations, which cover vast areas in the coastal regions within the ULM, including the Lake Sibaya groundwater catchment area, offer fewer employment prospects per hectare in comparison to other activities. The information from more than 200 respondents of the HH survey provides evidence of this.

To diversify their economies, households cultivate in wetlands to take advantage of the high-water table. However, the model did not consider the negative effects of a decline in the water table on wetland farming due to time constraints, the complexity of agronomic processes, and the lack of a fine scale Digital Elevation Model (DEM) which, it was discovered, would be needed to assess the water levels using the groundwater model in target points within wetlands to work out area available under varying groundwater conditions. It is recommended that future studies focus on the assessment of the value of wetlands in the area, including the impact of changes in the water table on wetland-related benefits and risks.

Ecosystem degradation, driven by the declining water table, has negatively impacted on households. Comments from household (HH) surveys shed light on the negative impact that the decline in the water table has had on natural resources, such as reeds used for craft, an important source of income.

The ULMCatchMOD revealed that bush encroachment also has negative impacts on cattle production. Given the relatively constant nature of bush encroachment in the model, future research can construct models or extend the current model to simulate the impact of bush encroachment in the area through the analysis of historical trends. These models can also explore possible strategies to alleviate the issue. The model can also cater for non-land-based scenarios such as the commercialisation of cattle, improved market access and different tourism occupancy rates.

SUMMARY MATRIX

The outcomes of various hypothetical land use choices were assessed under different climate future storylines. To achieve this, economic, climate and hydrological components were integrated in different ways throughout the project. This culminated in developing a very simple matrix for each climate future storyline to summaries and compare consequences of LULC choices in relation to water security, employment, economic wellbeing, and natural resource (ecosystem) integrity (for an example see Table 1-1).

Table 1-1 Summary matrix of impacts of different LULC scenarios under the warmer drier (C6Dry) climate future storyline relation to 4 key challenges. Green indicates a positive impact relative to the SQ, orange indicates a negative impact relative to the SQ, clear is no change. Red text indicates that, there is no allocable water for that scenario based on the water level in relation to the RQOs

Very dry few extreme rainfall events (C6Dry) Climate future storyline	Water	Employment	Economic status	Natural resource/ Ecosystem integrity	Net outcome
Bush Encroachment	Worse (-1)	No change (0)	Worse (-1)	Worse (-1)	-3
Dryland Crop	Better (+1)	Better (+1)	Worse (-1)	Worse (-1)	0
Irrigated Crop	Worse (-1)	Better (+1)	Worse (-1)	Worse (-1)	-1
Dryland Cassava	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Dryland Macadamia	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Dryland Marula	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Irrigated Macadamia	Worse (-1)	Better (+1)	Better (+1)	Worse (-1)	0
Irrigated Marula	Worse (-1)	Better (+1)		Worse (-1)	
Status quo +60% Tourism	No Change	Better (+1)	Better (+1)	Worse (-1)	1

Using the matrix in Table 1-1, it is easy to see that, under the C6Dry future, Dryland Macadamia, Cassava and Marula appear to be water wise economically viable choices, that provide better benefits then the SQ, whereas the SQ coupled with bush encroachment results in the worst outcomes for all challenges relative to the other choices tested.

The scale used in the summary matrix provides a proof of concept for a simple story board approach for engagement. It is currently too crude to pick up nuanced differences between choices, particularly in the extent of economic and employment returns. A broader scale range is recommended, but this should be based on more accurate parameterisation of the economic input data.

OUTCOMES FROM CO-GENERATIVE APPROACHES AND ENGAGEMENT

There is often a significant gap between global change research and the provision of appropriate information to support adaptation strategies for societal impact (Rodrigues and Shepherd, 2022, Oliver et al., 2023). Participatory approaches help to connect with the actual needs of the end users and in finding ways to address these together (Eriksen et al., 2021, Pörtner et al., 2023).

Co-generative approaches were used to ensure context-relevant information for the project. This started with workshops with TCs at the start of the project. These workshops advanced multiway knowledge sharing, where emergent opportunities were identified, such as the interest and constraints to the commercialisation of cattle farming in the region. Consequently, the project team arranged a knowledge exchange, in collaboration with WILDTRUST, to take nine members (three from each community area) to Matatiele to learn from Environmental Rural Solutions (ERS) and the communities they work with (November 2023). Despite some initial expectation challenges, this turned out to have a profound impact on those who participated. Later that November (2023), a second round of workshops was held with each TC to provide preliminary results on the project. Those who had participated in the knowledge exchange were also invited to share their feedback with the TCs.

In the second round of project feedback workshops with the TCs (November 2023), in the Mbila/Zikhali and Mabasa TCs, a growing awareness and appreciation of NRF-SAEON's research and its importance, particularly valuing the concept of long-term research to understand system changes, was evident. The fact that results are being fed back to TCs was very much appreciated, and helps to instil trust. The Tembe workshop was somewhat different, as those who attended were mainly cattle farmers and few of them had previously interacted with NRF-SAEON. However, after explaining the work, the concept of climate change and the uniqueness of the groundwater system, there was a general acceptance and interest in the results being presented. One of the community members emphasised the value of having an unbiased party (SAEON/project team) share information objectively to the larger community. In all three workshops, appeals were made to share the research activities being undertaken by NRF-SAEON and other researchers with the broader community as information does not filter down to the general population.

During conversations at the knowledge exchange and within all the TC workshops, concerns about loss of grazing due to bush encroachment and lack of water were issues raised repeatedly. NRF-SAEON was asked if it could help initiate research on how to address the bush encroachment problem.

Regarding alternatives to eucalyptus plantations, the concept of alternatives has been embraced with a common thread being the expressed need to take the next step. Workshop participants highlighted the need for agricultural alternatives, training, and tools, and a focus on cattle grazing and animal health. They expressed a willingness to participate in future workshops to explore the project outcomes but are most interested in how to achieve alternatives. In this regard, they requested the project team to connect them with NGOs, agricultural training entities, and “university professors” (research specialists) to assist with transitions to and implementation of alternatives. They are less interested in the fine-scale scientific results than they are in tangible steps forward. However, all pleaded for more information sharing with the broader community on the uniqueness of the groundwater system (sensitivity to rainfall and LULC) and climate change risks. All three TCs would like a copy of the full report from this project as well as a written summary in IsiZulu.

Feedback from the nine participants, hosted on the knowledge exchange, to the TCs proved powerful. In all three TCs workshops they fed back consistent messages. They expressed how they were inspired to see how communities in Matatiele worked together to solve their own challenges. During the trip, the project team observed that the attitude of the ULM participants went from one of expectation for external help to wanting to do something themselves to make a change. The even expressed interest in starting an NGO of the same nature as ERS in ULM. In their feedback to the TCs, the participants explained all they had learnt and emphasised the need for all three communities to work together towards common goals, including good land use planning and governance. This opportunity served to enhance awareness and local agency to promote adaptation.

The use of participatory approaches enriched the research process, illuminating several issues and opportunities that would otherwise not have been identified. It helped to root the work in the local context. There was also evidence of increased awareness of the risk of climate change as well as the vulnerability of the ULM water resources. The richness of experience and seeing challenges first hand by imbedding ourselves within the area “humanised” members of the project team that were involved, and motivated them to see how they could translate research findings into action by acting as boundary agents between communities and ethically responsible stakeholders who can facilitate community driven change aspirations. All engagements were humbling experiences, particularly as an invitation was extended to continue working hand in hand with the communities. This emphasises the value and importance of long-term relationships between communities and research groups.

In terms of the achievement of traction towards the rationale and openness to exploration of alternatives, this project has served to enhance a mutual understanding of risk and spur interest in trying alternatives. However, that will only be possible with good governance and multi-institutional support to facilitate identifying and taking the next tangible steps forward.

SYNTHESIS, RECOMMENDATIONS AND CONCLUSIONS

Anticipated impacts of climate change, which include an increase in the severity and frequency of extreme events, will exacerbate poverty and vulnerability if no proactive action is taken to empower communities to adapt. While temperature increases are inevitable, the trends in precipitation at local scales are less clear. Unpredictability in rainfall patterns and higher temperatures will impact food security and incomes derived from natural resource-based livelihoods.

To achieve sustainable development, as prescribed by South Africa’s National Development Plan (NDP), the challenge is to strike a balance between economic development, environmental sustainability, and resilience to anticipated climate change impacts. To date, this has been an elusive outcome in the ULM. Demand for water from various users has surpassed the available yield potential (Johnson, 2021). As a result, the adaptive capacity of vulnerable households within the region has declined, at a time when every effort should be made to enhance adaptation strategies in the face of climate change. Given the impact of land use on water security within ULM, considering land use options should be an important component in adaptation strategies. This project aspired to develop a means of empowering vulnerable local communities to make informed and “least regret” land use choices for the optimisation of beneficial outcomes in the context of an uncertain future climate.

The primary aim of this project, (Aim 1), was to integrate appropriately scaled climate, hydrological, and economic components and use this to explore the net effects of plausible future LULC scenarios under different future climate storylines within quaternary catchment W70A, focusing on the Lake Sibaya groundwater catchment. This was informed by climate analyses (Aim 2) as well as determining the relative impacts of LULC and climate on the hydrological response of the Lake Sibaya groundwater catchment from the past to present period (Aim 3 and Aim 4). Co-generative engagement processes (Aim 6) were used to inform potential future land use scenarios and several future climate storylines were developed (Aim 4). Household surveys and systems dynamics economic modelling were used to estimate the socio-economic consequences of these alternative land use scenarios under future storylines (Aim 5). This systems dynamic model (ULMCatchMod) integrated climate, economic, and hydrological information towards achieving Aim 1. As the hydrological modelling outcomes could not be fully coupled within ULMCatchMod, a simple summary framework was developed to provide comparative storyboards for contrasting the consequences of different land use choices under the different climate futures. These consequences are assessed against four context relevant challenges, as defined by TCs.

The No Forestry scenario vividly demonstrated the impact that commercial plantation forestry has had on the hydrological status of the Lake Sibaya groundwater catchment area. This impact has resulted in ecosystem degradation and livelihood impacts that would not yet have been experienced if commercial plantation forestry had never been introduced. Household responses provided significant narrative evidence for the negative impact of these declines on natural resources they depend on, such as loss of wetlands for cultivation and reeds for crafts. In hindsight therefore, this is a LULC choice that could be concluded as “regretful”, and serves as a lesson on how choices made today may impact on the future wellbeing of the area.

Economic and employment data from HH surveys, as well as system model simulations, disproved the notion that commercial plantation forestry provides major benefits relative to other sources of income and alternative land use options at the household and sector levels. Furthermore, most future land use preferences pointed to an aversion to commercial plantation forestry, both at the TC level and household levels. Some of the alternatives suggested by TC participants appear to be potentially feasible and would create more employment with better returns and less impact on the water table.

The impact of removing commercial plantation forestry will partly depend on the climatic conditions experienced. Under a middle-of-the-road climate future storyline, it is likely to have a positive effect, enabling the system to recover somewhat and reducing risk. Maintaining the SQ LULC is the worst option from a water security perspective, especially in combination with bush encroachment. Even in the best-case climate future storyline, if there is no change in the 2020 LULC (i.e. no reduction in plantation forestry), the groundwater system does not recover to previous high-stage levels based on the climate data used in the model simulations. This indicates a cumulative, and potentially escalating, deficit in the water resource, with knock-on consequences for natural resource-based livelihoods if the extent of commercial plantation forestry is not significantly reduced.

This was a first attempt to try and develop a dynamic and interactive decision support tool to explore consequences of land use choices made now into the future in a data poor environment. Progress was made towards this, however at this stage, only scenarios that have already been modelled hydrologically can be explored. The ULMCatchMOD has flexibility that can be optimised to greater effect, relating to non-hydrologically dependent activities, provided it is parameterised with appropriate data, to explore relative outcomes.

Rather than a decision support “tool”, the outcomes of this work were able to provide valuable storyboards, in a data poor context, which were used to demonstrate concepts when engaging with the communities. Engagements revealed that their interest was not in the “tool” itself, as the storylines were sufficient to focus their attention on alternatives. They were more interested in tangible assistance to work out fine-scale practical details about how to make changes they may want to make. In this regard, the onus falls on the project team to 'pass on the ball' by trying to link those interested in exploring alternatives, with appropriate implementation organisations.

In an attempt to integrate climate, hydrological and economic components, numerous challenges were encountered. These included scaling issues, data paucity, model limitations and inter-modelling coupling constraints. Despite this, several knowledge advances were made and a significant amount of hydrological, micro-metrological and household socioeconomic data was collected to inform integration processes, as well as aid in the interpretation of results.

Knowledge advancements, spurred by the need to integrate across disciplines, were achieved. An improved understanding of the hydrological system was gained through *in situ* measurements, isotope studies and climate analysis, which collectively demonstrated the importance of extreme rainfall events for recharging the groundwater table. This emphasises the importance of the further exploration of the controlling mechanisms that influence regional weather patterns in this area, particularly tropical storms, and how these are likely to change into the future. Furthermore, the study revealed that the indigenous

IOCBB grassland is the best land cover for achieving optimal recharge, but these are being rapidly transformed. A key recommendation from this project therefore is that every effort should be made to protect all remaining grassland areas within quaternary catchment W70A. This can only be achieved if they are providing value to the communities that live within them.

Some recommendations for scientific advancement include:

- Of primary importance is a rainfall record with high confidence that accounts for spatial variability;
- Continued and expanded *in situ* hydro metrological data collection;
- Continuous *in situ* measures of ET for different vegetation types and land uses using Eddy covariance and surface renewal systems;
- Open water (Lake Sibaya) observations including meteorological variables, to determine evaporation;
- Improved bias correction methodologies for downscaling Global Climate Models (GCMs) projections;
- Improved performance of GCMs through the incorporating *in situ* data and of local processes;
- Improved understanding of drivers of climate systems within this transition zone and how they may change into the future;
- Reconstructing the MODFLOW groundwater model based on new isotopic and geophysical data to improve confidence in various parameters including conductance. Pilot point calibration should also be included. A novel method for determining volumes of submarine discharge would be a major advancement;
- A fine scale digital elevation model for the region;
- A more accurate assessment of LULC change over a longer historic period;
- New coding or an alternative surface hydrological model that can operate a shallow groundwater routine in a gridded mode;
- Refined household survey design and the implementation of a longitudinal study;
- Improved parametrisation of the ULMCatchMod, and expansion to include feedbacks as well as natural resource asset evaluations; and
- Continuous engagement with communities to enrich the research as well and ensure it remains relevant.

In conclusion, this project aspired to develop a means to empower vulnerable local communities to make informed choices for the optimisation of beneficial outcomes in the context of climate change adaptation. The project aims were achieved through (i) scientific research to advance knowledge on the climatological, hydrological, and economic dynamics within the ULM; (ii) engagement and multiway knowledge sharing with people living in the area to ensure context relevance, enhance awareness of climate change risks and promoting personal agency in addressing these; and (iii) integrating information to provide decision support storylines that promote an understanding of the potential implications (risks/opportunities) of land use choices made today, on future outcomes under different climate futures.

The impact of nine land use choices on water security under three (in some cases four) climate future storylines was achieved. Climate, economic and hydrological parameters were integrated using a systems dynamic model to assessed the consequences of LULC choices. This was supplemented by a summary framework that incorporated additional hydrological consequences. These consequences were assessed in relation to water security, employment, economic status, and natural resource (ecosystem) integrity, under the different climate future storylines. Caricatured climate future storylines and “immediate” LULC switch scenarios were used to test if integration was possible. The integration achieved demonstrated a sound proof-of-concept which can now be refined, focusing on parameterisation. While the results from individual components provide useful insights, the net effect outcomes should be used for demonstration purposes only, until various components are more adequately parameterised. Feedback from workshops in November 2023 indicate that the project did serve to enhance awareness of climate change risks and was routed in the local context. The outcomes from the Knowledge Exchange proved a powerful intervention and served to promote personal agency in those who participated.

Results from the study underscore the interconnectedness of economic, environmental, and social factors in the ULM in general and the Lake Sibaya groundwater catchment, which emphasises the need for comprehensive and collaborative approaches to address current challenges and future uncertainties. There is a complex interplay between climate, land use, and economic factors which require integrated approaches to promote adaptive capacity in the face of evolving conditions.

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Charlene Russell, Nkosi Sithole Gugulethu Tshabalala	Groundtruth	WRC Project K5/00841: Citizen Science Online Training and Learning System
Mark Schapers	JG Afrika	Technical and advisory support and TTEM collaboration
Patrick Saunders	NRF	Editing assistance

Reference Group	**Affiliation**
Dr Brilliant Petja (Chair)	Water Research Commission
Dr Gregor Feig	NRF-SAEON-EFTEON
Dr Kgaugelo Chiloane	Adaptation Institute of Southern Africa
Dr Lulu Pretorius	WETREST
Mr Mark Schapers	JG AfriKa
Dr Heidi van Deventer	CSIR
Others	
	EKZNW
Jabulani Ngubani	Isimangaliso Wetland park
Tembe Traditional Council	Tembe community area
Mabasa Traditional council	Mabasa community area
Mbila/Zikhali Traditional Council	Mbila Zikhali community area
Lungisani Nxumalo, Eric Nxumalo VR Nxumalo	The Lake Sibaya Conservation and development trust
Andrew Whitely, Ayanda Tshembeni, Thulasizwe Zulu	WILDTRUST
Des van Rensburg and Atish Hoosen	DWS: NWRI-EASTERN OPERATIONS: SURVEY
Sissie Matela, Yonela Sipeka, Zuko Fekis and the ERS team	Environmental Rural Solutions (ERS)
Sabelo Nxumalo	Community member, daily rainfall sampling
All participants of household and sector surveys	

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ACRONYMS & ABBREVIATIONS

AMSL	Above Mean Sea Level
AOI	Area of interest
ARC	Agricultural Research Council
BGL	Below Ground Level
C6Dry	ERA5 Data bias corrected based in CMIP6 “Dry” projection
C6Wet	ERA5 Data bias corrected based in CMIP6 “Wet” projection
CMIP6	Coupled Model Inter-comparison Project
DEM	Digital Elevation Mode
DF	Damage Function
DO	Dissolved Oxygen
DPM	Disk Pasture Measure
EC	Electrical Conductivity
ECo	Eddy Covariance
ECMWF	European Center for Medium-Range Weather forecasts
EFTEON	Expanded Freshwater and Terrestrial Environmental Observation Network
EKZNW	Ezemvelo KZN Wildlife
ERA5	Refers to the Fifth generation ECMWF atmospheric reanalysis of the global climate
ERA5Dry	ERA5 adjusted data based on a “low frequency of extreme rainfall events period” -10%
ERA5Wet	ERA5 adjusted data based on a “high frequency of extreme rainfall events period” +10%
ERS	Environmental Rural Solutions
GCM	Global Climate Model
GEE	Google Earth Engine
HRU	Hydrological Response Unit
IPCC	Intergovernmental Panel on Climate Change
LEL	Local Evaporation Line
LMWL	Local Meteoric Water Line
LULC	Land Use Land Cover
LULC change	Land Use Land Cover Change
MAP	Mean Annual Precipitation
MCP	Maputaland Coastal Plain
NPV	Net present value
NRF	National Research Foundation
ORP	Oxidation Reduction Potential
RQOs	Resource Quality Objectives
SAEON	South African Environmental Observation Network
SANLC	South African National Land Cover
SAWS	South African Weather Service
SQ	Status Quo
SR	Surface Renewal
SSP	Shared Socioeconomic Pathway
SWSA	Strategic Water Source Areas
T	Temperature

TC	Traditional council
TDS	Total Dissolved Solids
ULM	uMhlabuyalingana Local Municipality
UM	Usutu Mhlathuze drainages regions "W"
UMDM	uMkhanyakude District Municipality
UNESCO	United Nations Educational, Scientific and Cultural Organization
WRC	Water Research Commission

NOTES ON TERMINOLOGY AND SPELLING

1. Terminology used in reference to traditional structures is take from the Traditional Leaderships and Governance Framework Act [No. 41 of 2003] as per the following definitions laid out in the act

   - "Community Area" means a traditional community recognised as such in terms of section 2 of the act

   - "Traditional Council" means a council established in terms of section 3 of the act

2. There are multiple references to the spelling of Lake Sibaya (Lake Sibhayi, Lake Sibhaya, Lake Sibayi) the spelling selected for this study is Lake Sibaya.

CHAPTER 1: BACKGROUND

By S Janse van Rensburg, ML Toucher, MH Maseko, S Maseko, S. Mfeka, LN Gule, J Blignaut, S Kebede, T Nsibande, M Pienaar, P Gordijn, RC Blamey, CJC Reason, N Mkhize and B Kelbe

1.1 INTRODUCTION

Water security is critical for economic development and the alleviation of poverty in South Africa, particularly in underdeveloped rural areas. However, 98% of the country's available water resources are already allocated (DWS, 2022). Underdeveloped rural social-ecological systems, where livelihoods are closely connected to water providing ecosystems, are especially vulnerable to diminishing water availability. In an era of change, associated with system-wide degradation, threats to life and livelihoods are escalating (Sintayehu, 2018, Dasgupta, 2021, Kwame et al., 2022, Pörtner et al., 2023). Cumulative impacts on water-providing ecosystems are reducing the potential of these ecosystem to provide water, which hinders prospects for poverty alleviation. These impacts are associated with two main drivers: firstly, climate change and associated extreme climate events (Condon et al., 2020), over which rural communities have little immediate control over; and secondly, anthropogenic impacts, including land use change, over which rural communities potentially do have some control.

Climate change impacts are already being experienced and are set to increase (Cullis et al., 2015, Lee et al., 2023). Humans have caused the planet to warm, primarily due to activities that emit greenhouse gases (Lee et al., 2023). Warming leads to changes in the weather and climate system, resulting in further impacts which include increased incidents of extreme events such as heat waves, more severe droughts, and heavier precipitation events leading to increased flooding (Lee et al., 2023). These physical impacts affect ecosystems and the associated services and livelihoods they provide (Sintayeh, 2018, Pörtner et al., 2023), health, infrastructure, settlements and various sectors, and ultimately impact on economic well-being (Howells et al., 2013). The severity of the impacts in the future depends on our ability to control and reduce greenhouse gas emissions (Lee et al., 2023) as well as our ability to adapt to inevitable changes and impacts.

Climate research aims to help predict future climates in relation to different greenhouse gas emission scenarios. Doing so is complex and hampered with various uncertainties (Arias et al., 2021). However, confidence in relation to large-scale indicators of climate change at the global scale has improved as the science advances (Arias et al., 2021, Masson-Delmotte et al., 2021). A recent advance is the Coupled Model Intercomparison Project (CMIP6) which provides a standardised framework for the assessment of different models under different greenhouse gas emission trajectories. CMIP6 models, in general, show improved performance (reduced model spread) at the global scale, compared to predecessors (CMIP5) (Chen et al., 2020). The latest report from the Intergovernmental Panel on Climate Change (IPCC) uses results based largely on CMIP6 (Masson-Delmotte et al., 2021). This provides a basis from which to develop mitigation and adaptation strategies.

Despite having the least responsibility for causing climate change, vulnerable communities will be the worst affected (Lee et al., 2023). In this context, vulnerability refers to the likelihood of being negatively affected. Increased vulnerability arises from factors such as high exposure to risk, limited capacity to cope and adapt, elevated levels of inequality, the status of the environment and, importantly, economic status, which is often linked to the ability to cope and adapt (Pörtner et al., 2023). The most recent IPCC report emphasised that immediate and rapid adaptation is required to reduce negative outcomes (Lee et al., 2023). The impact of anticipated climate change impacts on lives and livelihoods within communities will thus depend on how well prepared they are, the health of the ecosystems which support them and their and economic status (Turpie et al., 2002, Sintayehu, 2018, Pörtner et al., 2023) . Given that South Africa is water scarce, adaptations strategies that promote water security at local and national scales are of paramount importance. Integrated economic valuations are required to inform these (Howells et al., 2013, Auffhammer, 2018). By implication, the impact of climate change on intersections of water security, production systems and economic activity needs to be understood to inform such strategies.

Unfortunately therefore, research investment into the economic evaluations of climate change impacts has been disproportionally small compared to what is invested into climate research (Auffhammer, 2018). Climate change will impact on economic growth globally (Roson and Sartori, 2016, Pörtner et al., 2023). Economic impacts can be in response to directional changes, such as temperature increases and precipitation decreases (Bradshaw et al., 2022), as well as climate shocks and extreme events, such as floods (Fitchett et al., 2016). Turpie et al. (2002), in an assessment of the market and non-market climate change impacts for South Africa, argued that all impacts have their basis in changes to natural systems. This notion has been supported by more recent reviews (Sintayehu, 2018, Pörtner et al., 2023). Cullis et al. (2015), assessed the possible impacts of climate change on the water supply sector, dry-land agriculture, hydropower, roads, infrastructure costs and sea-level rise at the national scale for South Africa, and concluded that there is a high likelihood of an overall negative impact on GDP. While global assessments on multi sector impacts have been attempted per country (Roson and Sartori, 2016), there is a gap in in-depth research within South Africa, that utilises the updated climate projections, that explores on the relative impacts (and outcomes) of future climate change (and economic) scenarios on (for) different sectors (Ngepah et al., 2022).

Dasgupta et al. (2023) demonstrated a negative economic impact of temperature for South Africa, disproportionally affects poorer communities. A number of studies have demonstrated the likelihood of reduced agricultural productivity in general within South Africa (Mendelsohn et al., 2000, Olabanji et al., 2020, Odimegwu, 2022), and for important crops specifically, such as maize (Bradshaw et al., 2022). Negative impacts are anticipated for agriculture within KwaZulu-Natal (Ngepah et al., 2022). However, studies that specifically quantify the economic implications, including both reduced productivity and the costs associated with required adaptation strategies, under future climate scenarios for South Africa, are scarce.

Land is a major factor in production, at it provides economic and social benefits. Land use choices can impact ecosystems and water resources, which lead to feedbacks that influence both environmental and economic outcomes (Foley et al., 2005, Howells et al., 2013). Climate change will also have direct impacts on ecosystems services and land-based production (Sintayehu, 2018, Arias et al., 2021, Lee et al., 2023). Land use choices made now, and in the past, will either exacerbate vulnerability due to climate change related threats to water security or may assist in the reduction of such impacts. Today's choices may influence the adaptive capacity and future trajectory of economic and water security of a region. A decline in the water levels in South Africa's largest natural freshwater lake, Lake Sibaya, serves as a prime illustration of this critical juncture.

1.2 RATIONALE

The Umhlabuyalingana Local Municipality (ULM) (Figure 1-1), is a rural landscape that faces challenges such as high unemployment and poverty, ecosystem degradation and a decline in water security (Patrick, 2021). The regional aquifer is a Strategic Water Source Area (SWSA) of national and international significance (Le Maitre et al., 2018), and is the primary water source for local communities. Quaternary catchment W70A (Figure 1-1), within the ULM, is a unique groundwater-driven system, devoid of surface rivers that supply water to it (Figure 1-1). It falls within the UM drainage area (Figure 1-1). Its sole dependence on localised rainfall for recharge makes it exceptionally climate sensitive. Tapping into this aquifer, several water schemes have assisted in the provision of water to communities. However, only 8.76% of households within ULM have access to piped water (ULM 2020.). Most households still rely on unmetered water sources such as boreholes, springs, wells, wetlands, and rainfall water harvesting into tanks.

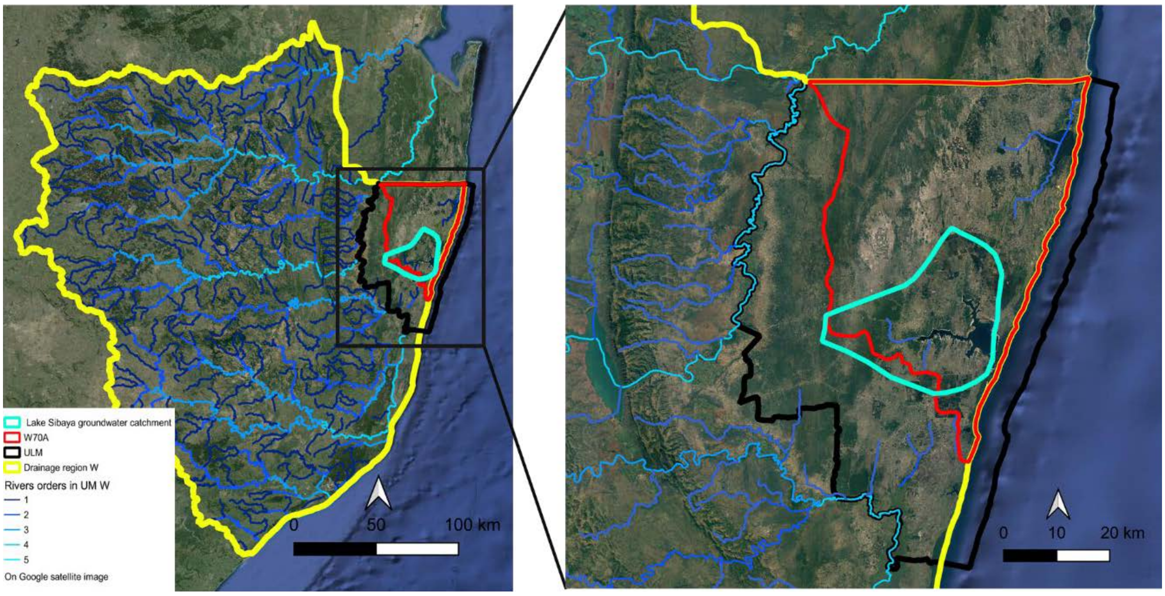


Figure 1-1 Location of the ULM (black boundary) and quaternary catchment W70A (red boundary), within the UM drainage region (yellow boundary). Note the absence of rivers within quaternary catchment W70A. The estimated (Kelbe, 2020) Lake Sibaya groundwater catchment area in relation to quaternary catchment W70A is shown in light blue

The ULM landscape has a diversity of terrestrial and wetland ecosystems with rich fauna and flora assemblages, including Lake Sibaya. The health of these ecosystems, both inside and outside protected areas, is strongly dependent on the status of the groundwater system in conjunction with changes in land use (Taylor et al., 2006, Colvin et al., 2007, Botha, 2015, Pretorius et al., 2016). Large tracts of "near-natural" areas are in formally protected conservation areas, and include: the Tembe Elephant National Park located in the north along the Mozambican border, Manguzi Nature Reserve, Sileza Nature Reserve and iSimangaliso Wetland Park which hosts Lake Sibaya and Kosi Bay systems, both of which are Ramsar sites. However, freshwater habitats are being degraded. For example, the freshwater habitat of Lake Sibaya is considered critically endangered, despite its location within a protected area (Skowno et al., 2019). Pressures identified include changes to the hydrological regime (due to land use impacts on the water resource outside of the protected area), climate, invasive species and habitat modification (Skowno et al., 2019, Van Deventer et al., 2021).

The area outside the protected area network is Ingonyama Trust land, comprised of several legally recognised traditional community areas which are each managed through their own respective traditional councils (TCs). In these areas, there are also "irreplaceable" and "important" ecosystems, crucial for the achievement of biodiversity conservation targets, which are under similar pressures to Lake Sibaya (Van Deventer et al., 2021). There is growing evidence that commercial plantation forestry and climate are the key drivers that affect the regions water security both inside and outside of protected areas (Smithers et al., 2017, Nsubuga et al., 2019, Ramjeawon et al., 2020, Johnson, 2021).

Commercial plantation forestry and tourism are two major sectors in the region. Commercial forestry, predominantly eucalyptus plantations, is a dominant land use outside of the protected areas and is perceived as an important source of income and employment. The regions diverse tourism opportunities, a potentially sustainable economic driver, are not yet fully optimised. However, there are plans to address this (pers. comm iSimangaliso Wetland Park). The recently completed tar road and Maputo-Katembe bridge that links Maputaland to southern Mozambique is likely to lead to an influx of tourists and increased cross-border trade to further fuel economic growth potential and associated pressures on natural resources in the region.

Households within the region use the land for cultural activities, dryland and wetland crop farming, resource use and livestock, which graze on communal areas. The many wetlands in the region, linked to the groundwater aquifer, provide important “key resource” areas for farming and water sources for livestock. Resource harvesting takes place in the terrestrial, e.g. tapping of Lala Palm for wine and aquatic systems, e.g. reed harvesting and fishing (traditional and gill netting methods), both inside and outside protected areas. People in the area are highly dependent on the wetlands and natural resources which play an important role in the enhancement of livelihoods (Cunningham, 1985, Grundling et al., 2013a). The decrease in the groundwater table is a source of concern for those reliant on these natural resources.

Since 2001, Lake Sibaya water levels, which reflect groundwater trends within the coastal areas of quaternary catchment W70A in general, and for the Lake Sibaya groundwater catchment in particular, declined by approximately four meters, reaching a record low in 2014/2015 (Janse van Rensburg, 2018) and continued to decline (NRF-SAEON data) to 2021, with the main basin reaching a record low of 14.66 m AMSL in the main basin in July 2020 (SAEON data). A 20% reduction in the surface area of the lake between 1992 and 2016 (Nsubuga et al., 2019) represents a massive volume loss given the conical shape of the lake. This decline is indicative of a regional drying trend, resulting in the decline of water bodies and wetlands by 36% and 49% respectively from 1986 to 2019 (Ramjeawon et al., 2020). Water dependent ecosystems, which people rely on, are degrading (Van Deventer et al., 2021), desiccating and burning (Grundling et al., 2021) but the economic consequences of this on people's livelihoods has not been assessed.

Below-average rainfall, commercial plantation forestry and, to a lesser extent, abstraction, have all contributed to the groundwater decline within quaternary catchment W70A (Weitz and Demlie, 2014, DWS, 2015, Smithers et al., 2017, Bate et al., 2018, Nsubuga et al., 2019, Ramjeawon et al., 2020, Johnson, 2021). The negative impacts of afforestation on the region in general (Vaeret et al., 2009, Bate, 2016) and on the Lake Sibaya region specifically (Weitz and Demlie, 2014, Smithers et al., 2017, Bate et al., 2018, Graham et al., 2020) have been demonstrated. There is evidence of a drying trend in precipitation for the region (Nsubuga et al., 2019, Ndlovu and Demlie, 2020, Mpungose et al., 2022). The driest year on record for the area was 2015/16, which fell within an anomalously extended dry period (Blamey et al., 2018, Mpungose et al., 2022). Concurrently, commercial plantation forestry activities have increased (Ramjeawon et al., 2020).

An assessment, commissioned by the uMkhanyakude District Municipality (UMDM), to assess the feasibility of an increase in the water supply from Lake Sibaya for human consumption, demonstrated that by 2014 the levels of development within the area were already unsustainable from a water yield perspective. Commercial forestry plantations would need to be significantly decreased to ensure the system's long-term sustainability and “release” water for human needs (Johnson, 2021). Forestry has however continued to increase. The increase in the water deficit has resulted in competition for water for human consumption, environmental needs, and stream flow reduction activities such as commercial plantation forestry.

Commercial plantation forestry is often defended by forestry companies and some residence in the area as a significant source of income and employment in an agriculturally poor area. Whether the benefits of forestry plantations outweigh their negative impact on water availability, water-dependent ecosystems, and associated livelihoods remains unclear. Previous attempts by the Department of Water and Sanitation (DWS) to restrict plantation expansion based on legality have failed. Even if there was a willingness to change, it is argued that there are no apparent alternatives.

An assessment of a recent historical period, characterised by higher-than-average temperatures and lower precipitation, demonstrated the likelihood of a negative impact on net agricultural income in South Africa (Blignaut et al., 2009). Anticipating that the impacts of climate change will worsen, the authors argued for the urgent need for alternative approaches to how production and water resources management are approached. The growth in the water deficit in the ULM compels land custodians to heed this advice. This project is a direct response to the societal need to assess alternative land uses under varied future climate change storylines, that may provide information to inform adaptation strategies at the local scale.

The need to provide enabling conditions to accelerate adaptation in our social ecological-systems is urgent (Lee et al., 2023). Such conditions include the improvement of knowledge about climate change and its associated risks and consequences, coupled with the exploration of adaptation options (Pörtner et al., 2023). These should be built on integrated resource assessments across climate, energy, land use and water strategies (Howells et al., 2013). These are important at the levels of political commitment, polices and appropriate frameworks, where clear goals can help to mobilize financial resources needed to achieve adaptation goals (Pörtner et al., 2023). However, while necessary, there are high risks of top down interventions resulting in maladaptive outcomes if there is insufficient understanding of the vulnerability context, meaningful stakeholder participation, and an immersive understanding of what “adaptation success” means to affected communities, among other factors (Eriksen et al., 2021). Eriksen et al. (2021) argues that cooperation with affected communities in the project design phase through the use of mutual learning processes should be a central objective of research related to adaptation. Participatory approaches have positive outcomes in promoting adaptation action which include, but not limited to, improved awareness of climate change risks and empowerment of personal agency (Oliver et al., 2023).

While general principles can inform global- and national-adaptation strategies, the provision of specific information about anticipated local future climate conditions is needed to empower vulnerable communities and households to make more informed decisions to reduce their vulnerability to climate change and choose “least regret” economic pathways. However, despite improvements through the CMIP6 project, uncertainties are still prevalent, particularly when downscaling projections to local scales, with varied regional performance and inconsistent results across indices for different CMIP6 model outputs (Chen et al., 2020). One approach which has applied in various ways to deal with the complexities and uncertainties related to climate change projections is the use of storylines (Masson-Delmotte et al., 2021, Young et al., 2021, Chan et al., 2022, Hurk et al., 2023).

The aim of this project was to conduct transformative research, that explores the net outcomes of potential land management choices, suggested by the community, on key challenges they identified, under future climate change storylines. To foster an understanding of the need to adopt water-sustainable livelihoods to improve adaptive capacity in the face of climate change, the project team endeavoured to align the research with the scale at which decisions are made. This involved grounding the research in the local socio-economic context and active engagement with decision makers in the research process to encourage ownership of the outcomes. The intended output was a pilot systems model, that integrates climatological, LULC, hydrological and economic components that could be used to model the future outcomes of land use decisions. The intended outcome was to facilitate improved awareness of the fact that some land use choices made today may can improve (or worsen) income and water security into the future, and consequently vulnerability and adaptive capacity, depending on the nature of the climate future.

1.3 PROJECT AIMS AND OBJECTIVES

The aims of the project were:

1. The development of a system-wide resource economics model with appropriately scaled and integrated climatological, land cover and hydrological components of the region as a decision

support tool to explore net effects of plausible future trajectories for quaternary catchment W70A with Lake Sibaya's groundwater catchment as the primary response variable;

2. To deliver a significantly new understanding of the regional climate processes for the northern part of KwaZulu-Natal and how these might change under climate change;
3. To determine the relative impact of different vegetation units and climate on the hydrological response of the Lake Sibaya groundwater catchment;
4. Identification of current as well as plausible future scenarios of climate and land use;
5. To estimate the net economy-wide impacts and consequences of several plausible trajectories of climate and compatible land use-land cover change for the catchment W70A region; and
6. To use co-generative approaches to ensure context relevant and plausible development alternatives that reflect the aspirations of local communities within the MCP, and in doing so advance multiway knowledge transfer and decisions support.

The achievement of these aims would result in the anticipated objectives that the project team intended to realise:

1. A system-wide economic model for quaternary catchment W70A, developed using a scenario-based approach to investigate the economic costs and benefits of various land use options within the context of different land use/land cover-climate futures within the area;
2. Improved climatological understanding of the UM drainage region (W) including historic rainfall patterns and potential climate change trajectories for the MCP within the UM drainage region;
3. Improved parameterisation of a groundwater model quaternary catchment W70A, using the Lake Sibaya groundwater catchment as a response variable, through ecohydrological LULC studies and climatological data from the climate component of the study;
4. A matrix of plausible land use/land cover-climate scenarios at an appropriate scale, with context relevant alternatives used to explore the consequences of economic decisions, informed by local stakeholders within the ULM, quaternary catchment W70A; and
5. Empowerment of local communities to make informed choices: the modelled benefits and costs of the land use options could be explored by decision makers which would allow them to see which options offered the most desirable future land use and thus to take decisions, in an informed way, seeking the least regret and highest beneficial impact pathway in the context of mitigating extreme climatic impacts.

1.4 SCOPE AND LIMITATIONS

This three-year project served as a pilot effort to integrate climate, hydrology, and resource economic information to assess the long-term impacts of hypothetical land use choices made today under future climate storylines. Participatory approaches with communities were used to develop plausible future land uses and identify key challenges that the impacts of these choices should be assessed against.

The focal region of interest was quaternary catchment W70A within the UM catchment area. The groundwater modelling domain encompassed almost the entire extent of quaternary catchment W70A and, in the west and south, beyond this. The Lake Sibaya groundwater catchment area was the focal area which served as the primary "response variable" that was used to translate the impact of different LULCs on the water resource. The UM catchment provide the appropriate scope for climate analysis.

Studies on the informal economy of the region are limited, hence the need for the collection of *in situ* data. Economic assessments focused on a 10 km zone around Lake Sibaya and included three traditional community areas: Tembe on the northern side of Lake Sibaya; Mabasa to the west; and Mbila/Zikhali to the south and east. The rationale for using traditional community areas stemmed from the understanding that economic decisions align with institutional structures. In this context, traditional community areas, governed by TCs, represent the most logical units for institutional decision-making. Ideally the Mshabane community should also have been included but NRF-SAEON has not developed a relationship with them yet. Through discussions, it became apparent that the economic modelling approaches are relatively coarse; hence extrapolations to institutional spatial scales are feasible. Responses to requests for sector surveys were poor, which limited localised sector-based data hence the project needed to rely on scant secondary sources of data, analogous to the area.

Climate specific analyses were focused at the scale encompassing the UM drainage area (Figure I). Climate data (precipitation and temperature) was a connector among the climate, hydrological and economic components and thus had to be source consistent. Data sources used for this project included ERA5 data, provided at a 30 km x 30 km grid scale, and CMIP6 data from two models, provided at a 100 km x 100 km grid resolution. Since the ACRU hydrological model required daily data, only those CMIP6 outputs in daily time steps could be considered. This narrowed the range and the two models selected were similar, with the wet scenario being only slightly wetter than the dry. These CMIP6 model outputs were not processed through any downscaling techniques. There are significant challenges and limitations in trying to match climatic variables from coarse global products with hydrological models which benefit from finer spatial scale data sets. Details on how this was addressed are discussed in section 8.2.2.

With a focus on integration, the in-depth research into individual components was limited. The focus was on aspects that would enhance integration efforts and improve the reliability of outputs. A combination of desktop modelling and *in situ* data gathering and analysis was used to achieve this.

Hydrological aspects encompassed surface and groundwater models as well as isotopic studies. Given the time constraints, the approach was to build on an existing groundwater model rather than developing one from scratch. In-depth model development was outside the scope of this work, but lessons learnt informed future model development focus areas. The economic model, required to integrate information across the disciplines, was developed from scratch.

The hydrology and economic components required field-data collection that would improve confidence in the project outputs and inform an integrated systems model. Continuous data records obtained from NRF-SAEON's instrument array were complemented with data from quarterly field trips over 18 months to gather supplementary hydrological data for isotopic and groundwater studies. Instrumentation challenges limited the number of vegetation types that could be measured to determine transpiration rates. The impact of an increase in elevated CO_2 on water use efficiency was not factored into transpiration data as this would require extensive experiment data which is not available for the region. A substantial time investment was allocated to the economic component, which involved participatory community engagements and workshops across all three traditional communities, as well as the undertaking of household (HH) surveys and sector interviews. Significant volumes of valuable data were collected for both the hydrological and economic components of the project. However, due to the constraints of brevity, not all gathered data could be included in this report.

Participatory approaches are inherently voluntary, so responses depend on the number of willing participants reached within the available time. The initiation of data gathering was delayed due to COVID lockdown, which led to subsequent impacts on components reliant on this data. The collection of physical data could start before any work that involved participatory approaches, thus placing a limit on the time available for engagement, surveys, and interviews. Climate studies focused on the analysis and characterisation of climate patterns from the past to the present, primarily through the use of global product datasets, which included ERA5 and CMIP6 model outputs.

The historical period assessed spanned from 1959 to 2020, while the future period extended from 2021 to 2050. The rationale for selecting 2050 is that it falls within the lifespan of community members and/or their children. This established a more meaningful timeframe connection to the project content. The economic component only addresses the future period.

This marks the inaugural attempt at a cross-disciplinary integration to evaluate the cumulative impact of present decisions on future outcomes. While substantial data gathering was achieved, the primary goal was to craft an integrated decision support tool through participatory approaches with communities. The project identified challenges and opportunities, and yielded valuable lessons that form a robust foundation for the enhancement of methodologies and generation of recommendations for the NRF-SAEON-EFTEON Social Ecological Systems program. Results will be featured in SARVA, and ongoing refinements, along with additional data gathering, will enhance the capabilities of this pilot initiative over time.

Climate modelling explainer

Greenhouse gas emissions change the energy balance of the earth. Increases in these gases contribute to “global warming”, otherwise known as radiative forcing, which then changes the climate system. Radiative forcing is the imbalance between incoming and outgoing energy in the earth’s climate system. The extent to which the climate will change depends on the future trajectory of greenhouse gas concentrations in the Earth's atmosphere and the associated radiative forcing. Representative Concentration Pathways (RCPs) have been developed to represent different levels of radiative forcing, which are dependent on the trajectory of greenhouse gas emissions. These include RCP2.6, RCP4.5, RCP6.0, and RCP8.5 with each number an indication of the level of radiative forcing estimated by the year 2100. For example, RPC8.5 is a “business as usual approach” where emissions continue to rise over this period, without any attempt to reduce these. Researchers use climate and earth system models to try and project what climate may be experienced in the future. Coupled Model Intercomparison Project Phase 6 (CMIP6) is a collaborative effort among climate modelling centers worldwide to compare and analyse the output from Global Climate Models (GCMs) and Earth system models (ESMs). The participating models in CMIP6 simulate various aspects of the Earth's climate system, and include the atmosphere, oceans, land surface, and sea ice. CMIP6 provides a standardised framework for model comparison and the development of future climate scenarios. The RCPs are used as input scenarios for climate models participating in CMIP6. The climate models use these scenarios to project future climate conditions based on different assumptions about greenhouse gas emissions.

In summary, the combination of RCPs and the climate model simulations from CMIP6 allows researchers to assess a range of possible future climate outcomes, in consideration of different levels of greenhouse gas concentrations and the resultant radiative forcing. Scientists use the output from CMIP6 simulations under different RCPs to understand the potential impacts of future climate change, such as temperature changes, sea level rise, and other climate-related variables

1.5 CAPACITY DEVELOPMENT

1.5.1 List of "Formal" Engagements with Communities

The following community engagement activities, adhering to the NRF-SAEON ethics guidelines, were achieve using this project

- Initial appoints with each TCs at their monthly council meetings to explain the project and seek approval (2021/22)

- Three initial workshops were completed with each of the three TCs. These were used to discuss the project and solicit participation. The level of understanding of climate change was assessed and knowledge gaps filled if required. Challenges within communities were identified and used to guide how the project should be contextualised. Current economic activities were explored. Alternative land use scenarios as identified by the TCs, reflected their choices of what land uses should be modelled. Multiway knowledge exchange and learning was achieved within all these workshops (Attendance registers available on request) (2021/2022).

- Members of the project team assisted the Mabasa TC to arrange and host a World Wetlands Day in February 2022. We were thus able to facilitate the participation of other researchers supported by the WRC, as well as the WRC itself, to particulate in the day. The event was used to provide feedback on working being done in the region by various researcher groups and organizations. Due to COVID the numbers had to be limited. The Mabasa TC Council members attended as well as representatives from the community. In total 52 people participated in the event (Attendance register available on request). Two WRC funded projected were profiled at the event (including this project) and Hlengiwe Cele from the WRC provided information on the broader role the WRC plays in supporting research in the water sector

- Householder surveys were conducted in all three traditional communities over a total period of about eight weeks, which provided an opportunity to reach more members within the community. At the request of TCs, two members from each traditional community area were selected to assisted within the respective traditional community areas with the surveys, which created short term local employment for six community members. They were briefed on survey techniques and learned more about the project as well as climate change risks to the area.

- Following the TC workshops, it became apparent that climate literacy was low. A brief double-sided pamphlet was developed with specific reference to the region. This was translated into Zulu and is being shared with household during HH surveys and anyone interested (Appendix S)

- A World Wetlands Day event took place on the 02 February 2023 at the Mabaso TC offices. The day involved multiple interactive activities, which included facilitating cross generational learning, and was well received.

- One knowledge exchange was achieved and is reported on in this deliverable (November 2023).

- Three feedback workshops were held in November 2023 with the three TCs to provide feedback and preliminary results. Outcomes are reported on in this deliverable

1.5.2 Student and Young Scientist Capacity Development

- Two students funded by the project graduated with MSc degrees in hydrology through the University of KwaZulu-Natural Centre for Water Resources Research; Thobeka Nsimande and Mkholo Maseko

- Mkholo Maseko was mentored on groundwater modelling using MODFLOW by Professor Bruce Kelbe

- MSc graduate, Sulinkhundla Maseko was mentored by Prof. James Blignaut on economic modelling using Vensim software

1.6 KNOWLEDGE DISSEMINATION

The following presentations were delivered:

- Thobeka Nsibande: Rainfall-groundwater relation, groundwater-surface water relation, and groundwater dynamics in the Maputaland Coastal Plain. Proposals presentation to UKZN university committee, December 2021

- Mkholo Maseko: Isotope Use in Plant Water Source Partitioning for Groundwater Modelling Under Climate Change in Lake Sibaya. Proposals presentation to UKZN university committee, December 2021

- Susan Janse Van Rensburg, NRF-SAEON activities report back. DWS KZN Integrated Regional Water Monitoring Committee, 26 May 2021

- Susan Janse Van Rensburg: Relative impacts of climate and land use on South Africa’s largest lake; Lake Sibaya. Closing the loop between Science and Action Great Lake Marathon, 21 November 2021

- Siphiwe Mfeka: Understanding the relative impacts of climate and land use on the water resources (and economy) of Lake Sibaya region. Mabasa World Wetlands Day, 11 February 2022.

- Susan Janse van Rensburg, on behalf of the project team profiled the project in an oral presentation at the 2022 Wetlands Indaba (24-28 October) entitled “Aiming for societal impact through engaged research and interdisciplinary integration in the Maputaland Coastal Plain wetland system”

- Susan Janse van Rensburg: Online Presentation. Wicked problems in the Maputaland Coastal Plain: A case for using Social ecological systems approaches and the need for transdisciplinary integration. NRF-SAEON Seminar; 7th October 2022

- Thobeka Nsibande: Poster presentation: Rainfall Groundwater Recharge Relationship, Groundwater Surface Relationship, and Groundwater Dynamics in Maputaland Coastal Plain. South African Hydrology Society conference 10-12 October 2022 Appendix

- Mkholo Maseko: Poster presentation: Groundwater modelling of Lake Sibaya under various landcover and climate scenarios advised by plant water source partitioning using isotopes. South African Hydrology Society conference 10-12 October 2022 Appendix

- Thobeka Nsibande, Groundwater Recharge Mechanism, Groundwater-Surface Water Connection and Groundwater Dynamics in the Maputaland Coastal Plain. NGCC, 31 Jan-3 Feb 2023

- Mkholo Maseko: Dynamic Groundwater Modelling of Lake Sibaya With A Perspective on Plant Water Source Partitioning Using Isotopes, NGCC, 31 Jan-3 Feb 2023

- UCT PhD student (Wanjiru Thoithi) gave a talk on the April 22 KZN floods at the South African Society for Atmospheric Sciences annual conference held last year at Wits (31/10-1/11). It was based on earlier results from the floods paper recently published

- Mkholo Maseko: Using New Data in Previously Developed Groundwater Models – Does it work? NRF-SAEON Seminar Series, 2023

- Mkholo Maseko Modelling the Groundwater System off Lake Sibaya – A Way to See the Invisible National Youth Indaba (June 2023)

- Janse van Rensburg S., et al. Madness or necessity? Attempting co-production of a decision support tool by integrating climate, land use, hydrology, and economics, guided by the aspirations of local communities. WCRP OSC 2023 (poster) 23-27 October.

- Maseko MHT et al, Dynamic Groundwater Modelling of Lake Sibaya. IAS 10-22 2023 September Cape Town

Papers published

- Mpungose, N., W. Thoithi, R. Blamey, and C. Reason. 2022. Extreme rainfall events in south-eastern Africa during the summer. Theoretical and Applied Climatology 150:185-201.

- Thoithi, W., Blamey, R.C. and Reason, C.J., 2023. April 2022 Floods over East Coast South Africa: Interactions between a Mesoscale Convective System and a Coastal Meso-Low. Atmosphere, 14(1), p.78.

- Mawren, D., R. Blamey, J. Hermes, and C.J.C. Reason, 2022: On the importance of the Mozambique Channel for the climate of south-eastern Africa. Climate Dyn., doi.org/10.1007/s00382-022-06334-w

1.7 STRUCTURE OF THE REPORT

The report structured as follows

- Chapter 1 Background
- Chapter 2 Study area description
- Chapter 3 Integrated modelling framework
- Chapter 4 Land Use Land Cover Change, current economic agents, and plausible future land use scenarios
- Chapter 5 Regional climate processes and plausible future climate scenarios.
- Chapter 6 Approach to advancing hydrological studies
- Chapter 7 Isotope hydrological study
- Chapter 8 Modelling the recharge using the ACRU model
- Chapter 9 Modelling hydrological outcomes using the MODFLOW groundwater model
- Chapter 10 Relative impacts of future land use-climate storylines on hydrological outcomes: implications for the systems model
- Chapter 11 Systems model: economic outcomes of future land use-climate storylines.
- Chapter 12 Summary framework
- Chapter 13 Outcomes from co-generative approaches and engagement
- Chapter 14 Synthesis discussion, recommendations, and conclusions

CHAPTER 2: STUDY AREA DESCRIPTION

By S Janse van Rensburg, S. Maseko and MH Maseko

2.1 OVERVIEW

The study area falls within the Indian Ocean Coastal Belt Biome (IOCBB) and the "Maputaland-Pondoland-Albany hotspot", considered to be one of Africa's most important biodiversity hotspots and centres of endemism (Van Wyk et al., 2001, Mucina et al., 2006, Smith et al., 2008, Dayaram et al., 2019) (Figure 2-1). Administratively it falls within the ULM (Figure 2-2) which is part of the uMkhanyakude District Municipality (UKDM).

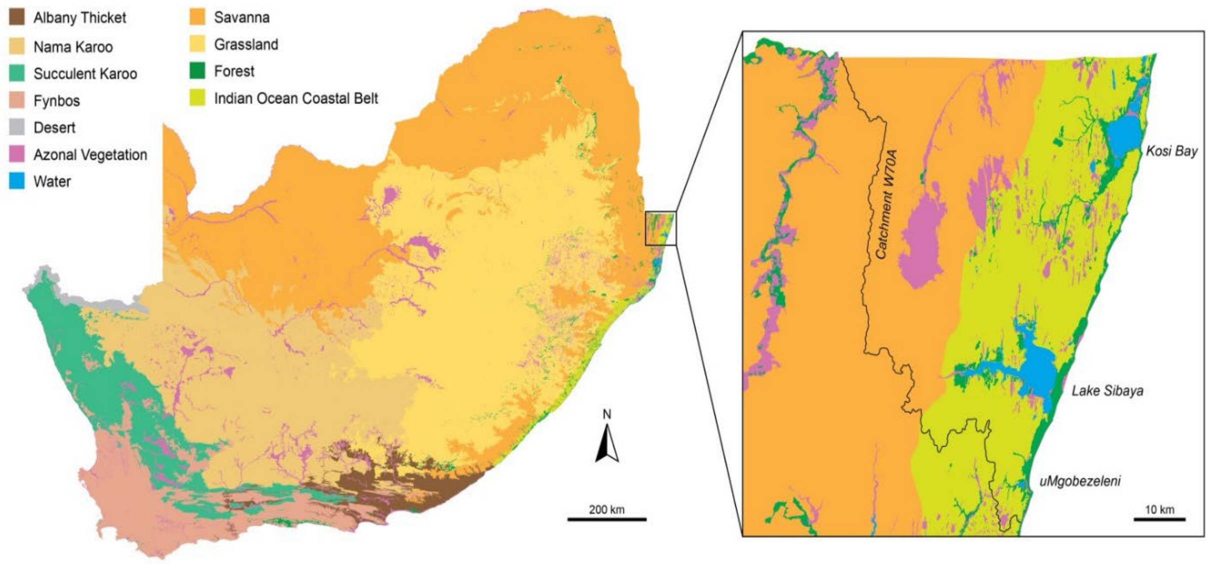


Figure 2-1 Location of study area relative to South Africa showing the biome distribution in South Africa following the National Vegetation Map 2012. Inset shows the biomes in the r the broader study region. Quaternary catchment W70A is delineated by the black line

Significant uses include protected areas (Figure 2-2), commercial plantation forestry, natural resources areas outside of protected areas (indigenous forests, wetlands, and grasslands), settlements, and cultivation. All areas outside of the protected area network fall under the Ingonyama Trust Board (ITB) (Figure 2-2) and are thus managed through traditional structures. The land adjacent to Lake Sibaya is administered by three TCs: Tembe is on the northern side of Lake Sibaya; with Mabasa to the west; and Mbila/Zikhali to the south and east (Figure 2-2).

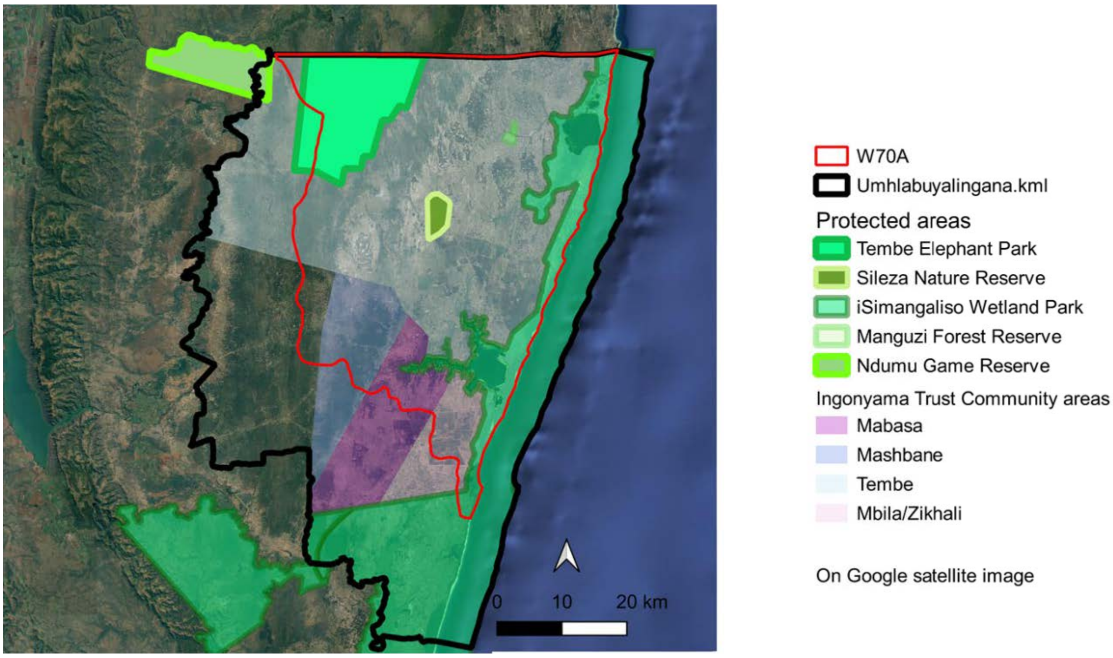


Figure 2-2 Map of the study region showing the boundary of the ULM (black line) in relation to quaternary catchment W70A, As well as the protected areas and the community areas within the ULM

Lake Sibaya itself is within the iSimangaliso Wetland Park (Figure 2-2) and thus under its authority. The Lake Sibaya groundwater catchment (recharge zone) (Figure 2-3) is essentially a proxy for the larger quaternary catchment W70A, where changes in the Lake Sibaya water level provide an indication of the groundwater status, particularly of the coastal groundwater recharge areas within quaternary catchment W70A (Figure 2-3). Within community areas (Figure 2-2), there are designated areas for cattle grazing, natural resource use and homesteads managed by the TCs. There is increasingly rapid densification of homesteads, road infrastructure and fencing within the rural areas from a near-natural baseline.

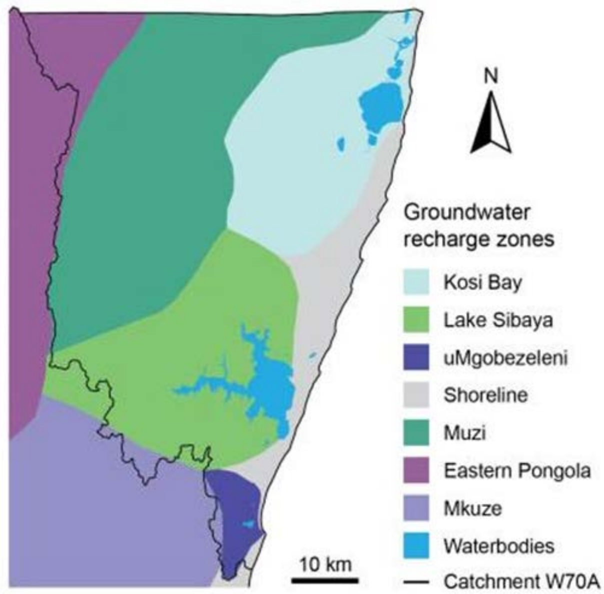


Figure 2-3 Estimated Groundwater recharge zones dictating localised groundwater catchment boundaries (Kelbe, 2020, taken from MCP EFTEON proposal)

2.2 BIOPHYSICAL CHARACTERISTICS

Quaternary catchment W70A forms part of the nationally important Zululand Coastal Plain groundwater Strategic Water Source Area (SWSA) (Le Maitre et al., 2018). This alluvial aquifer is considered to be among the largest unconsolidated aquifers in the country (Meyer et al., 2001, Meyer and Godfrey, 2003). It is a functionally interconnected aquifer that resulted in a unique geological and evolutionary history. It includes the Kosi Lakes, Lake Sibaya and Mgobolzeleni systems (see Figure 2-2 and Figure 2-3). These systems have interconnected yet distinguishable groundwater catchment recharge zones at local scales that shift depending on the level of the groundwater table (Bate et al., 2016, Kelbe, 2020). Of all the freshwater lakes in South Africa, the largest is Lake Sibaya (Kelbe and Germishuyse, 2010; Smithers et al., 2017). It is approximately 20 m above mean sea level (a.m.s.l.) when "full" with a maximum depth of 40 m.

The region is relatively flat, as indicated in the local municipality name, Umhlabuyalingana, which means "the flat place". There is a close relationship between the groundwater and surface water in the Lake Sibaya catchment due to the shallow water table, flat topography, and the catchments sandy substrate. Most landscape features are thus aquifer-dependent ecosystems (Taylor et al., 2006, Colvin et al., 2007, Botha, 2015). The highest area in the region is the coastal dune cordon which reaches approximately 170 m AMSL. The predominantly sandy substrate of the region renders soils nutrient-poor with low agricultural potential.

The western arm of Lake Sibaya is fed by the Mseleni "River", the northern arm is fed by the Velindlovu and KuMzingwane "streams". The western arms northern portion is fed by the Umsilalane stream and the southern portion is fed by the Iswati and Umtibalu streams (Smithers et al., 2017). All of these "rivers" and "streams", however, can be considered as groundwater discharge zones. These discharge streams depend on rainfall and groundwater levels within the Lake Sibaya catchment (Weitz, 2016, Smithers et al., 2017). Groundwater inflow largely maintains the lake water levels due to a limited amount of surface runoff related to the sandy substrate's high permeability that results in the occurrence of rapid infiltration (Bate, 2016).

Rainfall infiltrates the sandy system, with little overland flow, percolating vertically downwards to recharge the groundwater table (Weitz, 2016). Groundwater flows from the recharge areas down the groundwater gradient towards the discharge boundaries, such as the wetland and lake systems, which intersect the groundwater table.

Several geological and hydrogeological investigations have contributed to improved knowledge of the stratigraphy and history of the region and the land-lake-sea interface (Watkeys et al., 1993, Miller, 1998, Whyte, 1999, Wright et al., 2000, Meyer et al., 2001, Meyer and Godfrey, 2003, Botha and Porat, 2007, Porat and Botha, 2008, Barath, 2015, Botha, 2015, 2018). The various hydro stratigraphic and associated hydrogeological units relevant to Lake Sibaya's water system are covered in detail in these studies. A summary based on Botha (2018) is provided in Figure 2-4.

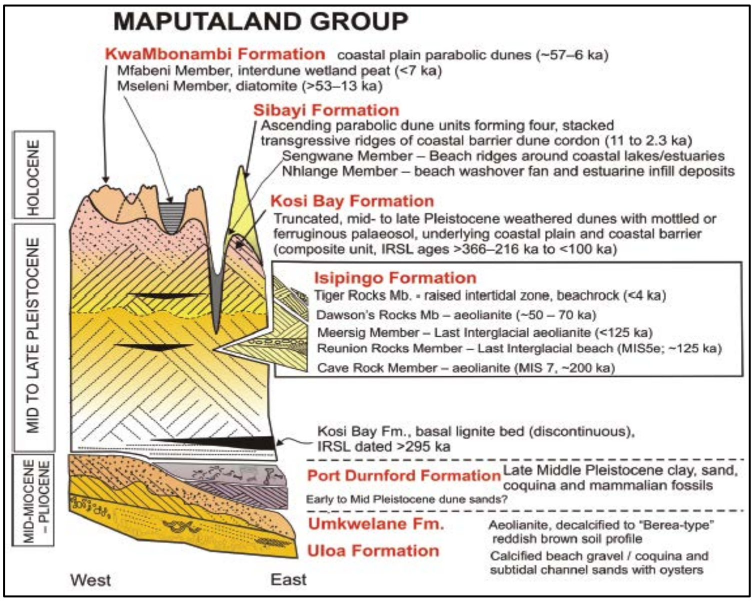


Figure 2-4: Schematic diagram indicating the formations and their relationship with units from the Maputaland Group (Botha, 2018).

The formations described in Figure 2-4 overlie the cretaceous bedrock rock which serves as an aquiclude that enables aquifers to develop in the formations above. Given that these are differentiated on the basis of their silt, sand and clay content (Kelbe et al., 2013), each has different hydraulic characteristics which have been summarised by Weitz (2016) from various sources pertinent to the Lake Sibaya area (Table 2-1).

Table 2-1: Various aquifer formations and their hydraulic characteristics within the proposed study area (Weitz, 2016) where K =Hydrologic Conductivity and T = Transmissivity

Aquifer name	Thickness (m)	K (m/d)	T (m^2/day)	Borehole yields (l/s)
Sibaya and KwaMbonambi Formation	20-30*	0.87-15.6 (mean: ~5)	1 490	0.5-5
Kosi Bay/Port Durnfort Formation	15-20*	4-5 (mean: 4.3)	-	2-10
Uloa/Umkwelane Formation	5-20	0.5-25 (mean: 4.5)	116	5-25
St Lucia Formation	900	-	-	<1

Rough approximations are used for the thickness of the different formations as indicated by *, due to the complex relationship between the Kosi Bay and KwaMbonambi formations.

Brief geological history

The primary aquifer consists of variably weathered deep sands that overlie the impermeable cretaceous layer (Botha, 2015). Some of the deeper sands have experienced marine transgression "wash-overs", that caused deposition such as the Port Dunford formation, which is thought to have been deposited at the last marine high stand about 120 000 BP (Miller, 1998). Planation is evident which coincides with marine regressions (sea level drops), the latest of which was at the Last Glacial Maximum, and lasted from 120 000 BP until about 18 000 BP with sea levels dropping to -130 m. The aeolian Kosi Bay formation is thought to have accumulated on top of the Port Dunford between about 100 000 to 45 000 BP. The more recent KwaMbonambi formation (typified by redistributed aeolian sands) accumulated on top of the Kosi formation during a wet period which saw the development of wetlands and lakes in the region (approximately 43 500 to 25 000 BP) with evidence of a large proto Lake Sibaya around 43 000 BP. This breached the coastal dune barrier between 24 000-18 000 BP (when sea levels were -130 m), which eroded some of these older layers away, and scoured the basin more than 40 m below m.s.l. (Miller, 1998). Subsequently in the Holocene, with the stabilisation of sea levels, lagoon conditions arose, which brought in marine sediments and significant aeolian deposits (15-20 m thick). There is also evidence of significantly reworked younger sediments. The coastal barrier re-stabilised around 5 610 BP to 5 030 BP and Lake Sibaya slowly started to fill with a slow transition from saline to fresh water conditions (Miller, 1998). Within the last 5 000 years the coastal dune barrier has accumulated sediment, which elevated the dunes from a shallow sand bare to dunes over 166 m a.m.s.l. Lake Sibaya itself is considered relatively stable, with little input of water or sediment from beyond the catchment boundary (Miller, 1998).

2.3 CLIMATE

Quaternary catchment W70A is located within the tropical to subtropical climate transition zone of South Africa, within a climate-sensitive region strongly influenced by regional oceanic and remote forcing (Mpungose et al., 2022). The region experiences a predominantly summer rainfall regime. The most important rain-producing weather systems for the region are cloud bands (or tropical-temperate troughs (TTTs)) (Hart et al., 2010, 2013), tropical lows (and occasionally tropical cyclones), cut-off lows (Singleton and Reason, 2007), ridging anticyclones and mesoscale convective systems (Blamey and Reason, 2009, 2013). Regional circulation systems, such as the South Indian Ocean High; the Mozambique Channel Trough; the Angola Low; the mid-level Botswana High; and the South Atlantic High are likely to influence the tracks, frequency, and intensity of these systems. In turn, large scale climate models, such as the El Niño-Southern Oscillation (ENSO); the Southern Annular Mode (SAM); the Indian Ocean Dipole (IOD); and the Subtropical Indian Ocean Dipole (SIOD) will also influence these systems as will long-term climate change (Reason et al., 2000; Washington and Preston, 2006; Morioka et al., 2010; Malherbe et al., 2016). However, the impacts of variability in these circulation patterns and weather systems over the region, e.g. in terms of precipitation available for groundwater recharge, have not been well quantified.

Paleo evidence indicates that the MCP is susceptible to extreme variations in precipitation (Neumann et al., 2008, Stager et al., 2013, Botha, 2015, Humphries et al., 2019). Due to its sandy nature, it may be particularly vulnerable to climate change given the nature of geomorphological processes that may emerge under increasing aridity (e.g. wide erosion causing coastal dune blowouts) (Botha, 2015).

There is a gradient in the mean annual precipitation (MAP) from east to west with the coastal areas receiving approximately 950-1 000 mm/yr while the western margin, part of Lake Sibaya's groundwater catchment, receives 700 mm/yr (Pitman and Hutchison, 1975, Weitz and Demlie, 2015). Peak potential evaporation rates are in the summer months (DWA, 2014; Smithers et al., 2017) with

A-pan potential evaporation rates for the catchment that range from 1 800 mm/yr to 2 000 mm/yr (Middleton and Bailey, 2009). Weitz (2016), using the Food and Agriculture Organization (FAO) Penman Monteith method estimated the catchment ET to be 1 090 mm/yr. One of the most difficult components of the water balance to quantify is the evaporation over Lake Sibaya. Using the Penman Combination Method Weitz (2016) estimated the mean annual evaporation rate for Lake Sibaya to be 1 495 mm/yr using land-based climatological variables.

2.4 BIODIVERSITY VALUE: A DIVERSE NATURAL LANDSCAPE TEMPLATE, RICH IN WETLANDS

Aitken and Gale (1921) conducted the first botanical survey, and noted that the region was "*unoccupied by white settlers*," except for the Mseleni Mission Station. The area was rich in wetlands with lakes and lagoons, and they observed how a slight terrain drop led to numerous vleis and bogs, especially towards the coast (Aitken and Gale, 1921). Their descriptions revealed a landscape with a high-water table and an abundant groundwater resource.

The dominant land cover was sand veld consisting of **open grasslands** dotted with "ilala" palm, relatively absent of tree forms other than scattered tree clumps which were more common towards the coast (Aitken and Gale, 1921). They noted a diverse herbaceous flora, rich with bulbs, corms, tubers and "*other such like storage organs*" (Aitken and Gale, 1921). Thicker bush was noted along streams like the Mseleni. The "Manguzi Bush" and the forest around the southern end of Kosi Lake were the only two true forests noted (Aitken and Gale, 1921).

Tinley and Van Riet (1981) synthesised all available information for the region and included maps of vegetation and major ecosystems. Their results provide an indication of a more wooded landscape compared to the early 1900s. This trend in increased woody vegetation is evident when aerial photographs from 1942 to 1957 are compared (Figure 2-5). By 2003 this is even more evident (Figure 2-5).

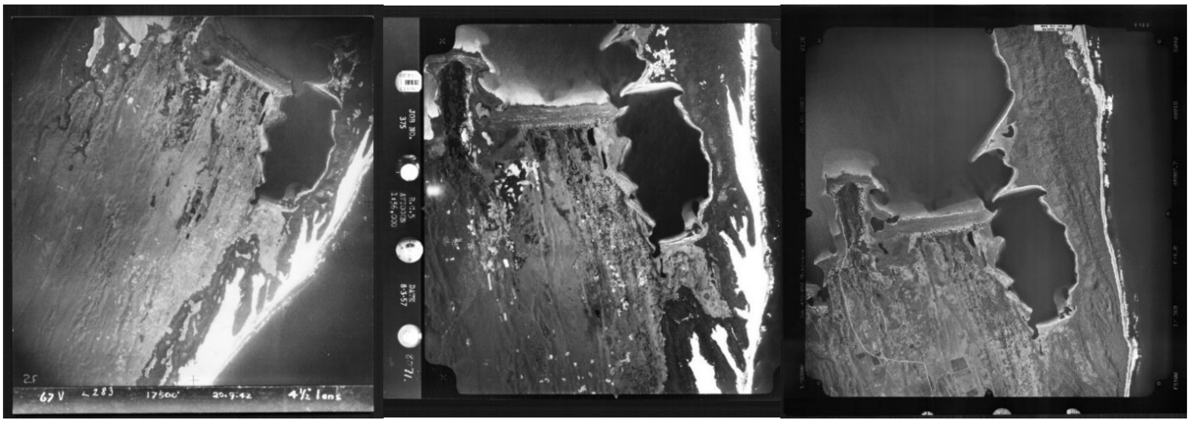


Figure 2-5 Aerial photographs of Lake Sibaya's south basin and vegetation characteristics compared between 1942 (left), 1957 (middle) and 2003 (right)

Terrestrial diversity is extremely rich with >2500 vascular plant species (Moll, 1980, Van Wyk and Smith, 2001) which occur in a mosaic of ecosystems and ecological zones. In addition to the diverse template of terrestrial ecosystems (grassland, thicket, and forest) there are many types of aquatic communities, with an exceptional diversity of wetlands (Kramer, 2003, Grundling et al., 2013a, 2018, Grundling, 2014, Gabriel et al., 2018). Notably, the region is one of the richest areas with respect to wetlands in the country. Peatlands (wetlands containing accumulated deposits of organic matter) are locally common on the MCP, and account for 60% of all South Africa's peat resources (Grundling et al., 2016).

The region's diversity is attributed, in part, to the fact that it is a transition zone between the tropics and the subtropics, which reflects a mixing point of biota from the subtropical, the temperate south and west, and the tropical north (Aitken and Gale, 1921, Lawrence, 1947, Bruton and Cooper, 1980, Perera et al., 2021). The region's status is of international conservation significance, as indicated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) world heritage status of the iSimangaliso World Heritage Park (IWHP) and boasts several RAMSAR sites, which include Kosi Bay, Lake Sibaya and the Pondoland Coast turtle beaches.

This diverse template provides a range of ecosystem services that includes regulating functions, food security, water, and livelihood benefits as well as economic opportunities. The subtropical grasslands that typify the region provide livestock forage and habitat for wild game. *Hyphaene coriacea* (the Lala Palm) is a classic feature of these grasslands and has been used for centuries to make wine which is an important source of vitamin C and nicotinic acid (Moll, 1972, Cunningham, 1985). The region is particularly rich in edible plant species where Cunningham (1985) recorded over 100 such species. Many plant species are also used for building material, fibre and crafts (Cunningham, 1985). The wetland habitats, provide essential services such as water storage and retention during drought periods, and carbon sequestration and carbon storage (Grundling et al., 2018). They are also used extensively for the harvesting of reeds (Cunningham, 1985) and farming (Grundling et al., 2013b, Atkinson and Barichievy, 2014).

Outside of wetlands, the soils are generally poor with limited agricultural potential. The access to fish and shell fish resources, wetlands with better soils near the coast, as well as the fresh water provided by the lakes and wetlands in these areas, were major determining factors of early settlement patterns from at least 1 600 BP (Hall et al., 1978).

In summary, the natural ecosystems provide a range of livelihood and potential economic benefits to the region and thus natural ecosystems and their associated services and resources, are important to consider in economic valuations.

2.5 SOCIO-ECONOMIC CHARACTERISTICS

The socioeconomic status of the study area is poor (Hazell, 2010, ULM, 2021). Of the four local municipalities within the UKDM, ULM is the poorest, with 44.9% of households having no source of income and a high dependence on social grants (ULM, 2021). The region is predominantly rural. High levels of unemployment, limited economic opportunities, poor infrastructure development and low literacy levels, which characterise the region, translate to low adaptive capacity in the face of climate change (Fairer-Wessels, 2017, Pörtner et al., 2023).

The current pattern of LULC in the study area are, to some extent, a relic of a somewhat complex history of the region addressed by various authors (Boteler 1835, Bruton et al., 1980, Carruthers, 1988, Mountain, 1990, Mthethwa, 2002, Kloppers, 2003, Van Rooyen, 2006, Mathebula, 2017). Historically, people in the region depended on natural resources and agricultural production. By the 1950s polices influenced LULC change in the region, including the expansion of protected areas, the introduction of forestry and the development of human settlements (Mthethwa, 2002, Van Wyk, 2003). These changes were meant to foster economic development in the region through employment opportunities, agricultural commodities and craft sales (Hearne and McKenzie, 2000). To promote economic development through land use change, it should be undertaken in a manner that benefits the various land users in communities. However, some people in the area were forced out of their lands and, according to Van Wyk (2003), these removals have adversely impacted the progress of development strategies in the MCP.

Natural resource use, dryland and wetland cultivation and livestock grazing are considered as important activities that contribute to livelihoods within the study area. Commercial plantation forestry and ecotourism/conservation are two important sector-based activities. Detailed assessments of the relative contributions from livelihoods and sector-based activities to the local economy is currently lacking. The general understanding of LULC within the study area in relation to associated economics activities is touched upon.

2.5.1 Settlements (Households and towns)

Historically, the area was infamously fever ridden (Owen 1833, Theron et al., 1975) due to the prevalence of various diseases including sleeping sickness, African trypanosomiasis (*Trypanosoma brucei*), from the tsetse flies which affected both humans and livestock, as well as malaria (*Plasmodium falciparum*). This likely deterred settlement. Population density in the early 1900s was thus relatively low (Aitken and Gale 1921, Bruton et al., 1980).

Tsetse and malaria control programs in the early 1900s led to an increase in settlement around Ingwavuma the Pongola flood plain and to some extent around the Kosi lake systems (Tinley and Van Riet, 1981). However, the area around Lake Sibaya, which had been proclaimed for rural development in 1936, remained “largely unspoilt”. By 1970 there were only 631 huts and 1 451 people within 5 km of Lake Sibaya (Appleton and Bruton, 1979).

Since the 1970s the ULM population within the MCP has grown, which has resulted in the expansion of settlements and emergence of small urban centres such as Mbazwana and Mseleni. Higher densities of human settlements are situated closer to these towns and along roads. Between 2001 and 2016 the number of households in the region increased from 26 324 to 39 614 (Statistics South Africa, 2011). Aggregated to the whole of the ULM, population figures have gone from 142 565 in 2001 to 156 736 in 2011 and 172 077 in 2016 with an 8.9% growth rate (ULM annual report 2021). Public infrastructure such as public health services (clinics or hospitals), schools and retail shops has increased, which has fostered some degree of socioeconomic development and employment.

2.5.2 Dryland Cultivation

While cultivation is a livelihood source for communities in the ULM, the extent and scale of this is small compared to other rural areas in South Africa, e.g. Eastern Cape (Taylor, 1988). This is due to the sandy nutrient poor soils in the ULM, especially the coastal areas within which the Lake Sibaya groundwater catchment is situated, which have low agricultural potential for most traditionally grown crops, (Mountain, 1990). The main dryland crops in the area include groundnuts, maize, and cassava. As with many rural settings, this cultivation is mainly practiced in small plots within household boundaries and under rainfed production (Jury et al., 2008). Some households sell crop produce to generate income. Damage by livestock, that destroy agricultural produce, is a challenge for these farmers (ULM 2021). While dryland cultivation is an important source of food and periodic income, due to the small-scale nature of production, employment in the sector is thought to be low.

2.5.3 Natural Resource Areas

The study area, was originally an expansive grassland, much of which has been transformed into commercial forestry plantations. The region also supports indigenous forest and wetlands. Collectively the grasslands, wetlands and forests provide a diversity of natural resources from which communities garner livelihoods.

2.5.3.1 Livestock

Households keep cattle and goats. They are often kept for traditional purposes – in Zulu tradition, cattle are a sign of wealth according to the old Zulu saying "Ubuhle bendoda zinkomo zayo". Livestock are a source of food and income. While some people are attempting commercialise cattle farming, access to markets is hindering optimal gains (Fairer-Wessels, 2017). The potential for commercial livestock farming in the area has not been fully explored.

Lake Sibaya has become the main water source for livestock, due to the degradation of surrounding small water bodies. Livestock need to cover long distances in search of water sources and, as a result, some households leave their livestock in the wild for an extended period and closer to water points or around the lake.

2.5.3.2 Natural resources use

The region's biodiversity provides an array of opportunities to support livelihoods. Dependence on these has historically been high (Cunningham, 1985, Hazell, 2010). Indigenous plants provide medicine, craft material, food, fibre, building materials and traditional beverages (Cunningham, 1985). A number of these products have commercial value such as palm wine (Cunningham, 1990) which contributes to livelihoods and could potentially increase economic income if commercialised (Martins and Shackleton, 2018).

According to de Wet et al. (2010) there are 23 different species of medicinal plants in the area, of which three are exotic. Historically these would have been used within communities. However, this has become a commercial trade and it is suspected that there is a high export of medicinal plants to other parts of South Africa. While there is evidence of extensive harvesting of medicinal plants, particularly noticeable in indigenous forests (pers. obs.), the ecological and economic impacts of this have not been quantified in recent years.

Reeds, such as *Phragmites australis* also provide economic benefits both through direct income from crafts as well as cost savings when used as an alternative to expensive "Western" building materials (Tarr, 2007). A common craft material from the grasslands comes from the Lala palm tree, which is used to make baskets and sold both locally as well as to tourists visiting the area. The Lala Palm grows across the grasslands is also used by households as means to generate income by sapping to make Lala wine (Cunningham, 1985, 1990). Marula trees are also found scattered within grasslands and forest areas, and the fruit is used to make traditional beverages (part of the Zulu tradition in the area).

2.5.3.3 Wetland cultivation

The only fertile soils found in the area are those associated with wetlands, especially those containing peat (Atkinson and Barichievy, 2014). Consequently, wetland farming is used for the cultivation of crops such as bananas, taro (amadumbe) and sweet potato which are normally dryland crops in other areas. Wetland farming provides households with high-value produce which is otherwise difficult to cultivate on dryland.

Wetland farming is a much more intensive activity and risky compared to dryland cultivation because of animals that inhabit the wetlands such as snakes. More wetland areas are being converted to cultivated areas over time, which demonstrates the value of these habitats for livelihoods and food production (Grundling et al., 2013a). However, some of these nutrient rich aquatic systems, such as swamp forest, are critically endangered, and have been over exploited (Atkinson and Barichievy, 2014). Others, which used to be wet, have dried up and are no longer useable.

2.5.4 Protected Areas and Ecotourism

Owing to its rich biodiversity, the protected area network in the region is significant and diverse. It includes the Tembe Elephant National Park (30 000 ha) located in the North along the Mozambican border; Manguzi Nature reserve (237 ha); Sileza Nature Reserve (2 124 ha); and ISimangaliso Wetland Park (332 000 ha) (Figure 2-2). This network incorporates reserves that are home to the “big five” as well stunning coastal beach and coral systems, forest, savanna, and grassland ecosystems. By all accounts, these should realise significant benefits to local communities, however several studies have indicated that beneficiation is sub-optimal (Jones, 2007, Fairer-Wessels, 2017). There are opportunities to improve local livelihoods through tourism (Mograbi and Rogerson, 2007).

The coastal protected areas border the Mbila/Zikhali and Tembe tribal areas. The protected coastal area is rich in biodiversity with coastal and swamp forests that provide habitat for rare and endangered species such as the Samango monkey and Pels fishing owl (IWP, 2019). The indigenous forest and “big five” game reserves are found in the Tembe area whilst the Mabasa area has no protected areas. Conservation agencies are thought to provide a reasonable number of employment opportunities.

The rich biodiversity and pristine landscape have attracted ecotourism investments over the years. Ecotourism is perceived to have the potential to promote equitable development in communities in the MCP (Fairer-Wessels, 2017). This is through the creation of job opportunities; markets of local goods; and conservation of environmental resources. Ecotourism infrastructure in the area is primarily focused around Sodwana Bay, Kosi Bay and Tembe Elephant Park. It includes accommodation (resorts, lodges, and campsites), and restaurants. Recreational activities include beach visits, fishing, and diving. Research has shown that, to fully maximise the economic potential of ecotourism, stakeholder participation with hosting communities is important (Jury et al., 2009, Aucamp, 2019).

2.5.5 Macadamia

Over the past few years, macadamia has received more attention from farmers as a high-value crop. In the ULM, small macadamia trial plots have been established with mixed success and cultivated as individual trees in some households. The perceived long-term benefits (returns) of macadamia make it attractive, however, it requires high capital investment and good management (ULM, 2019) and its impact on the groundwater is not well understood.

2.5.6 Commercial Plantation Forestry

In 1938, 1 000 exotic eucalyptus trees and a few dozen pine trees were planted by the Mseleni Mission Station with the rationale that, while indigenous trees were available in the landscape, there was a high likelihood that what was available would soon be “exhausted” (Theron et al., 1975). Up to a dozen gum trees were also planted at each of the many “out-stations” in the area and these could evidently still be seen as land marks as late as the 1970s (Theron et al., 1975).

Extensive afforestation programs started around Lake Sibaya in 1958 by the then Department of Forestry (Marwick, 1973). By the late 1970s these consisted of two forest stations: Manzengwenya, north of Lake Sibaya (which drew water for operations from a well near Vazi Pan (Bruton, 1979a)), and one in the south at Mbazwana. By the 1970s approximately 70 km^2 of the catchment area of Lake Sibaya was covered in pine and eucalyptus plantations and was the largest extent of modified land use on the terrestrial system (Allanson, 1979).

The intention to “hand over” these state-run forestry operations to locally owned forestry companies was first officially muted in 2007 in an address to the KZN legislature on the 8th of November 2007. Subsequently, the communities around Lake Sibaya formed the Tembe-Mbila-Mabasa Trust (TMM

Trust) with the intention to take over the management of the Manzengwenya-Mbazwana plantations. The details are contained in SA Forestry Online, in an article that headline this initiative as "SA's biggest land reform forestry project" on 18th December 2012, and detailed the role of Sappi and Mondi, as commercial plantation forestry industries, in activity promoting small growers in the region.

Following these announcements, there was rapid expansion of commercial eucalyptus plantations, particularly north of Lake Sibaya, as illustrated by (Ramjeawon et al., 2020). The extent of plantations doubled between 1986 and 2019 to over 40 000 ha, with the most dramatic increases being in the last decade (Ramjeawon et al., 2020).

Concerns have been raised with regard to the governance of such forest initiatives in ITB land and include specific reference to the Manzengwenya-Mbazwana plantations (Clarke, 2018). These include, but are not limited to, lack or pro-poor tenure reform; risk of capture of the industry by local elites; lack of information regarding on the assets; numbers, statistics, and governance issues relating to small growers; threats to development resulting from leadership conflicts; and confusion over the role of traditional leaderships and their status relative to that of the local Government.

Commercial plantation forestry is a declared stream flow reduction activity in the National Water Act (1998) and several hydrological studies have demonstrated that afforestation does negatively impact on the groundwater resource of the region (Weitz and Demlie, 2014, Bate et al., 2016, Smithers et al., 2017). While it is reasonable for residents to view commercial eucalyptus plantations as a crucial and economically viable land use, the key question is whether the rapid expansion of these plantations has fulfilled the intended promise of equitable economic development. This is especially pertinent given the well-documented negative impacts on regional water security. A key question of interest was what the direct impact on livelihoods from other displaced land uses and the indirect effects on water-dependent livelihoods, mediated by changes in the groundwater resource are.

2.6 STUDY AREA SPATIAL SCOPE

The UM drainage area, designated "W" by the Department of Water Affairs and Sanitation (DWS), provided the appropriate scale to assess climate processes for the study. The hydrological modelling domain (Figure 2-6) included the both the internal and external drainage boundaries associated with the estimated (Kelbe, 2020) Lake Sibaya groundwater catchment area (light blue line in Figure 2-7), thus incorporating the potential impacts of surrounding areas. The external boundaries of the hydrological model domain (Figure 2-6) were defined by the ocean to the far right (east), the Pongola River on the left (west), the Mkuze River to the south, and the Maputo River and Kosi Bay to the north. The model domain thus incorporated the majority of quaternary catchment W70A and extended to the western edge of the ULM (Figure 2-6).

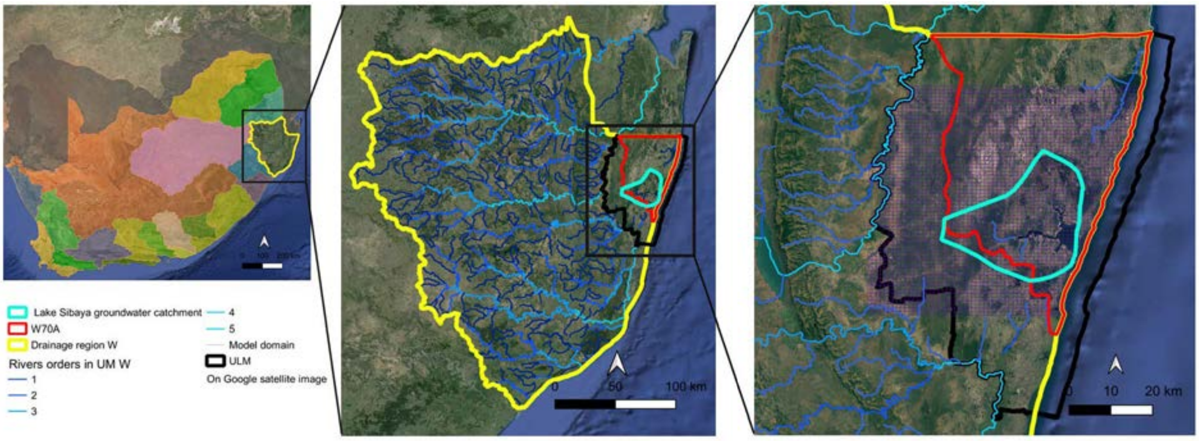


Figure 2-6 The location of UM catchment area (outlined in yellow) covered by the climate analysis for study. The extent hydrological modelling domain (purple grid) incorporated most of quaternary catchment W70A (red boundary) and extended to the western edge of the ULM (black boundary) with the estimated Lake Sibaya groundwater catchment area in light blue

The Lake Sibaya groundwater catchment (light blue line in Figure 2-7), which depends on local rainfall for recharge, formed the focal groundwater response area of the hydrological component of the study, serving as a proxy for quaternary catchment W70A. The peach boundary (Figure 2-7) indicates the area within which the alterative future LULC change scenarios were tested. The thick orange line in Figure 2-7 denotes the area extent for the HH surveys, most of which were, however, focused within the Lake Sibaya groundwater catchment area and covered three community areas adjacent to Lake Sibaya (Figure 2-7). The three community areas within the Lake Sibaya groundwater catchment that were included in the study were, Mbila/Zikhali to the south; Mabasa to the west; and Tembe to the north (Figure 2-7).

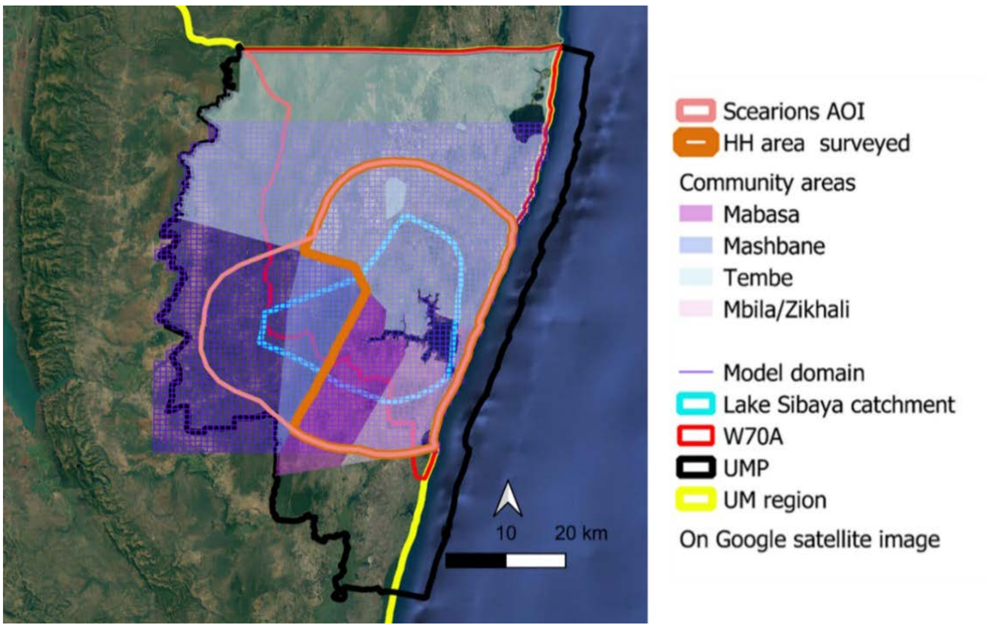


Figure 2-7 Map of the study region showing the various spatial extents of different components of the hydrological and economic components as all as the boundaries of the traditional community areas.

CHAPTER 3: INTEGRATED MODELLING FRAMEWORK

By: S Janse van Rensburg, Ross Blamey, James Blignaut, Nokwanda Gule, Seifu Kebede, Bruce Kelbe, Mkholo Maseko, Siphiwe Mfeka, Chris Reason, Michele Toucher

3.1 INTRODUCTION

This project aimed to use an integrated approach to assess the potential impacts of land use and climate change on the future well-being of the ULM. It was initiated in response to a societal need to improve water and economic security now and into the future. To achieve this, hydrological, climatological, and economic aspects had to be integrated. However, the spatial and temporal scales among these elements are generally misaligned. While challenges and limitations were anticipated, this work provided a platform from which to explore possibilities, describe in more detail what is achievable, and identify areas where further effort is required to enhance undertakings of this nature.

3.2 APPROACH

The approach involved "up-front integration, beginning with a conceptual model that outlined how components would link together. Subsequently, the team developed a model integration framework to clarify data and data flow requirements. Although the intention was to assess multiple scenarios, a key principle was to prioritise and test the workflow from start to finish for one scenario. Once feasibility was established additional scenarios could be tested. This approach allowed the team to identify and attempt to resolve issues and obstacles before additional scenarios were tackled. Regular iterations were necessary to address numerous expected and unanticipated challenges inherent in the novel nature of the work. The project team also had to acquire knowledge in each respective discipline to aid integration. During this process, assumptions, and perceptions about what was possible had to be adjusted regularly. As learning progressed throughout the project, the team adjusted and refined details as requirements became more specific. Limitations also became more apparent as the team delved into details and examined the results obtained.

3.3 MESSAGING

Despite advancements in climate change science, results from global climate products such as CMIP6 still exhibit a considerable range and degree of uncertainty (Masson-Delmotte et al., 2021), which leads to a "cascade of uncertainty" when applied to local scales (Chan et al., 2022). There is also a well-recognised gap between climate change science and reliably usable climate information for local scale decision support (Hewitt et al., 2020, Rodrigues and Shepherd, 2022). Careful messaging is thus imperative around discussions of "possible" future climate scenarios with local communities.

The study adopted a simple storyline approach, using "what if" scenarios, rather than talking about future projections which could be misconstrued as accurate realities. Throughout all engagements, it was reiterated that there is a lack specific knowledge about the future of the region, and the process should be viewed as a "game". Storyline approaches have been applied in various ways to address and explore uncertainty related to climate change (Masson-Delmotte et al., 2021, Young et al., 2021, Chan et al., 2022, Hurk et al., 2023). Data scarcity was also an issue for various components. It was reiterated, therefore, that the scenarios are not precise or predictive, and should rather be used as narratives relative to a baseline. Furthermore, the concept of the precautionary principle of "least regret" was applied.

3.4 CONCEPTUAL FRAMEWORKS

The team started with the collective development of a conceptual model of how the system works. This guided a model integration framework. The consensus conceptual model is shown in Figure 3-1. Climate and LULC impact on the hydrological resource. Land use impacts on the hydrological response include a range of economic activities. Some of these may have little or no impact, whereas others may have more significant impacts. In turn, the hydrological response, and climate extremes such as heat waves, will impact on both sectoral and household livelihoods and incomes. When modelled collectively this would provide the net impact on the system.

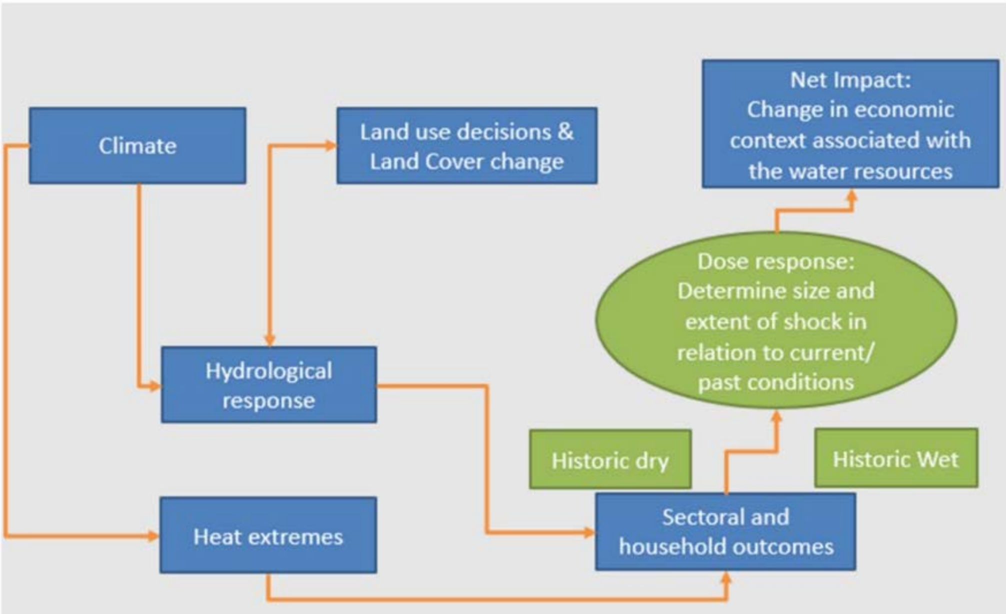


Figure 3-1 Conceptual understanding of the system showing how climate and land use data will be used to understand current hydrological and economic SQ and responses to past extremes

The final conceptual model, after refinements, presented to the TCs at the end of Year 3 is shown in Figure 3-2. The most challenging component of the integration was to see how to link the hydrological outcomes to the economic model.

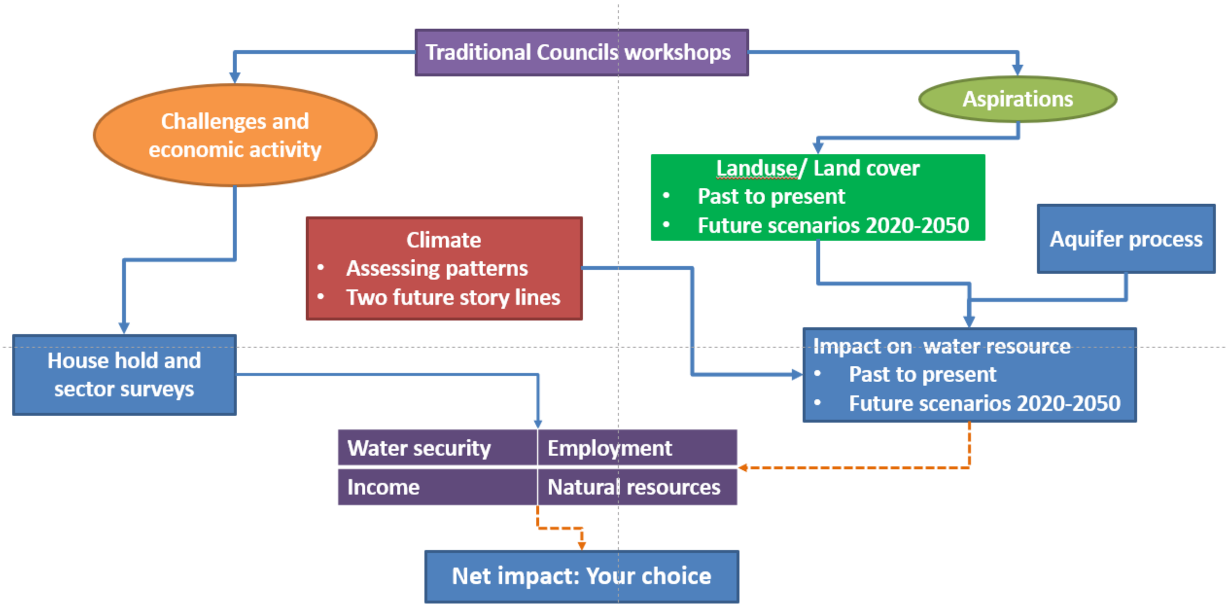


Figure 3-2 The finalised conceptual model as prepared for the TC feedback workshops held in November 2023

The initial model integration framework to clarify data needs and data flow requirements is presented in Figure 3-3 and further fleshed out per component in Figure 3-4, Figure 3-5, Figure 3-6 and Figure 3-7.

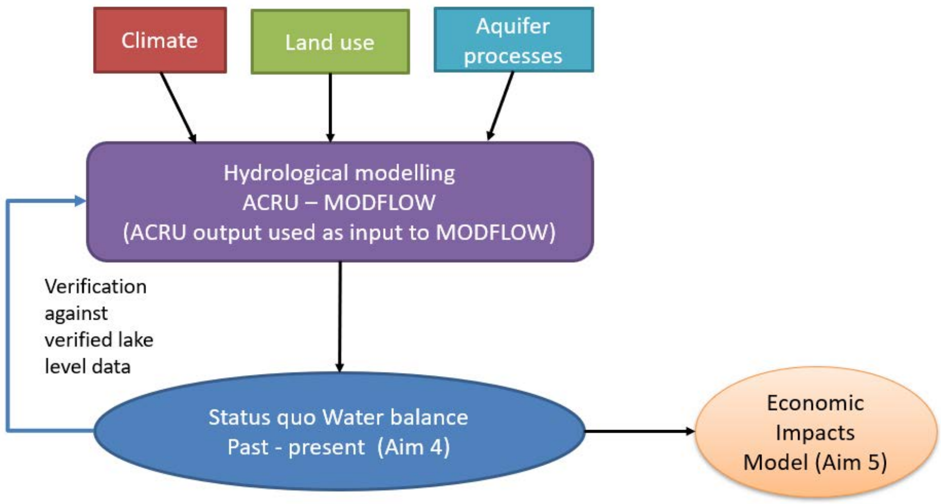


Figure 3-3 A broad overview of data pathway flows to understand the past to present dynamics (SQ)

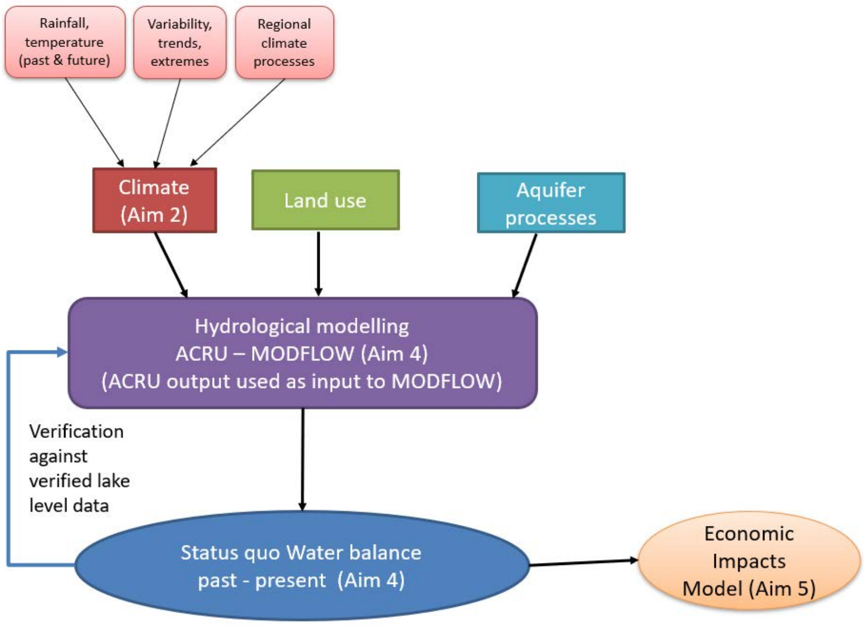


Figure 3-4 Details for the climate component

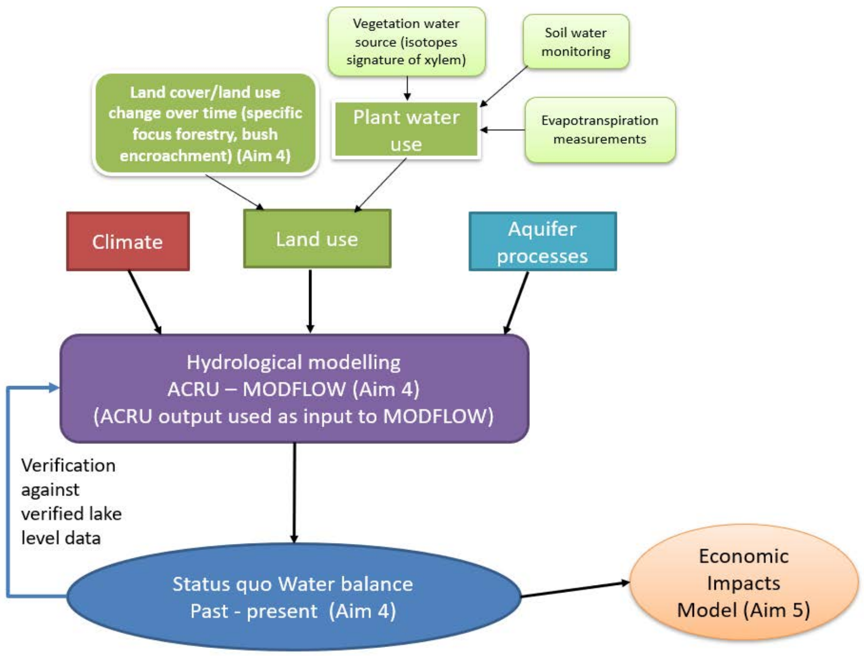


Figure 3-5 Details of land use and plant water use studies and how they feed into the land use component

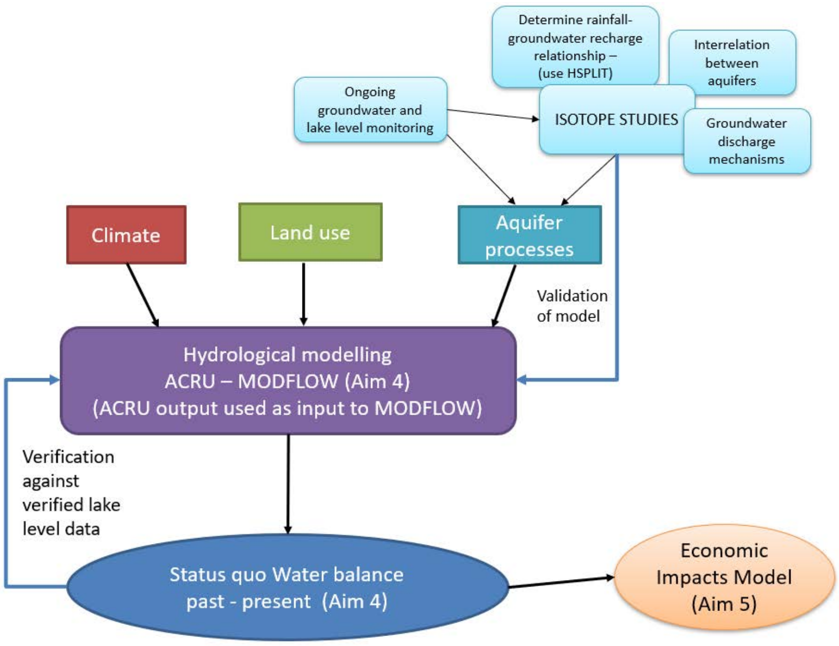


Figure 3-6 Details of aquifer process study components and how they feed into the data flows

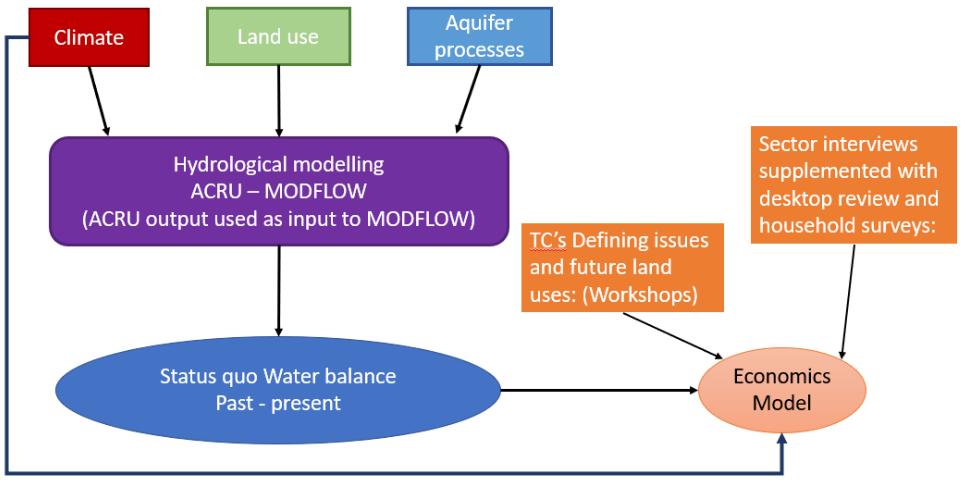


Figure 3-7 Details of the requirement for the economic component of the modelling and how other components feed into this

3.5 DATA REQUIREMENTS

To actualise this integrated modelling framework, specific data pathways were identified to inform what data is needed and how the different disciplines need to integrate to achieve the desired outcomes.

Key data requirements identified as relevant for integration included:

- Four key “talking points”/primary challenges as identified by the TC members that would be the variables against which impacts should be assessed.
- Current economic activities and their relative importance as perceived by the TCs.
- Potential future land use alternatives informed through engagement with the TCs.
- Sector and household responses in relation to current conditions (hence forth referred to as the “Status Quo” (SQ)), and past extreme conditions emerged as an important baseline data requirement to determine future scenario impacts. It was thus decided that sector and HH surveys would be required.
- An improved surface-water groundwater modelling approach to increase confidence in outcomes.
- A gridded dynamic LULC change data set. Prior hydrological models used “static” vegetation conditions, varying only the proportion of grass to plantations. Dynamic data, would enable the team to assess “real” changes over time.
- Gridded climate data matched between the surface water hydrology and groundwater model. This provided the added advantage of the capture of spatial rainfall gradients over the region. The climate periods were:
    - Past to present (SQ)
    - Two future scenarios. The intention was to use a “warmer wetter” scenario and a “warmer drier” scenario for two “story boards”
- A corrected lake level record for Lake Sibaya.

Specific details regarding the data collection methods for the above and the data requirements for each component are provided in the respective chapters of the report.

CHAPTER 4: LAND USE LAND COVER CHANGE, CURRENT ECONOMIC AGENTS AND PLAUSIBLE FUTURE LAND USE SCENARIOS

By: S Mfeka, S Janse van Rensburg, LN Gule, M Maseko, M Toucher M Pienaar and P Gordijn

This chapter addresses Aim 4: *Identify current as well as plausible future scenarios of climate and land use;* and Aim 6: *Use co-generative approaches to ensure context relevant and plausible development alternatives that reflect the aspirations of local communities within the ULM, and in doing so advance multiway knowledge transfer and decision support*.

4.1 INTRODUCTION

Economic development and population growth drive land use change (Foley et al., 2005). Certain economically-driven land uses impact on the water resource (Bate et al., 2016). To ensure environmentally and economically sustainable development, these impacts must be understood to inform integrated water resource management, land use planning, and adaptation strategies (Bailey et al., 2016, Pörtner et al., 2023). Understanding how past to current changes in land use have impacted on the system provides a baseline from which to assess the future outcomes of possible alterative choices made now. Alternative choices explored should also be assessed on how likely they are to improve or worsen current challenges into the future.

4.2 THE NEED FOR DYNAMIC LAND USE LAND COVER CHANGE INFORMATION

Several studies within the MCP have concentrated on quantifying the water use impacts of eucalyptus plantations and the effects of climate on water security in the area as well as abstraction (Kienzle and Schulze, 1992, Weitz and Demlie, 2014, Smithers et al., 2017, Nsubuga et al., 2019, Ramjeawon et al., 2020, Johnson, 2021). However, a major limitation of all these studies is that they do not account for actual dynamic changes in LULC. This makes hydrological modelling outcomes susceptible to scrutiny, particularly by individuals with vested interests in the commercial plantation forestry sector who may exploit this vulnerability to cast doubt on the results. In addition, bush encroachment, which is a feature of many landscapes within South Africa (O'connor et al., 2014), has not been accounted for in these hydrological studies. This highlights the need to use a more spatiotemporally representative LULC change data series as input data for hydrological models.

The assessment of land use change has been enabled with the advent of remote sensing; the standardisation of land use classification systems within South Africa; machine learning; and tools such as Google Earth Engine. These approaches are useful for the quantification of change objectively for the past several decades and are appropriate for the provision of a baseline of change over time.

There are several challenges associated with the development of accurate LULCs to assess LULC change dynamically. This is partially due to changes and advances in technology over time; differences in classification systems used through time; differences in projections; and differences in the resolution of various products. For example, the time series of South African National Landcover Classification (SANLC) products come from two different classification approaches and two different satellite products: 1990 and 2014 used Landsat's 30 m pixel imagery, whereas 2018 and 2020 used Sentinel's 20 m pixel imagery and different classification algorithms. A high degree of error and misclassification can thus be expected when using information from different sources to compare land use change over time.

The final approach selected for the assessment of LULC change is dependent on the objectives of the work. For detailed vegetation land cover change assessments methods are needed to reduce error, such as resampling different products as well as ensuring parity in the classifications classes and how these are lumped or split. While this is an ideal, it takes significant time. Unlike vegetation change studies, the hydrological studies generally use a much course scale input data for LULC.

4.3 CURRENT CHALLENGES AND FUTURE LAND USE SCENARIOS

To achieve the aims of this project, the impact of alterative land use choices on future hydrological outcomes needed to be simulated. While there is resistance to the removal of some or all the commercial eucalyptus plantations in ULM from certain quarters, linked to perceived economic benefits, others are not convinced of their value. People in the area are aware that eucalyptus plantations consume substantial volumes of water, but a lack of attractive economic alternatives frustrates them. The classic narrative is "*give us an alternative and we will change*". However, the impact of alternative land use options on the economy and water resource has not been assessed, let alone under climate change scenarios, paralysing efforts to promote more sustainable climate-smart alternatives.

Scientific assessments at global (Pörtner et al., 2023) and local (Jewitt et al., 2004, Smithers et al., 2017) scales recognise the interconnectedness between human societies, climate, ecosystems and biodiversity, and emphasise the vital importance of land use planning as an important tool to halt degradation and enhance the interdependent resilience of the water, livelihoods and ecological systems (Pörtner et al., 2023). Like legislative frameworks, science in isolation has thus far failed to have the desired impact. The challenges of the ULM are a mirror for the global condition.

South Africa's White Paper on Science, Technology and Innovation 2019 advances the need to transform the knowledge enterprise to be more inclusive and responsive to societal needs. As such, it promotes closer partnerships between science and society to address such failures. The co-production of science is advocated as one means to improve the value and relevance of science to society (Lemos et al., 2018). Naugle et al. (2020) promoted this approach to improve the impact of science when working with land custodians with the aim to sustain nature and people. Indeed, evidence has accumulated to show that participatory and co-learning approaches are increasingly effective in the enhancement of the impact of sustainable development initiatives (Burt et al., 2019, Vasseur, 2021). This study thus attempted to use participatory approaches with the affected communities to identify hypothetical future LULC change scenarios.

Since the aim was to explore the overall "wellbeing" of the area in the future, it was important to have a measure of the "success" of different futures against the current context-relevant issues facing the communities, as identified by them. The intention was to try to use future alternative land use choices for scenario simulations that aligned with the aspirations and ideas of the communities within the study area.

The most plausible alternative land use scenarios are likely to be those that depict a community's preferences. Within the study area, the members of the TCs are the leaders of communities within each ward. Traditional council members work closely with communities, and should also be aware of their challenges and land use aspirations. Moreover, the council influences decisions in their respective communities, including land use decisions (Mthethwa, 2002). Traditional councils were thus selected as the appropriate level with which to engage to identify key challenges; understand which current economic and livelihood activities are perceived as important; and to select a range of possible future scenario preferences. The intention was to then assess the outcomes of these scenarios against the challenges identified through these engagements.

Land use land cover change explainer

"Land cover" is the physical land cover type, e.g. wetland, grasslands, forest, whereas land use signifies how people use the land. "Land use" is largely a result of economic development and cultural activities (Foley et al., 2005). Thus, analysis of land use provides important information about the economy of a specific area. Land uses can be within natural vegetation land cover, such as harvesting of natural resources and edible fruits, or they can lead to the modification of the land cover.

Natural processes and anthropogenic impacts shape land cover. Anthropogenic impacts can be direct, such as the conversion of land cover from natural grassland to commercial plantations, or indirect, for instance, through CO_2 fertilisation, which leads to an increase in woody species (O'Connor et al., 2014) or the harvest of resources. Human-induced land cover change is often driven by development needs such as settlement, food security, and the imperative for economic growth. Changes in land cover impact on the environment such as the loss of biodiversity (O'Connor, 2005, Smith et al., 2006, Gaugris and Van Rooyen, 2010, Jewitt et al., 2015); impacts associated with global warming (Pörtner et al., 2023); and impacts on available water resources (Jewitt et al., 2004, Bate et al., 2016, Everson et al., 2019, Salem et al., 2023). Land use and land cover are referred to as LULC.

4.4 METHODS

The following data needs and processes were required

- LULC change from the past to the present;
- Using participatory processes, which identify the critical issues/talking points faced by the community that scenarios need to be assessed against to see if these are improved or made worse;
- Identification of the current livelihood and economic activities perceived as important; and
- Determination of the future land use scenarios that reflect the aspirations of the communities within the study area.

4.4.1 LULC Change from the Past to the Present

LULC change data across several time slices was required to assess the impact of LULC change on the hydrological response for the hydrological modelling domain from the past to the present. Currently, there is no reliable dynamic LULC change time series for the MCP. Consequently, it became an additional objective of this project.

The level of detail required for the ACRU model is course (1 km x 1 km) relative to the ideal scale for LULC change assessments. Each 1 km x 1 km pixel needed to be reclassified based on the dominant land cover. For example, if one pixel had 30% forest, 30% wetland and 40% grassland, the pixel was categorised as Grassland. While detailed LULC classifications make use of many categories, hydrological studies tend to aggregated these into far fewer classes. For the hydrological modelling in this study, the aggregation of the land use classes into eight classifications that could be distinguished hydrologically and confidently parameterised was decided upon. The methodology used to develop a LULC change time series is detailed below.

The following land cover products were used:

- 1990 and 2014 National land cover (SANLC) datasets using multi-seasonal 30 m resolution Landsat 8 Imagery (UTM 35 North (WGS84) map projection); and
- 2018 and 2020 National land cover (SANLC) using 20 m Sentinel 2 satellite imagery (Albers Equal Area projection (WGS84) map projection).

A cursory inspection of the SANLC images revealed changes in woody vegetation contrary to documented provincial and national trends (O'Connor et al., 2014). SANLC imagery suggested indigenous woody cover had largely decreased from 1990, whilst field studies have demonstrated woody thickening in the study region from this date (O'Connor et al., 2014). SANLC imagery was therefore systematically verified against available historic air and landscape photos (historic air photos from periods 1942, 1957, 1990, and orthophotos from 2012 (NGI 2023), plus imagery made available by Google Earth from 1984 to 2020 (Google Earth Pro 2023)). To stay within the scope of the current study and available skill sets, verification was done via a parsimonious systematic visual assessment. The primary intention was to ensure consistency in the classification categories (as opposed to "calcification accuracy") across time slices and identify actual change if it had taken place.

Details of the method used:

- SANLC LULC images were resampled, extracting the modal/dominant classes, to a (1 km pixel size) mask of equal origin and extent as the groundwater model domain (200 m pixel size) for the years 1990, 2014, 2018,
- SANLC image (1 km pixel size) LULC classes were simplified from their native 20 to eight classes that could be distinguished hydrologically and confidently parameterised (Table 4-1),
- To verify SANLC cover classes, LULC grids were systematically checked using QGIS (QGIS, 2024) 'ThRasE' (Corredor, 2020). Verification was done using a 1 km 2 checkerboard template outline for consistent perspective in visual assessment, and a minimum and maximum scale of 1:2000 and 1:8000. Acute local knowledge of the Maputaland landscape and historic landscape photographs and aerial images were used to inform reclassification decisions. A single expert was used to avoid discrepancies in observer bias within and between derived LULC images,
- The extent of wetlands in 1990 was limited to the 2018 NBA (Van Deventer et al., 2020) derived coverage, and a rule applied that this remains static over time unless a change to anthropogenic or indigenous woody plants occurred.

Table 4-1 Uncorrected but aggregated SANCL classes per time slice considered for the ACRU model, utilizing SANLC 1990, 2014,2018 and 2020 layers. Land cover classes indicated in red are those for which the trends do not agree with reality and other studies (Ramjeawon et al., 2020*). Percentages given in brackets*

Land use class	Class grouping	Area (km^2)			
		1990	2014	2018	2020
Indigenous forest	1	171 (5.0)	199 (5.9)	206 (6.1)	210 (6.2)
Thicket (including shrubland)	2	1 446 (42.6)	1 171 (34.5)	1 072 (31.6)	411 (12.1)
Planted commercial plantation forestry	3	230 (6.8)	242 (7.1)	255 (7.5)	256 (7.5)
Grassland	4	621 (18.3)	775 (22.8)	885 (26.1)	1 440 (42.4)
Wetlands and waterbodies	5	440 (13.0)	387(11.4)	398 (11.7)	413 (12.2)
Barren or eroded lands	6	0 (0)	2 (0.1)	5 (0.1)	49 (1.4)
Commercial agriculture	7	0 (0)	30 (0.9)	12 (0.4)	11 (0.3)
Subsistence agriculture and low-density settlements	8	487 (14.3)	589 (17.3)	562 (16.6)	605 (17.8)

4.4.2 Ground Truthing Issues, Economic Activities and Determining Future Land Use Aspirations.

As participation and co-production of knowledge are a central tenet of this project, permission was secured to conduct the project in the three traditional community areas within the Lake Sibaya groundwater catchment, namely Mabasa, Mbila/Zikhali and Tembe. In the introduction of the project to the councils, the team made it clear that we were not just seeking permission to conduct the work but that the project wanted engagement with the TC throughout the project and that the team would also require permission to conduct house surveys in the respective areas. Permission was granted by all three TCs.

One way to ensure stakeholder participation is through interactive workshops (Cairns et al., 2013). In terms of the project's planned engagements and data requirements, the initial step was to hold workshops with each of the TCs. Letters that outlined the aims of the workshop were provided and dates were subsequently secured for all three TCs. The aims of the workshops were:

- To provide a detailed overview of the project and its intentions;
- To dialogue climate change, co-learning towards a mutual understanding of what climate change is, what causes it and what its impacts might be; and
- To gather data required by the project team, including challenges, economic and livelihood activities perceived as important and to explore what kind of future alternative land uses they would be interested in seeing tested under the different future climate storylines.

At each workshop the principle of informed consent was explained. A PowerPoint presentation was used to facilitate initial discussions. While the presentation slides were in English, all verbal dialogues were conducted in isiZulu. Questions that could not be answered by the project team in IsiZulu, were deferred to the English speaker (PI) who then provided feedback which was duly translated.

At the plenary introduction in the workshops, participants were encouraged to ask questions, interject, and provide feedback regularly, and were encouraged to share their views freely. All efforts were made to create an informal dialogue, that recognised all voices with openness to learn. The team emphasised this as a collaboration and not a “lesson”. After the exchange of information on the project, the team posed questions to the participants about climate change. Where required, the team shared additional information to fill any knowledge gaps and showed gratitude for the TCs experiences and perceptions on the topic.

After this plenary session, the participants were split into randomised groups. Each group was allocated a project team facilitator to explain each activity. Splitting the participants into groups was done to spark creativity and encourage more equitable engagement from all participants. Three activities were facilitated.

4.4.2.1 Activity 1: Talking points/challenges

To determine the key challenges/talking points, groups were allocated a set time to draft a list of challenges faced by communities. At this point, the kinds of issues documented were not restricted as it was important to get a full view of the range of issues considered important in the area. Once this was completed, they were asked to denote the top five most pressing issues with a star. After this had been done at all three TC workshops, the four most important and relevant “talking points” related to the scope of the project were distilled. These became the measures against which the success or outcomes of the alternative future land use choices, under two future climate storylines, were assessed. Information gathered also informed components of the HH survey questionnaire.

4.4.2.2 Activity 2: Ground-truthing livelihoods and economic activities

To root the project appropriately in the local context, the project sought to understand the current livelihoods and economic activities, and which of these are perceived as important. In the second activity, each group was asked to list all economic activities that community members are involved in. Again, a time limit was set with some flexibility, and no restrictions were made on the “types” of activities that could be listed. The groups were asked to indicate which five of these were the most important activities. They were then asked to consider which of the activities on the list they would want more of and which they would want less of into the future as well as identify any additional (new) activities that they would like to see developed in the area.

4.4.2.3 Activity 3: Exploring alternative future land use scenarios with TCs

For the Mabasa and Mbila/Zikhali workshops, to facilitate discussions on alternative future land use scenarios, the most recent SANLC product for 2020 was used to develop a map of simplified LULC classes to capture the major land covers and associated land uses within the area (Figure 4-1). Boundaries of the community areas were included for reference. Several A3 maps were laminated and provided to each of the groups. Pens were provided to draw on the maps, initially white board markers that could be edited, and, once the final products were ready, these were captured with a permanent marker on the maps.

The groups were asked to envision what they would want the area to look like by 2050, when their child or grandchild born today, is 30 years old. The participants were encouraged to be creative and imagine that they had a magic wand to change current land uses. Ideas were sketched on the map with the aid of a facilitator, taking care to explain that an increase in one land use meant a decrease for another.

The exercise was pitched as a "game". It was made clear that no one was coming there to change land uses, the idea was simply that the project needed to understand what kind of activities they would like so that these could be modelled in relation to water security and economic outcomes. It was emphasised that we were not development agency and that we have no money to give effect to the changes they proposed.

An alternative approach was adopted in the Tembe workshop, which took place several months after the initial two. In this case they were presented with a list of eight possible alternatives distilled from the initial two workshops and ask to pick two, ranking 1 as most favoured and 2 being their second choice.

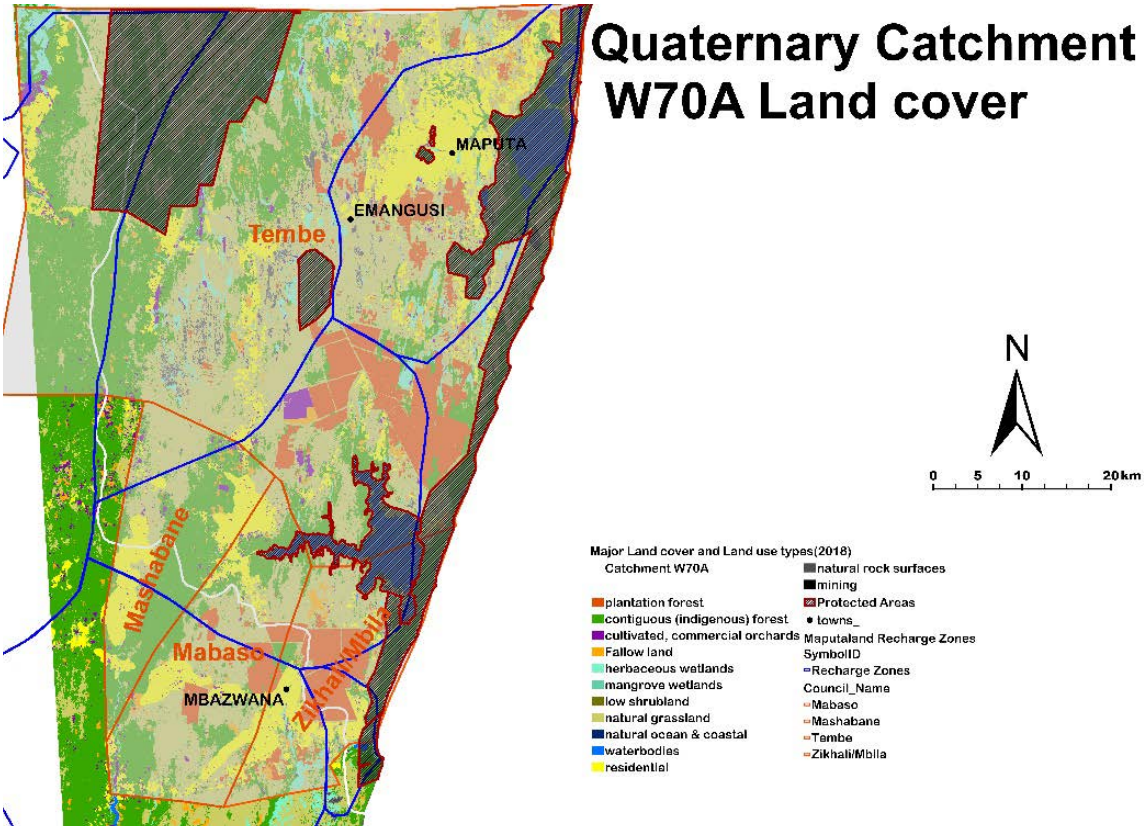


Figure 4-1 Spatial pattern of major land uses and land covers in the Maputaland Coastal plain, indicating also the traditional community area boundaries and groundwater catchment areas (blue)

4.4.3 Synthesising TC Aspirations into Future Land Use and Economic Scenarios

To assess the relative impact of changes in land use (as alternatives to forestry), the hydrological models required that all other land covers remain constant. This meant that only one major change could be modelled at a time to analyse its impact on water resources. Additional "non-land-based" economic activities that did not need to be included in the hydrological models but could be included in the economic model, were also summarised. The intention was to include some of these "activities" in the economic model to explore the financial and employment consequences of a variety of choices beyond the single major land use change used in the hydrological models. For modelling purposes economic activities were divided into two categories: 1) major land-based changes that significantly affect water resources and need to be included in both the hydrological and economic models; and 2) activities and feedbacks that are solely included in the economic model.

Following the completion of the workshops, inputs from Activity 2 (ground-truthing economic agents) and Activity 3 (the mapping exercise) were reviewed. Based on predominant/convergent preferences, novel suggestions, and concerns, as well as feasible scenarios for which appropriate data for the modelling was available, several plausible alternative land use scenarios were identified for the hydrological model and several for inclusion in the economic model. Given data availability limitations, not all community suggestions could be included in the modelling processes. Since the project aimed to explore alternatives to commercial plantation forestry, major land use change scenarios involved the substitution of part of the current formal forestry blocks with the proposed alternative land use preference.

The economic model relied on input data for the spatial extent of activities and land cover types. Similarly, the surface water ACRU hydrological model needed georeferenced data on LULC. The chosen area extent for testing the future scenario LULC changes was based on the estimated location of the groundwater recharge boundary for Lake Sibaya (Figure 2-7) which also defined the focus area of where HH surveys would be conducted (Figure 2-7). A 10 km buffer area around the Lake Sibaya recharge zone, that encompassed these regions defined the outer boundary of the "area of interest" (AOI) for future land use scenarios (refer to Figure 2-7) The AOI included part of the Mashabane community area, but this region was excluded from all calculations due to the absence of conducted surveys.

The AOI was deemed suitable as it covered the Lake Sibaya catchment area (hydrology component). This was important because the lake is a shared resource by the three traditional authorities (Mabasa, Tembe and Mbila/Zikhali) and a proxy for water security status in the area. All the major land uses were found within this area. Due to the complexities of the integration across the various disciplines as well as the extent of parameterisation required, the approach was to prioritise integration links rather than area extent. If the approach works, it can be parametrised for the broader area ULM area within quaternary catchment W70A, most of which is already covered in the hydrological modelling configurations (See CHAPTER 6: and CHAPTER 9:).

With a focusing on the three traditional community areas within the study, the total area per traditional community area within the AOI was determined (refer to Figure 2-7), as well as the total area per land cover type. The land use scenario changes were applied within this area once they had been finalised.

4.5 RESULTS

4.5.1 Land Cover-Land Use Change

The manual course scale re-classification of the 1 km x 1 km grids done as part of this study resulted in a more realistic pattern of change over time in line with other studies published for the area (Ramjeawon et al., 2020) and indigenous knowledge from the community. The “thicket woodland shrubland” class was difficult to distinguish from some grassland areas over time. It is possible that in some grassland areas there has been more bush thickening (as reported through indigenous knowledge provided). Likewise, the distinction between some indigenous forestry and thicket was difficult but the rule was that if no visible change within the grid cell over time was observed, the classifications were kept consistent with the 1990 re-classification.

Table 4-2 Revised extent of land use classes and change over time using "corrected" aggregated classes per time slice using SANLC 1990, 2014,2018 and 2020 layers for they hydrological modelling domain Percentage is shown in brackets

Land use class	Class	Area (km²)							
		1990	"Corr" 1990	2014	"Corr" 2014	2018	"Corr" 2018	2020	"Corr" 2020
Indigenous forest	1	171 (5)	247 (7)	199 (5.9)	286 (8.1)	206 (6.1)	328 (9.3)	210 (6.2)	372 (10.6)
Thicket (including shrubland)	2	1 446 (42.6)	1 134 (32.2)	1 171 (34.5)	1 074 (30.5)	1 072 (31.6)	1 086 (30.8)	411 (12.1)	1 042 (29.6)
Planted commercial plantation forestry	3	230 (6.8)	200 (5.7)	242 (7.1)	275 (7.8)	255 (7.5)	329 (9.3)	256 (7.5)	372 (10.6)
Grassland	4	621 (18.3)	512 (14.5)	775 (22.8)	454 (12.9)	885 (26.1)	378 (10.7)	1 440 (42.4)	313 (8.9)
Wetlands and waterbodies	5	440 (13)	892 (25.3)	387 (11.4)	668 (19.0)	398 (11.7)	568 (16.1)	413 (12.2)	490 (13.9)
Barren or eroded lands	6	0 (0)	4 (0.1)	2 (0.1)	4 (0.1)	5 (0.1)	4 (0.1)	49 (1.4)	6 (0.2)
Commercial agriculture	7	0 (0)	1 (0.03)	30 (0.9)	16 (0.5)	12 (0.4)	17 (0.5)	11 (0.3)	19 (0.5)
Subsistence agriculture and low-density settlements	8	487 (14.3)	533 (15.1)	589 (17.3)	746 (21.2)	562 (16.6)	813 (23.1)	605 (17.8)	909 (25.8

The manually corrected data indicates an increase in indigenous forest, commercial plantation forestry, bare ground, cultivated area, and developed areas (including subsistence cultivation) over time. Declining trends were found for grassland, thicket, and surface water bodies (Table 4-3). The most notable declines are in grasslands and water bodies and the most notable increases are in developed areas, commercial and indigenous forestry (Table 4-3). Notably between 1990 and 2020, 139 km² of grassland changed to the thicket class, and 79 km² of grasslands was converted to commercial plantation forestry. While thicket expansion into new areas was evident, the overall area declined. The declining trend in thicket was a result of the conversion of 89 km² of the thicket category to developed/subsistence area between 1990 and 2020, and 124 km² of the thicket category transitioned to forest. Note that the 1990 land cover represents a landscape in which thicket expansion relative to the early 1900s had likely already occurred. Ideally LULC change needs to be assessed in more detailed using aerial photographs as well as RS products over a longer time-period. Table 4-3 illustrates land cover classes area over the four time slices from 1990 to 2020. The water class had the highest decrease in area over the years while the developed class had the highest increase in spatial extent (see Table 4-3).

Table 4-3 Results of land cover area per class per time slices, based on manually corrected aggregated SANCL data used as inputs for the ACRU model

	1990	2014	2018	2020
Forest	247 (7)	286 (8.1)	328 (9.3)	372 (10.6)
Thicket, woodland and shrubland	1 134 (32.2)	1 074 (30.5)	1 086 (30.8)	1 042 (29.6)
Plantation	200 (5.7)	275 (7.8)	329 (9.3)	372 (10.6)
Grassland	512 (14.5)	454 (12.9)	378 (10.7)	313 (8.9)
Water (surface and wetland)	892 (25.3)	668 (19.0)	568 (16.1)	490 (13.9)
Bare ground	4 (0.1)	4 (0.1)	4 (0.1)	6 (0.2)
Commercially cultivated land	1 (0.03)	16 (0.5)	17 (0.5)	19 (0.5)
Subsistence agriculture and developed (low density residential)	533 (15.1)	746 (21.2)	813 (23.1)	909 (25.8

The NBA wetlands layer was used as a basis for the 1990 period and indicated a total of 892 km^2 of wetland area (Figure 4-3). By 2020, 402 km^2 of the original wetland area had been transformed. The biggest loss is to “developed areas”, which includes household subsistence agriculture, with significant changes over the grassland’s category, as defined as areas where buildings began to appear in the pixel. Perennial wetlands were kept as wetlands, even if dry. Hence this category represents both the lake systems (Kosi and Lake Sibaya which have water) as well as all the wetlands. Of concern is that 82 km^2 (representing 9.1% of the wetland area within the region) have been converted to plantations (Figure 4-3), in contravention of the National Water Act.

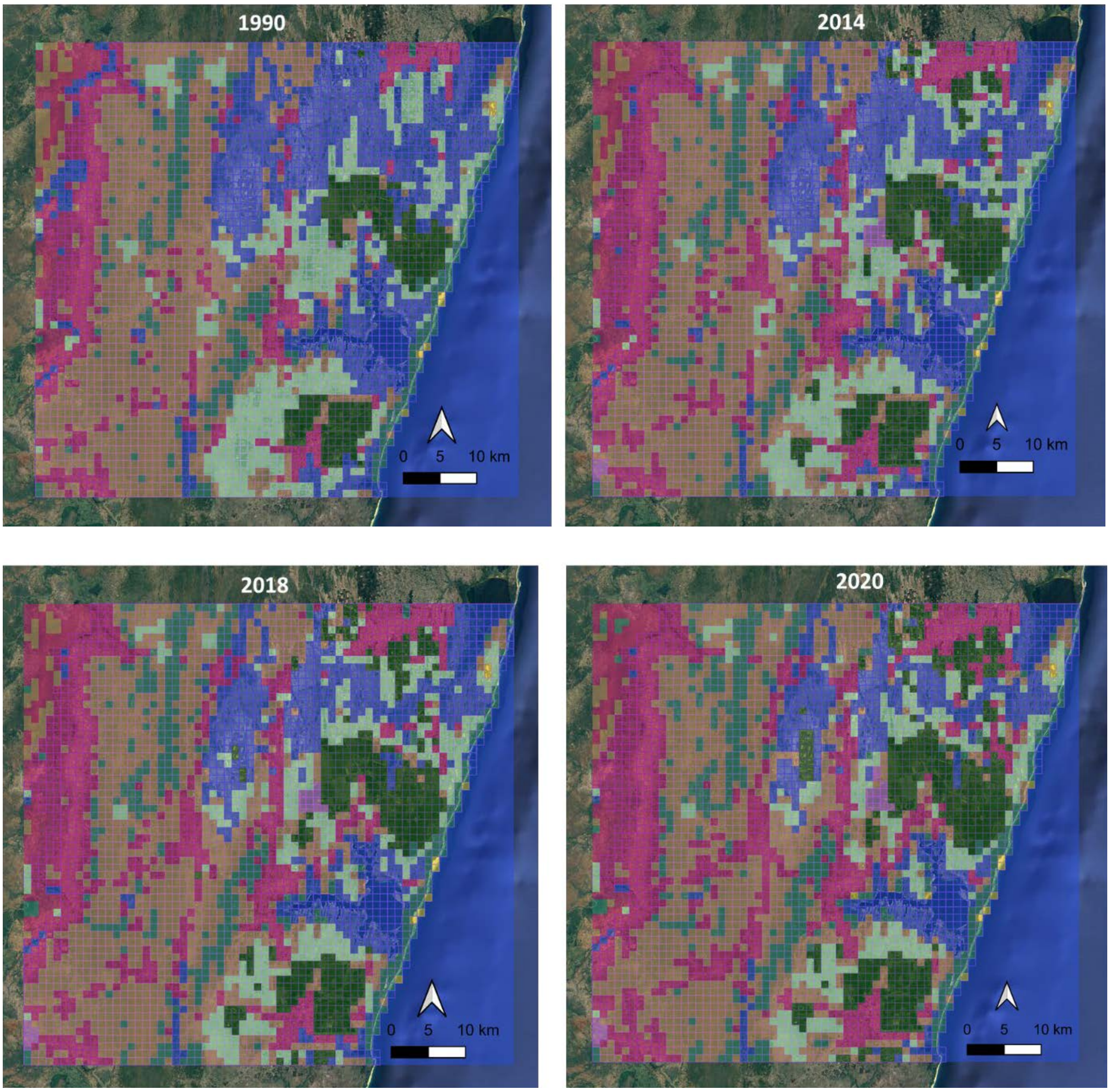


Figure 4-2 Modified SANLC land classifications for four time slices, based on manual reclassifications to ensure consistency of classes for cells with no change between time slices and appropriate class change where clear change had taken place in more the 50% of the cell.

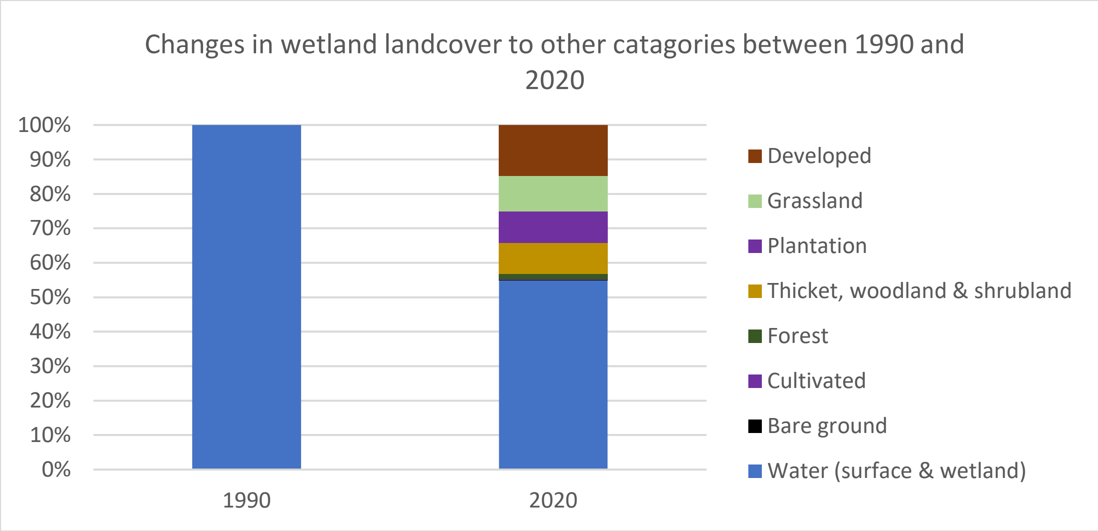


Figure 4-3 Wetland land cover change between 1990 and 2020

4.5.2 Ground Truthing Issues, Economic Activities and Determining Future Land Use Aspirations.

Dates were initially secured for January 2022 for the TC workshops but these were postponed due to the fourth wave of COVID-19. Revised dates were secured for February 2022 for all three TCs. Despite having secured dates, unfortunately the Tembe TC cancelled at the last minute citing the need to focus their efforts on arranging the upcoming Marula festival.

The first workshop held was with the Mbila/Zikhali TC on 16 February 2022. There were 16 participants, of which only one was female. The second workshop was held on 17 February 2022 at Mabasa TC. There were six participants, only one of which was female. The Tembe workshop was held on 15 August and included 19 participants, predominantly from the TC as well as some youths. There were more male than female participants.

4.5.2.1 Talking points

This section presents the results of the first activity from the TC workshops, which was to elicit talking points or challenges faced by communities. A total of nine groups from three TCs participated. Groups were asked to identify the top five challenges from their list (denoted with a *), providing a total frequency of 45. All responses from all groups are listed in Appendix A. For the purposes of reporting, issues were consolidated into common themes of unemployment, water, natural resources/natural resource challenges (including agriculture and livestock), infrastructure and social issues. Within these, common responses were aggregated into single categories, counting any issues identified as "important". Table 4-4 provides a summary of the categories, within the themes, which were identified at least once as important. Of these, "water shortage" was the issue identified as important (14/45), followed by "unemployment" (9/45). Six natural resource issues (including livestock and agriculture) accounted for 8/45 points. Issues related to infrastructure and education challenges accounted for 11/45. Three issues under the "social" theme made up 4/45 points.

All workshops identified and prioritised both water resources (scarcity) and unemployment as major issues. A diversity of issues related to natural resource, agricultural and livestock issues were identified with at least one such issue prioritised in each workshop. Within this theme, all workshops identified bush encroachment as well as alien invasive plants as issues but each only received one priority ranking point. In discussions, one group associated bush encroachment directly with a negative impact on grazing land. Lack of grazing land as well as an increase in the impacts of plantations were identified in all three workshops, with two workshops prioritising each of these. A lack of markets available to sell crafts and produce was identified by several groups but only prioritised in one. Two groups noted the lack of markets for cattle specifically, as well as several other issues related to cattle farming, but none of these were prioritised. Interestingly, following this activity, in the Mabasa TC, a lively discussion emerged around the desire to commercialise cattle herds and the interest in securing appropriate extension and advisory interventions related to this. This led to a knowledge exchange facilitated by the project team for three members from each of the community areas (see CHAPTER 13: section 13.3)

Lack of general infrastructure, including roads, schools, tertiary education facilities and factories were identified and prioritised in all three workshops These are an indication of the economic challenges of the area. Cell phone networks were a common issue between various groups, but only prioritised in two. All three workshops had identified high crime as an issue but only one prioritised it whereas drug and alcohol abuse were identified in two workshops and prioritised in both.

The assessment of both the full suite of issues (Appendix A) as well as frequency issues ranked as important (Table 4-4), revealed a complex set of challenges which are interrelated. Water shortage, unemployment, lack of market access, poor infrastructure, bush encroachment, and lack of grazing are among the common challenges faced by communities. Based on their commonality, importance frequency, and relevance to the aims of this study, the following talking points were included in the HH surveys: employment (economic impact), food security (as it related to cultivation activities and farming), crop yield (as it relates to both land use and climatic pressures including shortage of rainfall), grazing land (links to cattle aspirations and natural resource harvesting), surface water levels (links to water scarcity), and biodiversity (links to natural resource use including crafts, medicine and edible resources). These were consolidated into four issues; water security, employment, economic status, and natural resource integrity, against which the outcomes of future scenarios were assessed.

Table 4-4 Talking points that were noted as important by one or more groups, consolidated according to themes: water (blue), employment (yellow), natural resource related (green), infrastructure and education (grey), social challenges (light blue)

Challenges	Mbila/Zikhali	Mabasa	Tembe	Total "Important"
Water shortage/lack of rain/drought/more people	5	3	5	13
Unemployment/poverty/petrol cost	3	2	5	10
Lacking of grazing land/distance to water/afforestation/plantations on wetlands/invasive species/bush encroachment/lack of market for crafts/crops/restrictions to park	2	2	4	8
Poor roads/infrastructure/transport challenges/lack of education facilities /lack of skilled works force/poor environmental awareness /poor network	3	3	3	9
Drug abuse/theft	1		2	3

4.5.2.2 Current economic livelihoods

In the activity aimed at ground-truthing economic agents in the region, a total of 41 economic activities were identified during the three workshops (see Appendix A for unabridged list), with significant overlap seen in the types of activities recorded (Table 4-5). Of these, 16 were marked by at least one group as important contributors to livelihoods relative to the others. All nine groups identified “crop farming (wet and dryland)/selling vegetables” as important with six priority ranking points allocated to this category. This was the only category identified and ranked by all nine groups. Crafts, fishing, and Lala wine were all identified by eight out of the nine groups, with frequency points of seven, five and three, respectively. Noteworthy is that agriculture, livestock, and natural resource-based incomes, including tourism (green highlighted cells in Table 4-5), all of which are dependent on healthy ecosystems, account for 64 out of 106 or 60% of “hits” (frequency they were recorded). This indicates a high degree of dependence on natural and land-based resources for income in the region, as was previously documented by (Cunningham, 1985, 1990). Forestry was also identified by 8 of the 9 groups as important and had an equal frequency of points to crafts and carvings (seven). In general, the results indicate the perception that forestry does generate significant income, but the combined frequency of important activities pertinent to agriculture, livestock and natural resources provide significantly more sources of income for communities.

Table 4-5 List of all livelihoods identified, with the frequency of times noted and indicated as important

Economic activities	Frequency	Importance (Top 5)
Crafts and wood carving	8	8
Gum trees/timber	7	8
Crop farming (wetland and dryland)/selling Vegetables	9	6
Fishing	8	5
Livestock (Cattle and goat)	6	4
Lala Palm wine	8	3
Grant/pension	5	3
Selling medicinal plants/Traditional medicine	5	2
Constructions/Brick laying/Builder	4	2
Employment: ecotourism	6	1
Transport/Taxi driving/Truck driving	3	1
Grooming (beauty)/salon	2	1
Ncema (reeds)	1	1
Employment general	3	
Small business/tuck shops/retail/tavern	3	
Herbalist/traditional healer	2	
Selling honey	2	
Monkey apple and orange products	2	
Marula/wine	2	
Employment: forestry	2	
Employment: Government jobs	2	
Selling goods from Mozambique or Durban	1	
Property rental	1	
Hunting	1	
Homemade mahewu	1	
Selling cannabis	1	
Homemade aMmahewu	1	
Ihlala juice	1	
Macadamia	1	
Employment hospital	1	
Employment: Self employed	1	
Culture activities	1	
Sewing	1	
Workshops/mechanic	1	
Car wash	1	
Gambling	1	
Crime	1	
Total score	106	

4.5.2.3 Activity 3: Defining future land use scenarios with TCs

At this point, the Mbila/Zikhali and Mabasa workshop groups were asked to give preferences on what they want more or less of in the future (see Appendix A). Farming, including livestock and crops (both dryland and wetlands), was commonly identified. None of the groups expressed an interest in gum plantations, and the majority advocated for a decrease in this land use. At all three workshops, groups were also asked to list any new activities they would like to see in the area (see appendix A). In the Mbila/Zikhali and Mabasa workshops this was translated into a physical mapping exercise (Figure 4-4).

In a comparison of the land use futures generated from the Mabasa TC, the two groups shared preferences for an increase land under cultivation (crops); a decrease in land under commercial eucalyptus plantations as well as an increase in the size of conservation areas. Both groups opted to transform large portions of forestry land either to macadamia or crop farming. Divergence was observed for grazing land with Group 1 preferring increased grazing land while Group 2 preferred that grazing land should not change in extent. One group emphasised their concern regarding increases in natural woody encroachment (bush encroachment). In the Mbila/Zikhali workshop, three groups resulted in more diverse preferences. As with the Mabasa workshop, there were positive preferences for an increase in land under cultivation as well as the expansion of conservation areas/activities. Two of the three groups preferred fewer commercial eucalyptus plantations.

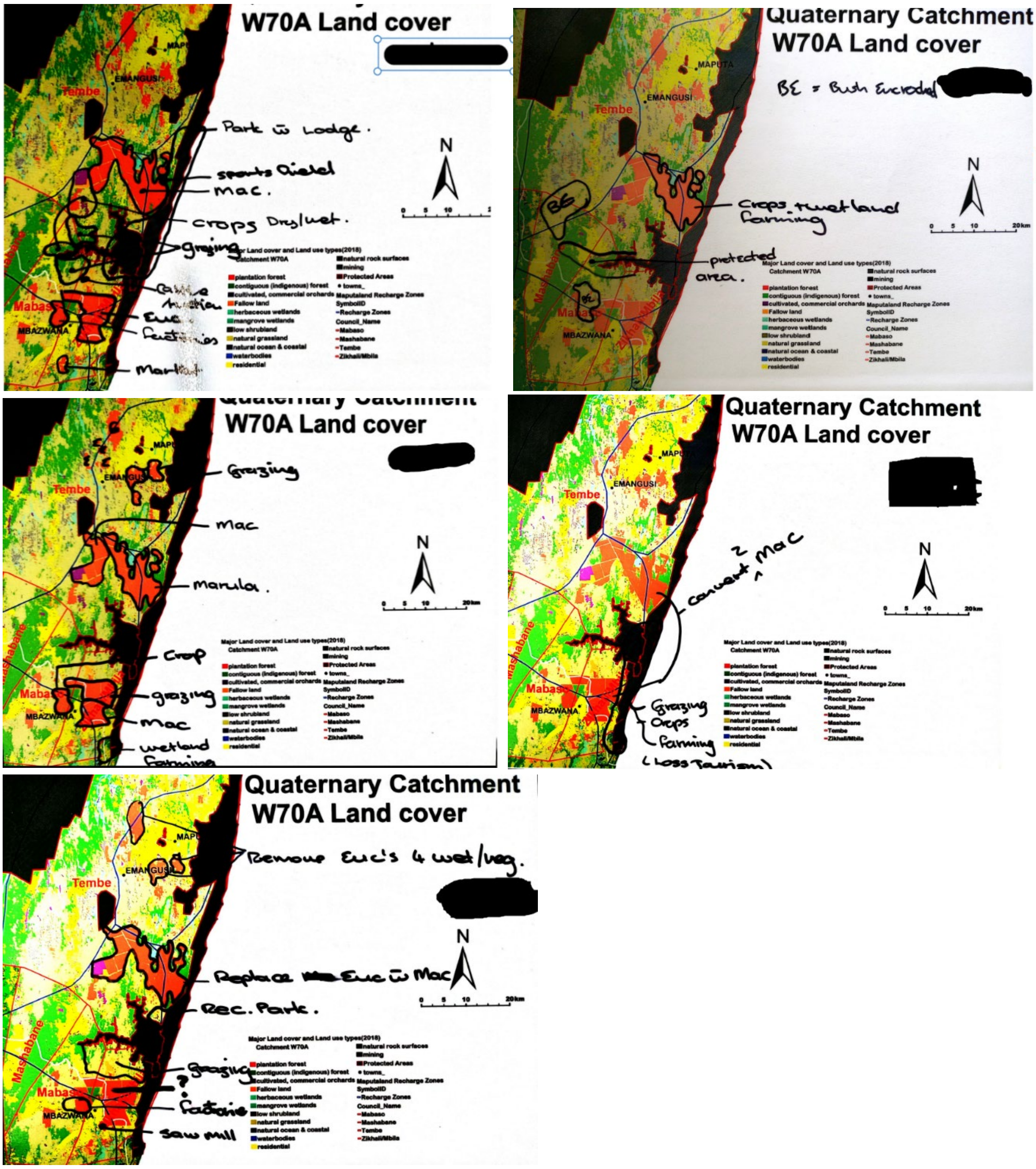


Figure 4-4 Sketches of potential future land use maps developed during the TC workshops

Before the Tembe workshop, preference trends from the initial two workshops were distilled into eight tentative LULC options (Table 4-6). These options were presented at the Tembe workshop. Instead of asking them to draw preferences on a map, each group was asked to select two land use change options, ranking these 1 (most preferred) and 2 (second preference) from the eight options (Table 4-6).

Table 4-6 Scenario options for the Tembe workshop where groups had to select 2 land use changes from the options below

LULC change preference choices	G1	G2	G3	G4
Hold current 2020 steady				
Change half Euc to Mac		1		
Change half Euc to Marula				
Change Half Euc to Cattle grazing		2	2	1
Change 50% grassland to bush encroachment				
change all Euc to Mac	2		1	
Change half Ecu to Crop	1			2
Change half grasslands to Euc				

Interestingly, none of the groups wanted to increase eucalyptus plantations (S8). However, each of the groups had different preferences on what alternative economic land use activities they would prefer, with a change of half of the area from eucalyptus plantations to cattle grazing (grasslands) (S4) as the most preferred.

My take home from the TC workshops

"*The interesting find is that all councils essentially say the same thing. They want less eucalyptus and pine trees and more cattle and crop farming, as well as macadamia orchards. But some people did not support the macadamia orchards idea because they were demanding and expensive. Another reason for the lack of support for macadamia is that some community members who tried to farm macadamia had failed as all the seedlings got burned when the temperatures got high.*"

Project team member

4.5.3 Synthesising TC Aspirations into Future Land Use and Economic Scenarios

As explained in section 4.4.3, the change scenarios are focused within an AOI. Table 4-7 provides the relative areas of each land class per traditional community and their totals. The plantation land use class has the largest area compared to other land use classes in the Mbila/Zikhali and Tembe tribal areas. Whereas grassland makes up the largest area in the Mabasa area, one of the groups preferred that the grazing area (grassland) remain the same.

Table 4-7 Area in ha per land use class within the AOI for the three traditional community areas within the study (percentage reflected within brackets)

Land Use Class	Mabasa	Tembe	Mbila/Zikhali	Grand Total
Bare ground	100 (0.4)	100 (0.1)	100 (0.5)	300 (0.2)
Cultivated	0 (0)	1 300 (1.8)	0 (0)	1 300 (1.1)
Developed	5 200 (19.5)	9 400 (12.7)	3 300 (15.6)	17 900 (14.7)
Forest	1 400 (5.2)	2 500 (3.4)	2 600 (12.3)	6 500 (5.3)
Grassland	7 400 (27.8)	13 900 (18.7)	2 100 (9.9)	23 400 (19.2)
Plantation	4 200 (15.7)	19 900 (26.8)	6 900 (32.5)	31 000 (25.4)
Thicket, woodland and shrubland	6 500 (24.4)	9 300 (12.5)	3 700 (17.5)	19 500 (16.0)
Water and wetlands	1 800 (6.7)	17 800 (24.0)	2 500 (11.8)	22 100 (18.1)
Grand Total	26 600 (21.8)	74 200 (60.8)	21 200 (17.3)	122 000 (100)

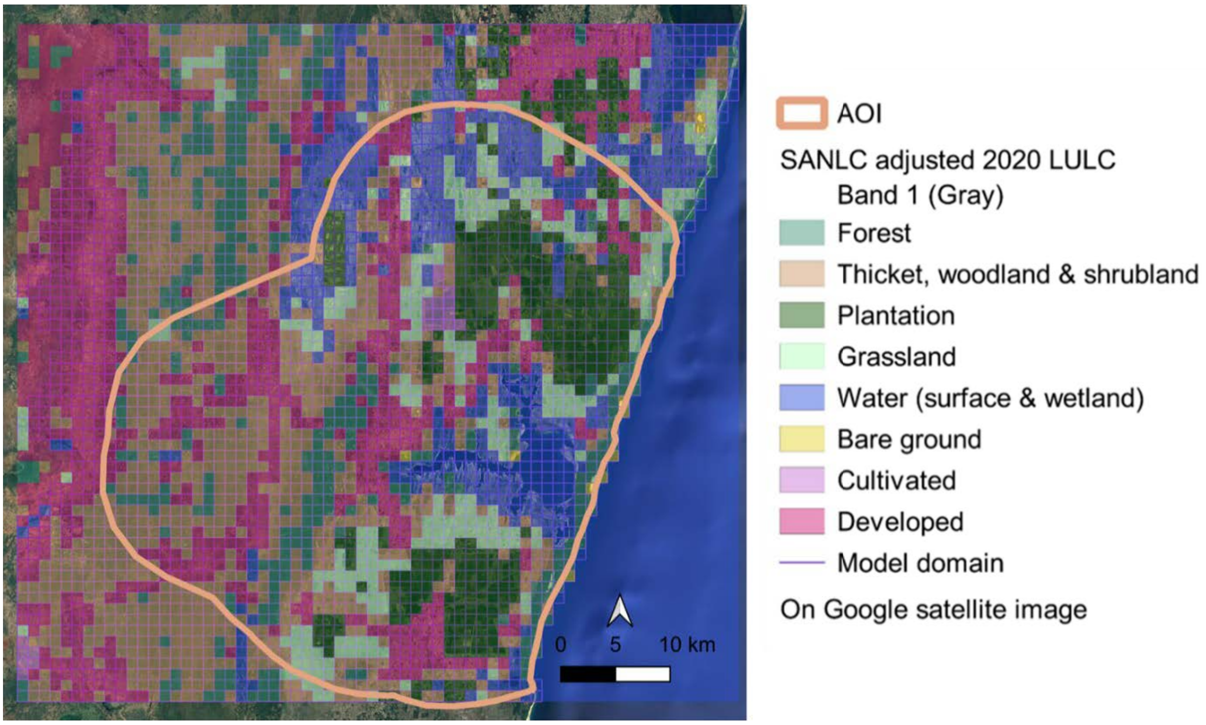


Figure 4-5 Landcover classes within the Area of Interest (AOI) as of 2020

After evaluating the inputs from the TC workshops as well important suggestions from the project team and feasibility with respect to the data availability, scenarios were identified for the hydrological and economic models. A SQ scenario was included as a baseline, under the assumption that no changes occur into the future. Furthermore, a "No Forestry" scenario from "past to current" was selected to illustrate the impact of forestry on water resources between 1959 and 2020. The rest were based on preferences emergent from the TC workshops. The list of scenarios selected for hydrological and economic modelling is provided in Table 4-8. Several irrigated scenarios were proposed. The irrigation aspect was only considered in the MODFLOW model due to constraints encountered in ACRU. However, there is a strong connection between MODFLOW and the economic model in the context of irrigation scenarios.

Table 4-8 List of scenarios considered in the hydrological modelling to be run under alterative future climate storylines

	Past to present	Future LULC Scenario
0	Dynamic (LULC change 1990,2014,2018, 2020)	SQ (2020 LC)
1	Dynamic, but with all commercial plantation forestry changed to grassland (No Forestry*)	2020 layer with all forestry change to grassland (No Forestry*)
2	Dynamic	2020 LULC with 50% loss of grassland to bush encroachment (thicket)
3	Dynamic	2020 LULC with 50% Forestry* block converted to Dryland Crop
4	Dynamic	2020 LULC with 50% Forestry* block converted to Irrigated Crop (Irrigation only in MODFLOW)
5	Dynamic	2020 LULC with 50% Forestry block converted to Dryland Macadamia
6	Dynamic	2020 LULC with 50% Forestry block converted to Irrigated Macadamia (Irrigation only in MODFLOW)
7	Dynamic	2020 LULC with 50% Forestry block converted to Dryland Marula
8	Dynamic	2020 LULC with 50% Forestry block converted to Irrigated Marula. (Irrigation only in MODFLOW)

**Note: Forestry denotes plantation forests and not indigenous or natural forests*.

For the bush encroachment LULC scenario, 50% of the grasslands area within the AOI of the 2020 land cover map, was randomly converted to “thicket”. To assess the alternative land use scenarios, 50% of the total forestry (plantation) area within the AOI was designated as a “change area”. This was done proportionally for the relative areas, within each traditional community “owned” per traditional community based on the 2014 TMM Business Plan (Figure 4-6). The 50% change areas were allocated the 50% in proportion to ownership. This 50% was selected from within the formal forestry blocks (see Figure 4-6). All the alternative LULC scenarios took place within this 50% change area.

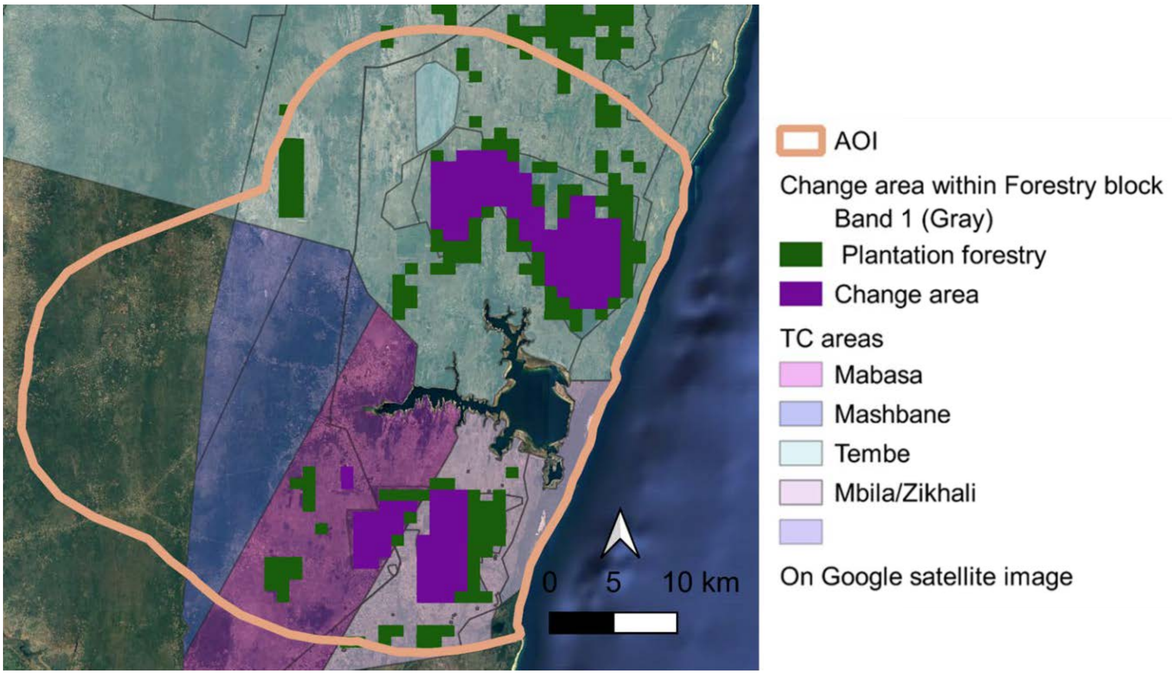


Figure 4-6 Map indicating the areas selected within the formal forestry blocks as the "change area"

Table 4-9 Number of ha of forestry plantation per community area selected for the "change area"

TC	50% of total forestry plantation selected as “change area” in hectares (ha)
Mabasa	2 100 ha of 4 200 ha
Mbila/Zikhali	3 500 ha of 6 900 ha
Tembe	9 900 ha of 19 900 ha

For the Irrigated and Dryland Crop scenarios the change area was further subdivide into various crops, again allocated proportionately to the different TC areas (see Table 4-10 and Figure 4-7).

Table 4-10 Proportion of different crop types allocated within the 50% change area for each traditional community area with ha of land area in brackets

	Ground nuts	Cassava	Maize	Vegetable	Total% (ha)
Total	49 (7 600)	25 (3 900)	20 (3 100)	6 (900)	100 (15 500)
Mabasa	6 (1 000)	3 (500)	3 (400)	1 (200)	13 (2 100)
Mbila/Zikhali	11 (1 700)	6 (900)	5 (700)	1 (200)	23 (3 500)
Tembe	32 (4 900)	16 (2 500)	13 (2 000)	3 (500)	64 (9 900)

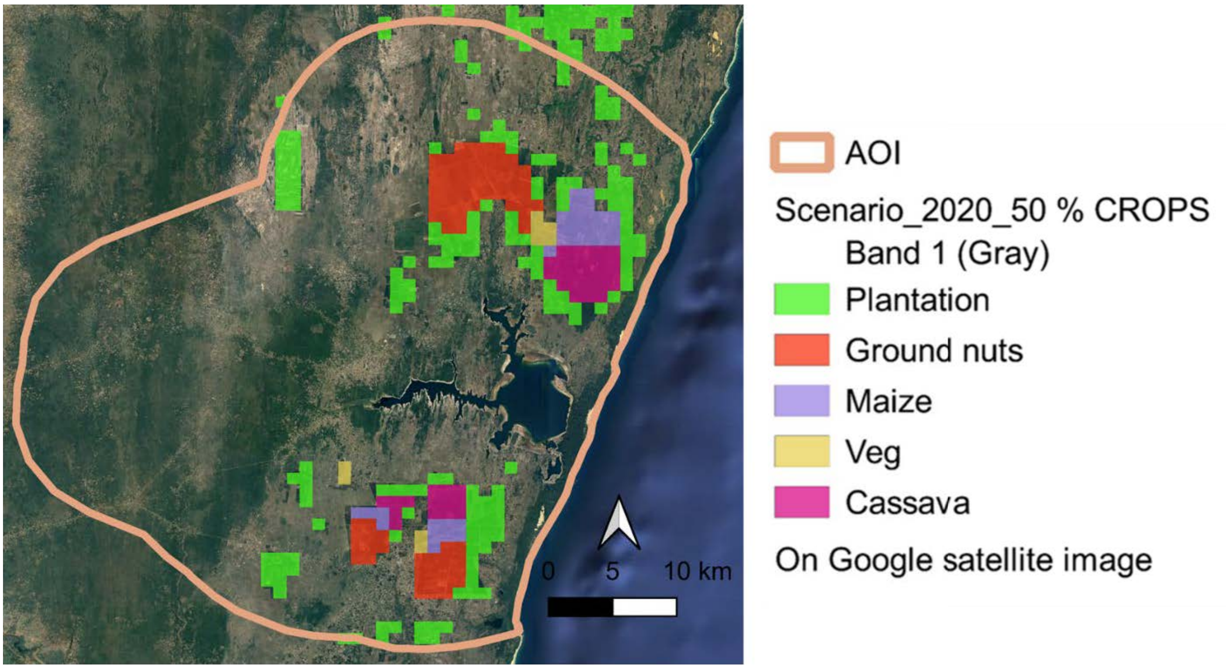


Figure 4-7 Spatial allocation of the proportion of different crop types per traditional community area within the "change area"

4.6 SUMMARY

A course scale time slice series was developed to reflect past-to-present LULC change. Declines in grassland cover and increases in development (low density residential and subsistence agriculture) and plantations were dominant trends and associated with declines in wetlands and open water bodies.

Interactive workshops were used as stakeholder engagement mechanism with TCs, which act as community representatives. Stakeholder engagement is a foundation of good land use governance (Aucamp, 2019; Makaya et al., 2020), through the creation of a framework in which actors share views, knowledge, and information to yield fair outcomes. The workshops were designed to identify key talking points or challenges; validate economic activities; and solicit alternative future land use scenarios from each TC, and which could be consolidated into feasible scenarios for hydrological and economic modelling under different future climate storylines.

The workshops validated cultivation, forestry, conservation/ecotourism, natural resource use, and livestock farming as major current land uses and livelihood sources for the area. Four key concerns were distilled from workshops that were used to assess the relative success of the different future land use scenarios in addressing these issues (CHAPTER 10: and CHAPTER 11:). Water security was the primary concern identified. Unemployment, and the associated poor economic status, were also prioritised, as well as a range of issues that can be grouped under “ecosystem integrity” as this impacts on livelihoods.

When deciding on the scenarios to run, the hydrological team recommended a focus on one land use change at a time to assess its impact on the hydrological cycle. Additional commodity-based activities could be integrated into the economic model. Various scenarios were chosen for modelling, including a SQ scenario as a baseline, under the assumption of no changes into the future. A “No Forestry” scenario from the “past to current” was included to illustrate the impact of forestry on water resources between 1959 and 2020. This aimed to underscore how land use decisions made long ago affected water resources today, as will today's decisions impact future water security. The remaining scenarios were consolidated from emergent preferences and concerns from the workshops.

CHAPTER 5: REGIONAL CLIMATE PROCESSES AND PLAUSIBLE FUTURE CLIMATE SCENARIOS

By: RC Blamey, N Mpungose, W Thoithi, and CJC Reason

This chapter addresses Aim 2: *To deliver a significantly new understanding of the regional climate processes for the northern part of the KZN and how these might change under climate change*; as well as Aim 4: *Identify current as well as plausible future scenarios of climate and land use.*

5.1 INTRODUCTION

At the broader scale, in relation to climate processes, the project study area covered the UM catchments. The region represents a transition zone between tropical and subtropical ecosystems found along the Indian Ocean seaboard of Southern Africa (Mpungose et al., 2022). It is bordered to the west by the 400-800 m high Lebombo Mountain Range in eSwatini and central KZN and to the east by the Northern Agulhas Current. The UM area provides an appropriate regional scale context from which to assess climatic parameters for the Lake Sibaya study area.

For the purposes of this project, the rainfall and temperature characteristics for the study area from past to present are described. The focus was on the characterisation of the regional rainfall patterns, extreme events, and their interannual variability as well as heatwaves. Climate data sets from past to present were also provided in a spatially gridded format to input into the hydrological models for which a methodology and “constructing” of two alternative climate future scenarios were achieved. These were used to test the relative impacts of changes in climate and land use on the hydrological and economic outcomes of the region. Importantly the construction of climate data series used for past to current in the hydrological models had to be consistent with what is available to determine potential future scenarios.

5.2 EXTREME RAINFALL EVENTS

5.2.1 Background

A major contribution to this project is an analysis of the UM catchments area. Most of the work has now been published by members of the project team in (Mpungose et al., 2022) which is reproduced and adapted below.

As with almost all of Southern Africa, the UM area is classified as a summer rainfall region and is prone to drought and occasional flood events. Some of this variability may be associated with ENSO which impacts strongly over the sub-continent in summer (Lindesay, 1988, Nicholson and Kim, 1997, Reason et al., 2000, Blamey and Reason, 2023), typically leading to below (above) average rainfall totals during El Niño (La Niña) episodes. On longer time scales, northern KZN experienced below average rainfall in almost all summers during 2001 to 2016 (see Fig. 5 in Blamey et al. (2018)). As described in this report, water levels in Lake Sibaya have decreased substantially in the last two decades which has exposed large areas that used to be under water. A component of this project aimed to enhance the understanding of the relative drivers of the long-term decline in lake levels, comparing the relative impacts of LULC change and changes in precipitation-evaporation patterns. What is known is that occasional extreme rainfall events may directly impact on lake levels (Bruton, 1979b). The enhancement of our understanding of extreme events in the MCP region is crucial for the assessment of climate risks faced by vulnerable rural communities. The exploration of the links between these events and groundwater lake levels is vital for informed water resource management and conservation efforts to protect the unique biodiversity and associated benefits crucial for livelihoods. This understanding also forms the basis for the evaluation of potential future changes and their implications for the groundwater resources relied upon by communities.

5.2.2 Data and Methods

CHIRPS rainfall data (Funk et al., 2015) was used to investigate daily precipitation extremes over the UM area. These data merge satellite-derived rainfall with gauge records to provide robust estimates of daily rainfall on a quasi-global (50°S - 50°N) 0.05° resolution grid for the period 1981 to near present. Various studies have used CHIRPS in comparison with other products to investigate rainfall variability and evaluate their performance over East Africa (Toté et al., 2015, Dinku et al., 2018, Gebrechorkos et al., 2018). In general, CHIRPS showed a high correlation with station data and lower regional biases, moreover, observed daily and decadal rainfall was well represented by CHIRPS in most validation regions of East Africa compared to other products (Gebrechorkos et al., 2018). For Southern Africa, CHIRPS has been found to compare well with observations over northern Namibia and Botswana (Moses et al., 2021), the Eastern Cape province of South Africa (Mahlalela et al., 2020) and north-western South Africa (Thoithi et al., 2021).

The detection and ranking of daily extreme rainfall events are performed using a method initially proposed by Hart and Grumm (2001) and modified by Ramos et al. (2014, 2017) for the Iberian Peninsula. This method is appropriate for the UM area because it considers not only the precipitation intensity but also its spatial extent, i.e. the area affected by the event. Precipitation anomalies above two standard deviations, which corresponds approximately to the 95th percentile, are calculated for each day and each grid-point. For the extended summer season (October-March), only grid points with wet days were considered (here defined as a day receiving rainfall amounts above 1 mm day^{-1}). A seven-day running mean is applied to the 95th percentile for each grid point to smooth the daily mean and the noisy climatological time series. To calculate the anomalies (N) the smoothed 95th percentile (μ) values are subtracted from daily rainfall totals as follows:

$$N = precip_{c,i,j} - \mu_{c,i,j} \qquad \text{5-1}$$

Extreme events are ranked based on their magnitude (R) given by an index that is obtained as the product:

$$R = N.M \qquad \text{5-2}$$

Here, N is the percentage of grid points with anomalies above the 95th percentile in the daily rainfall record and M is the mean values of these anomalies for all such grid points.

This ranking method is sensitive to the smoothing filter such that some events may appear in different rank order if a 21-day running mean (instead of a seven-day) is applied (Ramos et al., 2014); however, this does not significantly alter the actual days included in the top 50. Additionally, some events which had severe socio-economic impacts over the region may not appear in the top rank and vice versa, i.e. events with no known severe impacts may be ranked higher. This method has also been successfully applied for the Limpopo River Basin of Southern Africa in Rapolaki et al. (2019). Two thresholds were used to define rainy days following Rapolaki et al. (2019).

In addition to these extreme events, moderate rain day frequency (≥10 mm) and heavy rain day frequency (≥25 mm) were determined by computing a percentage of grid points exceeding these thresholds within the study region. Days with at least 25% (10%) grid points exceeding the 10 mm (25 mm) thresholds were then selected for time series analysis.

ERA-5 reanalysis data (0.25° resolution) (Hersbach et al., 2020) were used to examine circulation patterns associated with the events. Moisture fluxes at a particular level were computed from the product of the specific humidity and the wind at that level. To assess areas of relative uplift associated with the events, the 500 hPa vertical velocity was used. SST anomalies were assessed using the National Oceanic and Atmospheric Administration (NOAA) daily high-resolution-blended analyses which have a spatial grid resolution of 0.25° (Reynolds et al., 2007). In addition to the reanalyses, gridded satellite data (GridSat-B1), and synoptic weather charts from the South African Weather Service, were used to identify the weather system such as cut-off lows and mesoscale convective systems (MCSs) associated with the top 50 extreme rainfall events during 1984 to 2019. Output from the tracking OLR algorithm of Hart et al. (2012) was used to identify tropical-extratropical cloud bands while the International Best Track Archive for Climate Stewardship (IBTrACS) data (Knapp et al., 2010) were used to identify tropical lows and tropical cyclones.

5.2.3 Results

5.2.3.1 Rainfall patterns

To put the results for the Maputaland Coastal Plain (MCP) study area into context within located north of the coastal region in South Africa that can receive a significant amount of rainfall during the summer half of the year from ridging anticyclones (Weldon and Reason, 2013; Engelbrecht et al., 2015; Ndarana et al., 2020) but south of the zone in Mozambique which experiences rainfall from tropical storms/cyclones either making landfall or passing sufficiently close by in the southern Mozambique Channel, the MCP area is a transition zone meteorologically. Climatological rainfall maps (Figure 5-1) show that the coastal MCP area is drier than the rest of the South African east coast to its south in both early and late summer as well as the Mozambique coast to its north in late summer. In general, one would expect a subtropical east coast to receive more rainfall the closer to the tropics it lies and thus the relatively dry MCP compared to southern KZN in terms of seasonal totals seems counter-intuitive. This highlights the need for more detailed studies within the focus region for this study.

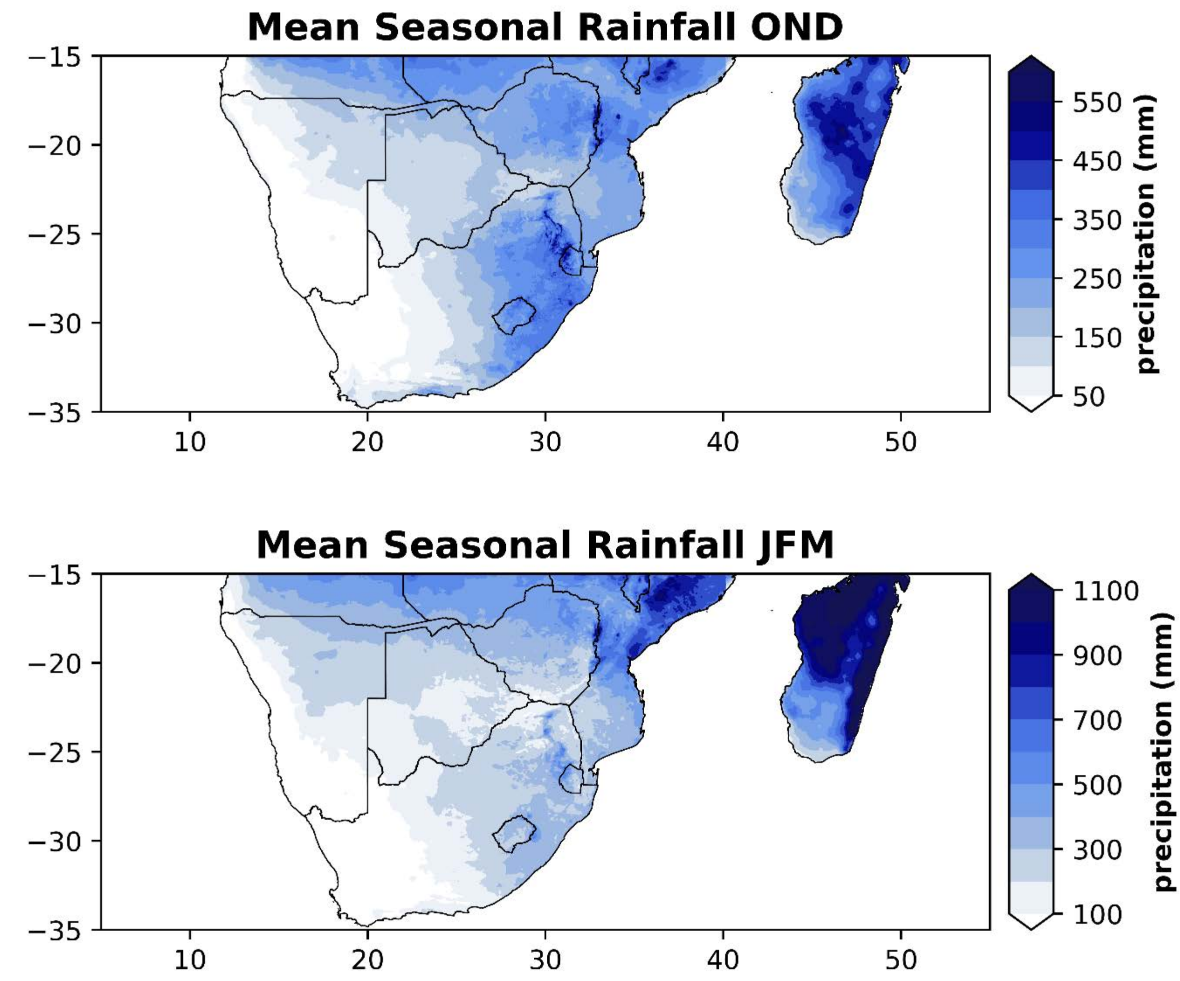


Figure 5-1. Mean seasonal rainfall derived from CHIRPS data (mm) for (top) OND and (bottom) JFM

An analysis of rain day frequencies gives further information. Figure 5-2 plots the average occurrence of moderate and heavy rainfall days across subtropical Southern Africa in early (OND) and late (JFM) summer as well as light (2-9 mm) rain days and those which are considered dry (0-1 mm). Over the MCP area, OND days with rain are more often in the light category but in JFM (Figure 5-2 b), moderate wet days are about as common as light. North of the MCP, in Mozambique, there are clearly more moderate than light rain days in JFM. The MCP area is also like Southern Mozambique, and different from inland areas of South Africa to its west or to southern KZN, in the greater occurrence of dry days particularly in JFM, which helps explain its relative dryness in terms of totals. At the other end of the spectrum, there are very few, if any, heavy rainfall days on average in OND except for a few isolated pockets near high topography in northern South Africa and patches along the east coast of Madagascar (Figure 5-2). These regions, now with most of Madagascar and a large part of Mozambique included, more obviously show greater numbers of heavy rain days than elsewhere in JFM (Figure 5-2) due to increased tropical low activity, including land-falling or nearby tropical cyclones in the case of Madagascar, and infrequently, Mozambique. Only the northwest of the MCP area experiences 5-10 heavy rainfall days on average. Note that these heavy rainfall days also include the extreme event days analysed in the next section. However, while it may give the impression that heavy rainfall days are typically not very important for the MCP area, when they do occur, the impact on the hydrology may be vital. Having provided the background rainfall climatology, the next section analyses extreme rainfall events which occurred in the last few decades.

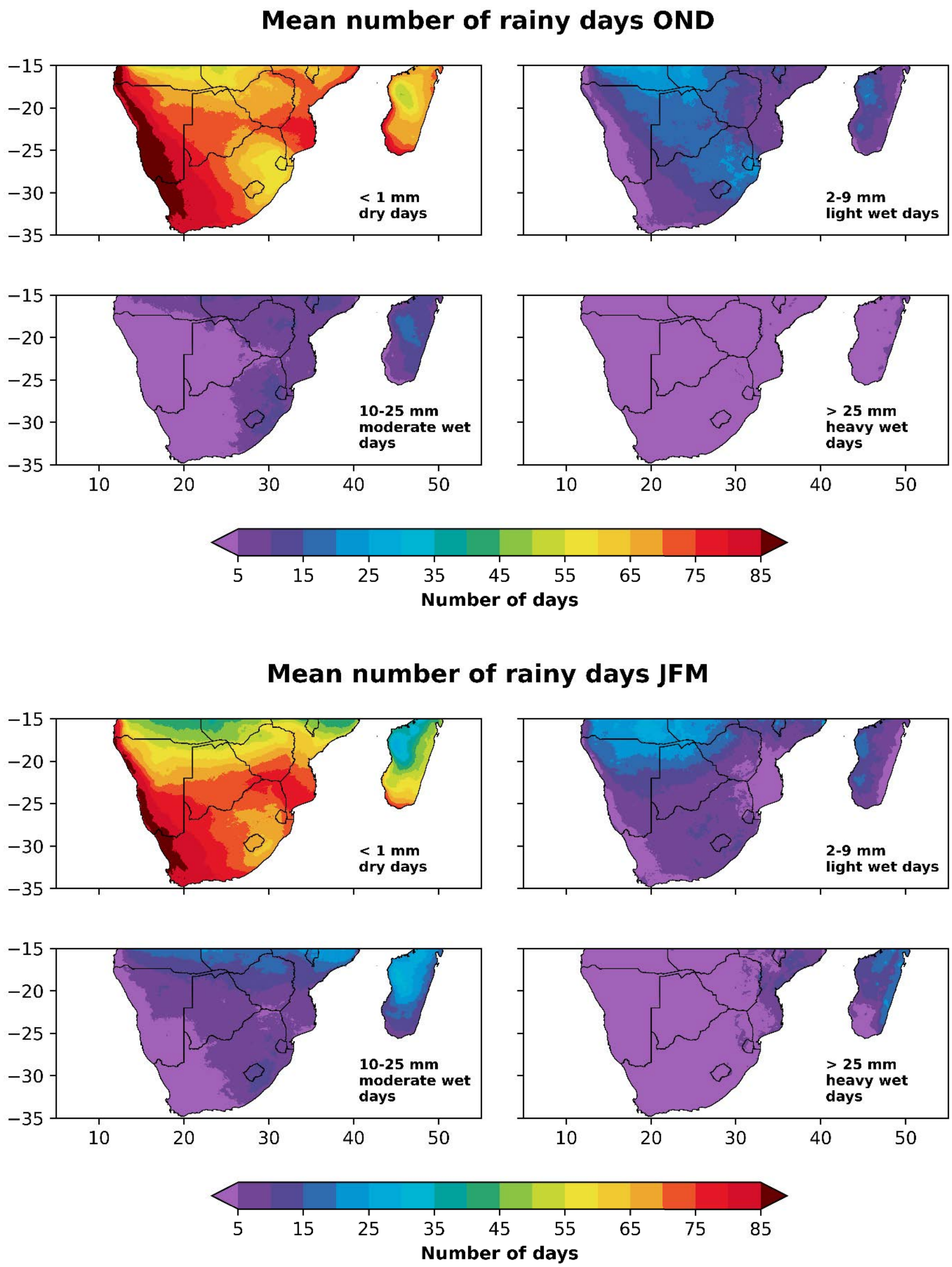


Figure 5-2. Mean number of dry, light, moderate and heavy rain days derived CHIRPS data for (top)) OND and (bottom) JFM

5.2.3.2 Spatial distributions of the extreme events and synoptic classification

Figure 5-3 shows the spatial rainfall distributions over subtropical Southern Africa of the top 20 events calculated for the UM catchment areas in the last few decades. In each case, the maximum daily rainfall and the associated synoptic type is given in the bottom right-hand corner. Note that this maximum is for a particular grid point somewhere in the UM area so a higher maximum does not mean that the event concerned will be ranked above another event whose maximum grid point rainfall is lower because, as described in the Data and Methods section, the ranking is based on the product of the percentage of grid points with rainfall above the 95th percentile and the mean anomaly value for those grid points. Also note that these are daily extremes so in the case of the top two events, they both correspond to the same system, namely Tropical Storm Domoina.

There are only three cloud band cases in the top 20 which, as seen in Figure 5-3, is a rather smaller percentage than in the top 50. The NW-SE orientation of these systems from an easterly disturbance somewhere over tropical Southern Africa to a westerly disturbance passing south of the continent means that substantial rainfall can also occur over semi-arid areas such as the Kalahari Desert in Botswana and north-central South Africa as evident for events #7, #13, #16. Cut-off lows are also very large systems and can also cause large amounts of rain over the dry north-western interior of the domain plotted in Figure 5-3 as can be seen in several cases. On the other hand, tropical lows tend to be smaller in scale and are not often associated with much rainfall a long way inland from the MCP unless other synoptics are favourable. MCSs also typically lead to more spatially confined rainfall. Tropical Storm Domoina (#1, #2) tracked through the MCP so its outer rain bands led to very heavy rainfall over not only the MCP but also almost all of KZN and the escarpment. The escarpment area also received very heavy rains in many of the other 18 events plotted in Figure 5-3 as well as the coastal strip in the MCS event and most of the tropical low cases.

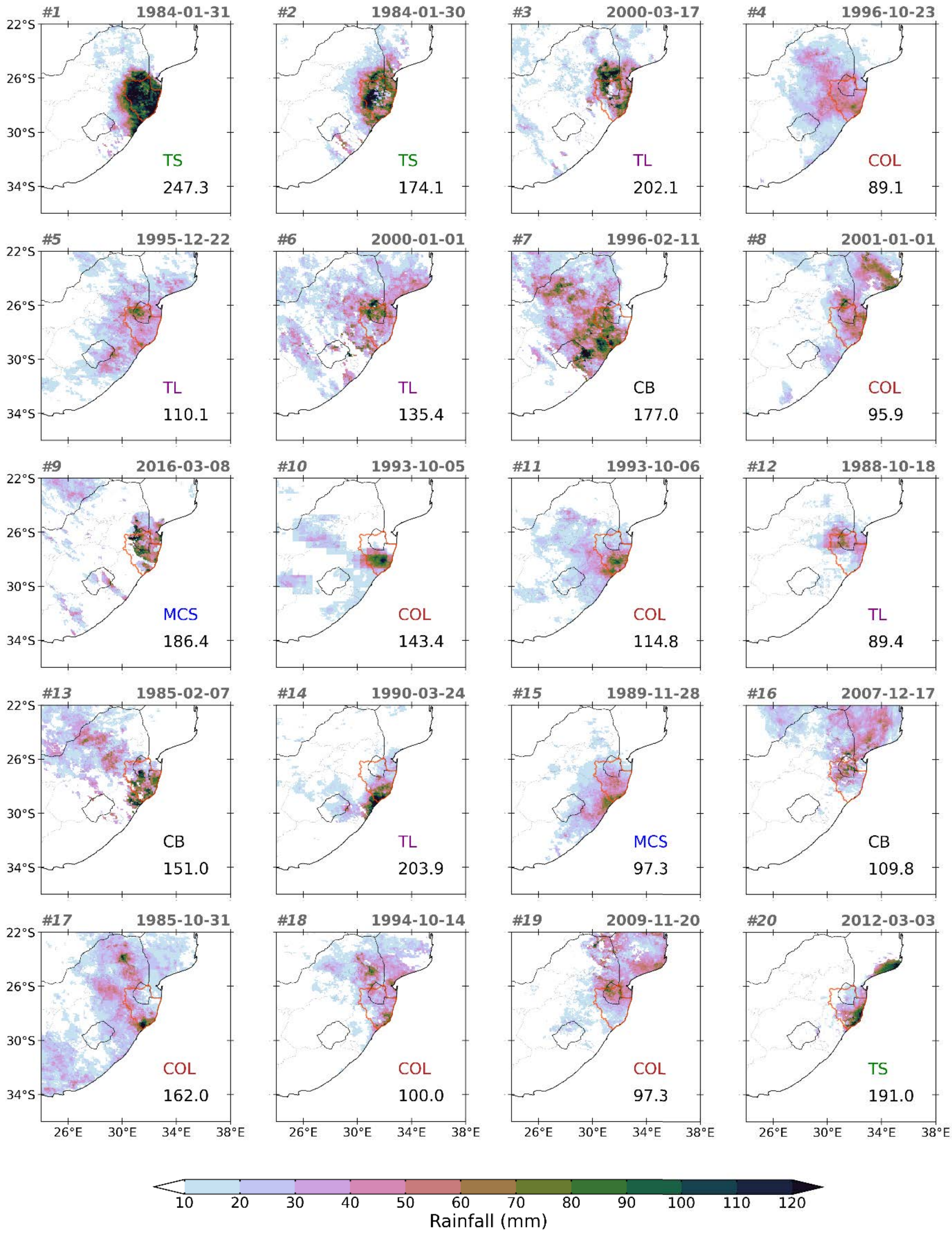


Figure 5-3. Spatial rainfall distributions of the top 20 extreme rainfall days along with the responsible weather system and the maximum recorded rainfall

5.2.3.3 Seasonality cycle of event occurrence and synoptic type

Monthly rainfall totals spatially averaged over the MCP increase each month from the winter minimum (not shown) through early summer to a peak in January after which the totals decrease rapidly (Figure 5-4). On average, April rainfall (not shown) is well below half of that for March. By contrast, the monthly distribution of the top 50 events in Figure 5-4 shows relative peaks in early summer (November) and late summer (March) with a relative minimum in December (none are found during the dry winter half of the year for the periods of this study). A limitation of this analysis is that it does not capture extreme events outside of the typical OND/JFM seasons which may be important to hydrological processes within the study area.

There is a sharp increase in the number of events after the December minimum with the March maximum recording more than three times as many events during the period. While rainfall totals in March are less than all the other summer months except October, it is the month of maximum SST, favouring tropical low development and deep convection. Morake et al. (2021) found that February and March have the largest number of days of favourable CAPE (over 1 000 Jkg^{-1}) over the region extending from the southern Mozambique Channel towards southern Mozambique/northern KZN. Indeed Figure 5-4 shows that more tropical lows occur in this month over the MCP than in any other month, consistent with what Rapolaki et al. (2019) found for the Limpopo River Basin. Only a few tropical cyclone cases have affected the MCP; however, Mavume et al. (2009) found that intense tropical cyclones in the southern Mozambique Channel were more common later in the cyclone season (January to March). MCS numbers also peak in March with a weaker secondary peak in November. On the other hand, cut-off lows peak in October and sharply decrease thereafter with none contributing in February and March. This seasonality is consistent with Singleton and Reason (2007) who found that cut-off lows in the 20-30°S, 27-40°E region within which the MCP falls were more common in early than in late summer. Cloud bands are more evenly distributed throughout the season but with a peak in February and a weaker peak in November. This February peak in cloud bands is consistent with Hart et al. (2013) and Rapolaki et al. (2019) for South Africa as a whole, and the LRB respectively. Because of this intra-seasonal variability in the frequency of weather systems which tend to produce heavy rainfall, the average monthly distribution of extreme events is not in phase with that in monthly rainfall totals.

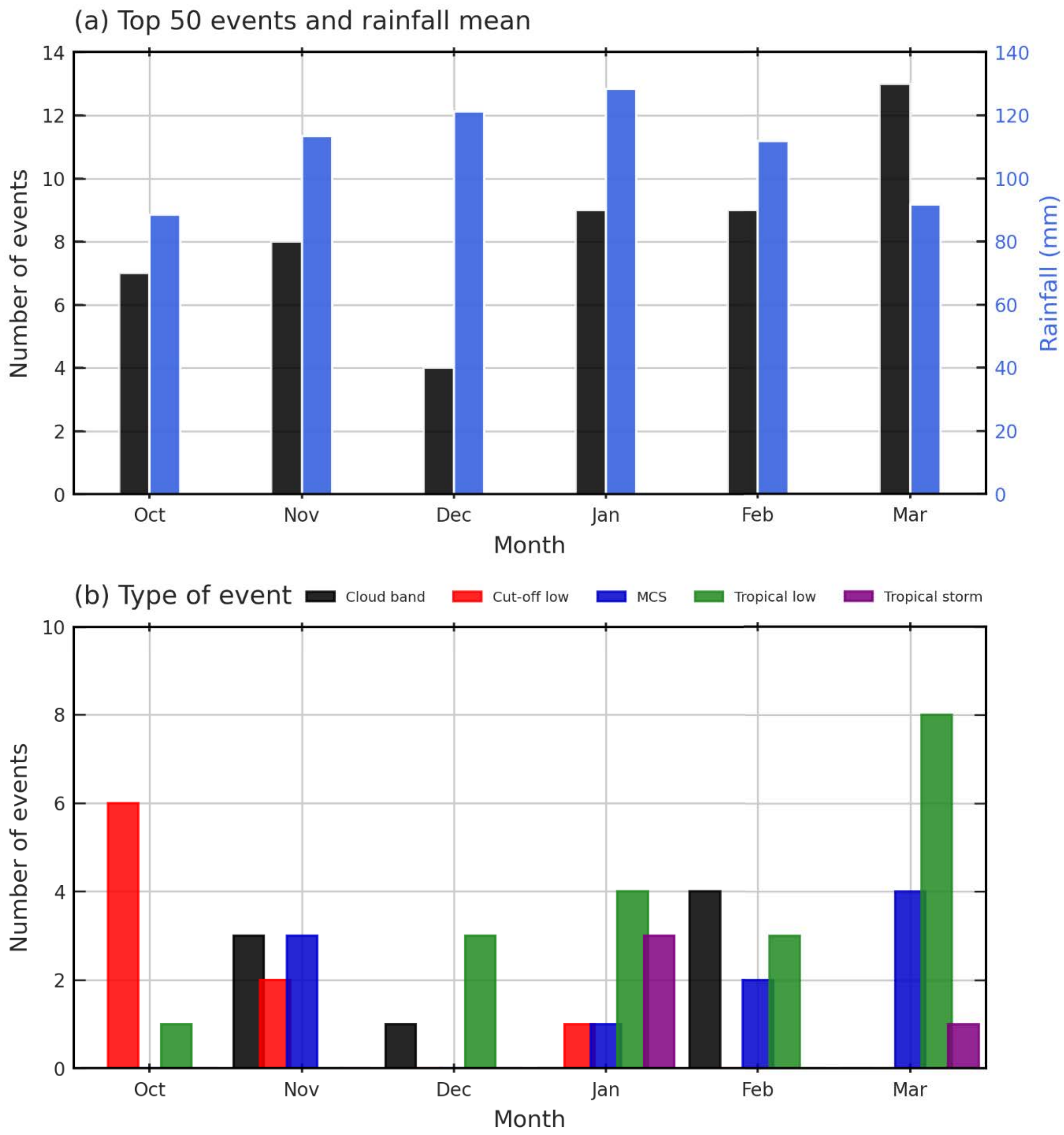


Figure 5-4. Monthly distribution of rainfall amounts (blue bars) and the top 50 extreme rainfall events (black bars) (a) and the responsible weather systems (b) during ONDJFM

5.2.3.4 Interannual variability

Standardised rainfall anomalies for the UM area and of the numbers of extreme rainfall events are compared for the early (OND; Figure 5-5) and late (JFM; Figure 5-5) summer, to help understand the potential impact of extreme rainfall events on the interannual variability of summer rainfall. There is substantial interannual variability in both OND and JFM rainfall totals as well as extreme events. However, JFM seasons of anomalously low or high rainfall totals are not necessarily preceded by similarly dry or wet OND seasons, suggesting that, for the entire summer, the early and late summer anomalies may sometimes cancel out to some extent. For example, OND 1990 was somewhat dry whereas JFM 1991 was very wet and OND 2006 was very wet and JFM 2007 very dry.

For OND (Figure 5-5), the extreme events are both fewer as a proportion of the top 50 as well as more clumped compared to JFM (Figure 5-5). None occurred during the last 10 OND seasons or middle five and most happened during the nine seasons of 1993 to 2001. Although there are a few wet seasons with no extreme events, there is a relatively good correlation between rainfall totals and extreme event occurrence (r = 0.51, significant at 95%). An even higher correlation is found between extreme event occurrence and ≥ 25 mm rain day counts (r = 0.59). OND seasons with strong positive rainfall anomalies (Figure 5-5 a) (1989, 1995, 1998, 1999, 2000, 2006) also had mainly an above average number of ≥ 10 mm and ≥ 25 mm rain days and several extreme events (Figure 5-5 b, c). Correlations with OND rainfall totals are higher than for extreme event occurrence (r = 0.86 for days ≥ 10 mm, r = 0.81 for days ≥ 25 mm, both significant at 95%).

OND 1989, 1993 and 2000 stand out as seasons with at least three extreme events with 1989 (2000) as the wettest (fourth wettest) while OND 1993 also received well above average rainfall. However, anomalously wet 1998 and 1999 both had no extreme events (Figure 5-5 b, c). These results are consistent with the findings of Rapolaki et al. (2019) for the Limpopo River Basin where anomalously wet seasons were due to both an increased frequency and intensity of rainy days and extreme events. Most of the seven anomalously wet OND seasons correspond to a La Niña event (Figure 5-5 d) but 1989 was neutral. The strong negative rainfall anomalies during the early summers of 1991, 2002, 2004, 2014, 2015 and 2018 occurred during El Niño events, whereas 2003 was neutral and 2011 was La Niña (Figure 5-5 d). This anomalously dry 2011 season (both in terms of totals and rain day counts) as well as OND 2006, which was El Niño but experienced very wet conditions with well above average numbers of rainy days (both thresholds) are analysed in terms of their circulation anomalies in the next section to see why these rainfall anomalies may have occurred. Note that the expected ENSO-rainfall impact over eastern South Africa is below average summer rainfall during El Niño and above average during La Niña (Lindesay, 1988; Reason et al., 2000). Correlations between the ONI ENSO index and rainfall metrics over the UM region for OND are relatively high (respectively, r = -0.45, -0.43, -0.39 all significant at 95% for rainfall totals, ≥ 10 mm and ≥ 25 mm rain day counts).

However, no significant correlation is found between ENSO and extreme event occurrence (r = -0.11). While the asymmetry between seven extreme events happening during La Niña seasons and only three during El Niño is consistent with the general expectation of wetter (drier) summers during La Niña (El Niño), it must be noted that four of the seven La Niña extreme events occurred in OND 2000 (Figure 5-5 cd). Furthermore, there were no extreme events during any of the OND 2010, 2011, 2016, 2017 La Niña seasons, hence the lack of a significant ENSO correlation for OND. Nor are any significant correlations found between any of the rainfall metrics and the South Indian Ocean subtropical dipole or with the Southern Annular Mode, except between the latter and ≥10 mm rain day counts (r = 0.33, 95% significant).

Comparison of Figure 5-5a and Figure 5-6 a indicates that OND rainfall anomalies tend to be greater in magnitude throughout the record than JFM. For JFM, ten of the twelve 2007 to 2018 summers were dry with only slightly above average rainfall in 2009 and 2013. After this decadal dry period, JFM 2019 received ~0.6 standard deviation above average rain. As a result, unlike for OND, the JFM record (Figure 5-6) suggests a declining trend in rainfall totals; however, this is not significant when a Mann-Kendall test is used. This extended dry period seems unusual since seven of these 13 seasons were La Niña summers (Figure 5-6 d**)** when much of Southern Africa generally experiences above average rainfall (Lindesay, 1988; Reason et al., 2000). As a result, the JFM relationship between rainfall totals and ENSO (r = -0.28) throughout the 36-year record is much weaker than for OND and is not significant. No correlation was found for > 10 mm rain day counts either. However, a moderate correlation is found between ENSO and extreme event occurrence (r = -0.36, significant at 95%). Figures. 7 c and d indicate that 18 (3) extreme events occurred during La Niña (El Niño) JFMs; however, half the La Niña cases occurred during only two seasons (JFM 1996, 2000) and thus the correlation, while significant, is not very large. A much stronger correlation with ENSO is found for ≥ 25 mm rain day counts (r = -0.49), significant at 95%. No significant correlations were found for any of the rainfall metrics and either the Southern Annular Mode or the South Indian Ocean subtropical dipole. However, JFM extreme event frequency is significantly correlated (r = 0.35-0.40) with SST off the coast of northern Namibia/southern Angola and in the southern Agulhas Current/Agulhas Return Current region. The former region has previously been linked with extreme rainfall over southern Mozambique/north-eastern South Africa (Hansingo and Reason, 2009; Manhique et al., 2015) while warm SST anomalies in the southern Agulhas/Agulhas Return current have been previously associated with increased summer rainfall over eastern South Africa (Mason, 1995; Reason, 1999). A critical next step is the assessment of these long-term trends more specifically from the Lake Sibaya study area, and the incorporation of data from the increased network of rainfall stations implemented by NRF-SAEON to validate remotely sensed products.

The 2007 to 2018 period would have been even drier were it not for five extreme events (Figure 5-5 c) of which two are ranked in the top 20, pointing to their role in potentially mitigating some seasons against a severe drought. Thus, the MCS event in March 2016 (ranked as the ninth most extreme event in the record) helped prevent the mature phase JFM 2016 El Niño summer from being as severely dry in the UM area as it was elsewhere in subtropical Southern Africa (Blamey et al., 2018). The relative contribution of this MCS event is further highlighted by the fact that JFM 2016 experienced well below average numbers of moderate or heavy rain days (Figure 5-5 b).

JFM 1984, 1985, 1991, 1996, and 2000 all experienced two or more extreme events as well as large positive rainfall anomalies while 2004 and 2006 were also very wet and experienced one extreme event (Figure 5-6 a and c). Note that very wet 1984 only received three extreme event days; however, two of these were the top two in the entire record (Tropical Storm Domoina). Other categories of rain event also made important contributions during these anomalously wet seasons as can be seen for 2000 and 2006 – the former has the largest number of ≥ 25 mm days in the record while the latter only experienced one extreme event but had well above average counts of ≥ 10 mm and ≥ 25 mm rain days (Figure 5-6b). Overall, rainfall totals and extreme event occurrence are well correlated (r = 0.59, significant at 95%). Correlations of rainfall totals with ≥ 10 mm rain day (r = 0.75) and ≥ 25 mm rain day counts (r = 0.79) are somewhat higher than those for extreme event occurrence. Given that rain-bearing systems in this region are essentially convective, these relatively high correlations between rainfall totals and days with at least 10 mm or more of rain are not surprising.

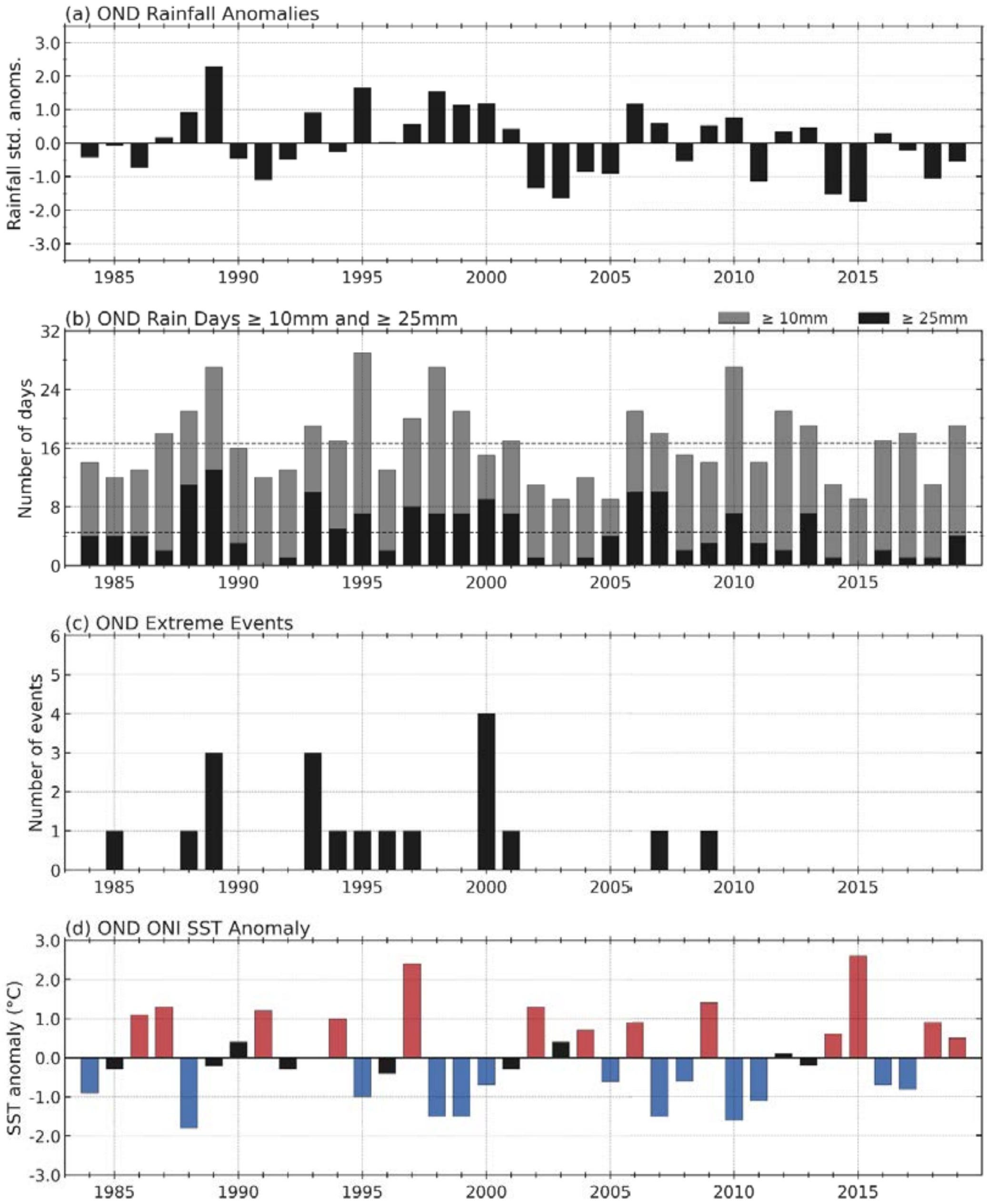


Figure 5-5. OND standardized rainfall anomalies (a), number of moderate (≥ 10 mm) and heavy (≥ 25 mm) rain days (b), number of extreme events (c), and Niño 3.4 index (d) for 1984 to 2019

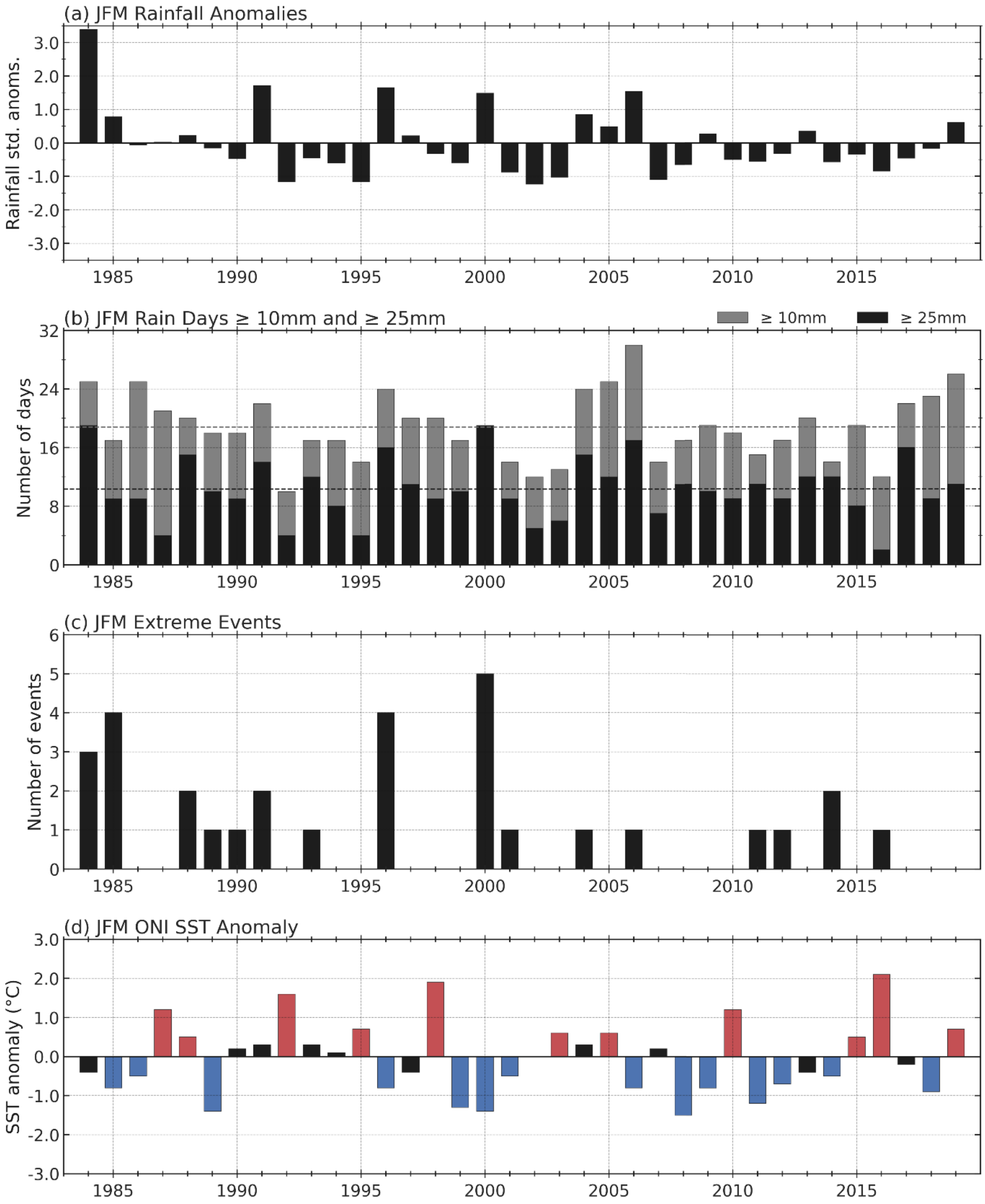


Figure 5-6. As for Figure 5-5 except for JFM

5.2.3.5 Some anomalous cases

5.2.3.5.1 Anomalously wet OND 2006

Circulation anomalies during the El Niño of OND 2006, which was anomalously wet with above average numbers of both categories of rain days, are now examined. Relative to climatology, Figure 5-7 shows enhanced easterly moisture flux from the tropical western Indian Ocean that feed more moisture into northern Madagascar right across the northern Mozambique Channel towards northern Mozambique. Over southern Tanzania/far northern Mozambique, there were south-westerly anomalies in opposition to the climatological flux, which lead to moisture convergence there. Similarly, the southerly moisture flux anomalies over northern South Africa, Botswana, and Zimbabwe (Figure 5-7 **a**) oppose the mean flux, with the result of low-level moisture convergence near the KZN coast, favourable for wetter conditions during this season. Comparing Figure 5-7a with the El Niño composite (Figure 5-7b) suggests that the main difference in OND 2006 was stronger southerly anomalies over northern South Africa and Botswana; the lack of strong divergence in the southern Mozambique Channel; and the presence of easterly anomalies over northern Madagascar in the northern Mozambique Channel. The latter may have been particularly important for the development of wetter conditions since the Mozambique Channel and, indeed, the entire South West Indian Ocean experienced above average SST during OND 2006 (not shown). Warm SST anomalies in this region have previously been highlighted as favourable for wetter summers over eastern and northern South Africa (Reason and Mulenga, 1999) and in the tendency for cloud bands to be located over the landmass rather than offshore (Fauchereau et al., 2009).

Obvious differences appear in comparison of the mid-level omega fields which show an enhanced subsidence over most of subtropical Southern Africa in the El Niño composite (Figure 5-8 b) but in the case of OND 2006, relatively strong uplift over most of northern South Africa, which includes parts of the MCP area (Figure 5-8 a). The NW-SE orientation of these negative omega anomalies which stretch from southern Angola diagonally across subtropical Southern Africa and out over the South West Indian Ocean suggests a cloud band type pattern. Typically, during El Niño OND seasons, there are significantly fewer cloud bands over eastern South Africa/southern Mozambique while in OND 2006, cloud band numbers were close to average (Hart et al., 2018). Furthermore, the number of long-lived MCSs over eastern South Africa was slightly above average during OND 2006 (Morake et al., 2021), consistent with this season being wetter than average with above average heavy rainfall days.

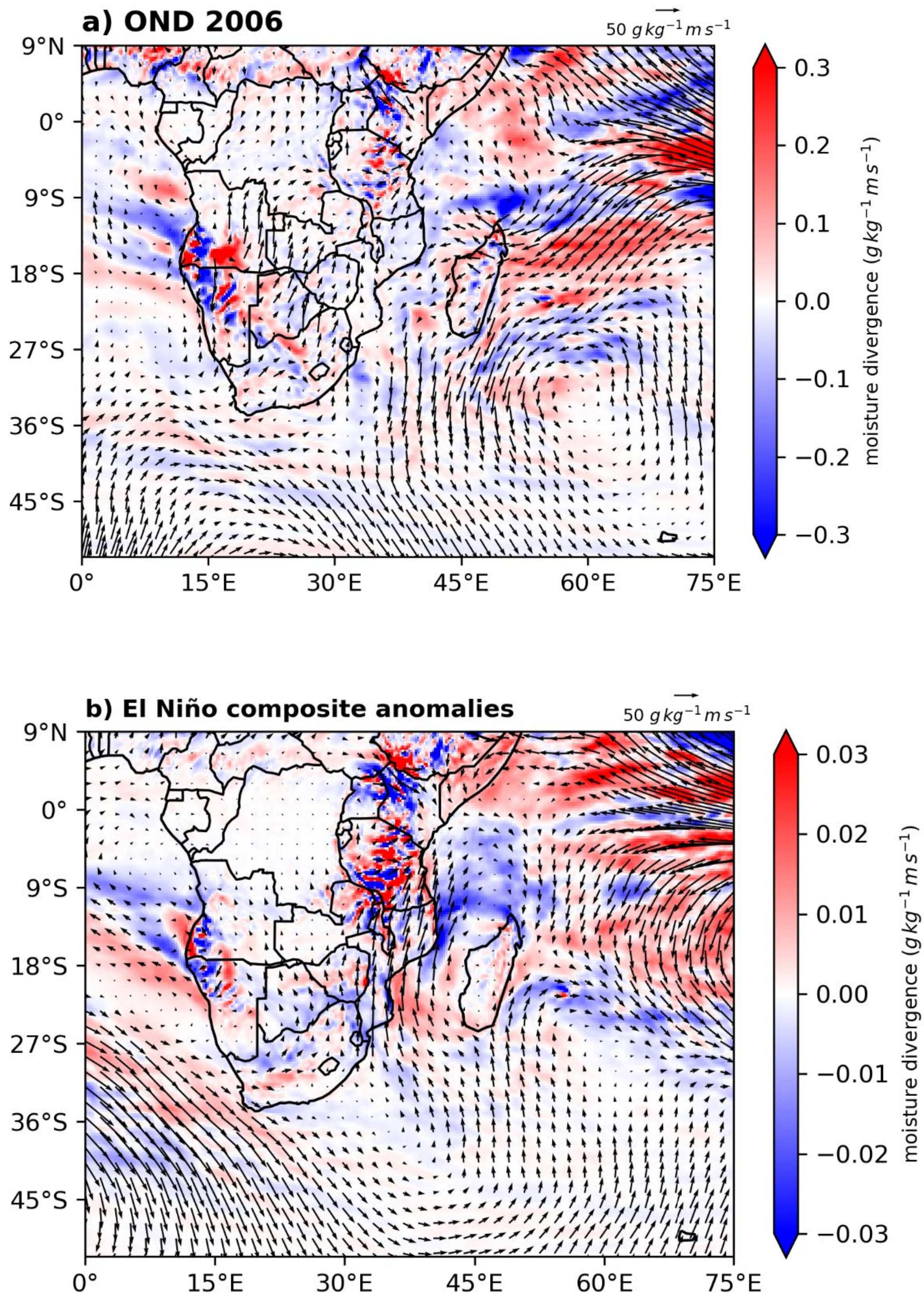


Figure 5-7. 850 hPa moisture flux and divergence anomalies for a) OND 2006 and b) OND El Niño composite

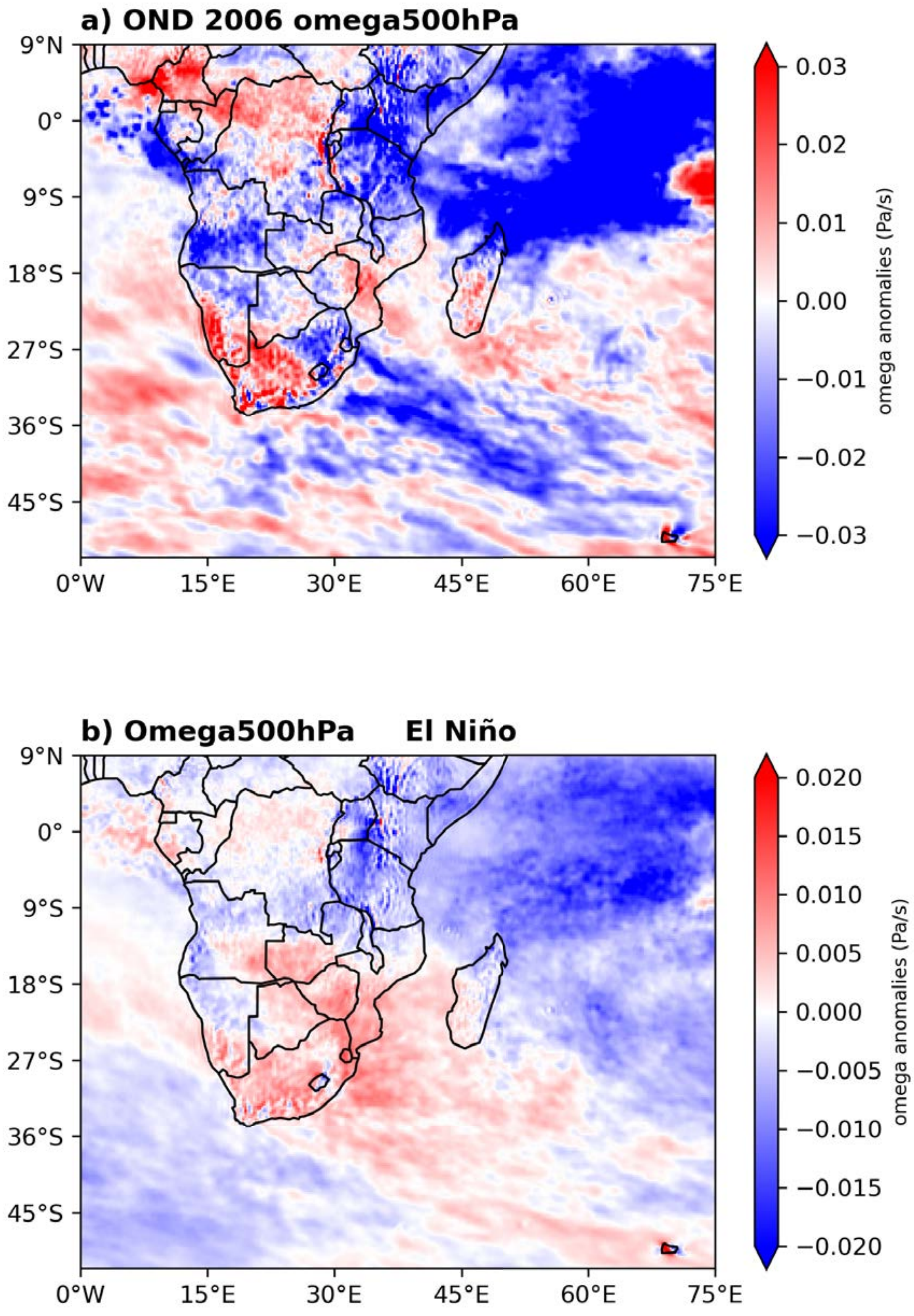


Figure 5-8. As for Figure 5-7 except omega at 500 hPa

5.2.3.5.2 Anomalously dry OND 2011

OND 2011, which experienced relatively strong La Niña conditions according to the ONI, received well below average rainfall, and below average numbers of both ≥ 10 mm and ≥ 25 mm rain days (Figure 5-5 ab). Cloud band numbers were slightly below average and no extreme events were experienced. Compared to climatology, Figure 5-9 a shows a strong cyclonic anomaly south of South Africa which leads to westerly anomalies and low-level divergence over the southern half of South Africa. These types of anomalies imply a greater presence of cooler and dry South Atlantic air over the country associated with dry summers over north-eastern South Africa (Mulenga et al., 2003). This cyclonic anomaly is not present in the La Niña composite (Figure 5-9 b) when wetter conditions are expected. Westerly anomalies are also apparent over and east of Madagascar and the southern Mozambique Channel in OND 2011, the implication of which is less moisture flux from this source towards subtropical Southern Africa. This pattern is also not apparent in the La Niña composite (Figure 5-9 b). In this composite, there are enhanced north-easterly anomalies over northern Mozambique and the coastal ocean which implies more NE monsoonal air towards these areas whereas, in OND 2011, the flow here is close to climatology (Figure 5-9 a). Over the MCP area, there is relative moisture flux divergence in OND 2011, unfavourable for rainfall, unlike in the La Niña composite.

SST anomalies during OND 2011 (not shown) were not as expected over the Indian Ocean during this phase of a La Niña event (Reason et al., 2000) since almost the entire basin showed warm anomalies. An exception was the Agulhas Current region which experienced cool SST anomalies, unfavourable for summer rainfall over northern and eastern South Africa (Mason, 1995; Reason and Mulenga, 1999). Although Figure 5-10 a shows some areas of relative uplift near the coast of the UM area, much of eastern South Africa and the Mozambique Channel, as well as the oceanic areas to its south, show relatively strong positive omega anomalies. The positive anomalies over eastern South Africa extend to the northwest (central northern Namibia) while there is a swath of negative anomalies further north. These patterns suggest that conditions for convective storms may have been more favourable further north over Zimbabwe, Limpopo and southern-central Mozambique than the MCP area of interest. By contrast, a broad area of relative uplift exists across south-eastern Africa during the La Niña composite (Figure 5-10 b). Thus, compared to what typically happens during La Niña, circulation and regional SST patterns were unfavourable for good rainfall during OND 2011.

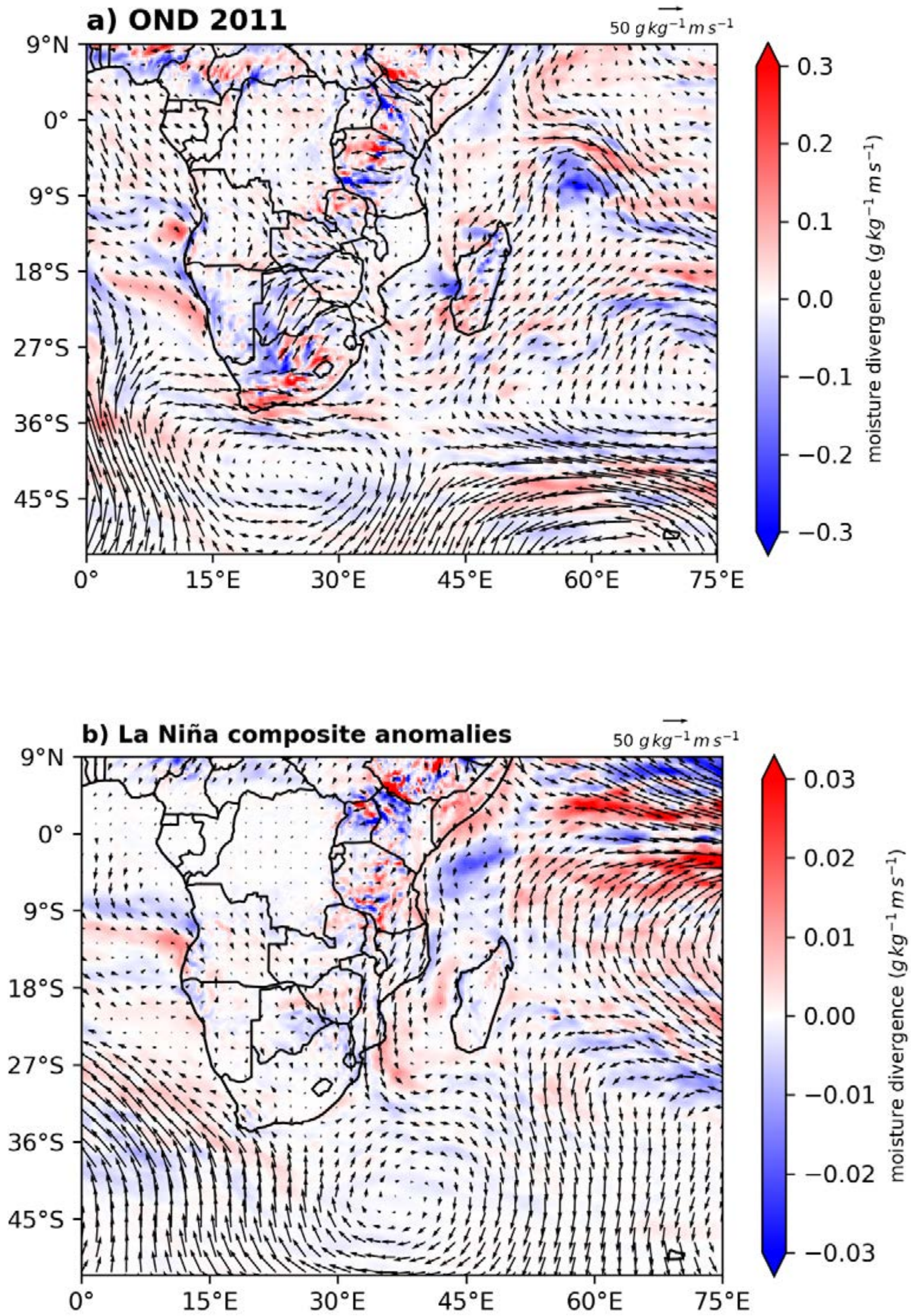
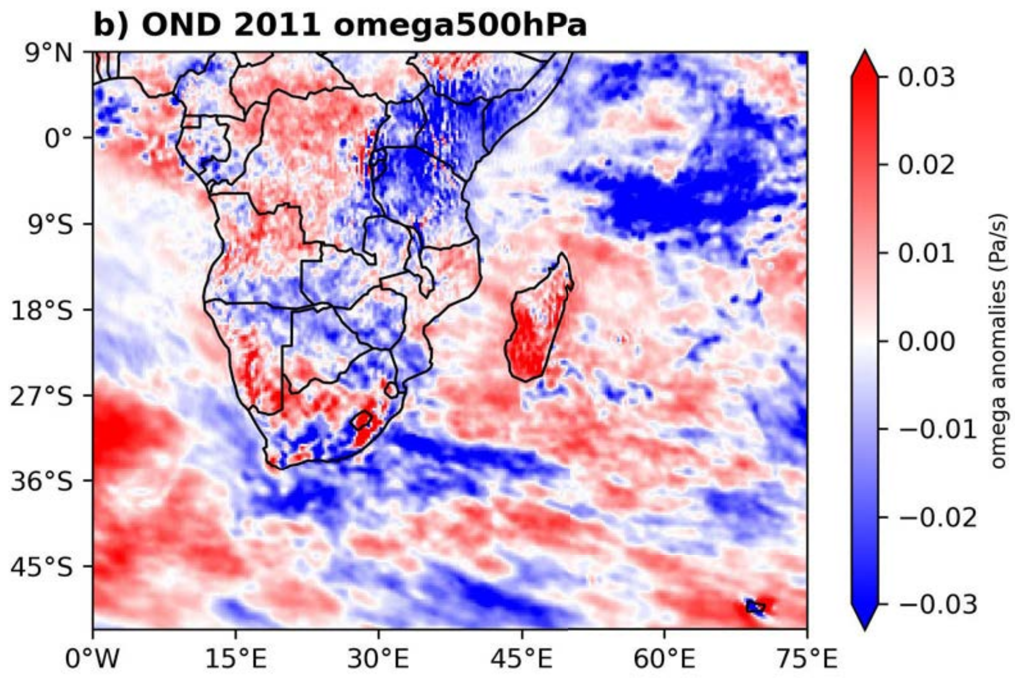


Figure 5-9. 850 hPa moisture flux and divergence anomalies for a) OND 2011 and b) OND La Niña composite



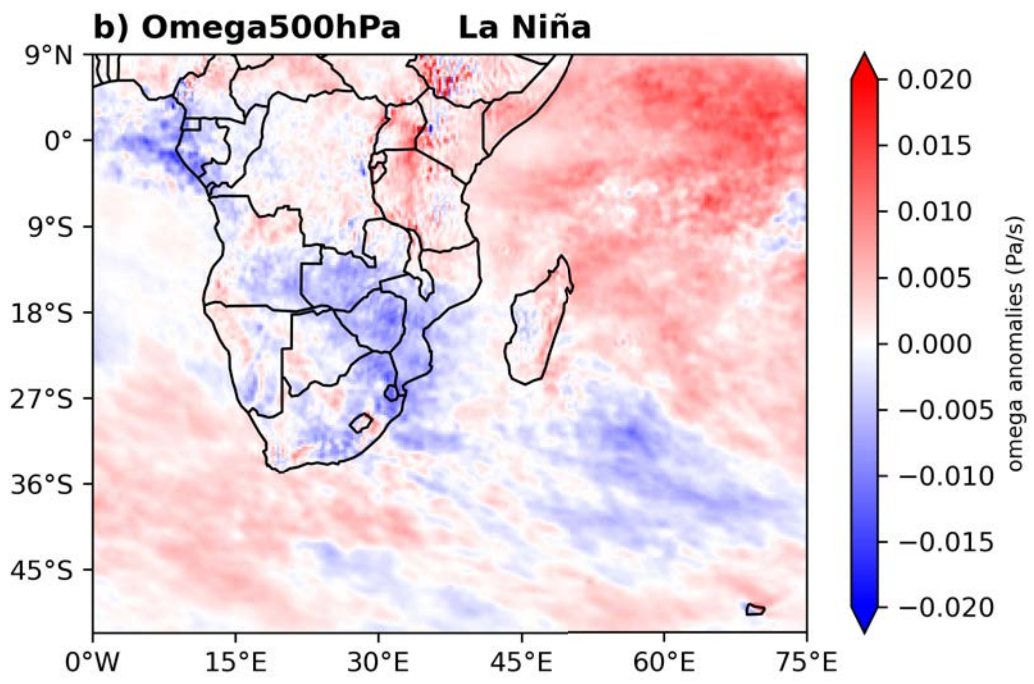


Figure 5-10. As for Fig. 5-9 except omega at 500 hPa

5.3 THE ROLE OF TEMPERATURE EXTREMES

The results above have highlighted several cases of multi-year droughts in the MCP region and indicated that had extreme rainfall events not occurred in some of those seasons, the drought would have been worse. In addition to a lack of rainfall, drought can also impact through anomalously high temperatures. Thus, an analysis of the occurrence of cases where the daily maximum air temperature exceeded the 90th percentile for three consecutive days (defined as a heat wave) in the MCP is provided below along with the climatological distribution of such days over subtropical Southern Africa. The results were obtained using two-metre air temperature from 0.25° resolution ERA5 reanalyses (Copernicus climate change Service, 2017; Hersbach et al., 2020).

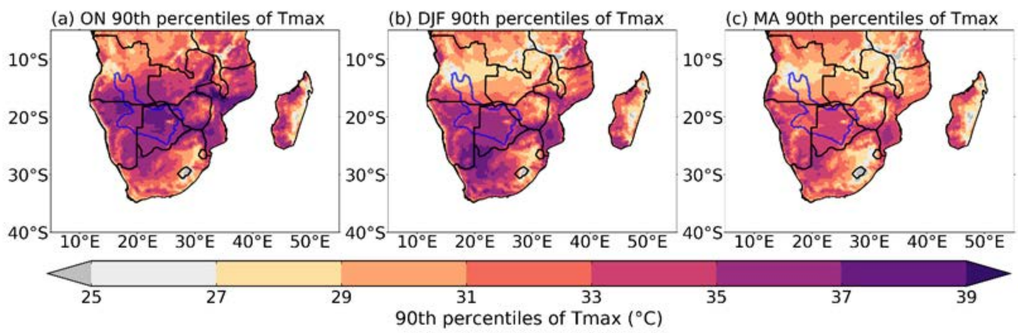


Figure 5-11. October-November, December-February, March-April climatological distributions of extreme temperatures over subtropical Southern Africa. Adapted from O. Moses (PhD in prep.), UCT

In early summer (ON), the largest values of the 90th percentiles of maximum temperature occur over northern Namibia, Botswana and extend through the Limpopo and Zambezi River valleys into the southern half of Mozambique (Figure 5-11 a). In South Africa, these extremes have the largest values over Limpopo, the Kalahari and the MCP. Values over the MCP are higher than elsewhere over coastal South Africa. In DJF (Figure 5-11 b) the pattern is similar to that for ON, but the values are now lower over the northern ORB and Zambezi River valley, as cloud cover and the tropical rain belt shift further south over Southern Africa. Over South Africa, the highest values are found over the Kalahari and Karoo deserts due to the maximum insolation at this time of year. Although the MCP displayed greater values than elsewhere in coastal South Africa in ON, for DJF this is no longer the case due to the relatively large number of clear sky days and high insolation levels near the south-western Cape coast. In MA Figure 5-12 c, the 90th percentiles of maximum temperature show patterns that are similar to those for DJF, but with values that are lower than those for both DJF and ON, as the maximum insolation has now shifted north to lie near the equator. Along the South African coast, magnitudes are similar for the west and south coasts as found in MCP which may be due to the increasing likelihood of occasional berg wind events along the former coasts in late summer.

Figure 5-12 plots time series of standardised anomalies in the number of heat waves over the MCP region of KZN during 1981 to 2021. Simplistically, one might expect more heat waves during El Niño summers and the opposite during La Niña, especially during DJF when ENSO typically projects strongest over South Africa. While this is true in some cases, e.g. DJF 1992, 2003, 2019 for El Niño and DJF 1989, 1999, 2000 for La Niña, there are some obvious exceptions such as DJF 1983 and 2016 which correspond to very strong El Niño summers but had below average frequencies of heat waves. What is more obvious are long runs of consecutive seasons of below average cases such as ON 2005 to 2010 and DJF 2009 to 2014 as well as a few cases with unusually high numbers of heat waves (ON 1985, 2004; DJF 1986, and MA 1985, 2004).

Although heat wave frequencies do not appear to be significantly correlated with ENSO, anomalies in the MCP spatial average daily maximum air temperature are strongly correlated in DJF (r = 0.54) (Figure 5-12) and, to a lesser extent, in MA (r = 0.37), both significant at 99%. The correlation in ON is not statistically significant. No significant correlations were found with the SAM. The lack of a significant ENSO correlation with heat wave numbers may result from the fact that heat waves need to meet the criterion over at least three consecutive days. Heat waves also seem to be less frequent in South Africa than in larger landmasses such as North America, Eurasia, or Australia since the oceanic influences on day-to-day weather over the relatively narrow South African landmass are strong with conditions that tend to change more frequently. Unlike these other regions, there are no large midlatitude landmasses here to anchor blocking highs and hence promote heat-wave inducing weather over lengthy periods.

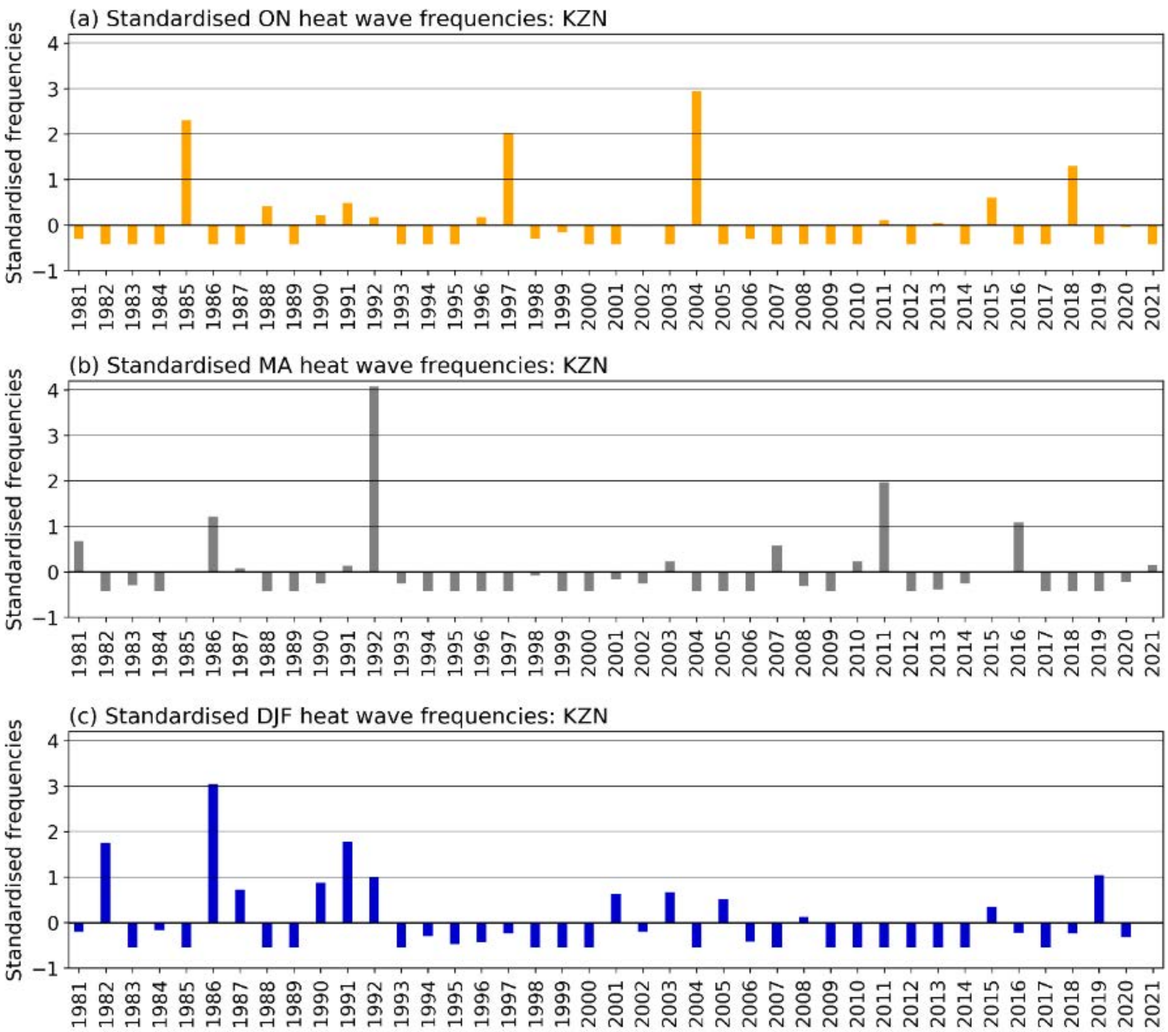


Figure 5-12 Standardised anomalies in the number of heat waves occurring in the MCP during early (October-November), mid- (December-February) and late summer (March-April).

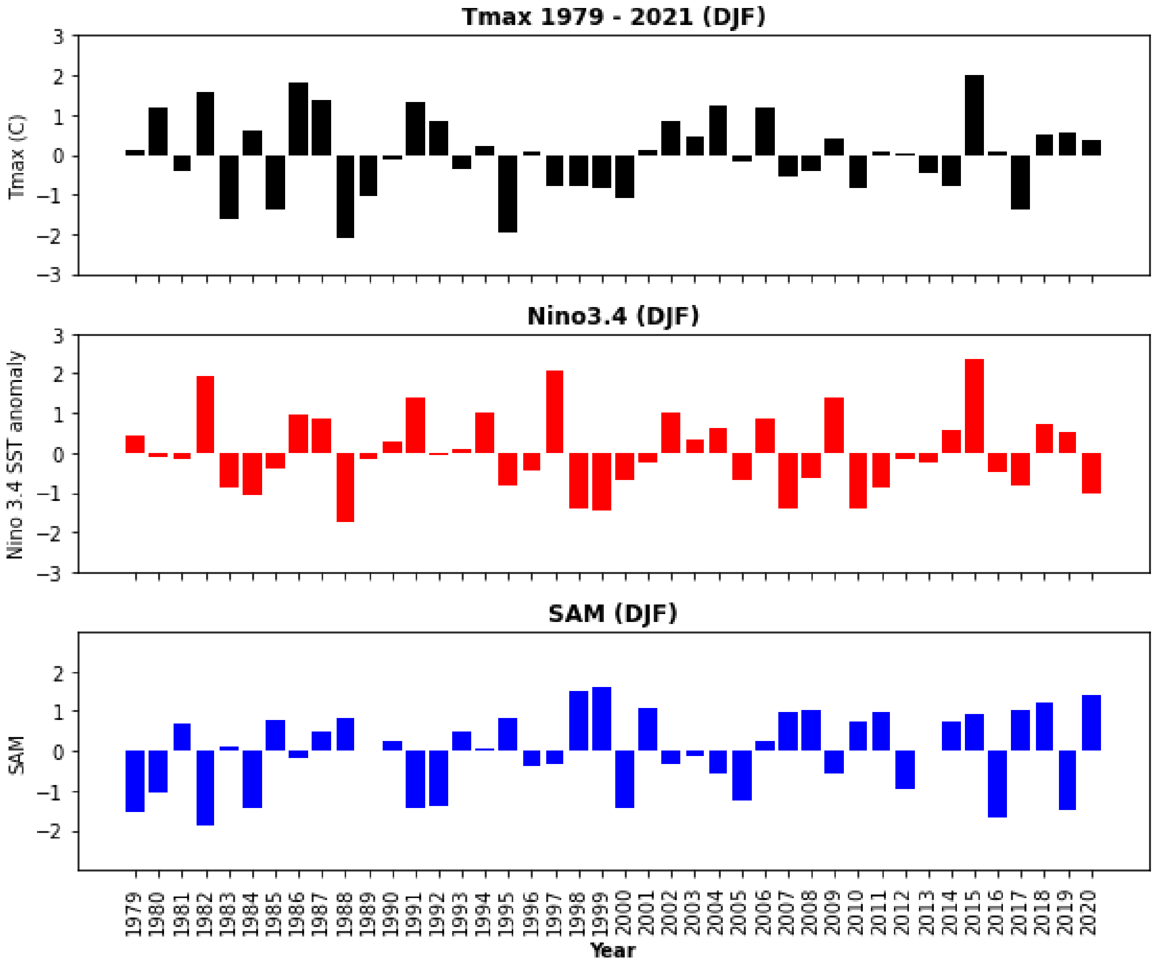


Figure 5-13 Standardised anomalies in MCP maximum air temperatures and ENSO, SAM indices for DJF

5.4 PONGOLA-MTAMVUNA RAINFALL IN MULTI-MODEL SPACE

5.4.1 The CMIP Models

To consider future rainfall changes in the region, 32 models from the Coupled General Circulation (GCM) Model Intercomparison Project Phase 6 (CMIP6) ensemble (Eyring et al., 2016) are used, including both historical simulations and future projections. A 30-year historical period (1979 to 2009) and 30 year mid-21st century future period (2040 to 2070), under the high energy-intensive narrative, Shared Socioeconomic Pathway (SSP) Number 5, with radiative forcing of 8.5 W/m^2 at the end of the century, is used (hereafter, SSP5-85). This scenario can be understood as an update of the CMIP5 scenario RCP8.5, now combined with socio-economic reasons. Only one ensemble member (r1i1p1f1) per model is included in the analysis.

For ease of comparison, daily rainfall and temperature in the models are re-gridded by bilinear interpolation to a common 1.5°×1.5° grid. Rainfall from the models is compared with satellite-based estimates from the Global Precipitation Climatology Project (GPCP) monthly precipitation data set (Adler et al., 2003) and Climate Prediction Center Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1997). Like that of the CMIP6 models, the observation data are re-gridded to a 1.5°×1.5° grid, but for the period 1979 to 2009. Figure 5-14 illustrates the re-gridded data used for the analysis of the

UM domain (note – the hydrological model domain would be too small for the CMIP models). Note only one cell covers the hydrological domain within the project study area, most of which is over the sea.

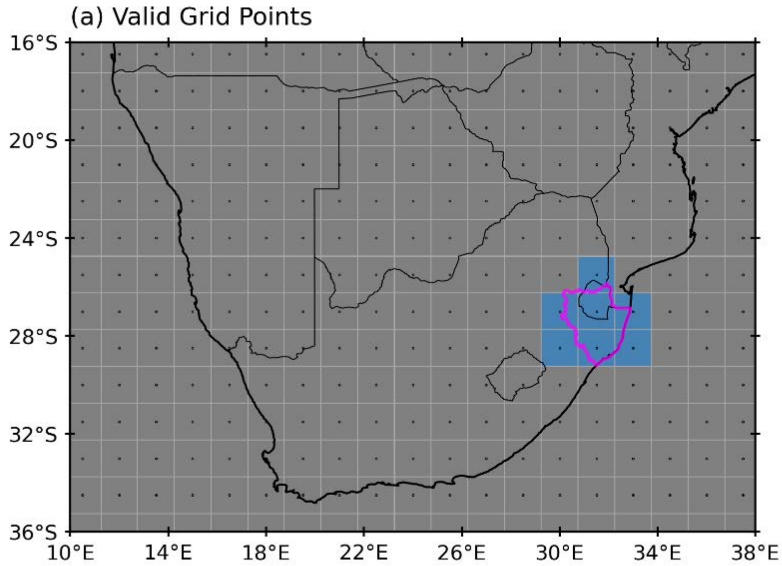


Figure 5-14 The valid grid points (blue shading) of the re-gridded CMIP6 data that highlights the UM domain

5.4.2 Historical and Future Climate

Figure 5-15 a shows that although the CMIP6 models generally represent the annual rainfall cycle of the UM relatively well, most models severely overestimate the rainfall over the region. This figure suggests that many models have a wet bias in the summer months. Rainfall biases and large uncertainties are persistent in climate models over Southern Africa (Dieppois et al., 2015, Lazenby et al., 2016, Munday and Washington, 2017, 2018, Barimalala et al., 2022). It is for this reason that the concept of processed-based evaluations of model outputs (James et al., 2018) has become a more acceptable means of understanding how models resolve Southern Africa climate. For example, Munday and Washington (2017) found that improvements in the simulation of the Angola low in the CMIP models could improve the representation of rainfall in Southern Africa. James et al. (2018) found that CMIP5 models reproduce the observed circulation features of the tropical-extratropical cloud bands, one of the biggest rainfall contributors (Hart et al., 2013), but with large intra-model differences. More recently, Barimalala et al. (2022) found that in CMIP6 models, the link between the Mozambique Channel Trough and Southern Africa summer rainfall is not well represented in the models. Given that ridging high pressure systems play an important role in rainfall days in summer rainfall in Southern Africa (Ndarana et al., 2021), the rainfall bias for the east coast of Southern Africa found here could also be linked to the model bias in representing the South Atlantic and South Indian high pressure systems (Mahlalela et al., 2019). Overall, this highlights the complexity of the different processes that drive rainfall across Southern Africa and why models may struggle to resolve the rainfall cycle.

When looking at the projected future rainfall change for the UM region it is evident that, although models suggest an increase in summer (Oct-Mar) rainfall, there is still a large model spread (Figure 5-16). This spread ranges from a -7% decrease in summer rainfall to an increase of +19%. However, changes in future rainfall are a lot more nuanced throughout the summer. A feature that appears to be consistent in the different iteration of CMIP models is that of early summer drying across Southern Africa (e.g. Lazenby et al., 2018; Munday and Washington, 2019). The early summer drying is also found in the

UM region in the CMIP6 ensemble (Figure 5-15 c and Figure 5-17). Here, most models appear to show a consistent drying pattern for large parts of Southern Africa. The cause of the early summer drying over Southern Africa is not entirely clear, but has previously been related to changes in convection and decreases in relative humidity (Chadwick et al., 2013) and changes in the South Indian Ocean Convergence Zone (Lazenby et al., 2018) through to strong warming in the northern tropics (Munday and Washington, 2019). Caution is still needed over the confidence in this early summer rainfall decline given that models that simulate the extreme future drying simulate larger present-day biases over Southern Africa (Munday and Washington, 2019). This again highlights the need to better understand present day climate dynamics, which could help constrain the models.

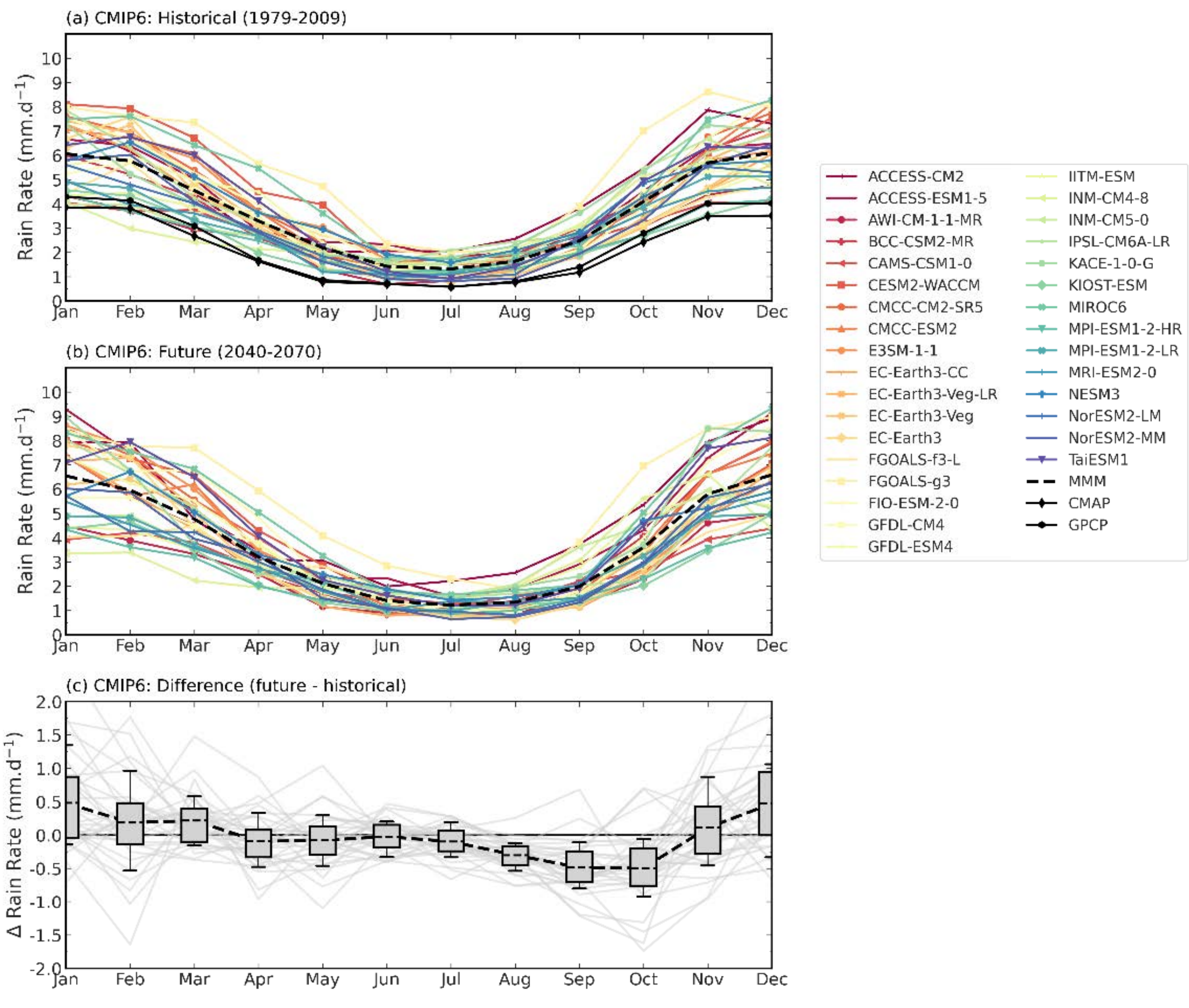


Figure 5-15. The annual cycle of rainfall (as rain rate; mm per day) in the UM region of South Africa (see Fig. 4-14) in 32 of CMIP6 models for (a) the historical runs for the 1979 to 2009, (b) the mid-21st century projections (2040 to 2070) and (c) the difference between the mid-21st century projections and the historical runs. For comparison, two observation products (CMAP and GPCP) are included in panel a (black solid lines). The multi-model mean (MMM) is represented by a black dashed line in all three panels. Box plots in panel c cover the 10th-90th percentile range of a change in rain rate

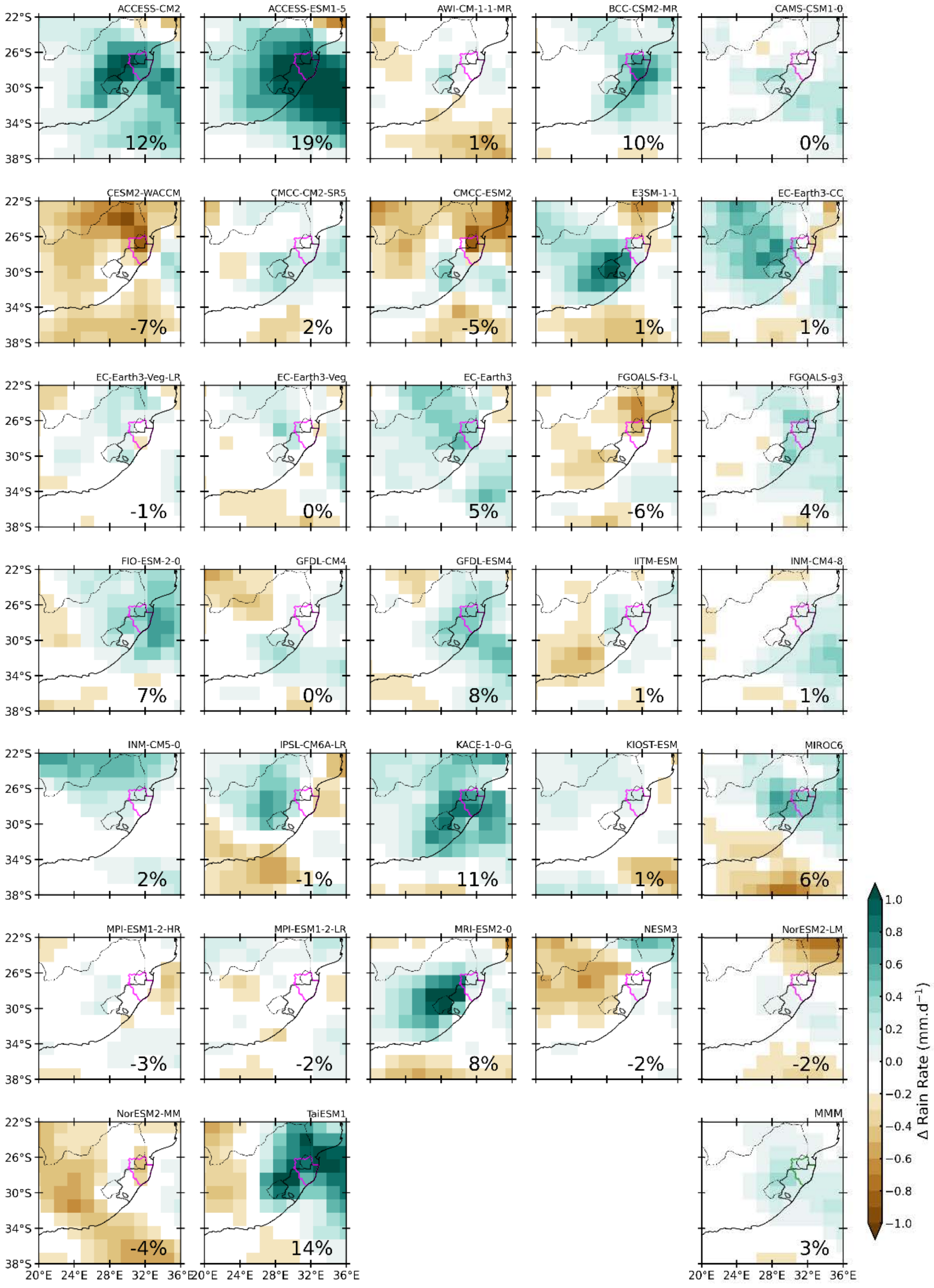


Figure 5-16 Mid-21st century (2040 to 2070) projected changes of the summer (Oct-Mar) rainfall (shaded; in mm per day) in comparison to the historical period of 1979 to 2009 of 32 CMIP6 models. Green colours indicate wetting, while brown colours indicate a decrease in rainfall. All products have been re-gridded to a 1.5°x1.5° common grid. The percentage change (%) within the UM (pink polygon) compared to the historical period within each model (or multi-model mean; bottom right-hand corner) is provided in the bottom right of each panel.

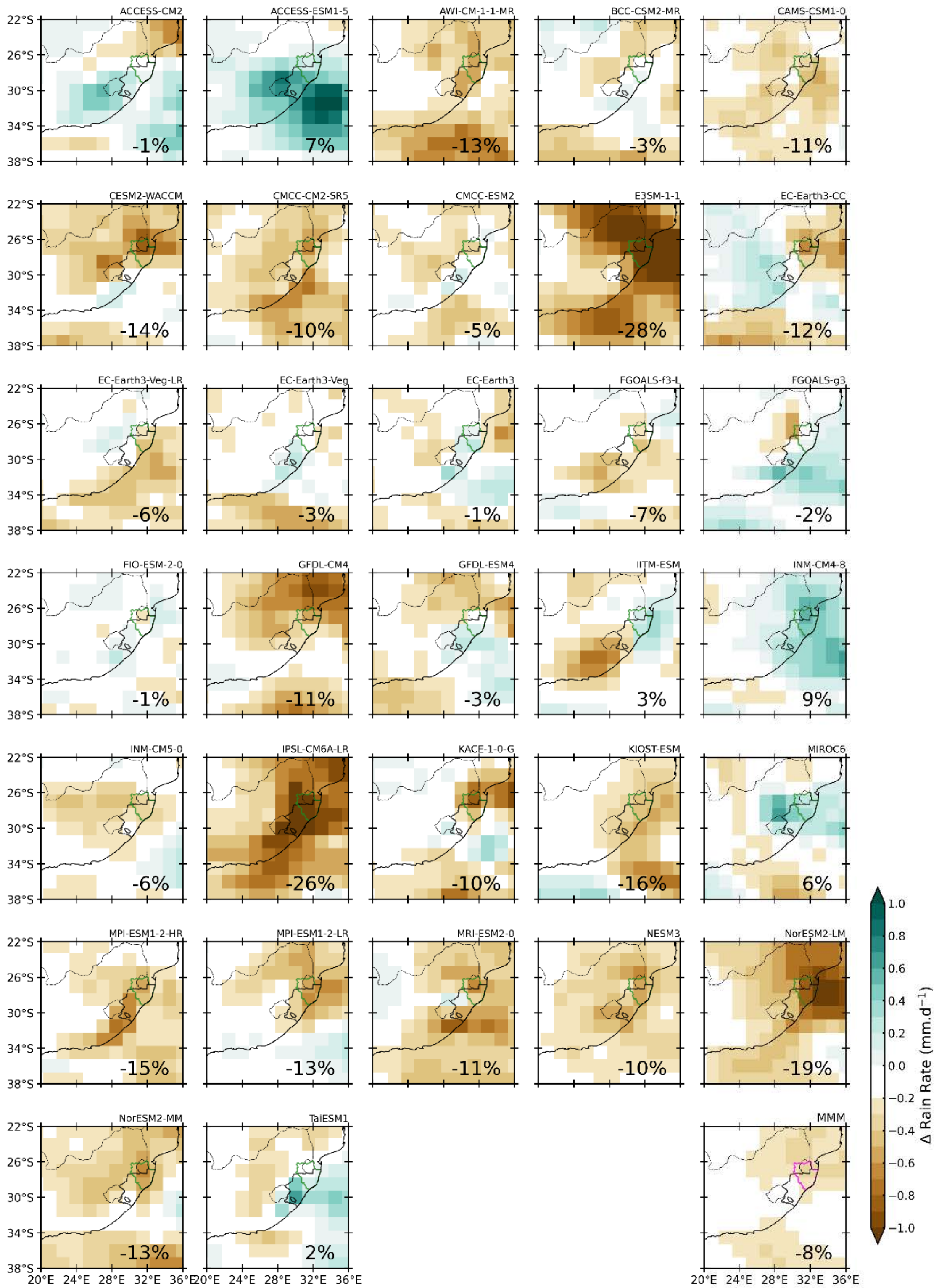


Figure 5-17. Mid-21st century (2040 to 2070) projected changes of the early summer (Sep-Nov) rainfall (shaded; in mm per day) in comparison to the historical period of 1979 to 2009 of 32 CMIP6 models. Green colours indicate wetting, while brown colours indicate a decrease in rainfall. All products have been re-gridded to a 1.5°x1.5° common grid. The percentage change (%) within the UM (green polygon) compared to the historical period within each model (or multi-model mean; bottom right-hand corner) is provided in the bottom right of each panel.

5.4.3 Construction the Future Climate Scenarios

Both CMIP6 (coarse scale projections) and even downscaled projections (finer scale projections) include a range of uncertainties. As spatial scales become finer, there are more uncertainties introduced into the modelling, therefore the range of possible climate response widens. This means that it is a challenge to identify a robust message at smaller spatial scales, such as over a municipality or small water management area. There are various sources of this uncertainty, which can be linked to methods/tools used, uncertainty in the emission scenarios/socio-economic conditions of the future, among other things. Some uncertainty issues can be addressed through improved methodologies. As alluded to earlier, a process-based evaluation is one way to improve the understanding of the regional climate in the models. However, some proportion of uncertainty will always remain, particularly with future climate.

One way to understand the possible range of projected future changes is to combine as many models as reasonably possible under one emissions pathway. What results is a range and a best estimate of likely change (probabilistic approach). Another way to handle the uncertainty is through a storylines approach, e.g. Shepherd et al. (2018). Essentially, this is a method to describe plausible future pathways. For this study, a storyline approach was taken where two scenarios are developed based on the model results presented earlier, which showed a warming world, but contrasting rainfall during the summer period. Thus, the two scenarios developed consist of “warmer and wetter” and “warmer and drier” worlds. These two storylines were created through an ensemble of four CMIP6 models each that typically showed a warmer and wet or warmer and drier summer in the future (based on the 2040 to 2070 future period) and presented in Figure 5-16.

It is reminded that there is evidence to suggest that wetting/drying during a summer will not be consistent throughout the summer as some models show dry early summer, but wet core summer. Thus, this method does not consider early summer drying that may be present in the model. Furthermore, a difficulty in the determination of the dry scenario here for the storylines was that most models show a wetting during the full summer period or at least very little change to a minor decrease in summer rainfall (see Figure 5-15). The models also showed considerable decadal variability. For example, as shown in Figure 5-18, there are periods in the future climate where the dry scenario appears wetter than the wet scenario. Further to that, not all summers within a wet (dry) scenario will be wet (dry). However, a consistent pattern that has emerged from the models is that temperature will continue to increase throughout the century if no drastic measures are taken to reduce the warming at a global scale.

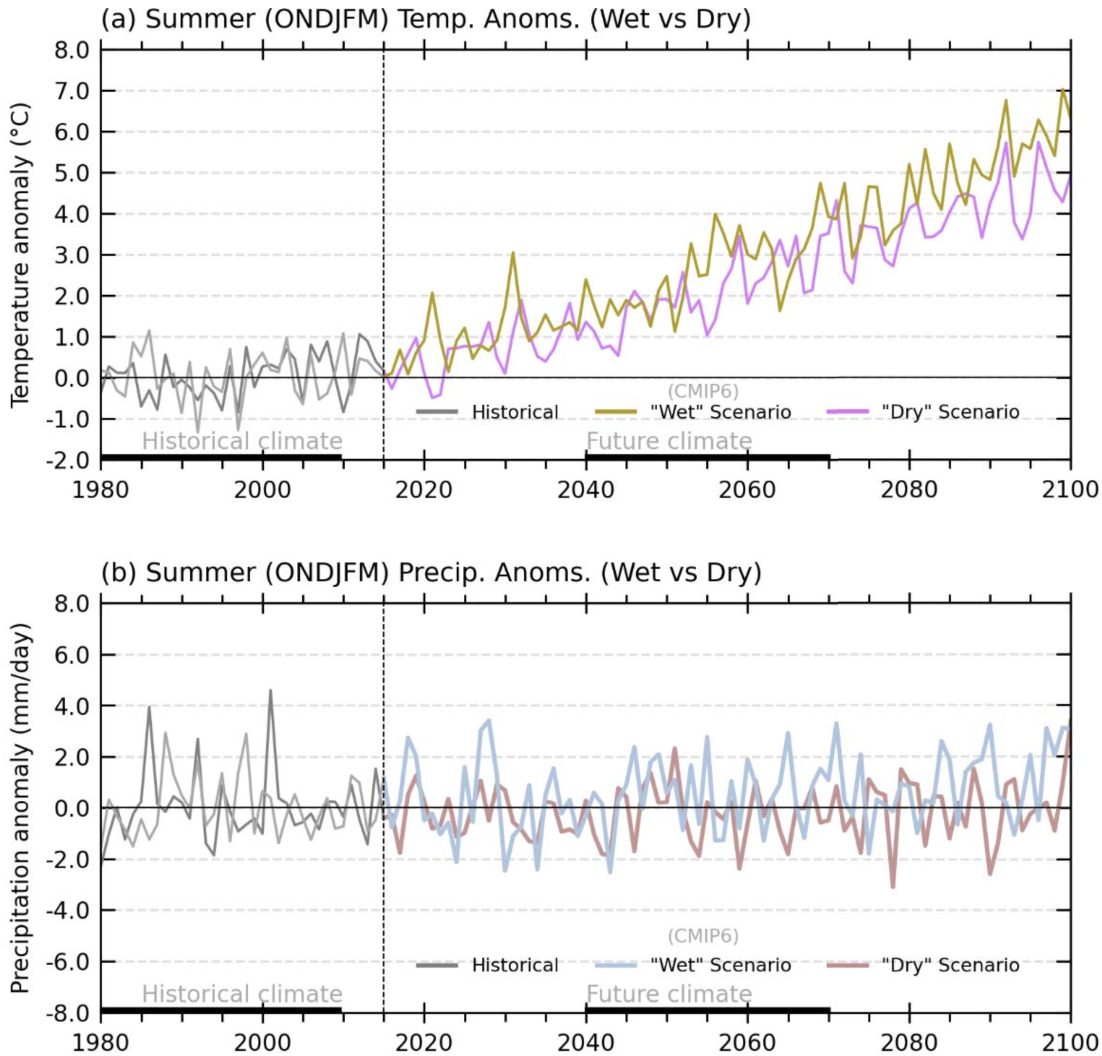


Figure 5-18 A time series of the mean a) temperature and b) rainfall anomalies during the summer period (Oct-Mar) from 1980-2100 for the "dry" and "wet" scenario each based on four models of the CMIP6 ensemble (see text). The grey lines pre-2009 represent the historical runs (see black bar on x-axis), while the coloured lines are the future scenario. The wet and dry scenarios are based on rainfall anomalies between 2040 to 2070 (see black bar in x-axis).

5.5 CHAPTER CONCLUSION

The MCP area in northern KZN, and the southern extremities of Mozambique is a highly biodiverse and sensitive area which acts as a transition zone in south-eastern Africa between tropical and subtropical weather patterns as well as species distributions and whose climate is not well understood. It is an area highly prone to drought as well as to occasional devastating floods that are the result of extreme precipitation events. The nature of the latter as well as other characteristics of the summer rainy season here were examined in this study. Over 60% of the top 50 extreme events occurred during January-March. Of these, 19 resulted from tropical lows during the second half of summer, particularly in March. Only one tropical low extreme event occurred in early summer. COLs produced nine events of which all but one occurred in the early summer months of October and November. The second biggest contributor was MCS events (10) while tropical-extratropical cloud bands were responsible for eight events. Neither October nor March experienced any cloud band or MCS events. The remaining events correspond to named tropical storms (Domoina and Imboa in January/February 1984 and Irina in March 2012).

During the 36-year record, most of the OND extreme events occurred during the 1989 to 2001 period whereas those for JFM were more evenly distributed. This OND distribution contributed to a multi-year drought during 2002 to 2005 which was ended by well-above average numbers of ≥ 10 mm and ≥ 25 mm rain days in OND 2005, 2006. There is a moderate but significant correlation between extreme event occurrence in OND and rainfall totals which strengthens further in JFM. Both seasons show higher correlations between totals and counts of ≥ 10 mm or ≥ 25 mm rain days. An exception is JFM 2014 which experienced two extreme events in the top 50 but whose seasonal total rainfall was about 0.6 standard deviations below average. The wettest overall seasons (OND 1989, 1995; JFM 1984, 2000) all experience extreme events as well as above average numbers of moderate (≥ 10 mm) and heavy rainfall (≥ 25 mm) days. ENSO relationships with rainfall totals are stronger in OND than in JFM while the reverse is true for extreme event occurrence and heavy rain days. Although many more extreme events occur during La Niña seasons than during El Niño (particularly for JFM), as expected from the general ENSO-rainfall relationship over Southern Africa (Nicholson and Kin, 1997; Reason et al., 2000; Blamey and Reason, 2023), it must be noted that for OND there is one particular La Niña season which contains over half of the extreme events, and for JFM two of the La Niña seasons experienced half of all the extreme events.

Particular exceptions to La Niña (El Niño) generally being wet (dry) over the region, occurred in OND 2006 and OND 2011. Firstly, the OND 2006 El Niño season received well over one standard deviation above average rainfall and well above average numbers of moderate and heavy rain days. Secondly, the OND La Niña season of 2011 shows rainfall totals of about 1.2 standard deviations below average as well as below average moderate and heavy rain days and no extreme events. Analysis of the circulation and SST anomalies during these two unusual seasons in comparison to those typically experienced during El Niño and La Niña events revealed some interesting differences.

For the OND 2006 case, during a moderately strong El Niño, there was little change in moisture flux convergence over the southern Mozambique Channel (unlike the strong divergence present in the El Niño composite), and there were easterly anomalies over northern Madagascar in the northern Mozambique Channel with above average SSTs throughout the Channel and the greater Agulhas Current system, favourable for increased rains (Reason and Mulenga, 1999). Strong relative uplift was present over the MCP region and most of northern South Africa in contrast to the marked relative sinking in the El Niño composite. Cloud band numbers were close to average unlike the reduction typically seen during El Niño (Hart et al., 2018). Based on the analysis of 1985 to 2008 Huang et al. (2018) data, MCS numbers in the region were slightly above average. These cloud band and MCS numbers contributed to this season having a well-above average number of moderate and heavy rain days and hence being very wet in terms of the seasonal total rainfall despite being an El Niño season.

A strong cyclonic anomaly south of South Africa was present during the relatively strong La Niña season of 2011 which, unusually, received well below average rainfall. This cyclonic anomaly is not present in the La Niña composite and has previously been associated with dry conditions of northern South Africa (Mulenga et al., 2003) since it leads to advection of cooler and dry South Atlantic air over the country. Westerly anomalies were also apparent over and east of Madagascar and the southern Mozambique Channel, implying less moisture flux from this source towards subtropical Southern Africa. This pattern is also not apparent in the La Niña composite. Over the UM area, there was relative moisture flux divergence in OND 2011, unfavourable for rainfall, unlike in the La Niña composite, while most of the Indian Ocean showed SST anomalies more like an El Niño than a La Niña, including cool SST anomalies in the Agulhas Current region, unfavourable for summer rainfall over northern and eastern South Africa (Mason, 1995, Reason and Mulenga, 1999).

Although this study has contributed towards a better understanding of extreme daily rainfall events over the UM region, it is important to remember that there are relatively few rainfall stations here. Thus, the CHIRPS data used in this study rely mainly on satellite data which may not be completely reliable near the coastline or in the far northwest where there are steep topographic gradients, e.g. Dinku et al. (2018). Nevertheless, the broad differences between the early and late summer in terms of the synoptic classification and extreme event frequency are corroborated from satellite imagery, synoptic charts and ERA5 reanalyses and are, therefore, robust. While extreme events can cause loss of life and significant damage, they also help to lessen the severity of droughts during certain key periods in the region. Overall, drought is considered to be the most damaging natural disaster for Southern Africa. A multi-year drought occurred throughout 2001 to 2003 while every JFM from 2007 to 2018 received below average rainfall except for two seasons which were slightly above the mean. The dry conditions during these two periods would have been much worse had seven of the top 50 extreme events not occurred then. These results highlight the importance of extreme rainfall event analysis for the region.

The final part of the analysis involves better understanding of how the climate may change in future. Overall, the CMIP6 models appear to capture the seasonal cycle reasonably well for the UM region, but they do produce too much precipitation. As described previously, biases and uncertainties are persistent in the global climate models, e.g. Munday and Washington (2017). This is one of the reasons why process-based evaluations of models are becoming more favourable, particularly for Africa (James et al., 2018). This entails the evaluation of specific processes or features known to influence regional climate, such as the Angola low (Munday and Washington, 2017) or the Mozambique Channel Trough (Barimalala et al., 2022), to better understand the drivers behind the biases. The results from such work then help identify where model improvement is needed, such as better resolving orography across Africa.

The next generation of high-resolution models will add even more details to resolve climate processes. The convection permitting model for Africa (CP4A; Stratton et al. (2018)), run at 4.5 km horizontal resolution, will help isolate the impact of convection parametrization and resolution on Africa climate. As a reminder, relatively coarse resolution (around 100 km grid spacing) is used for global climate models and as such, require convection to be parameterized. Results show that such resolution better simulates rainfall characteristics, such as the frequency in rain days (e.g. Kendon et al. (2019)). However, computation restrictions of such high-resolution models limit the volume of model simulations performed. For CP4A, only two ten-year periods that represent present and future climate were produced. Thus, the low resolution CMIP6 ensemble is still an accepted dataset available to understand how climate may change in future throughout the 21st Century.

An analysis of the CMIP6 models presented here, using the SSP5-8.5 scenario ("business as usual”/ “worst case”), indicates that the summer months appear to be getting slightly wetter in future, but there is a lot of uncertainty with this given the model spread. There appears to be more of a consistent message of future drying during the early summer months, with a large portion of the models projecting a general drying for the Southern Africa region during the mid-21st century during this period. There is also evidence that suggests the core summer months (Dec-Feb) will see an increase in rainfall, which results in the overall summer rainfall total not changing significantly. However, this implies a shorter rainy season with more heavy rainfall events. This is consistent with the IPCC AR6 which suggests an increase in extreme rainfall events in future.

A more robust signal that emerged from all models is the considerable increase in temperatures towards the end of the century. The full model ensemble suggests that temperatures could rise by 2°C or more (some models suggesting 8°C increase) by the end of the 21st century. These warmer temperatures, coupled with decreases in early summer could have a significant impact on agricultural activities during the start of the summer. However, there is evidence that reanalysis data (ERA5) underestimate actual temperatures so while the trend holds true the actual temperature figures are underestimated (Raymond et al., 2020). For anomaly analysis this is not an issue but it will need to be considered for the crop models in the economic modelling which uses actual data where a degree or two can make a big difference.

Currently global climate models (the most common source of future projections) are likely too coarse to provide relevant local messages of climate change (Arias et al., 2021). It is evident from the extreme event analysis present here that one or two extreme rainfall events can have a huge impact on seasonal rainfall totals. Thus, the approach adopted here is one of storylines, as presented by Sheppard et al. (2018). Simply put, two scenarios of data were created from an ensemble of four models each to highlight a warmer and wetter MCP or a warmer and drier MCP. These are two likely scenarios that appear to be plausible in the future. It should be noted that given the uncertainty of future climate for the region, it does highlight the dangers of using a single climate model or a single high-resolution product for decision making. Thus, the storylines approach is potentially a more robust way to understand the impact of climate change in future at the local level. Given the precipitation biases in the CMIP data, a correction was required to provide a more plausible dataset for the hydrological modelling.

CHAPTER 6: APPROACH TO ADVANCING HYDROLOGICAL STUDIES

By: M Toucher, M Maseko, B Kelbe, S Kebede, and S Janse van Rensburg

This chapter outlines our approach to addressing Aim 3: *Determine the relative impact of different vegetation units and climate on the hydrological response of the Lake Sibaya groundwater catchment*.

6.1 RATIONALE

Radical intervention is considered essential to secure the decline in groundwater resources within the MCP (Johnson, 2021). However, undertaking disruptive activities necessitates a comprehensive understanding of the various components of the system to furnish defensible information that justify interventions. Consequently, the reliability of hydrological outcomes should be as robust as possible.

Hill (1969) and Hill (1979) presented the first detailed descriptions of the hydrological components of the lake, with a focus on bathymetric and morphometric measurements. The first hydrological model developed specifically for Lake Sibaya utilised the Pitman mathematical model to simulate lake levels from October 1914 to September 1973 (Pitman and Hutchison, 1975). This provided a preliminary water budget for the lake through the utilisation of available data, along with a set of recommendations for future work (see Pitman and Hutchison (1975)). Subsequently several studies have assessed the hydrological dynamics of the system, including the impact of commercial plantation forestry, abstraction and climate on the water resource, through the use of a variety of approaches (Weitz and Demlie, 2014, 2015, Ndlovu and Demlie, 2016, Smithers et al., 2017, Kelbe, 2019, Nsubuga et al., 2019, Johnson, 2021). While the advancements made provide a platform to build on, there are still several challenges and limitations that need to be addressed to improve the confidence of hydrological study outcomes.

There are several approaches available that can be used to improve our knowledge of the hydrological dynamics of the area. For example, hydrological models are highly useful tools in the assessment of the impacts of land use and land, and changes thereof on hydrological responses of catchments through scenario analysis. However, models have drawbacks associated with them due to inherent uncertainties related to both insufficient knowledge of the processes represented, and simplification of processes in the model. There are also uncertainties regarding input data quality and the spatial representativeness of the data. Hydrogeochemical approaches can assist in the improvement of conceptual groundwater models, but are not useful when scenarios of change are considered.

To enhance confidence in the outcomes of the hydrological studies in this project, a multi-pronged approach, which drew on isotopic and numerical modelling methodologies, complemented by extensive *in situ* data gathering, including previously unmeasured parameters, was used to address various persistent challenges and limitations identified in previous studies.

6.2 ISOTOPE STUDIES

Pitman and Hutchison (1975) advocated for studies water chemistry to enhance knowledge of the circulation of water as well as groundwater and rainfall interactions and to assist in the determination of the water balance of Lake Sibaya. Subsequently, several hydrogeochemical studies have been undertaken (Meyer et al., 2001, Weitz and Demlie, 2014, 2015, Ndlovu and Demlie, 2016). Despite the studies undertaken no clear relationships between rainfall and recharge have been established and further work towards understanding the aquifer properties, hydraulic relationship between aquifers and identifying groundwater flow paths is needed.

Isotopes studies were therefore used to determine the relationship between rainfall and groundwater recharge; investigate aquifer characteristics; and improve on the conceptual model flow paths; and explore the use of isotopes to assess tree water source partitioning (CHAPTER 7:).

6.3 A LOOSELY-COUPLED SURFACE-WATER GROUNDWATER MODELLING APPROACH

Pitman and Hutchison (1975) concluded that the Lake Sibaya system functions as a groundwater aquifer, with the lake level an indication of the exposed water table. They suggested that the use of groundwater assessment approaches should be used rather than mathematical modelling and emphasised the need for improved data (Pitman and Hutchison, 1975).

Subsequently, three models have been documented for Lake Sibaya, (Weitz, 2016, Kelbe, 2019, 2020). The more recent models by Kelbe (2019, 2020) explore a coupled modelling approach with the ACRU model to better represent the impact of vegetation on recharge. This approach is supported by various studies that have shown that coupling surface water models, e.g. Soil and Water Assessment Tool (SWAT), with MODFLOW can provide more accurate results compared to the MODFLOW model by itself (Peranginangin et al., 2009, Diaz et al., 2020, Jafari et al., 2021).

For this project, a similar approach was used. The ACRU model was loosely-coupled to the MODFLOW groundwater model, with recharge output from the ACRU model being used as an input to the MODFLOW groundwater model, similar to previous studies (Smithers et al., 2017, Johnson, 2021). Both the suitability of the ACRU model, e.g. Kienzle and Schulze (1992), and the MODFLOW model, (Kelbe, 2020, Johnson, 2021), to the study area have been demonstrated in previous studies. These studies also identified limitations that this work attempted to address.

6.3.1 Linking ACRU Derived Recharge to a Gridded MODFLOW Configuration

An advancement to previous ACRU simulations for this area, was to use a gridded configuration for the ACRU model that was spatially compatible to the MODFLOW grid. Recharge simulated for each grid by the ACRU model was used as an input to the MODFLOW model. Configuration of ACRU as a grid could only be undertaken due to vertical recharge being the only output from ACRU model that was of interest. For the simulation of the lake water balance in MODFLOW, rainfall and lake potential reference evaporation from the ACRU model were used.

6.3.2 Incorporating Actual Dynamic Land Use-Landcover Change Impacts on the Water Resource

Concerns about the impacts of an increase in afforestation in the study area on the water table have been raised by several authors, dating from Nannie (1966). Using ACRU, Kienzle and Schulze (1992) simulated the negative potential impact of different percentage areas of afforestation on the groundwater level within MCP. They attributed the negative impact to abstraction by tap roots and depth to which the roots reached. Likewise, Meyer et al. (2001) using a numerical model and five different evaporation rates demonstrated afforestation's negative effect on groundwater, which was exacerbated by drought, for the Lake Sibaya area. Other studies (Smithers et al., 2017, Johnson, 2021) have simulated the system with and without commercial plantation forestry at a static time, without changing other LULC types. Accounting for changes in land cover over time is a common limitation of all prior studies, particularly given the known expansion of afforestation over time in the area.

In numerous engagements both prior to and during this project (See CHAPTER 4: and CHAPTER 13:), bush encroachment emerged as a significant concern. The prevailing narrative suggests a substantial increase in indigenous woody species (bush encroachment) over time. Communities have rightfully expressed concerns that these expansions may contribute to the decline in groundwater resources. This highlights the need to assess actual dynamic LULC change within the region, not just commercial plantation forestry.

The matched ACRU-MODFLOW gridded approach described above allowed us to incorporate dynamic vegetation change into the ACRU model to account for more representative spatiotemporal LULC change. The LULC change time series developed is explained in CHAPTER 4:. Importantly, this assessment was conducted across the entire model domain (see section 6.3.4), in contrast to other studies that limited their “change” simulations to the groundwater catchment area (Smithers et al., 2017, Kelbe, 2020).

6.3.3 Improved Representation of The Rainfall Gradient and Spatial Variability

A rainfall gradient from east (wetter) to west (drier) exists over the study area (Pitman and Hutchison, 1975, Weitz and Demlie, 2015). Previous studies have not captured this gradient adequately. The reasoning for this is, in part, that observed rainfall data for the study area is sparse as well as often poor of quality. Given the sparse rainfall stations present over the study area, and the poor quality of the data, the gridded ERA5 rainfall and temperature products were used for the historical climate period from 1959-2020. The ERA5 product was compared against *in situ* data (cf. CHAPTER 8:) with an evident underestimation. However, the strength of the product was that it allowed for the spatial variability of the rainfall across the study area to be captured using an internally consistent rainfall product.

6.3.4 Increasing the Model Domain

Pitman and Hutchison (1975) recommended an improvement in the delineation of catchment boundaries. However, since groundwater dominates the water balance of Lake Sibaya, the recharge zone for the lake is associated with the groundwater catchment rather than the topographically delineated surface water catchment. The groundwater catchment extent is larger than the surface water catchment, as the groundwater catchment is determined by divergent flow paths created by geological ridges and not topographical features, as demonstrated by groundwater flow direction maps (Kelbe, 2019; 2020).

The geo-hydrological system is interconnected (Wright et al., 2000) and can be considered as “open”. Thus, the extent of the area that influences the Lake Sibaya groundwater system may be variable depending on the groundwater level and hydrogeological conditions (Merz, 2012). Indeed, as demonstrated by Bate et al. (2016), the groundwater catchment boundaries within this region are likely dynamic. Thus, for this study, the model domain was extended in the ACRU surface water model beyond the groundwater catchment of Lake Sibaya, to cover the spatial extent conceptualised by Kelbe (2019, 2020). Figure 6-1 represents the domain extent used for both ACRU and MODFLOW.

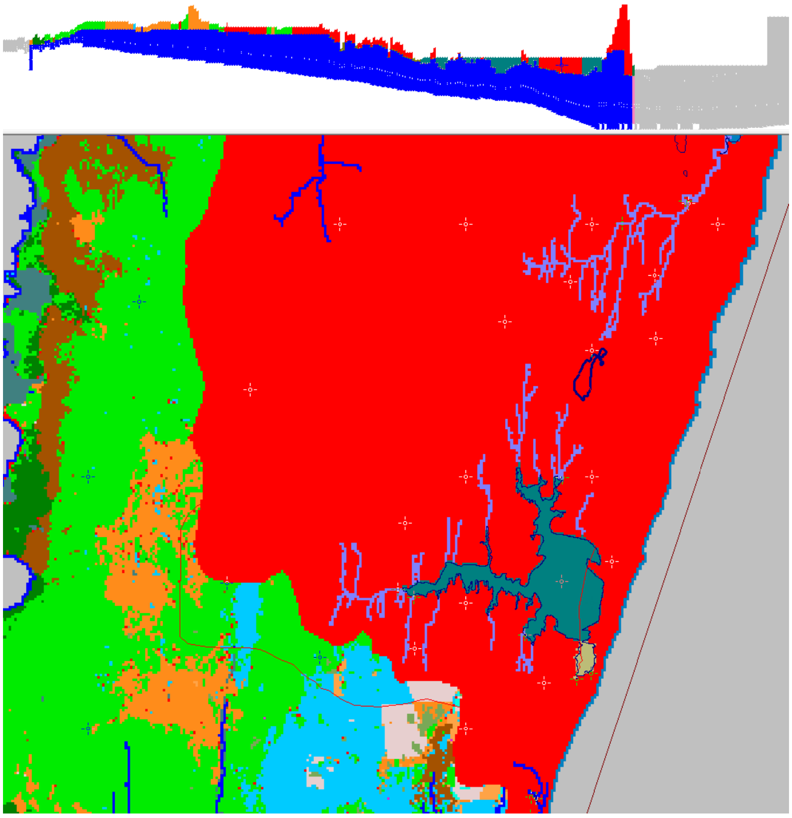


Figure 6-1: Spatial extent of the gridded MODFLOW groundwater model domain which informed the ACRU input grid

6.3.5 *In Situ* Data

In situ measurements constituted a crucial component of this study. The targeted variables included those recommended in prior studies, chosen for their feasibility and significant potential to reduce uncertainties and enhance the representation of the groundwater system.

Previous studies have relied on crop coefficients from readily available databases where the crop coefficients have been derived for other areas (Weitz and Demlie, 2015, Smithers et al., 2017). Given the relatively unique sandy hydrogeological setting, there is uncertainty regarding how well these crop coefficients match reality. In this project, total evaporation and energy balance components were monitored over several vegetation types to calculate crop coefficients specific to the site. This was done through the use of continuous measurements from NRF-SAEON Eddy Covariance, surface-renewal systems and the NRF-SAEON weather station array. These instruments, and the data they provide, have been used as a key component of this project and incorporated into ACRU CHAPTER 9:.

Pitman and Hutchison (1975) also recommended a more extensive rainfall network with at least four rain gauges within the catchment boundary. Given that this is a rainfall dependant system it is a surprise to see that the only weather station recording rainfall was at Mbazwane, which falls just outside the groundwater catchment boundary. However, within the last six years NRF-SAEON has addressed this through the addition of a rainfall gauge network that provides improved spatial coverage of rainfall within, and on the boundary of, the Lake Sibaya groundwater catchment area, complemented by strategically positioned weather stations. This data was used to complement various aspects of the project.

6.4 IMPROVING LAKE LEVEL DATA QUALITY

In the assessment of lake level dynamics in relation to drivers of change over time, it is essential to ensure water levels are reported in relation to a fixed reference point (Hill, 1969). In May 1966, Nannie (1966) surveyed the Lake Sibaya area and established a benchmark at Banda MBA Zwane Bay (21.976 m above mean sea level (a.m.s.l), which served as the reference point for the Department of Water Affairs (DWA) water level gauging station where the gauge plate's zero point was set at 18.623 m AMSL. The water level on the day of the survey was reported as 20.115 m AMSL. A number of the early hydrological, ecological and limnological studies stemming from the Rhodes Hydrological Research Unit, which maintained a research station at Lake Sibaya, used these reference points and the associated DWS data (Allanson, 1969, Hill, 1979, Allanson and Van Wyk, 1969, Hill, 1969, Bruton, 1973, 1979c, Allanson and Hart, 1975, Pitman and Hutchison, 1975, Appleton, 1977a, 1977b, Appleton and Bruton, 1979, Bruton and Allanson, 1980). Up until May 2008 water levels were measured in relation to height above the benchmark, after which the units were changed to metres AMSL. At least three known sites were used to record lake water level.

Post 1980, numerous authors, in their attempt to understand the dynamics of Lake Sibaya, have indicated that the official water-level record from the DWS is problematic, particularly the pre-1980s period (Meyer and Godfrey, 2003, Brown et al., 2015, Smithers et al., 2017, Nsubuga et al., 2019). However, the pre-1980 studies provide good data, with no "issues" identified. Whereas, the post 1980 study's point to unresolved datum issues; a nonsensical linear increase in the early periods of the record (inconsistent with a "natural system"); and irregularities in the latter (post 2012) portion of the record.

When requesting electronic data from DWS for Lake Sibaya through HydstraS@dwa.gov.za one is provided with station W7R001 record 100.00 as the "official" lake level record from data extracted from the current Hydstra database. The pattern in Figure 6-2 indeed indicates a system filling up, inconsistent with historic studies (Allanson, 1969, Hill, 1969, 1979, Pitman and Hutchison, 1975). Furthermore, the record is inconsistent with a known major flood event which took place in 1977 and which led to the evacuation and closure of the Rhodes Research Station located on the eastern shore of the lake (Bruton et al., 1980).

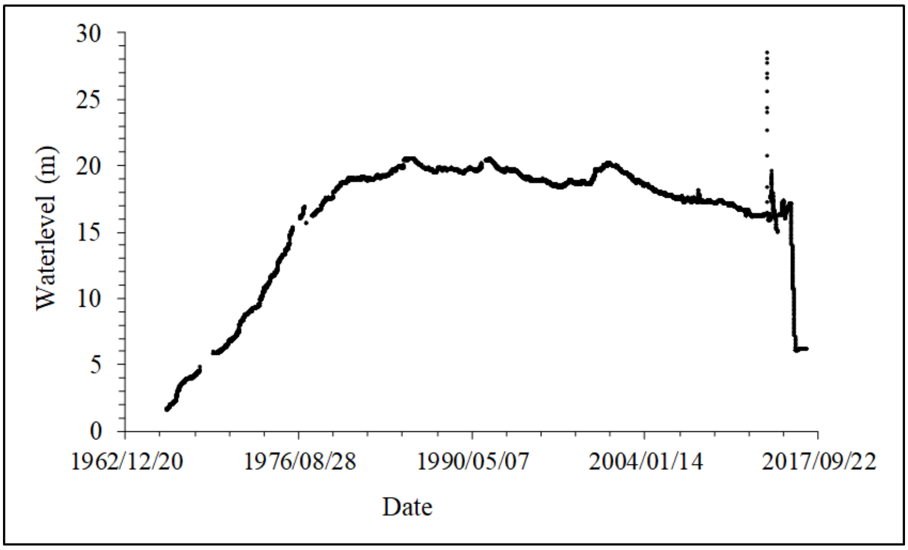


Figure 6-2: Lake Sibaya lake water level data for station W7R001 reflecting the 100.00 coded record from Hydstra received when requesting lake level data for the system

Significant effort was put into the verification of the long-term Lake Sibaya water level records, which included working with DWS to survey all historic gauge sites through the use of a standard set of benchmarks (see Appendix B for detailed corrections). Results (Figure 6-3) match photographic evidence presented in Brown et al. (2015), though the numerical values they provided are different. They applied a blanket correction, whereas the corrections proposed here are more nuanced, based on more detailed assessments as well as revised survey heights of all gauging stations to a set standard.

A key insight is that all prior data had potentially inflated figures for water level relative to the “actual” m AMSL, determined by NRF-SAEON DWS surveys (Appendix B). Importantly, several “jumps” in the record were cross-checked with historical data on storm events and most jumps corresponded to storm events. Those upward jumps identified, which took place during known drought periods, with no evidence of storms, were consider more likely to be errors and duly corrected. Based on the revised record, the historic lowest lake level record was broken in May 2011, with the lake level dropping below 16.20 m a.m.s.l. Thereafter there was a continued declining trend (Figure 6-4).

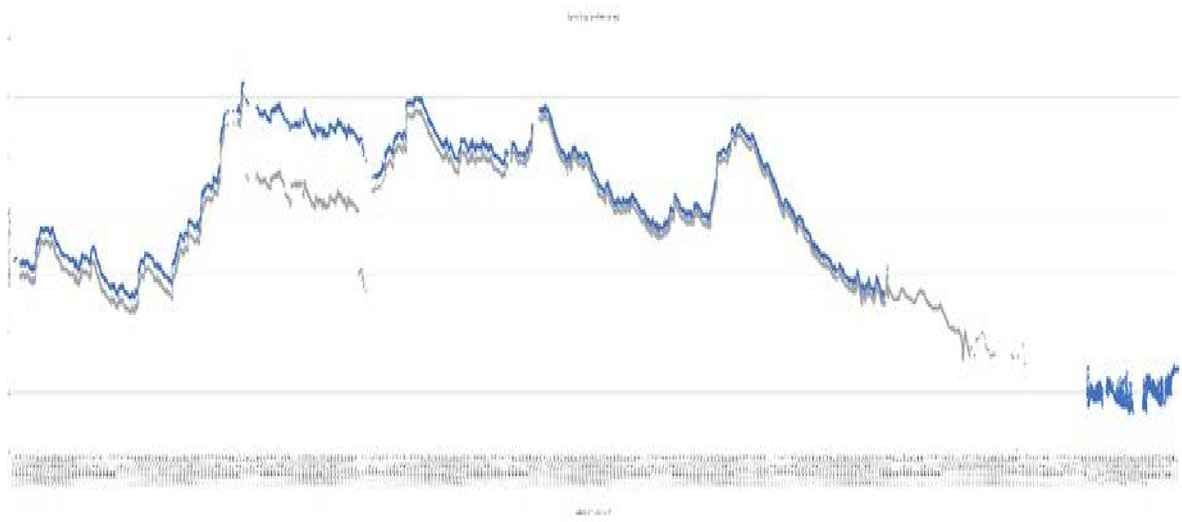


Figure 6-3: Lake Sibaya lake level record showing corrected series (blue) with all data adjusted to m AMSL. The grey line indicates the input data used tied into a standard point in m AMSL to demonstrate the extent and areas where corrections were applied.

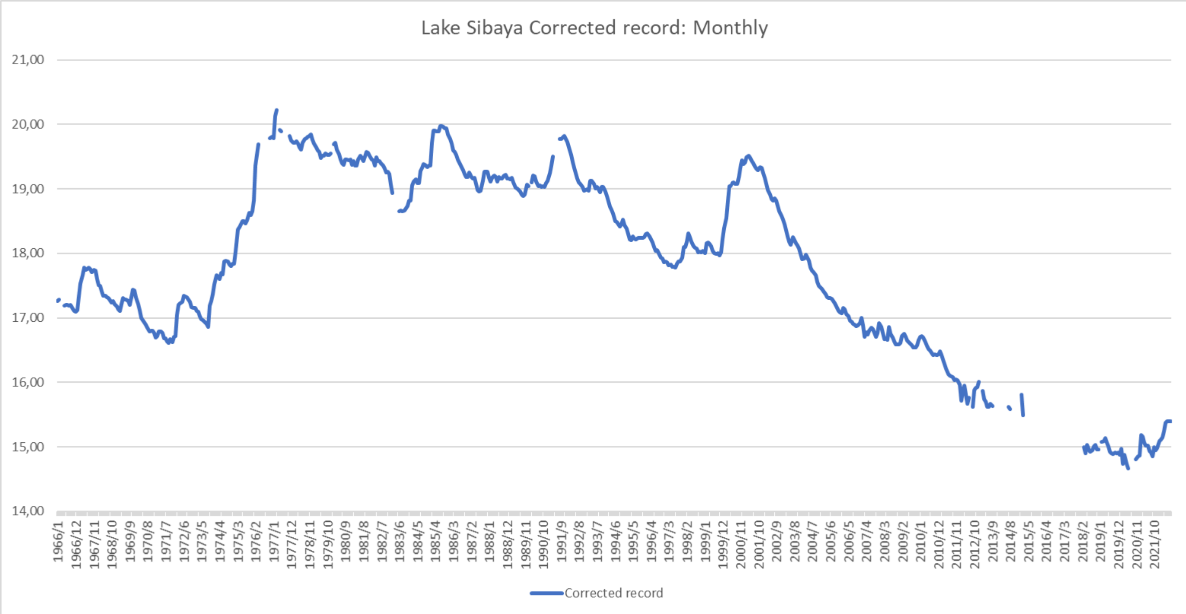


Figure 6-4 Corrected Lake Sibaya monthly lake level data

6.5 SUMMARY

To enhance confidence in hydrologic outcomes, this project addressed several limitations, data quality issues and knowledge gaps through a combination of isotope studies, coupled hydrological modelling, and *in situ* measurements. A central approach involved the employment of a loosely coupled, grid-matched surface water-groundwater model. This facilitated an improved spatiotemporal representation of climate and vegetation parameters across the entire model domain. Additionally, several measurements undertaken as part of this project were unprecedented, with the aim to enhance the defensibility of model outcomes in the assessment of the impacts of past and current LULC change, as well as future outcomes. Ensuring confidence in the attribution of impacts on the water resource to specific drivers, such as climate and different LULC types, is of key importance in informing adaptation strategies.

CHAPTER 7: ISOTOPE HYDROLOGICAL STUDY

By: S Kebede, M Maseko, T Nsibande, and S Janse van Rensburg

This chapter outlines isotopes studies that contribute towards Aim 3: *Determine the relative impact of different vegetation units and climate on the hydrological response of the Lake Sibaya groundwater catchment.*

INTRODUCTION

The qualitative representation of the hydrological dynamics of a system (including hydrogeochemical, hydrological and geophysical information) and associated hydrogeological units based on principles of hydrogeology, is referred to as a conceptual model (Baalousha, 2009, Kiptum et al., 2017). The architecture for a conceptual model and inherent aquifer properties is developed through defining the conceptual domain (or hydrogeological domain) (Merz, 2012). This then guides the deliberation of the physical processes that occur within the domain of the model, such as groundwater-surface water interactions or recharge (Merz, 2012).

The sustainability of groundwater withdrawals is controlled in part by groundwater recharge, yet the conversion of rainfall into recharge remains inadequately understood, particularly in the tropics (Xu and Beekman, 2019). Understanding the recharge process and its relationship to rainfall is critical to the management of the groundwater system in MCP and can be explored through the use of hydrogeochemical methods. Such approaches also contribute to the improvement of our understanding of the connectivity of the aquifer systems and sources of water within the ecologically and economically important wetland ecosystems. In the context of this project, the investigation of the groundwater recharge mechanism is needed to help predict the likelihood of future (ground)water availability under changing rainfall patterns. Key gaps in our knowledge include understanding whether recharge is taking place from focused sources along preferential paths or if it is diffused recharge throughout the landscape. The other unknown is what minimum/threshold rainfall amount produces groundwater recharge, particularly in consideration of potential future rainfall decline/increase/changes in the frequency and nature of extreme rainfall events.

The other control of aquifer response to external forcing is the aquifer structure, which included its saturated thickness, depth of flow (shallow, deep), interconnection between different aquifer layers, presence of regional flows, and the storage capacity of the aquifers, etc. Numerical groundwater flow models allow the discretisation of these properties to predict hydrological changes in aquifers. In this respect this study aims to help refine the existing conceptual aquifer structure model. This entails a) investigation the hydraulic relation between the shallow and deeper aquifers; and b) identification of groundwater flow paths.

To answer the various key questions around groundwater recharge mechanism and aquifer structure, isotope hydrology was used as the principal tool. Water isotopes ($\delta^{18}O$-$\delta^{2}H$) are proven tools to answer questions raised above. This necessitated a carefully designed sampling of rains, groundwater, streams, lakes, and wetland waters.

An isotopes is the element that has the same atomic number but different atomic weight due to varying numbers of neutrons in the nucleus (Fetter, 2018). The use of stable isotopes, such as ^{2}H and ^{18}O, is based on water fractionation during phase changes. $H_2{}^{16}O$, for example, has a higher vapor pressure and diffusivity than $\delta H_2{}^{18}O$, which results in a higher ^{18}O content in water undergoing evaporation. Similarly, $^{2}H_2O$ and $^{1}H_2O$ fractionate as well, but to a greater extent than water with different oxygen isotopes due to a greater relative mass difference (Hunt et al., 2005). Isotopic enrichment refers to the degree to which the heavier isotopes (^{18}O and ^{2}H) are present in the water sample, as the greater their presence, the more positive the isotopic ratio value ($\delta^{18}O$ and $\delta^{2}H$) (Gat et al., 2001). Isotopic depletion refers to lower amounts of heavier isotopes. The more depleted the sample, the more negative the isotopic ratio ($\delta^{18}O$ and $\delta^{2}H$) will be (Gat et al., 2001).

Because of the various degrees of fractionation caused by different processes, ^{2}H and ^{18}O can be used to investigate hydrologic systems in a variety of ways. Thus, stable oxygen and hydrogen isotopes are increasingly used to study groundwater /surface-water interactions. The technique is also used to trace groundwater's provenance and is effective in the identification of processes that change the isotopic composition of rainfall prior to infiltration, such as evaporation or mixing from different rainfall events (Baijjali et al., 1997). Furthermore, water from various sources, such as precipitation, rivers, and groundwater, have distinct isotopic signatures, which can be used to gain insight into the interactions between these components (Reynolds et al., 2007). Stable isotopes ^{18}O and ^{2}H thus are ideal conservative tracers of water movement because they are part of the water molecule (Hunt et al., 2005) as long as there are no phase changes along a flow path. As a result, these isotopes have been used to locate and confirm groundwater discharge locations (Oxtobee and Novakowski, 2002), quantify groundwater discharge to surface water (Space et al., 1991), and differentiate the sources of groundwater recharge (Blasch and Bryson, 2007).

The local meteoric water line (LMWL) usually serves as a reference line, and the amount-weighted average precipitation value is regarded as the meteoric input signal (Bagheri et al., 2019). LMWLs represent the site-specific long-term (two to three years) covariation of ^{2}H and ^{18}O stable isotope ratios. LMWLs have practical utility as a hydrologic framework and as benchmarks for the evaluation of hydroclimatic processes, e.g. recharge, mixing, evaporation, tracing source of water(Putman et al., 2019). For example, groundwater that is recharged from evaporated waters (such as floods, open water bodies) plot below the reference LMWL and form a line called the Local Evaporation Line (LEL) (Kendal and MacDonnell, 2012). Fast selective recharge from heavy rains produce groundwater that plots in the negative end of the ^{18}O-^{2}H space on the LMWL (IAEA). Groundwater recharged from adjacent water would plot on the mixing line between the enriched surface water and depleted groundwater end members on the ^{18}O-^{2}H space (Kebede et al., 2010). The $\delta^{2}H$ and $\delta^{18}O$ values of groundwater and their relationship to the LMWL can be used to determine whether recharge is delayed or immediate, as well as to identify possible processes that altered the isotopic composition of precipitation prior to recharging the groundwater.

Meyer et al. (2001) utilised stable isotopes to distinguish between seepage from lakes and groundwater in their study of Lake Sibaya. Both Meyer et al. (2001) and Weitz and Demlie (2014) confirmed, through isotope analyses, that the fresh water seeps on the beach, noted by Nannie (1966), opposite Lake Sibaya, originate from the lake. Weitz and Demlie (2014) produced a hydrogeological conceptual model based on piezometric, environmental isotopes, and hydro-chemical data. This study indicated the degree of interaction (connectivity) of the Lake Sibaya water system. Weitz and Demlie (2015) used isotopes to explore the relationship between different water sources within the Lake Sibaya catchment.

Weitz (2016) notes that the lake is fed primarily by groundwater on its western side due to a higher groundwater head compared to the lake stage. Conversely, on the eastern side, the lake contributes to groundwater with a subsequent submarine groundwater discharge (SGD) into the sea through the dune cordon, given the higher lake levels. Meyer et al. (2001), based on stable water isotope data, corroborated these observations. Additionally, they proposed that the seepage of lake water into the ocean on the southern parts of Lake Sibaya is facilitated through two wide paleo-channels.

The Lake Sibaya water level is coupled closely with rainfall (Hill, 1979, Smithers et al., 2017). Rainfall is the primary recharge mechanism for the linked groundwater lake system. A close relationship between the lake level and “cumulative deviation of annual rainfall from the Mean Annual Precipitation (MAP)” has been demonstrated (Smithers et al., 2017), confirming sensitivity of the system to long term fluctuations in rainfall where below average rainfall from 2001 to 2011 was a key driver of lake water level declines (Smithers et al., 2017). As demonstrated in CHAPTER 5:, the study region receives rainfall from a range of different rainfall systems such as cut off lows, tropical storms, tropical cyclones, cloud bands, and mesoscale convective storms which represent different sources of moisture for rainfall in the area, the relative contributions of which to the groundwater systems are unknown for this region. Likewise, the relationship between the nature of rainfall events, e.g. amount and intensity, with groundwater recharge dynamics is important to understand. Rainfall events are generally light ≥ 10 mm to moderate ≥ 25 mm with occasional extreme events (Mpungose et al., 2022). Isotopes studies can assist in the exploration of both the sources of moisture for the rainfall events as well as the impact of the amount of rainfall on recharge.

Given the demonstrated link between land use and the groundwater system, in conjunction with concerns raised by community members that the increase in indigenous woody species (bush encroachment) in the area may impact on the water table as much eucalyptus plantations, parameters pertaining to the uptake of water by different species are important for hydrological models (for example see Kienzle and Schulze (1992)) but actual data is limited. The extent to which different tree species tap into different soil water sources and the depth to which this occurs is not well quantified in general and specifically for the study area. Stable water isotope composition measurements have, over the years, also become incorporated in vegetation studies such that there is already a number of methods established to quantitatively determine water use by plants, however, it is difficult to determine the source waters of these plants (Walker, 2005). Differences in endogenous composition of isotopes of source waters forms the basis of this method. Isotopic fractionation occurs due to transport processes as well as phase changes through the biosphere, lithosphere, and atmosphere. The varied degrees of isotope fractionating processes in soil moisture, stream water and groundwater, will result in varied isotopic values from which the plants source water can be deduced (Walker, 2005). Plant water source partitioning using stable water isotopes has previously been applied in South Africa for different reasons. February et al. (2013) looked at the water sources and potential competition between two savanna plant families (non-*Aizoaceae* and *Aizoaceae*) and their inherent species, along the west coast of South Africa. Holdo and Nippert (2015) made use of stem and soil stable water isotopes to assess soil moisture partitioning by *Terminalia sericea, Pterocarpus angolensis*, and surrounding grass species, in the savanna biome of Limpopo, South Africa. This was aimed at the quantification of the functional rooting profiles of the tree and grass species under investigation. Priyadarshini et al. (2016) looked at sources of water for grasses and trees within a Savanna vegetation type using stable water isotopes, in Andover Game Reserve, Mpumalanga. This study focused on the importance of hydraulic redistribution in semi-arid savanna tree species as well as grass and tree water sources across seasons. Although slightly dissimilar to what is being discussed, stable water isotopes in groundwater and municipal tap water have been used to aid in the understanding of the spatial variation of stable water isotopes across South Africa (West et al., 2014). From the reviewed literature, plant water source partitioning was not identified as having been used in aiding groundwater modelling practices in South Africa, whereas this study proposed an indirect way to use plant water source partitioning methods to aid modelling practices. This was done to address the gap in knowledge regarding where different tree species are sourcing their water from.

The study thus aimed to improve the conceptual groundwater model for the Lake Sibaya groundwater catchment area in the MCP with hydrogeochemical approaches to:

- Determine the relationship between rainfall and groundwater recharge;
- Investigate aquifer characteristics and improve on the conceptual model; and
- Explore the value of isotopes studies to assess tree water source partitioning.

7.1 METHODS

7.1.1 Hydrogeochemical Studies

To address the questions related to groundwater recharge mechanisms and aquifer structure to improve the conceptual model, proven tool of water isotopes (^{18}O-^{2}H) were used. This necessitated a carefully designed rainfall, groundwater, streams, lakes, and wetland waters sampling plan.

Five sampling campaigns were conducted to collect *in situ* data and water samples. The trips took place in September 2021 (spring); October 2021 (summer); April 2022 (autumn) May 2022 (early winter) and August 2022 (later winter/early spring). Timing of the trips was somewhat constrained and influenced by the COVID-19 situation. During sampling, *in situ* physiochemical parameters, such as EC, pH, DO and water temperature, were also measured for all the sampling sites. Rainfall samples were collected for most rainfall events by a community member living in the area. A total of 157 samples were collected from groundwater, surface water, lake, and rainfall sources.

Secondary data on pumping tests was secured from various sources and hydro chemical data was obtained from the National Groundwater Archive and Groundwater Resource Information Project (GRIP), as well as borehole logs from JG Afrika.

7.1.2 Determining Rainfall-Groundwater Recharge Relationship

To estimate the relationship between rainfall and groundwater recharge., groundwater, streams, and wetlands, rainfall samples were collected for stable isotope and *in situ* parameters (EC, DO, pH, etc.). Results from stable isotope analysis and EC from different sources were then assessed against meteorological data to determine the relationship between rainfall and groundwater recharge. In addition, water level data from observation wells inserted to different levels of the aquifers were used to gain insight on the relationship between rainfall and groundwater recharge.

7.1.3 Determining Aquifer Connectivity

Aquifer connectivity is determined by the ability of water to travel vertically and horizontally between aquifers. This is heavily reliant on local and regional hydraulic pressure and aquifer system orientation. Because aquifer systems are dynamic in nature, the gradient changes as groundwater enters and exits the system. Pumping tests were initially attempted as a method to determine the permeability, transmissivity, and hydraulic conductivity characteristics of the aquifers. However, due to the nature of the sandy aquifers in the Maputaland Coastal Plain, this method was deemed unfeasible as sufficient drawdown could not be achieved.

The alterative was to assess geological logs which is a useful method because it is the primary record of the geologic formations penetrated by the boreholes. Stable water isotopes methods where then used to analyse the connectivity between aquifers. To determine the connectivity between aquifers three sites, each with two nested boreholes, were sampled. For each site there was one “deep” borehole and one shallow borehole. Details are provided in section 7.1.4.

7.1.4 Sampling Sites and Procedures

Sites for groundwater, surface water (including lake and wetlands), as well as streams to be sampled were identified during an initial reconnaissance field trip. At all sites, *in situ* dissolved oxygen (DO), electrical conductivity (EC), temperature (T), oxidation reduction potential (ORP) and total dissolved solids (TDS) measured as ppm (parts per million) measurements were recorded using the Hanna HI

9828 multiparameter water quality meter. All sample bottles were rinsed vigorously three times with the lid on before taking the actual sample.

7.1.5 Groundwater

A total of 20 boreholes across the study area were sampled on each field trip. Eight of these are "inactive" boreholes (monitoring) wells, representing five sites (three with paired shallow and deep wells) that were pre-selected for the study. Seven of these are being monitoring by NRF-SAEON with groundwater level loggers. Following the pilot visit, an additional 12 "production" boreholes that were deemed logistically feasible were selected for inclusion. These included boreholes in schools, community wells, households, tourism facilities, and agricultural wells (see Figure 7-1 and Figure 7-2 as well as Table 7-1 for details). Over the sampling period, a total of 94 groundwater samples were collected.

The eight "observation" wells, were sampled following the procedure for general groundwater sampling detailed by Weaver and Talma (2007). Drilling Log data was obtained for the seven monitoring wells to determine the characteristics of the well including depth of well (Jeffers and Green, 2012; Terratest, 2019). On arrival at each site for each well a sample sheet was filled in with all the relevant information of the boreholes:

- Name of borehole,
- Coordinates,
- Depth of borehole, (cross-checked with borehole log)
- Time borehole was opened,
- Water level within the borehole, and
- Diameter of the casing.

Before any measurements were taken, a borehole inspection was conducted to ensure that it was free of obstacles and, therefore, safe to use. Then the groundwater level within a borehole, as depth to the water using the electronic water level meter, was measured. Calculations were made to determine the volume of water in the borehole and the time it would take to purge the borehole three times, as per general procedure (Weaver et al., 2007). The pumping rates relative to the pump used at the different borehole sites was determined by the time it took to fill a 10 L bucket for each borehole, as the pump rate varies depending on the borehole parameters. The standing volume of water in litres was calculated by substitution in the formula:

$$V = \pi x \left((d/2)/ 1000\right)^2 x\ h \qquad 7\text{-}1$$

During the pumping, water quality parameters that were measured included DO, EC, T, ORP and TDS measured as ppm (parts per million). Dependent on the pumping rate and purging duration, these water quality parameters were measured at certain intervals until they began to stabilise, to validate that the water being sampled is groundwater from the aquifer and not the stagnant residual water in the borehole casing. After these purges, the final measurements were taken and replicate groundwater samples were taken using 15 mL plastic container jars that were subsequently wrapped in parafilm, placed in plastic bags, and stored in a cooler box. The groundwater samples were collected directly from the pump outlet that discharged into a bucket. On return from the field trip each day, samples were stored in a fridge. At the end of each field trip they were transported in a cooler box and then again later stored for isotopic analysis at 4 °C (in refrigerators) (Geißler et al., 2019). A stainless-steel Mega-Monsoon XL was used for the pumping.

Active wells, such as community wells, were left to run for 10 minutes, then samples were collected, and *in situ* parameter measurements were taken.

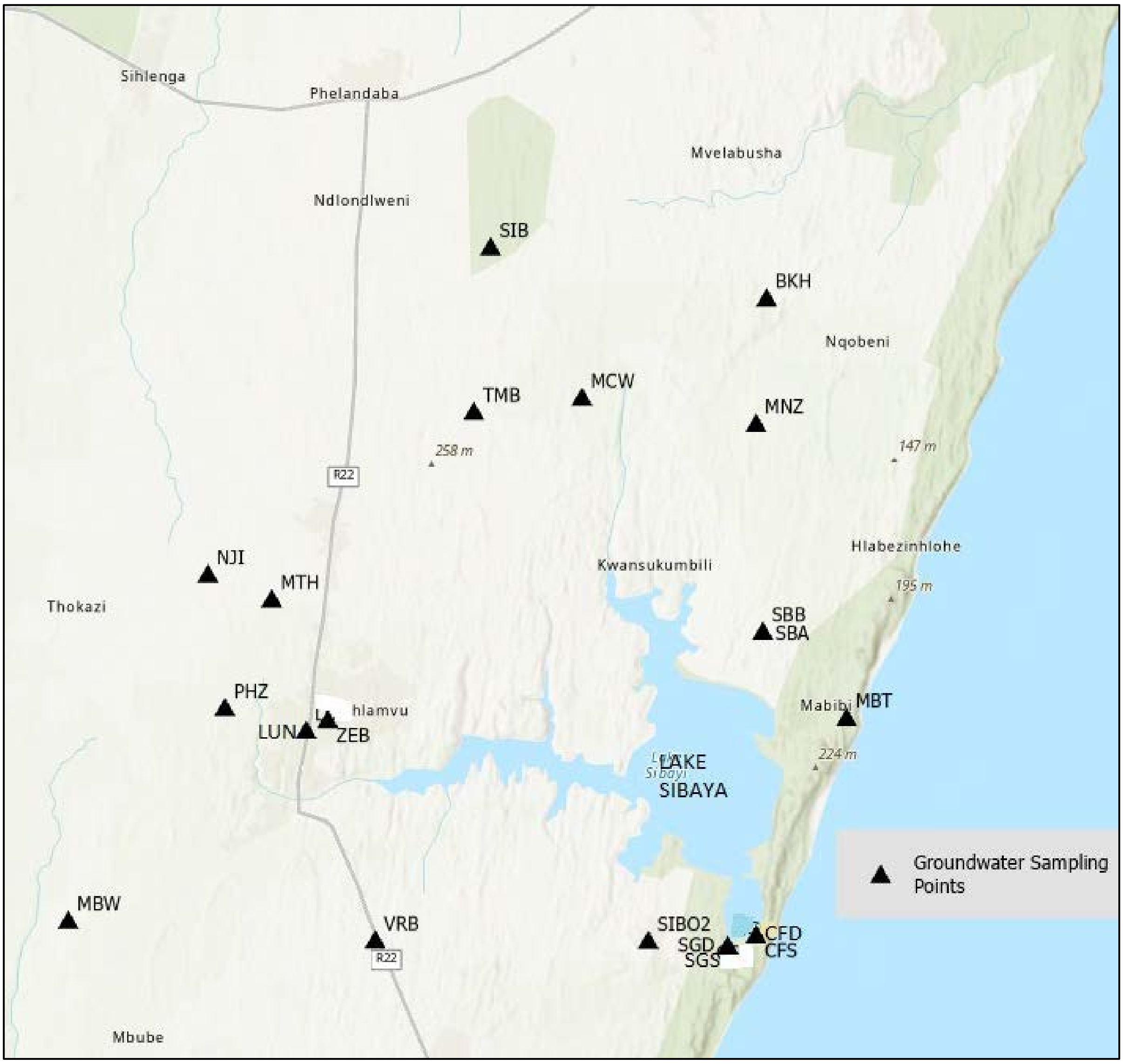


Figure 7-1: Locations of groundwater sampling sites.

*Table 7-1 Groundwater sampling sites matching full name with code names and associated location. Names donated with * are the wells where water level are actively monitored by NRF-SAEON.*

Name	Code	Longitude	Latitude
Tembe borehole (agric. high pump rate)	TMB	-27.207329	32.596585
Sileza borehole (inactive)*	SIB	-27.3083	32.56706
Bukhosini lower well (household)*	BKH	-27.161883	32.713556
Manzengwenya nursery (agric. high pump rate)	MNZ	-27.212064	32.709368
Mabibi borehole treatment works (tourism high pump rate)	MBT	-27.329729	32.745554
VR borehole (household and community sharing)	VRB	-27.418550	32.557220
Mbuweni borehole (household)	MBW	-27.410808	32.434484
Lungisani borehole household, supporting swimming pool)	LUN		
Jikijela High School	JIK	-27.25188	32.54007
Phuzemthonjeni School	PHZ	-27.32565	32.49707
Ezemvelo borehole (medium pump rate)	EZB	-27.201445	32.640450
Old Mac well (observation well)	MCW	-27.20159	32.63977
SG01A shallow (observation well) *	SGS	-27.42091	32.69811
SG01B deep (observation well) *	SGD	-27.42091	32.69815
CF01B deep (observation well) *	CFD	-27.41656	32.7094
CF01B deep (observation well*	CFS	-27.41656	32.7094
Zenzeleni Secondary School	ZEB	-27.330500	32.538200
Njinji Primary School	NJI	-27.272330	32.490330
Mthalane borehole	MTH	-27.282220	32.515770
SIB01B (observation well)	SBB	-27.29523	32.71206
SIB01A (observation well)	SBA	-27.29526	41.146

The log details available for the nested boreholes used for the aquifer connectivity study are as follows:

- SG01A (shallow) (KZN180369) and SG01B (deep) (KZN180368) are located at the south basin of Lake Sibaya. The site consists of the shallow and deep boreholes drilled a few metres apart. Log details were provided by Terratest (2019). The shallow well (SG01A) was drilled to 20.4 m with a diameter of 100 mm and 20,9 m AMSL. The screen is from 18-21 m below ground level (BGL). The deep well (SG01B) was drilled to 53 m, with a borehole diameter of 100 mm and static water level reading of 11.26 m below surface. These wells were drilled in July 2019. The water level record has been measured since 2020.

- CF01A (shallow) (KZN180371) and CF01B (deep) (KZN180370) boreholes are locate on the eastern edge of the south basin of Lake Sibaya on the lake side lower slope of the forested dune cordon between the lake and the sea. Log details were provided by Terratest (2019). CF01A (shallow) was drilled to 36 m, has a borehole diameter of 100 m and is 27.69 m AMSL. Two distinguishable layers were described in the log with the upper layer being described as "*Light orange brown very slightly silty fine to medium Sand*", to a depth of approximately 24 m BGL. Below that the layer is described as "*Very light brownish grey khaki clean medium sand with minor fine and coarse lenses*" The screen is in the lower layer from 27-36 m BGL CF01B (deep) was drilled to a depth of 66 m, also with borehole diameter of 100 mm and is 27.93 m AMSL. Six layers were distinguishable in the log with the deepest being described as "*White mottled brown Calcareous* Sandstone" and the screen was within this layer (60-66.0 m BGL). These well were drilled in July 2019.

The SIB01A (shallow) and SIB01B (deep) pair of boreholes are located just north of the main basin (closest point 2.7 km) and east alongside the northern arm (closest point 2.2 km) in open grassland. Jeffares and Green (2012) provided log details for the wells. SIB01A (shallow) was drilled to 26 m, has a pipe diameter of 125 mm and is 41.18 m AMSL. Five layers were distinguishable from the drilling and the screen was placed in the middle of these (18-20.84 m BGL) in a layer described as "*Khaki to very light grey moderately sorted loose medium to medium coarse Sand*". SIBO1B was drilled to 46 m, has a pipe diameter of 63 mm and is 41.15 m AMSL. Twelve layers were distinguishable during the drilling and the screen (43.16-base) was placed in the lowest of these which was described as "*Green calcareous SANDSTONE with numerous shells from 41-43 m*". These wells were drilled in November 2011.

7.1.6 Surface Water (lake stream and wetland) Sampling

Surface water samples were taken directly from the water bodies (lakes, streams, and wetlands), and sampled whenever possible during sampling trips. Some sites were reached by vehicle and on foot (side samples) whereas others were sampled within the lake by boat (Figure 7-2). For boat sampling, a pop bottle was used to sample at a depth of one metre below the surface of the water. For lake and wetland edge samples the pop bottle was thrown into the deepest section at the site and pulled back immediately when reaching a depth of approximately 1 m, however this was not as accurate as the more controlled sampled by boat. For shallow streams, samples were collected directly into bottles below the surface as far as the depth would allow without disturbing the streambed and debris. Due to some logistical difficulties, not all sites were sampled consistently on every trip. A total of 78 surface water samples were collected.

Figure 7-2 Lake Surface water lake and wetland sampling points

Table 7-2 Surface water lake and wetland sampling sites match full description with code names and location

Name	Code	Source	Longitude	Latitude
Western arm edge	WWM	Wetland	-27.360898	32.567035
Western arm upstream of wetland (forest wetland culvert)	WAF	Wetland seep zone flowing towards lake	-27.363230	32.564950
Western arm south bank wetland mouth	WAE	Wetland	-27.360641	32.567152
Banda Banda Bay cut-off pool	BBB	Wetland/cut off pool	-27.396740	32.711010
South basin; eastern edge near Banda Banda Bay	SBE	Lake	-27.417470	32.697720
South basin: pump house inlet	SBP	Lake	-27.417455	32.697945
Northern arm on western side. shallow littoral zone	NAW1	Lake	-27.302140	32.670990
Northern arm off boat (1 m)	NAW2	Lake	-27.298660	32.670240
Lake Sibaya centre deep point	DTT	Lake	-27.34411	32.69376
SW basin "unknown lake upstream", flowing into SW basin	SWU	Wetland	-27.390280	32.653610
SW basin Lake Sibaya, cut-off pool SW, not flowing	SWC	Wetland	-27.395030	32.659220
Eastern edge shallow littoral zone	EES	Lake	-27.33571	32.70559
Northern arm at DWS pump house, Lake Sibaya, near pipe inlet,	DFF	Lake	-27.28053	32.683602
Lake Sibaya east/Mabibi	LSE	Lake	-27.327442	32.710163
Old Research Site	ORS	Lake		
Eastern section off boat Lake Sibaya (shallow – 1 m)	STT		-27.368200	32.695780

In addition to the lake and wetlands around the lake, several streams were sampled (Figure 7-3), some of which flowed directly into the lake and others not. All samples were subsurface samples but due to the shallow nature of the streams, samples were generally taken from maximum depths which ranged from approximately 10-30 cm.

Figure 7-3 Surface water sampling sites for streams and wetlands within the study area

Table 7-Stream sampling sites with code names and location

Code	Source	Longitude	Latitude
NAS	Stream	-27.274629	32.681846
NAS2	Stream	-27.275593	32.684837
USI	Steam	-27.481708	32.582053
MSL	Stream	-27.327080	32.713070

7.1.7 Rainfall Sampling

A community member, living near the western arm of the lake in the Mseleni area (27.33482 N, 32.52963 S) was selected and trained to collect rainfall samples for all rainfall events.

Rainwater samples were collected daily (if rain fell) using two differently designed rain collectors. This included use of two ordinary plastic rain gauges and the standard Palmex rain sampler RS1. The rain gauges were placed at two different heights, one at 1.2 m above the ground and the other on a rooftop. The standard Palmex rain sampler was mounted on a wooden bar 1.2 m above the ground. A total of 92 rainfall samples were collected between July 2021 and August 2022. The reason for the installation of the ordinary plastic rain gauge samplers was to test the usefulness of such devices as a citizen science tool for community-based rainwater sampling. A comparison of the isotope data from the two sets of samplers has been made to investigate the usefulness of the ordinary devices. The Palmex collector was developed at the IAEA and it allows virtually evaporation-free rain sampling for subsequent water stable isotope analysis. It is designed for the collection of composite daily to monthly samples. The collector has the advantage of minimizing necessary staff time for sampling by easy and fast changes of sample bottles to avoid any need of oil for prevention of evaporation to be inexpensive in construction; to be installed easily; and to be used in remote areas (unattended for one month). Tests performed at the IAEA have proven that water stored in the sampler for nearly one year did not suffer significantly from any evaporation effect (Gröning et al., 2012). Further comparisons performed at sampling stations of the Global Network of Isotopes in Precipitation (GNIP) show excellent performance of the new collector with advantages over some conventional precipitation samplers (Gröning et al., 2012).

The Palmex rain sampler RS1 was used as the benchmark sampler as it is designed for the collection of monthly or daily samples as requested for stable isotopes precipitation networks and it is evaporation-free. The other two samplers were used as a backup. To minimise evaporation, samples were collected daily at 8:00 am in the morning. To prevent evaporation, samples were kept in 50 ml or 100 ml bottles, depending on the amount of water received, with a minimal headspace, and stored at 4°C prior to analysis.

Figure 7-4 Rainfall samplers from left to right Palmex rain sampler RS1; rooftop rain gauge and rain gauge at 1.2 m

7.1.8 Sampling Procedures for Plant Water Use Studies and Stream Flow Measurements

From the above sampling points, several sites were sub-selected for tree and soil sampling for the tree water source partitioning study (Figure 7-5).

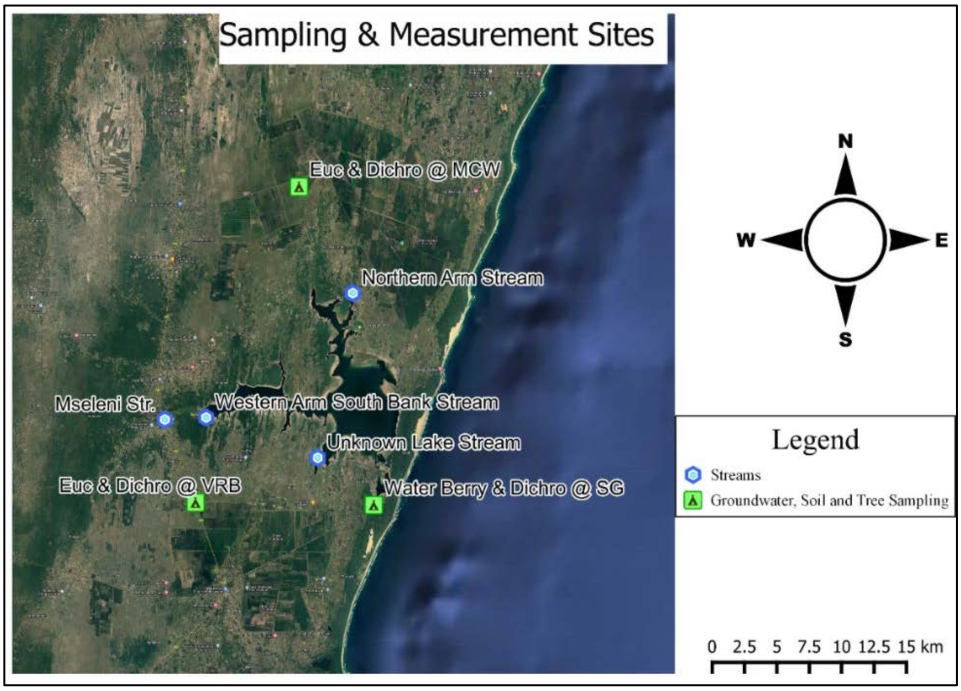


Figure 7-5 Illustrating the sampling locations for groundwater, streams (streamflow measurements for MODFLOW), soil and tree sampling points for tree water partitioning study

7.1.8.1 Tree sampling

Community members raised concerns with regard to the increase in wood indigenous woody species such as *Dichrostachys cinerea* (bush encroachment). Turpie (2019) confirms that *Strychnos madagascariensis* and *D. cinerea* (also known as false acacia) are common bush encroachment indicator species across South Africa. Another common indigenous tree species that typifies the Maputaland region is the *Syzygium cordatum* (also known as Waterberry tree) (Clulow et al., 2013), which is known to be associated with the groundwater table. For this project *D. cinerea* was selected as an encroacher species, and *S. cordatum* was selected as an established common tree species, within the area and its association with the groundwater/wetland systems. *Eucalyptus grandis* (Gumtree) was selected as encroacher from the forestry species.

Initially, tree branch samples were collected for moisture to be extracted using the pressure bomb technique. Sun-exposed branches were taken before midday (Carrière and Simioni, 2020, Carrière et al., 2020, Landgraf and Soulsby, 2021). These branch samples were selected based on size to fit inside the pressure chamber. To prevent loss of water, the branches were separately wrapped in parafilm, plastic wrap and tin foil, and were then bagged and placed in a cooler box to prevent transpiration and any water loss (Geißler et al., 2019). The second approach followed the traditional transparent plastic bag over tree leaves or shoots technique, as detailed by Menchaca et al. (2007) and Chakraborty et al. (2018). This technique consists of the creation of a saturated environment using transparent plastic bags sealed over a tree shoot with leaves to prevent further evaporation and to allow evaporated transpired water to eventually mix with transpired unevaporated xylem water. The moisture that collects within the plastic bag is then sampled (Menchaca et al., 2007).On sunny days, a transparent plastic bag was placed directly over certain branches with leaves (still connected to the tree or bush) and sealed using tape (Figure 7-6), at the selected sites for soil sampling. The transparent plastic bags were laboratory grade and theoretically did not permit diffusion of water through the plastic bags.

Figure 7-6 Placing plastic bags over a Waterberry tree (Syzygium cordatum) branches with leaves on a sunny day

The tree species selected were the same as those selected for moisture extraction using the pressure bomb. The bags were left on for the entire day and the transpired water was collected in the late afternoon (Chakraborty et al., 2018). The collected water was stored in 15 ml plastic container jars that were subsequently wrapped in parafilm, placed in plastic bags, stored in a cooler box, and later transferred into a refrigerator (4°C). The aim was to not leave air space within the jars, but in cases where this was not possible, the sample was still taken and this was noted. For the collected branches and leaves, immediately prior to xylem water extraction using the pressure bomb, the individual branches were cut again to obtain a straight and fresh cut which was then placed quickly into the pressure chamber using clamps, with the branch side that was prepared facing outwards. The intention was to achieve xylem water that flowed steadily from the branch, pushed out by the continual increase in the chambers' internal pressure (Geißler et al., 2019). However, this was not achieved as the most moisture that was obtained, was water that bubbled from the *E. grandis* sampled branches with no clear drops or liquid flow. No moisture was obtained from the other sampled species. The cryogenic vacuum distillation (CVD) technique was not used mainly due to high potential for organic matter contamination.

7.1.8.2 Soil sampling

To keep isotopic enrichment at a minimum due to the evaporation of soil moisture, soil samples were taken in the morning before 10:00 am (local time) with reference to Wang et al. (2021). An auger was used to obtain soil samples (Figure 7-7, left) (Barbeta et al., 2018; Geißler et al., 2019; Carrière et al., 2020). Initially, samples were taken at a depth of 10 cm and later, after advisement and review of the soil type, this was changed to 50 cm to reduce the impact of evaporation on isotope composition (Penna et al., 2013, Carrière et al., 2020, Wang et al., 2021). All soil samples/pits consisted of sandy soils. The soil samples were collected close to the sampled trees. Samples were placed into well-sealed transparent plastic bags, taking care to remove as much air as possible and then stored in a cooler box (Figure 7-7, right), until refrigeration on return from the field (4 °C).

Figure 7-7: Using an auger to obtain soil samples (left) and packing the samples in zip-lock bags (right) at the SGO1 site next to a Waterberry tree (Syzygium cordatum)

The cryogenic vacuum distillation (CVD) technique was used for the extraction of soil moisture from the soil samples, following a method adapted from Orlowski et al. (2016). This procedure required weighing an empty flask followed by weighing the flask with the wet soil (original sample), prior to heating the soil sample using a heating mantle set at 15 to 20% voltage for four to five hours. The samples were cooled for an additional three to four hours. During the distillation process the condensing water was collected in a weighed glass sample bottle. After the extraction process, the flask with the dry soil was weighed as well as the glass sample bottle, prior to and after obtaining the extracted water. These measurements were used to calculate the water extracted from the soil and the water captured using the distillation process. The sample bottles were then labelled and stored in the refrigerator to later undergo isotopic analysis (Orlowski et al., 2016, Carrière et al., 2020). Communication with soil scientists advised against the use of the centrifugation method for the extraction water from very sandy soils as the soils would not be sufficiently wet. Rewetting of soils using distilled water (Orlowski et al., 2016) was considered, however, the isotopic content of the distilled water would have to be corrected from the isotope analysis results, therefore this was not opted for.

7.1.9 Meteorological Data

For all isotope studies, the daily observed climate data was obtained from the nearby Science Centre weather station (-27.16409; 32.71436) monitored by NRF-SAEON. Figure 7-8 indicates the locations of the NRF-SAEON weather stations, and rain gauge network groundwater, lake and stream-water level monitoring sites that provided meteorological as well and groundwater and lake level data required for the project.

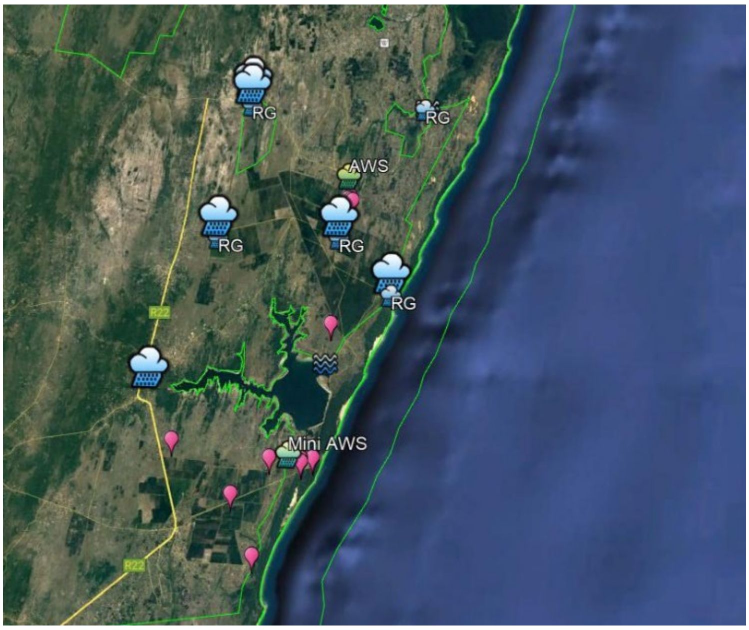


Figure 7-8 NRF-SAEON Automatic weather stations (AWS), rain gauges sites (RG) lake level/stream level (water icon) and groundwater monitoring points (pink icons)

7.1.10 Stable Water Isotope (^2H and ^{18}O) Analysis

The stable isotope analysis of the rainfall, groundwater, stream, soil, and lake samples were performed at University of Stellenbosch using the Los Gatos T-L-WIA-45-EP stable isotope instrument. All the samples that were analysed were stored at 4 °C for less than six months, which is the standard laboratory sample holding time for stable water isotope analysis (MDH, 2022). To prepare the samples for analysis, a 1.9 mL liquid sample was filtered using a syringe filter (0.22 FilterBio cellulose acetate syringe filter, with a diameter of 25 mm) for each sampled in 2 mL glass vials and PTFE septum caps. To prime the system, deionized water was used followed by three LGR working standards (two calibration standards (1E and 5E) and control standard (3E) unknowns, and then another standard). This array of standards and unknowns were repeated up to a maximum of four times (40 unknown) for a single run. Each standard or unknown was individually measured with nine injections. The results from each vial were then averaged. Two runs were conducted for each of the stable water isotopes ($\delta^{18}O$ and δ^2H) of each sample, and mean values from both sets of runs were determined.

Stable water isotopic ratios (heavy isotope and light isotope) are $^{18}O/^{16}O$, $^{17}O/^{16}O$, and $^2H/^1H$ (IAEA and UNESCO, 2001). Delta values (δ) are used to express a water samples concentration of heavy isotopes (Mook, 2000). Stable water isotopes are quantified using the delta notation calibrated against VSMOW and expressed as (Sodemann, 2006):

$$\delta^{18}O = \left(\frac{^{18}R_{sample} - ^{18}R_{std}}{^{18}R_{std}}\right) \times 1000 = \left(\frac{^{18}R_{sample}}{^{18}R_{std}} - 1\right) \times 1000 \text{ (‰)} \qquad 7\text{-}2$$

Where: $^{18}R_{sample}$ = denotation for samples isotopic ratio, and

- $^{18}R_{std}$ = denotation of standard isotopic ratio is.

The amount effect was used to determine the relationship between the amount of precipitation and ^{18}O. The amount effect means that the more rainfall there is, the lower the ^{18}O amount and the more depleted it is. Less intense or lower rainfall is more likely to result in enriched rainfall and high ^{18}O levels. A correlation analysis was done, plotting rainfall amount on the X-axis and stable isotope signature on the Y-Axis to visualise the amount effect on each day.

The amount-weighted monthly and annual stable isotope signatures were calculated using the daily stable isotope signature and the daily rainfall amount. The monthly amount-weighted isotope signature was determined by first calculating the fraction of daily rainfall amount to the total rainfall for that month and multiplying the fraction by the isotope signature (δ2 H and δ18O) of rainfall for that day to get the isotopic weight of daily rainfall. Comparison of the groundwater isotope data with the waited mean values gives insight on the recharge processes and deciphers which rainfall condition (average, heavy, light) is responsible for groundwater recharge.

7.2 RESULTS

7.2.1 Isotopic Composition of Rainfall and Constructing the Local Meteoric Water Line

Three rainfall samplers were utilised to collect rainfall for isotope analysis, one placed on the roof and one placed at 1.2 m above the ground, and the Palmex RS1 rainfall sampler. The ^{18}O-^{2}H plot from three different samplers and the best fit line (Local Meteoric Water Line) (LMWL) through the data sets are shown in Figure 7-9. The three samplers show slightly different LMWL. The slope of the LMWL constructed from the Palmex sampler is slightly higher than the slopes of the lines through the data points from the rain gauge samplers. Lower slope in the rain gauge samplers reflect evaporation from the rain samples prior to collection. This was expected. Thus, the LMWL obtained from the Palmex sampler was used as the reference LMWL for the study area (Figure 7-10). The equation of the LMWL for the region was thus taken as $\delta^{2}H=7.2\delta^{18}O+15.72$.

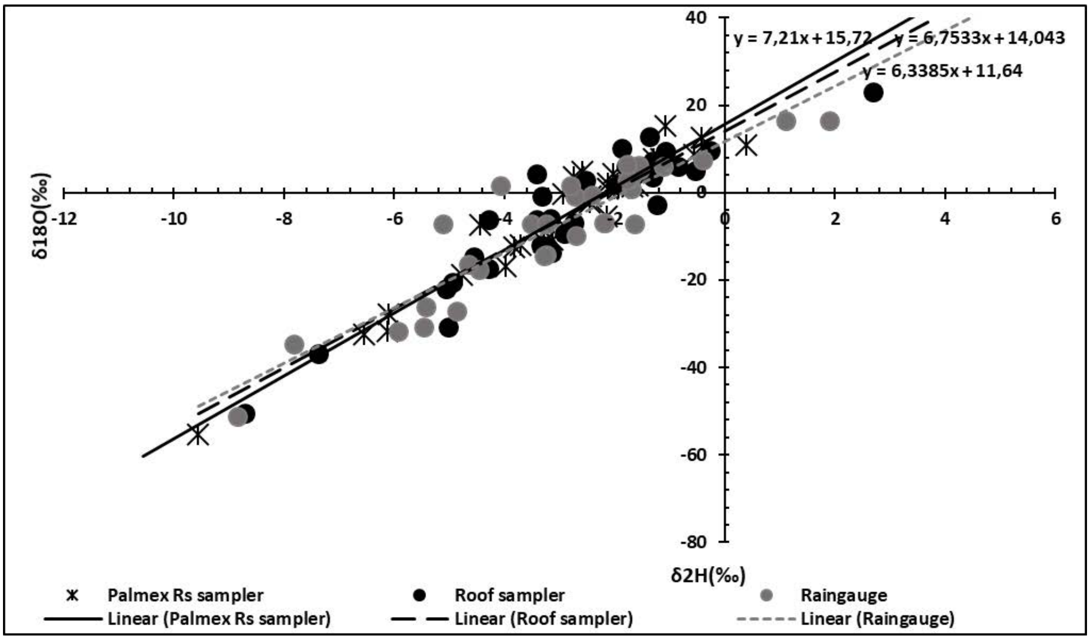


Figure 7-9: Stable Isotopes of rainfall samples from three different samplers

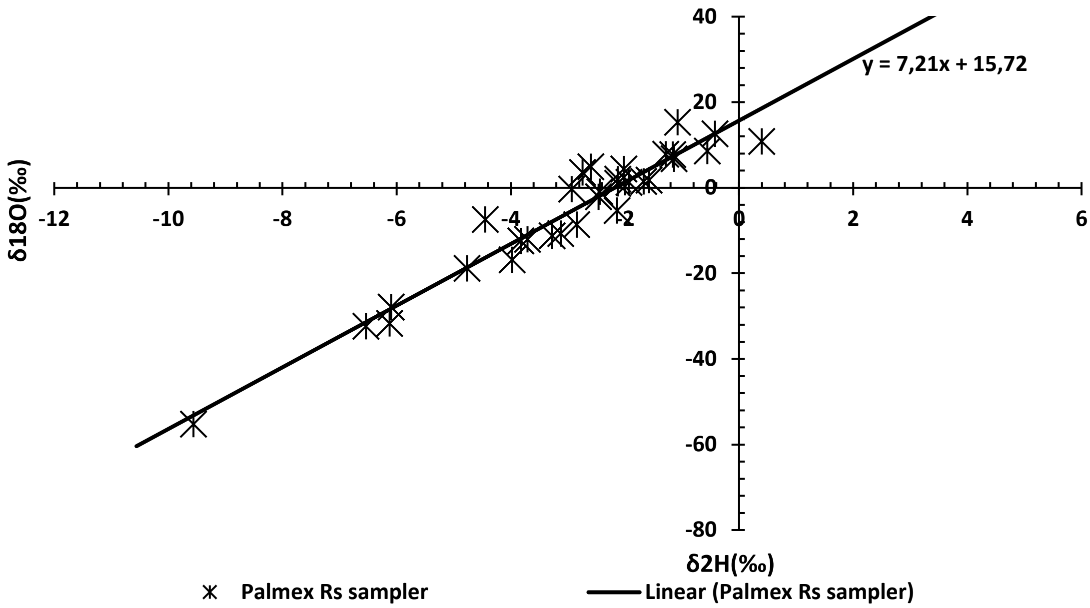


Figure 7-10 The Isotopic data for precipitation collected using a Palmex Rainfall Sampler

7.2.2 Isotopic Composition of Groundwater

The stable isotope composition of groundwater reflects that precipitation in the recharge area seeps through the soil and the unsaturated zone to reach the water table. The potential infiltration of precipitation into the soil and the unsaturated zone is, in principle, an isotopically non-fractionating process. The isotopic signatures of the 83 groundwater samples taken within the Lake Sibaya groundwater catchment are clustered into three groups (Figure 7-11).

The $\delta^{18}O$ vs. $\delta^{2}H$ for all groundwater sampled generally plotted below the LMWL indicated that these samples have undergone evaporation prior to recharge (Figure 7-11). The most positive $\delta^{18}O$ and $\delta^{2}H$ grouping (CFS and CFD; medium grey triangles) is from one site with a nested pair of wells (CF01A and CF01B) located in the eastern dune cordon next to the south basin of Lake Sibaya, near Banda Banda Bay (see Figure 7-1). The enriched ^{18}O-^{2}H values from this site fall on the far right of the LMWL with a value ranging from 1.2 to 2.17 and 16.6 to 20.6‰, in ^{18}O and ^{2}H -28‰ respectively. This water flows eastwards from the lake into the ocean.

A second grouping (MBT: light grey triangles) is also from a single site located on the eastern coastal dune, as with the CF wells, but is more to the north and further away from the lake. For this site, values fall below and around the LMWL showing slight enrichment with a $\delta^{18}O$ and $\delta^{2}H$ ranging from -1.908 to -2.75 and -4.68 to -7.47‰ in 18O and 2H respectively.

The third grouping consists of all the remaining inland sites (dark grey triangles). The sites are located close to but below the LMWL, with the implication that there is some evaporation prior to recharge but to a lesser degree when compared to the coastal sites. These represent sampling sites to the north, west and south of the lake. The best fit line through the groundwater samples intersects the LMWL at about ^{18}O=-6‰ and ^{2}H=-28‰. The value of the intersection point is often taken as a proxy for the original isotopic composition of the rainfall water that produced/recharged the groundwater (Yi et al., 2008).

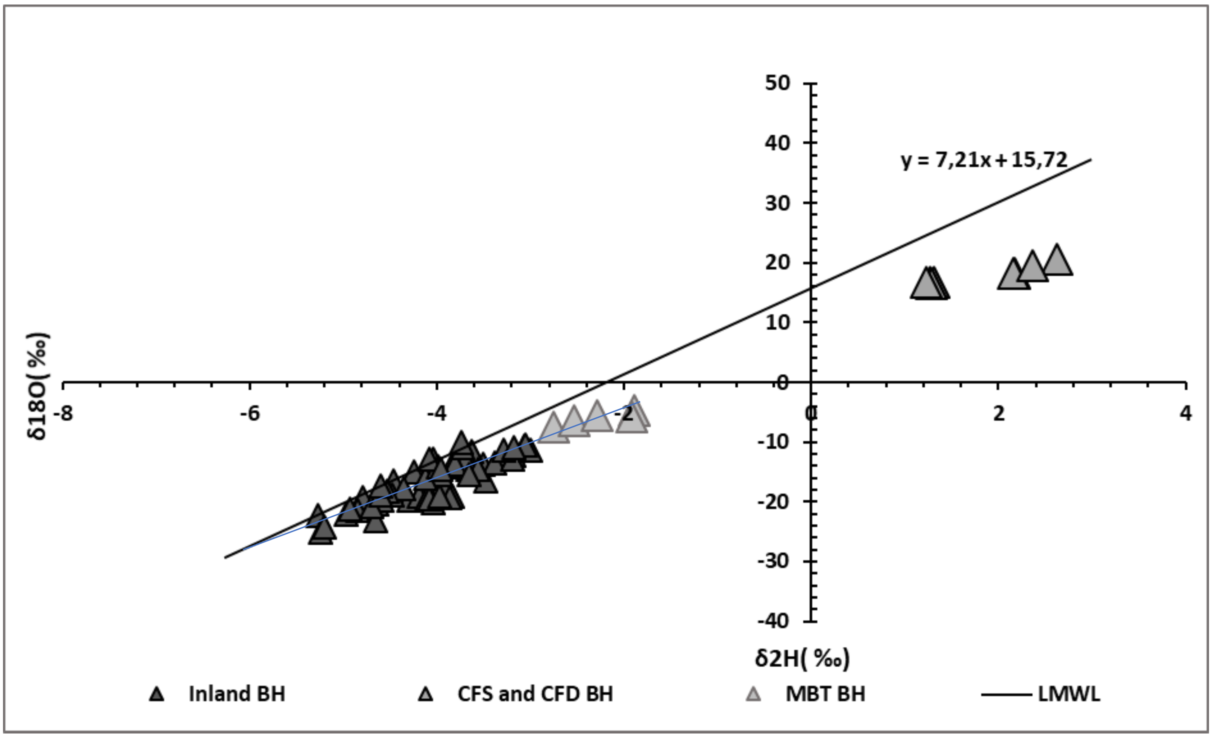


Figure 7-11: Scatter plot of groundwater samples Isotope composition

7.2.3 Rainfall-Groundwater Recharge Relation Revealed by Amount Effect

To estimate the minimum amount required to see recharge of the groundwater aquifer, the isotope composition of the daily rainfall has been plotted against the corresponding rainfall amount of the day (Figure 7-12). Precipitation isotopes mainly correlate negatively with precipitation amounts on a monthly scale and sometimes on a daily scale. This empirical inverse correlation between water isotope ratios and the amount of rainfall, known as the "amount effect", is used as a rationale to infer groundwater recharge mechanisms. The amount effect is explained by the preferential isotopic exchange of the smaller droplets, which are predominant in light rains and drizzle, with the near-surface moisture.

Figure 7-12 shows the ^{18}O-rainfall amount plot. There is a strong correlation between the rainfall amount and its $\delta\ ^{18}O$. This relationship is used to estimate the minimum amount of rainfall required to recharge groundwater. Comparing this with the groundwater isotope signals provides an indication of the minimum amount of rainfall needed to see a recharge effect in the aquifer. For the sites around Lake Sibaya, (the "inland grouping" in Figure 7-11 representing sites to the north west and south of the lake) recharge becomes evident at roughly 30 mm/day. However, for the north-eastern coastal dune site at Mabibi (MBT) both small and large rainfall events contribute to groundwater recharge (Figure 7-12). Notably the site with paired wells in the coastal dune cordon close to the lake (CFS and CFD) have enriched values to the extent that they cannot be plotted on the graph. This indicated rainfall input generally does not impact on recharge at this location and the primary source of recharge is from the enriched lake water that flows through the dune field from Lake Sibaya to the sea. Given the likelihood that the main recharge area for the lake comes from the more "inland" sites to the north west and south. It is therefore postulated that rainfall events of greater than 30 mm are important to have sufficient impact for the recharge of the groundwater and connected Lake Sibaya system.

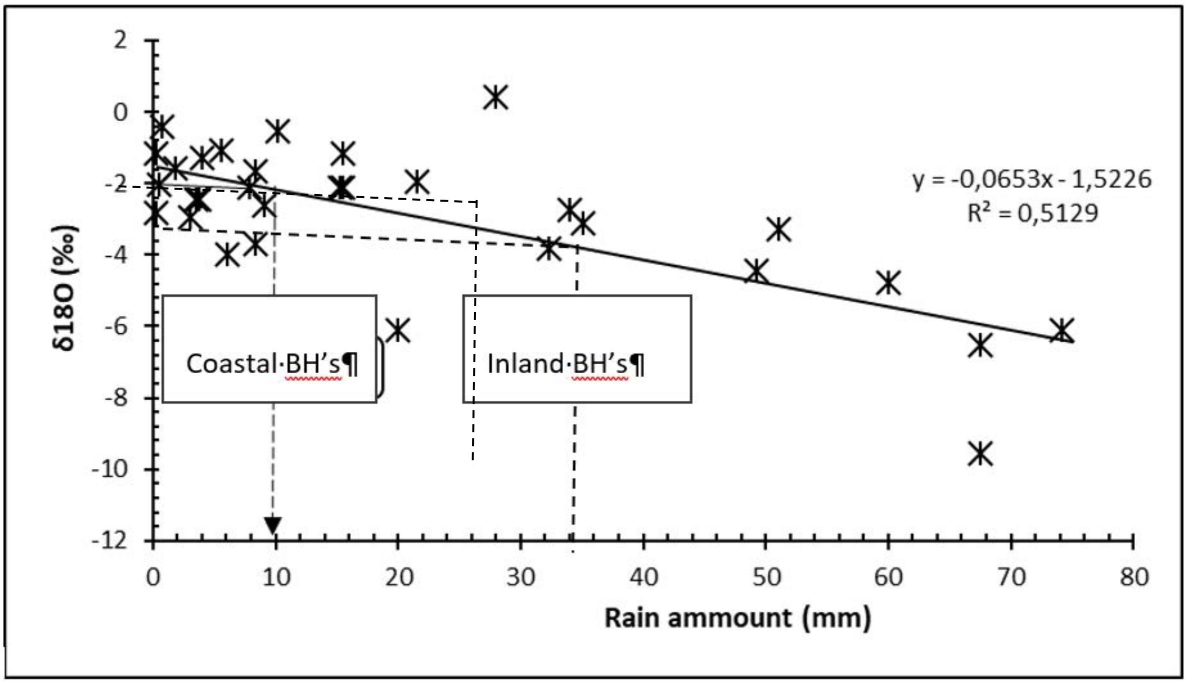


Figure 7-12: Rainfall isotope versus rainfall amount relationship plotted to determine how much rainfall is required to have an impact on groundwater recharge

The daily and monthly weighted average isotopic composition of the rainfall water (Figure 7-13 and Figure 7-14), is relatively more enriched than that of the isotopic composition of the intimal recharge water computed from the intersection of the LMWL and the evaporation line fitted through the groundwater. This reveals the importance of selective heavy rainfalls in recharging the aquifers. Furthermore, there is a very strong similarity between the isotopic composition of the computed initial recharge water (revealed from the intersection between LEL and LMWL) and the isotopic composition of the heavy rains of April 2021, which revealed that groundwater recharge took place from selective heavy summer rains similar to heavy rains that occurred in January and April 2022 (heavy storm exceeding 30 mm/day) (Figure 7-15). The contribution to groundwater recharge in the small rain months of Oct, Nov and Dec was minimal within the study period.

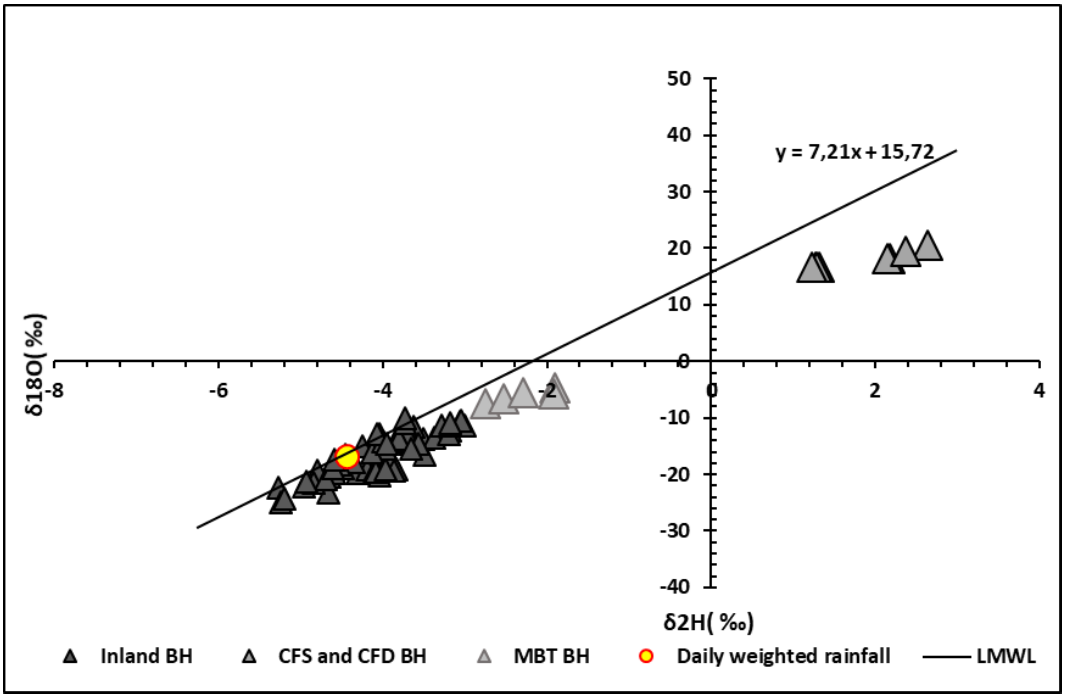


Figure 7-13: Daily weighted rainfall

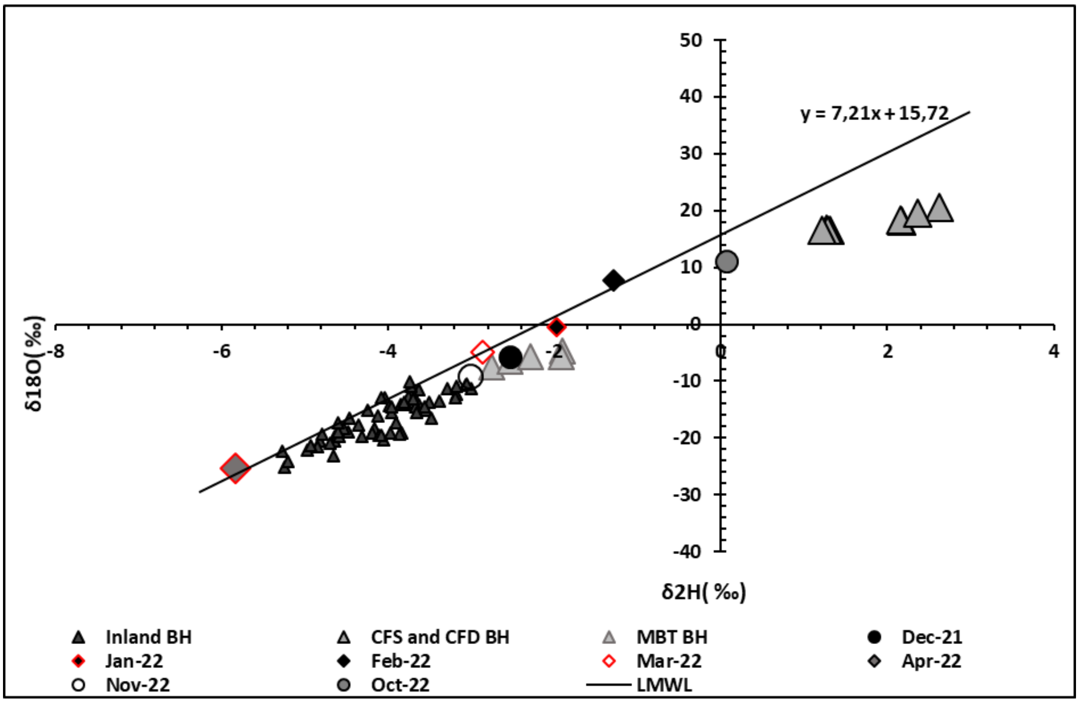


Figure 7-14: Monthly weighted average rainfall

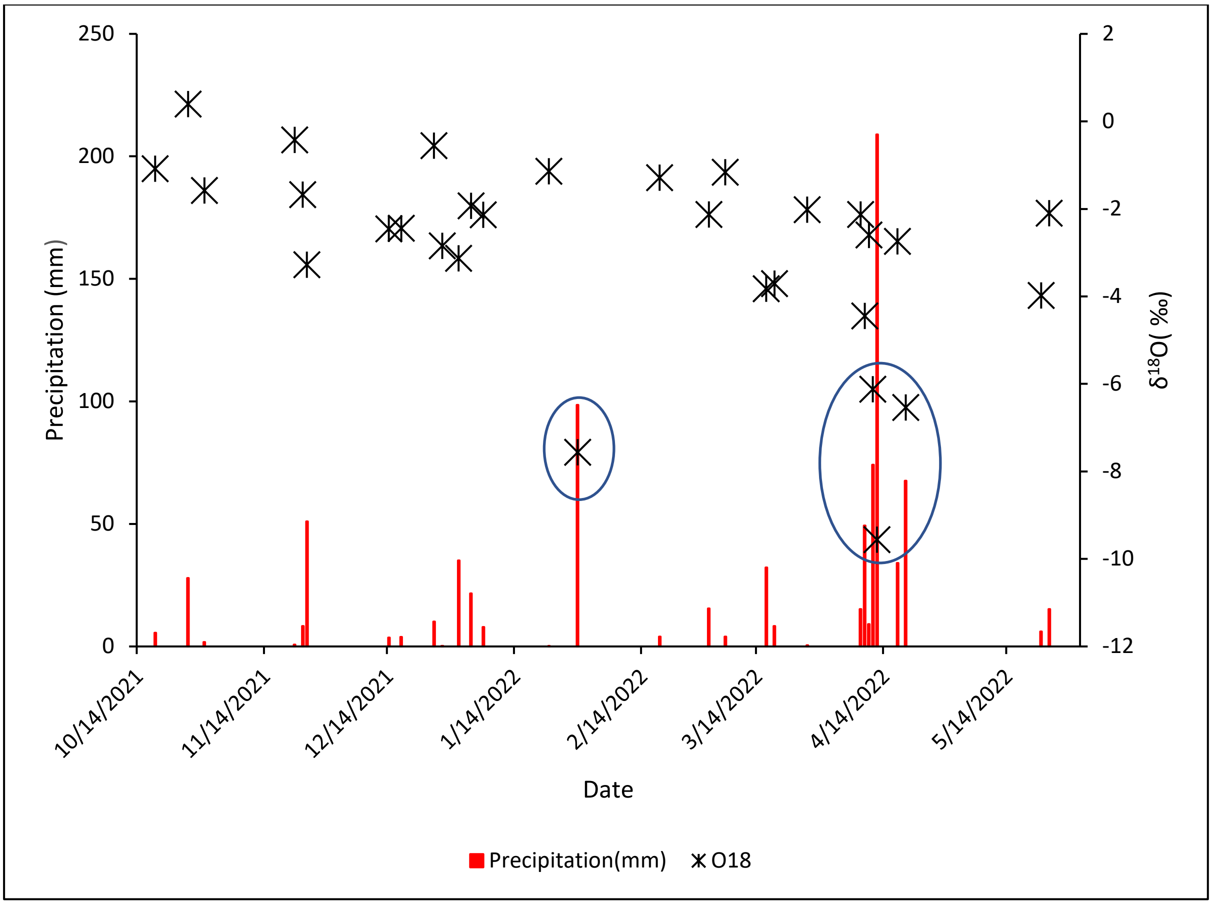


Figure 7-15 Plot of rainfall daily amount and the isotopic composition of rainfall

7.2.4 Aquifer Connectivity Revealed from Isotopes and Water Level Records in Nested Observation Boreholes

Modelling of the hydrological response requires a well-constructed realistic conceptual model on interconnectivity between aquifers. In this study paired deep and shallow wells were sampled to assess the connectivity between aquifers. The assumption is that aquifers (groundwater bodies) not connected to each other will have distinct isotopic compositions from each other while aquifers connected to each other will have uniform isotopic compositions because of mixing. The paired boreholes that were sampled were located in different areas around Lake Sibaya (Figure 7-1): The CFD: CFS pair is located within the forested section next to the road on the eastern dune cordon between the lake and the sea, just south of Banda Banda Bay. The SGD: SGS pair is also located on eastern dune cordon, but further south near the south eastern edge of the south basin within the old Ezemvelo gate house compound. Lastly the SBB: SBA pair is located to the north of the lake in the grassland between the Manzengwenya Forest and Lake Sibaya.

The similarity in the isotopic signatures of the three nested boreholes across the seasons (Figure 7-16), illustrates the connection between the deep and shallow groundwater. The isotope signatures ^{18}O, ranged from **3.28 to 2.17** for shallow**; -4.046 to 2.629** for deep groundwater. For ^{2}H -11.39 to 20.62, shallow, and -12.87 to 20.62 deep groundwater, the differences between the shallow and deep groundwater is very small, an indication of the presence of connection between aquifers, regardless of their depth, and yet a further indication of a hydraulically well-connected aquifer system.

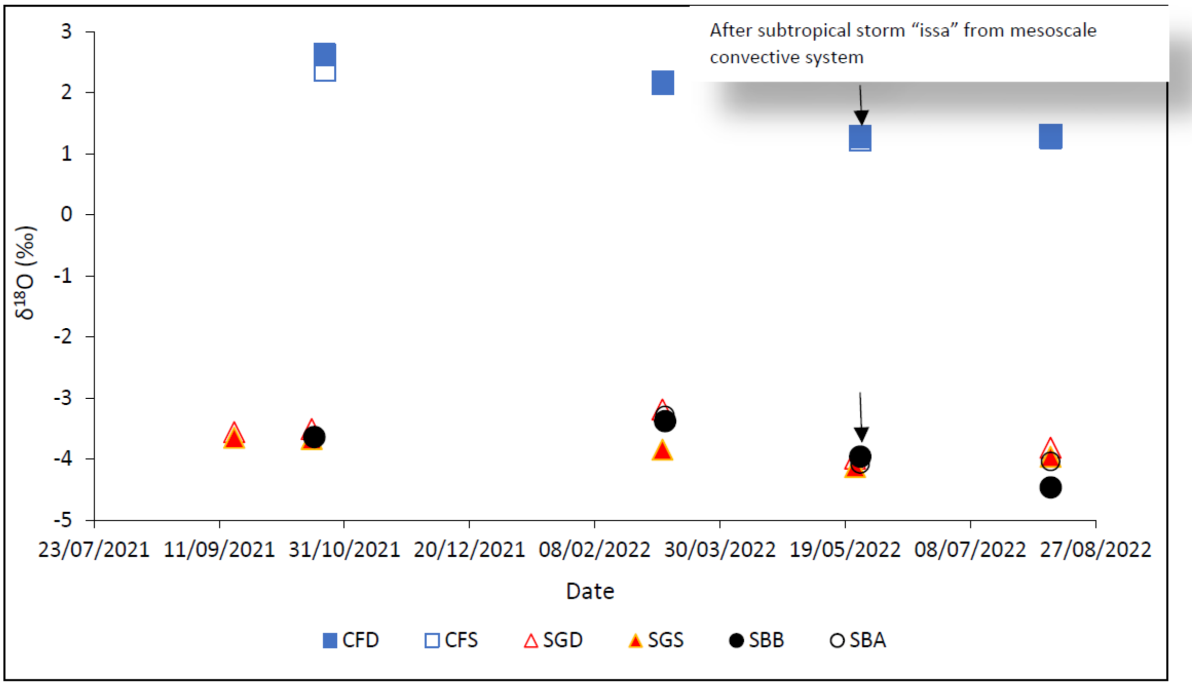


Figure 7-16 Isotopic composition of the nested boreholes (shallow and deep borehole)

Figure 7-17, Figure 7-18 and Figure 7-19 show the groundwater level vs. the daily rainfall in the nested observation wells inserted to the different aquifer levels. The water levels fluctuate in response to heavy rainfall (exceeding ~ 30 mm/d and above), a confirmation of the previous observations from isotopic evidence that demonstrates the "amount" effect. Following high rainfall, the water level increases rapidly then starts to decline and there was a lack of response in relation to low rainfall events in both shallow and deep boreholes. This pattern, however, changed for the SG and CF wells after an extreme rainfall event (>140 mm in one day) in February 2023, where after a continued rise/stable level was evident, with rapid responses in relation to rainfall events of >30 mm. Notably, it was at this time (late February/early March 2023) when the main lake basin overtopped and started to flow into and fill up the south basin which is west of these two wells. This response was not evident in the SB01 wells (Figure 7-19) which are to the north of the main basin, nor was it evident in the SB02 well which is to the south of the lake (Figure 7-20) which is included here as a reference point towards the south east of the lake. It is likely, therefore, that the inflow from the main basin into the south basins has resulted in a sustained recharge of the CF and SG wells which lie to the east of the lake in the coastal dune cordon where there is then outflow to the sea. Thus, the postulate that rainfall of more than 30 mm is needed for groundwater recharge still holds for wells within the groundwater catchment that feeds the lake.

The shallow and deep boreholes of the nested wells show similar response to rainfall events (Figure 7-17, Figure 7-18 and Figure 7-19). For the SG wells the head is similar, however there is an approximate 0.5 m difference in the levels of the two CF wells. The difference in the heads between the SB01A and SB01B wells is most significant (over six metres), with the deeper well having a much higher water table then the shallow well. Despite variable differences in head, the shallow and deep boreholes in all nested pairs responded in a similar fashion to each other. The similar pattern of response to rainfall by the shallow and deeper aquifers thus appears to reveal interconnection between the two systems.

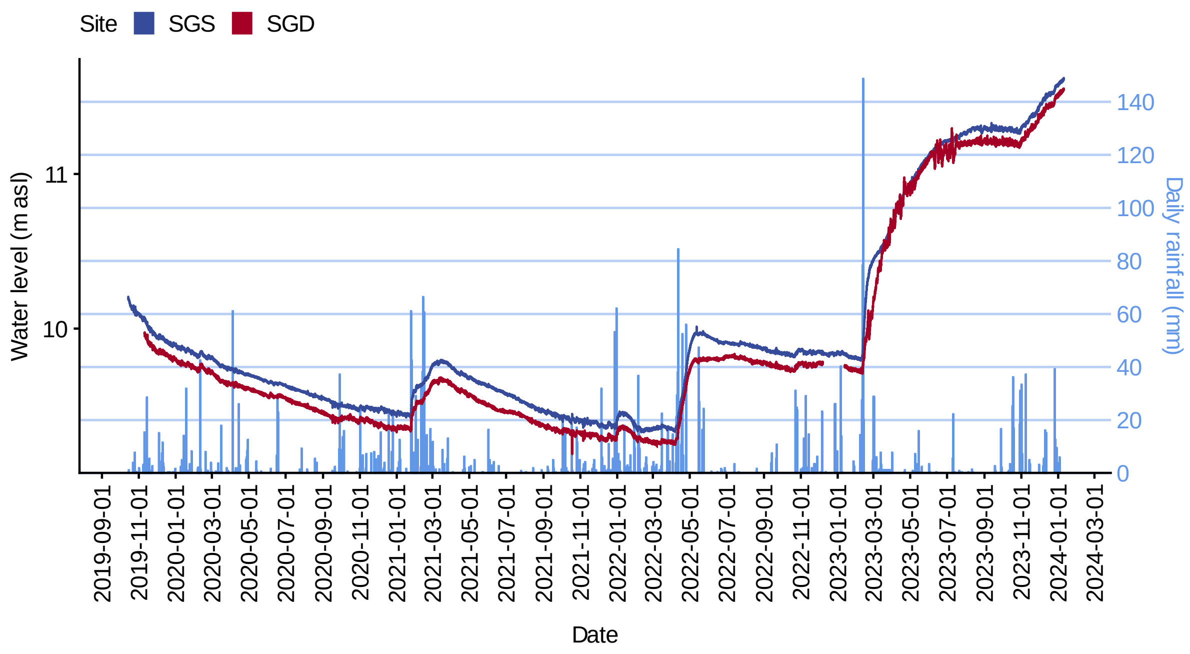


Figure 7-17 Water level of SGD (which is 53.1 m deep) and SGS (20.0 m deep) monitoring wells on the south eastern edge of the south basin with rainfall data from Vasi weather station.

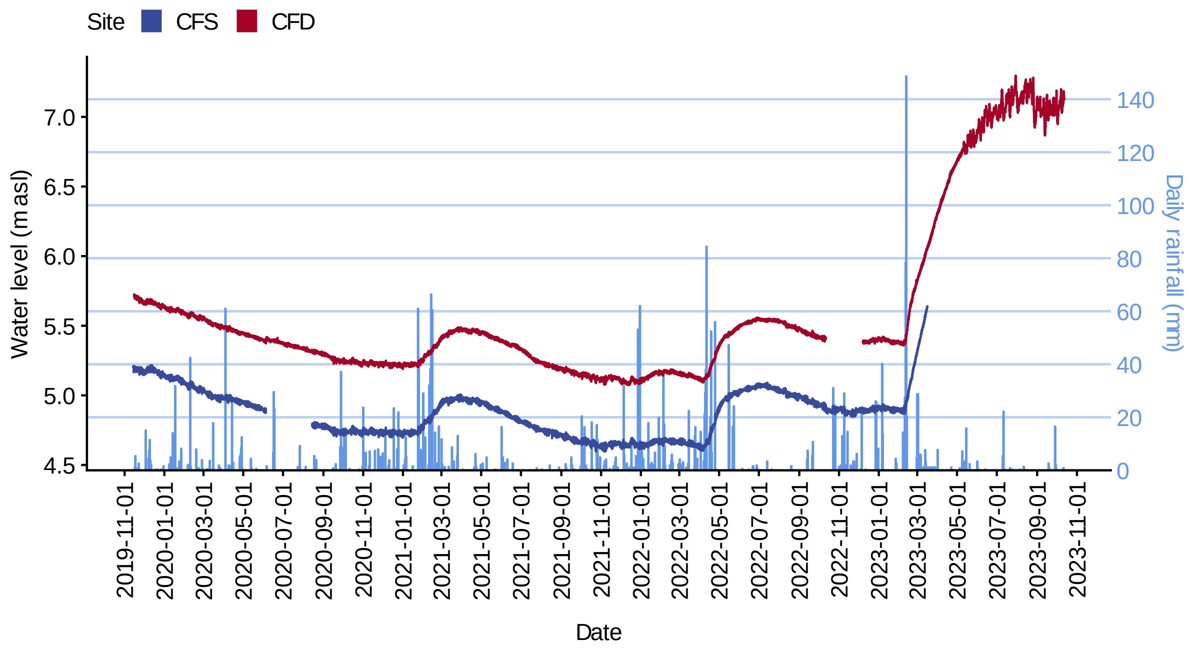


Figure 7-18 Water level of CFD (which is 64.1 m deep) and CFS (36.7 m deep) monitoring wells situated east of the south basin between the lake and the sea, with rainfall data from Vasi weather station

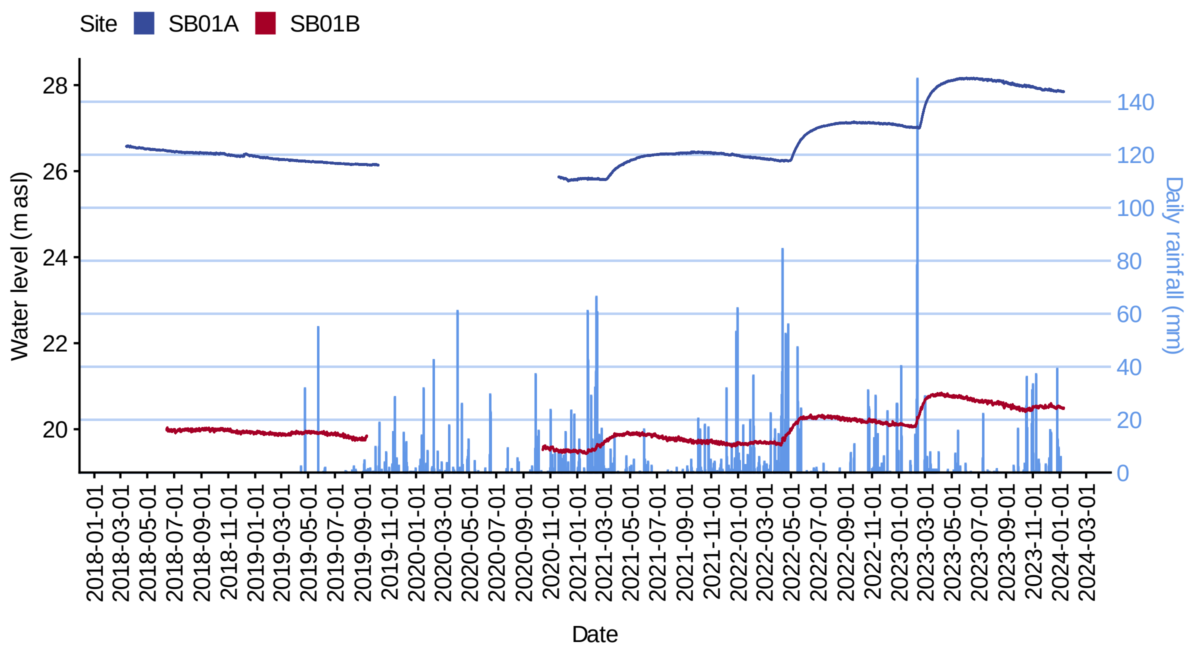


Figure 7-19 Water level of SB01A (which is 26.0 m deep) and SB01B (which is 46.0 m deep) monitoring wells (north of the lake), with rainfall data from Vasi weather centre.

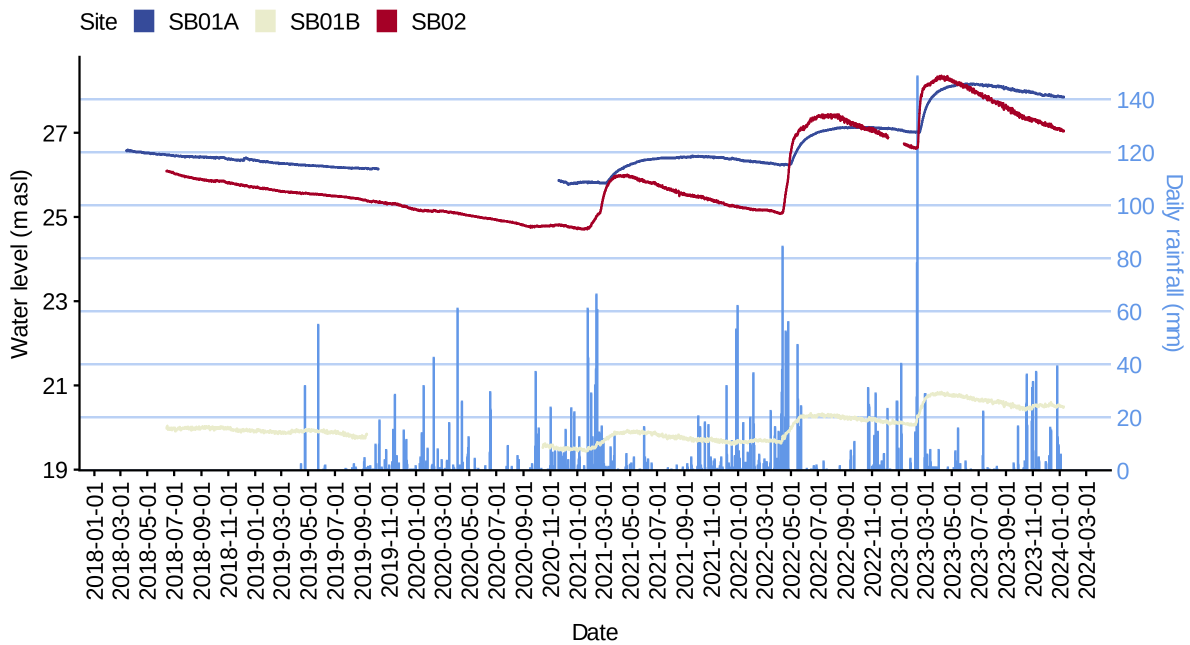


Figure 7-20 Water level of SB01A (which is 26.0 m deep) and SB01B (which is 46.0 m deep) monitoring wells (north of the lake), with rainfall data from Vasi weather centre. Figure also includes SB02 (60.0 m deep) which is further south and inland of the SG wells

7.2.5 Isotopic Composition of Stream Samples

Samples taken from the streams show a similar composition to that of the groundwater, with the implication that there is connection between the two systems and closely related to that of surrounding groundwater (Figure 7-21), an indication that the streams are fed by groundwater flow.

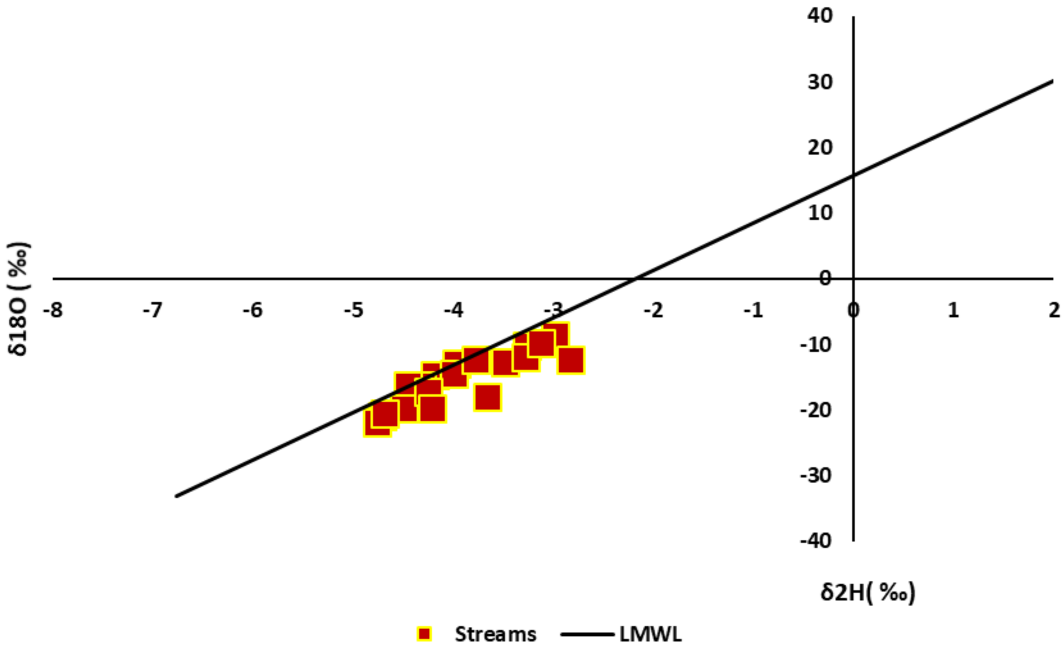


Figure 7-21 Isotopic composition of all samples collected from different stream water resources

7.2.6 Isotopic Composition of all Water Resources Sampled

The isotopic signatures of stream water samples were identical to those of groundwater samples, which revealed the source of stream water and subsequent discharge of the streams to the lake without extra significant evaporation (Figure 7-21). Western arm wetlands also had a similar isotopic signature as groundwater samples, which revealed recharge from groundwater. Samples from CFS and CFD, had similar isotopic signatures as the lake samples, which indicated a mixture of lake water and groundwater and lake recharging the groundwater. Samples from "unknown" lake from the South Western Bay plotting on the lower slopes, showed depletion. The lake samples collected showed a large spread in isotopic composition. This is likely due to some samples having been taken from the edge of Lake Sibaya, whereas others were from a boat. The eastern and main basin of the lake showed high enrichment compared to the western arm and south-western bay, which shows that the inflow to the lake is from the western, southern, and northern parts. The Banda Banda Bay samples was a portion of the south basin that was cut off from the basin by a sand bar to form a small, isolated wetland between the south basin and the dune cordon.

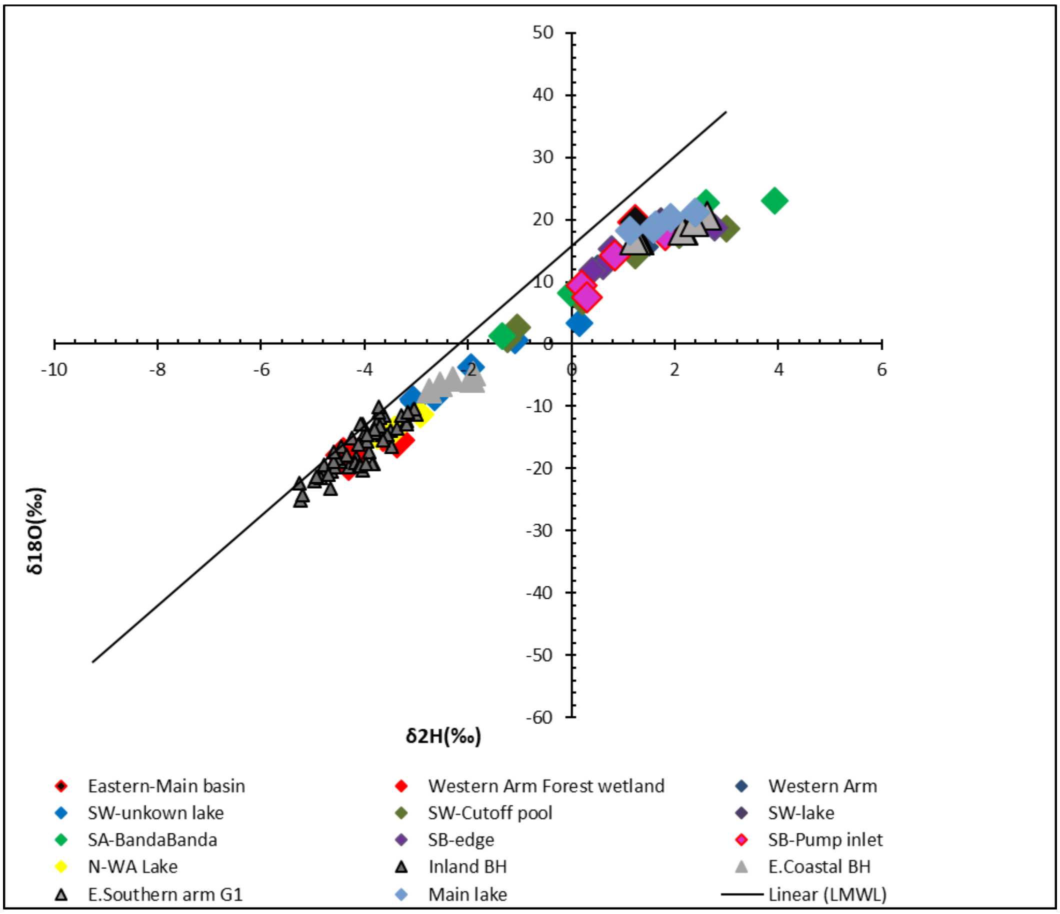


Figure 7-22 A summary plot between δ18O and δ2H from various water resources sampled within the study are in relation to the LMWL

7.2.7 Isotopic Composition of the Lake and Lake Water Balance Computed from Isotope Balance

Lake Sibaya water samples were collected on the arm and centre of the lake with 57 samples gathered and the isotopes analysed. It should also be noted that samples were collected from both the south basin and the main basin. Results are shown in Figure 7-23.

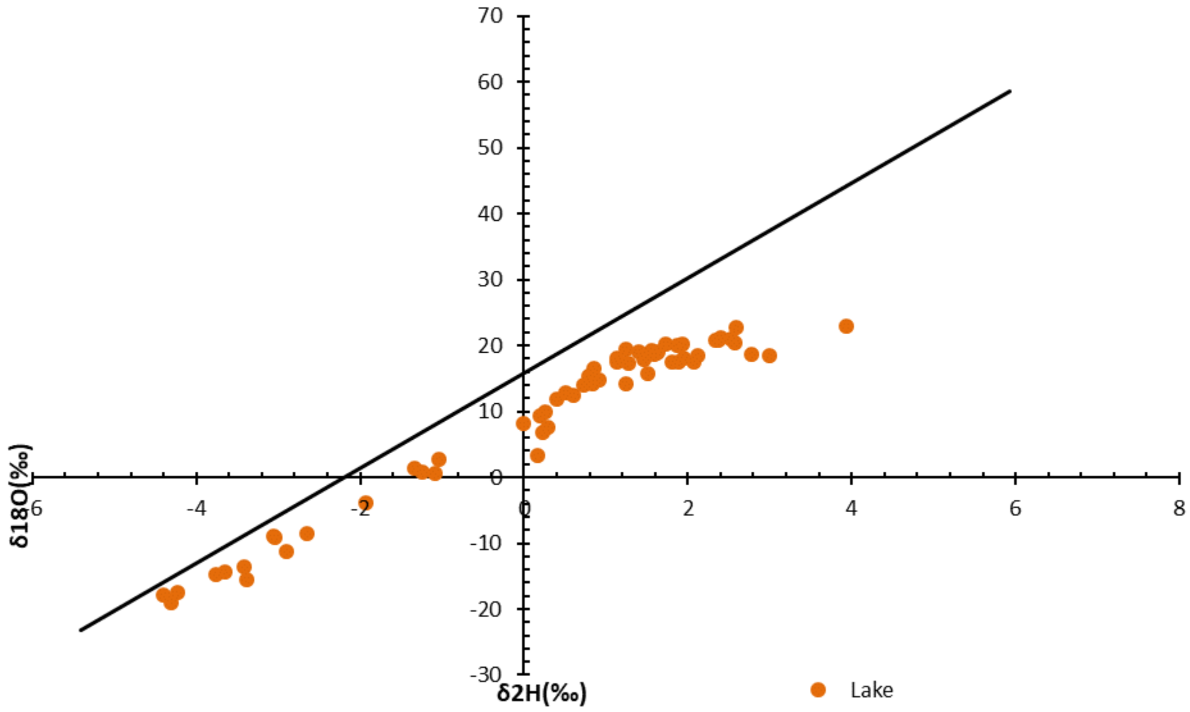


Figure 7-23 Isotopic composition of lake water

The Lake Sibaya water samples show a relative isotopic enrichment with respect to the inflowing groundwater, which is a result of evaporation enrichment. The lake waters plot along the LEL defined by a slope of 5.4, typical of a slope of evaporated open waters. The large spread in the $\delta^{18}O$ and $\delta^{2}H$ of the lake shows a poorly mixed lake. However, some samples were collected near the inlet of the various streams while others were collected from the edge of the lake and still others from s boat in the main lake, hence the large spread was expected. The samples collected from lake shore in its western and northern arms are isotopically more depleted than those collected from the eastern sector of Lake Sibaya, which implies that major water inflow zones are from the western part of the lake.

It is to be noted that the isotopic enrichment of a lake is the function of its evaporation to inflow ratio. A lake with E/I =1 (a terminal lake) will have more enriched ^{18}O-^{2}H compositions compared to a lake with E/I <1. A lake with E/I=0 means there is no evaporation in the lake and all inflow leaves the lake without undergoing evaporation. The more enriched the ^{18}O-^{2}H composition, the higher E/I ratio. Given the evaporation rate over an open water body, the E/I can then be used to infer the total inflow and further decompose it to groundwater inflow, rainfall, and runoff to the lake.

The isotopic composition corresponding to a given E/I ratio is specific to a given region and depends on the mean relative humidity; the isotopic composition of the ambient moisture; and the mean isotopic composition of inflow waters. If there is data on these three parameters (h, δ_a, and δ_I), the isotopic composition corresponding to any value of E/I ratio can be computed. In other words, given there is data on mean relative humidity; isotopic composition of ambient vapour; and the isotopic composition of inflow waters to lakes, the isotopic composition of lake water corresponding to a given evaporation to Inflow ratio can be estimated. The comparison between the computed value and the measured value can serve as the basis for the evaluation the water balance of a lake in a given region. The physical basis of the isotope balance equation is the Craig et al. (1965) isotope enrichment model. By combining the Craig-Gordon equation with the water balance equation of lakes, the following mathematical formulation (Gibson, 2002) can be applied which can be used to compute the isotopic composition a lake water corresponding to the regional conditions. The details of the formulation of the equations given below can be found in Gibson et al. (2016), Gonfiantini (1986) and Kebede et al. (2010).

$$\delta_{ss} = \left[\frac{\delta_I + mx\delta^*}{1 + mx}\right]$$

7-3

Where δss stands for the steady state isotopic composition of the lake and δ_I is the isotopic composition of the inflow. The parameters *m* and δ* are expressed by the following formulas (Gonfiantini, 1986):

$$m = \frac{h - \varepsilon/1000}{1 - h + \Delta\varepsilon/1000}$$
$$\delta* = (h\delta_A + \varepsilon)/(h - 10^{-3}\varepsilon)$$

7-4

ε stands for the total isotopic separation factor which is the sum of the equilibrium ε* and the kinetic (Δε) separation factors. ε is obtained from the equilibrium vapor-liquid isotope fractionation (a temperature dependent constant) at the temperature of evaporating surface. The kinetic fractional factor is computed from the consideration of relative humidity whereby Δε=Ck(1-h), Ck is a constant.

For a given environmental setting where the annual average values of the input parameters in the above equation (h, δ_A, δ_I, ε*, Δε) can reasonably be estimated; it can determine simultaneously δss for ^{18}O and ^{2}H corresponding to a given E/I ratio (or x in the above equation).

Using the above equations to compute water balance requires data on h, δ_A, δ_I, ε*, Δε. These data were obtained making the following assumption

- h= 0.7 average value of measured relative humidity

$\delta_{A,}$ was estimated at -10 ‰ for ^{18}O and -77 ‰ for ^{2}H. The basis of the estimation is the proximity of the MCP to the Indian Ocean and the values taken represent the isotopic composition of ambient vapour over the ocean surface. Δε is computed taking a relative humidity value of 0.7.

Consequently, Figure 7-24 is produced. The figure shows the computed steady state isotopic composition that corresponds to any given evaporation to inflow ratio. For the Lake Sibaya groundwater catchment, a terminal lake with E/I ratio of 1 would have a ^{18}O-^{2}H composition of 3.2‰ in ^{18}O and 31‰ in ^{2}H. A lake with E/I ratio of 0.5 (a lake that loses half of its inflow to evaporation and the remaining half to combined surface and groundwater outflow) would have a ^{18}O-^{2}H composition of 1.2‰ in ^{18}O and 17‰ in ^{2}H.

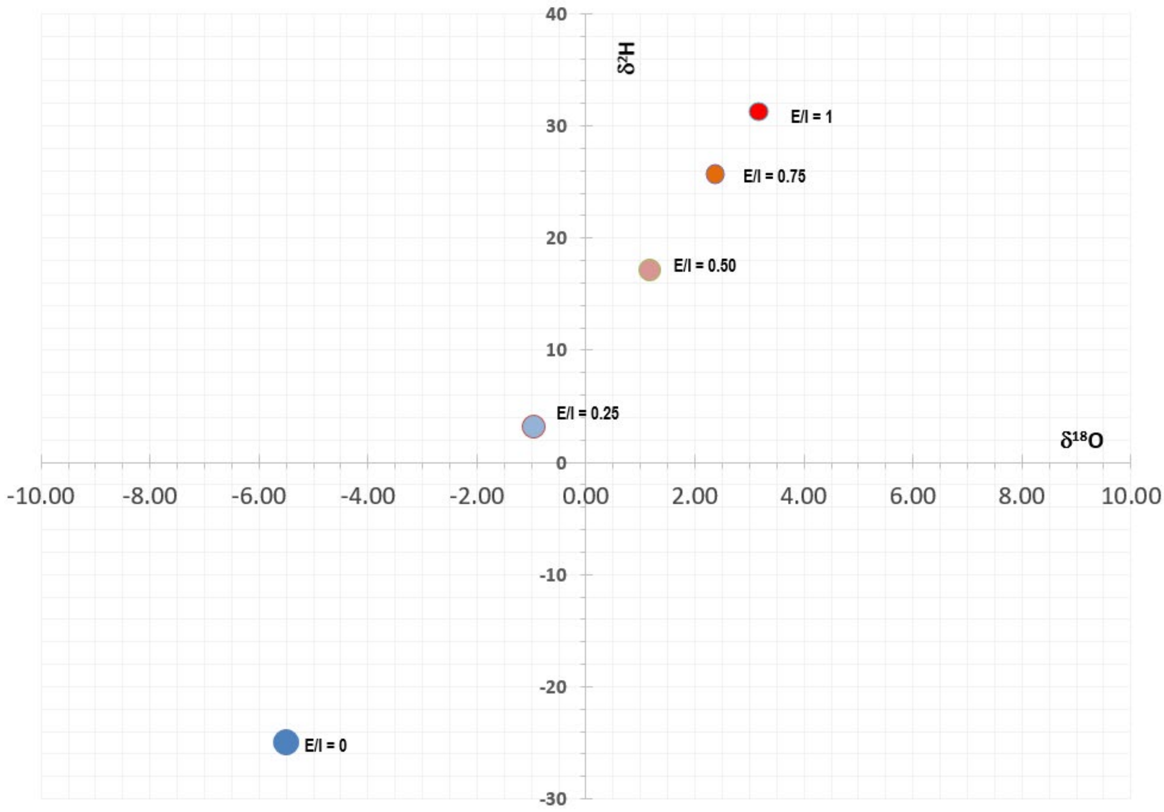


Figure 7-24 Modelled isotopic composition of hypothetical lakes of variable E/I ratio under steady state

By taking the measured isotopic composition of Lake Sibaya from the well mixed part of the lake, i.e. the Eastern and Central part, and populating the model graph (as in Figure 7-25) the water balance of Lake Sibaya was computed. Accordingly, the lake shows an evaporation to Inflow ratio of 0.7 (Figure 7-25).

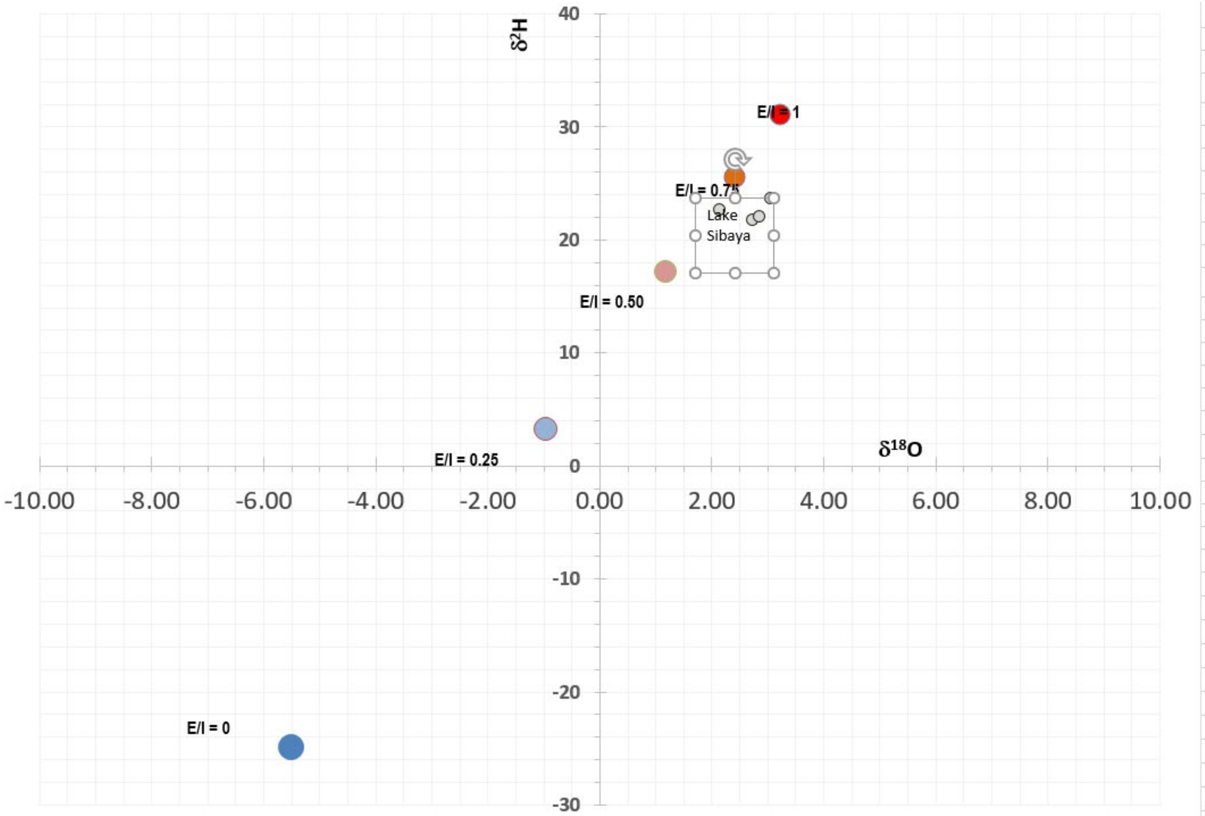


Figure 7-25 Modelled isotopic composition of hypothetical lakes of variable E/I ratio under steady state in the MCP for Lake Sibaya.

Since the total annual evaporation from the lake was computed at 109 million m^3 (Weitz and Demlie, 2014), the individual water budget component of the lake is estimated in Table 7-3.

Table 7-3 Water balance and groundwater inflow and outflow computed from Isotope balance equation

Lake Evaporation, 10^6 m^3/yr (Weitz, 2016)	E/I (isotope based)	Total inflow (including groundwater, rainfall on the lake and runoff) 10^6 m^3/yr	Groundwater outflow, 10^6 m^3/yr	Groundwater inflow 10^6 m^3/yr	Precipitation on the lake 10^6 m^3/yr (Weitz, 2016)
109	0.7	156	47	77	74

7.2.8 Water Chemistry

Hydrogeochemical processes regulate the chemistry of water and are commonly used to determine the source of groundwater as well as problems with its quality (Kumar et al., 2013). According to Baijjali et al. (1997), hydro-chemical analyses are effective tools to determine the origin of mixed waters in groundwater and surface water systems. To determine the relationship between groundwater and rainfall, the hydro-chemical parameter EC was measured in various boreholes, including the nested ones. The pattern observed for most inland boreholes showed a decline in EC as rainfall amounts increased. After the heavy April rains, the differences are visible.

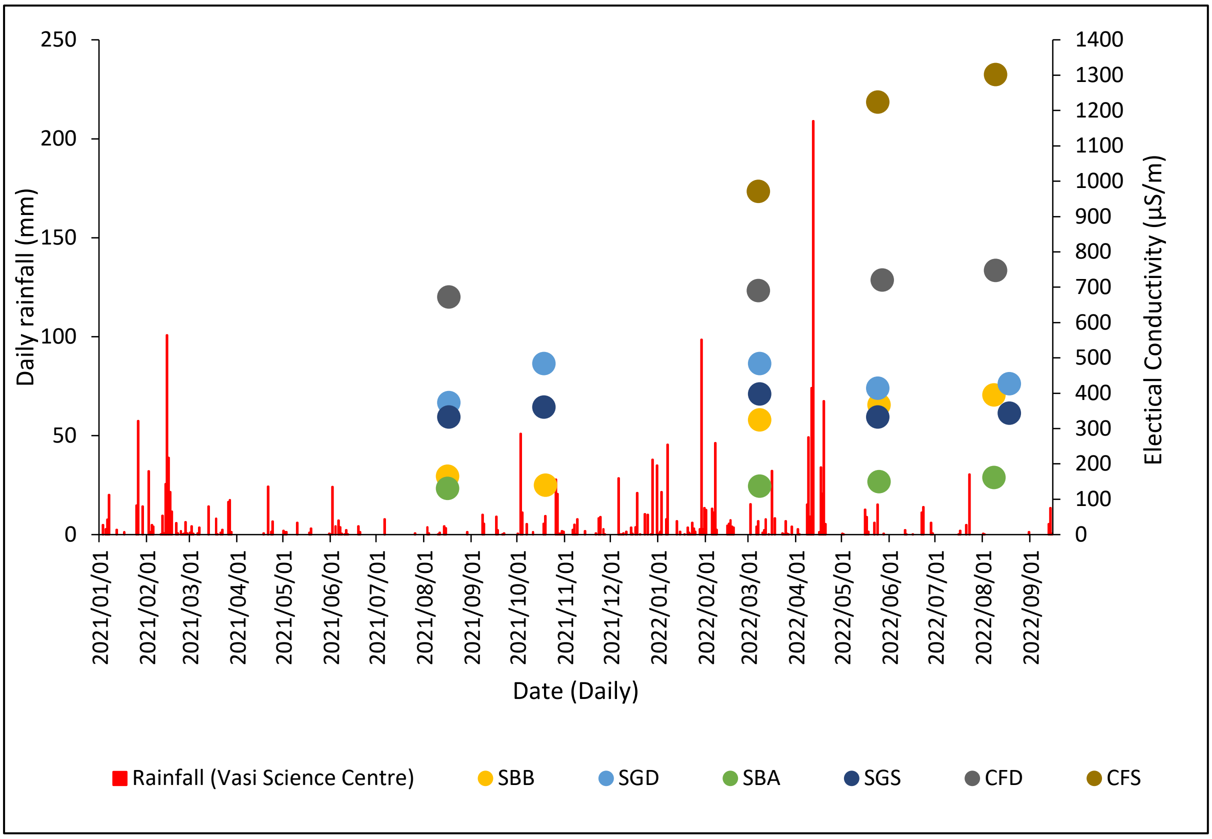


Figure 7-26 Electrical conductivity for all groundwater sampled for this study

The EC from the nested boreholes (Figure 7-26) showed a similar pattern of response between the shallow and the deep boreholes. For the boreholes on the south eastern edge of Lake Sibaya (SGD and SGS), the EC decreased with increased rainfall amount/after the rainy month of April 2022. In contrast, however, the maximum concentrations of EC were observed in coastal boreholes (CFS and CFD) after the heavy April rains, which are just north of the SGD and SGS pair. The shallowest CFS borehole shows a sharp rise in EC compared to the deeper equivalent (CFD). The increased EC in the CFS and CFD boreholes are remarkably higher than the increase in the other nested boreholes located inland. The isotopic analysis showed that the water in these wells is lake water the flows towards the sea. These boreholes are very close to the ocean, as are the SGD and SGS wells. The increase in EC becomes marked in SBA and SBB boreholes following the heavy rains of April. These well are to the north of Lake Sibaya and relatively inland from the SG and CF pairs. These results warrant further investigation.

7.2.9 Plant Water Source Partitioning Using Isotopes

The results for the plant water source partitioning involves soil moisture ^{18}O and ^{2}H isotope results as well as partitioning of the plant transpired water to the relative source waters.

7.2.9.1 Soil moisture stable water isotopes

The delta values obtained from the soil moisture samples were erroneous due to spectral contamination (Table 7-4). Two runs for $\delta^{2}H$ and $\delta^{18}O$ analyses were conducted for each of the 13 samples. For each of the samples, there is a row showing the $\delta^{2}H$ and $\delta^{18}O$ results for the original samples (2nd row of each sample) and the analysis results of the treated (distilled samples; 1st row of each sample) to reduce the spectral contamination. Each sample had replicas, hence the similar labelling but different isotopic results.

All 13 soil water samples showed unacceptable contamination amounts. This contamination appeared to be present as carbon chain alcohols longer than 2 C chains in length (ethanol or greater) as shown by the 'CH_4' and 'C_2 + Alc' columns. BIOGRIP staff performed a short travel distillation represented by the 'C2+Alc' column, and were able to reduce the contamination by a% value indicated in the '% decrease of contamination' column. The samples were then re-analysed to produce the results in the first row (1.) of each sample (distilled samples). The percentage of organic matter contamination removed ranged from a minimum of 27.5094% to a maximum of 40.8859%. It was observed from most of the results that the isotopic values for the same species at each of the sites, showed a degree of correlation. This, therefore, indicated a consistent error which provided guidance on where the cause of the erroneous values may have come from.

Table 7-4 Stable water δ^2H and $\delta^{18}O$ results from soil moisture extracted using the cryogenic vacuum distillation (CVD) technique, at three different sites corresponding to Eucalyptus grandis, Dichrostachys cinerea and Syzygium cordatum plant species

Sample ID	$\delta^{18}O$‰	StdDev^{18}O	δ^2H‰	StdDev^{2}H	CH_4	C_2+Alc	% decrease of contamination
1. VRB Site *D. cinerea* (Distilled)	10.224	0.05	9.66	0.34		25.5114	32.3943
2. VRB Site *D. cinerea*	13.173	0.149	19.32	1.02		37.7356	
1. VRB Site D. *cinerea* (Distilled) – replica	6.81	0.102	6.43	0.48		37.6304	35.7735
2. VRB Site D. *cinerea* – replica	10.937	0.109	20.75	0.82		58.5902	
1. SIBO2 Site *S. cordatum* (Distilled)	4.809	0.032	14.38	0.31		30.8286	31.9994
2. SIBO2 Site *S. cordatum*	7.787	0.075	25.29	0.55		45.3358	
1. MCW Site *D. cinerea* (Distilled)	5.364	0.077	-3.5	0.56		20.1896	33.339
2. MCW Site *D. cinerea*	7.521	0.072	5.29	0.41		30.287	
1. MCW Site D. cinerea (Distilled)	10.038	0.052	7.19	0.2		28.3754	27.5094
2. MCW Site *D. cinerea*	13.13		18.3			39.1436	
1. VRB Site *E. grandis* (Distilled)	8.535	0.178	8.24	1.11		39.541	35.4822
2. VRB Site *E. grandis*	12.898	0.125	21.47	0.75		61.287	
1. VRB Site *E. grandis* (Distilled)	10.909	0.179	12.18	1.33		22.0948	34.633
2. VRB Site *E. grandis*	13.604	0.052	20.76	0.51		33.8012	
1. MCW Site *E. grandis* (Distilled)	23.882	0.095	47.45	0.45	-6.6468	97.1092	28.072
2. MCW Site *E. Grandis*	31.636	0.081	72.46	0.44	-11.971	135.009	
1. MCW Site *E. grandis* (Distilled)	13.483	0.033	7.93	0.2		28.6504	32.4779
2. MCW Site *E. grandis*	16.488	0.124	17.86	0.6		42.4312	
1. SG Site *D. cinerea* (Distilled)	0.008	0.08	-6.79	0.62		7.6426	40.8859
2. SG Site *D. cinerea*	1.14	0.102	-1.05	0.44		12.9286	
1. SG Site *S. cordatum* (Distilled)	6.578	0.178	30.27	1.37		10.9736	38.8704
2. SG Site S. cordatum	7.865	0.146	33.2	1.57		17.9514	
1. SG Site *S. cordatum* (Distilled)	22.836	0.117	35.24	0.16	-6.6088	88.7886	30.1625
2. SG Site S. cordatum	30.431	0.132	59.89	0.77	-11.346	127.136	

7.2.9.2 Plant water source stable water H and O results

Using the two source waters, i.e. rainfall and groundwater, as references, the plant stable water isotope results were analysed with consideration to potential isotopic fractionation in different phases of sample collection and isotopic analysis. The Craig-Gordon (1965) theory of evaporation slope for liquid water evaporation was applied to plant water samples that underwent enrichment. This allowed for the use of the plant water sample trend lines to trace the plant water samples back to their source waters, hence the analysis of the graphs from right to left. The degree of isotopic enrichment or depletion was used to characterise the isotopic signatures of the different samples (including source water). The rainfall samples had a general isotopic signature that was more enriched than groundwater, whereas groundwater had a more depleted signature (Figure 7-27). This was used as the basis for distinguishing whether the plant obtains water from deeper sources with more depleted signatures thus leaning towards a deeper soil moisture or groundwater as a source water. Conversely more enriched signatures would represent a shallower water source, and therefore shallower soil moisture. Soil moisture in shallow to deep layers are represented by rainfall isotopic signature samples and the LMWL.

Figure 7-27 illustrates the plant water sources for the three different plant species, i.e. *E. grandis*, *D. cinerea* and S*. cordatum,* at the three sites selected, i.e. VRB site – southwest of the main basin, SG site – south of the south basin, and MCW site – north of the main basin). These samples were taken in the summer months spanning October 2021 to May 2022.

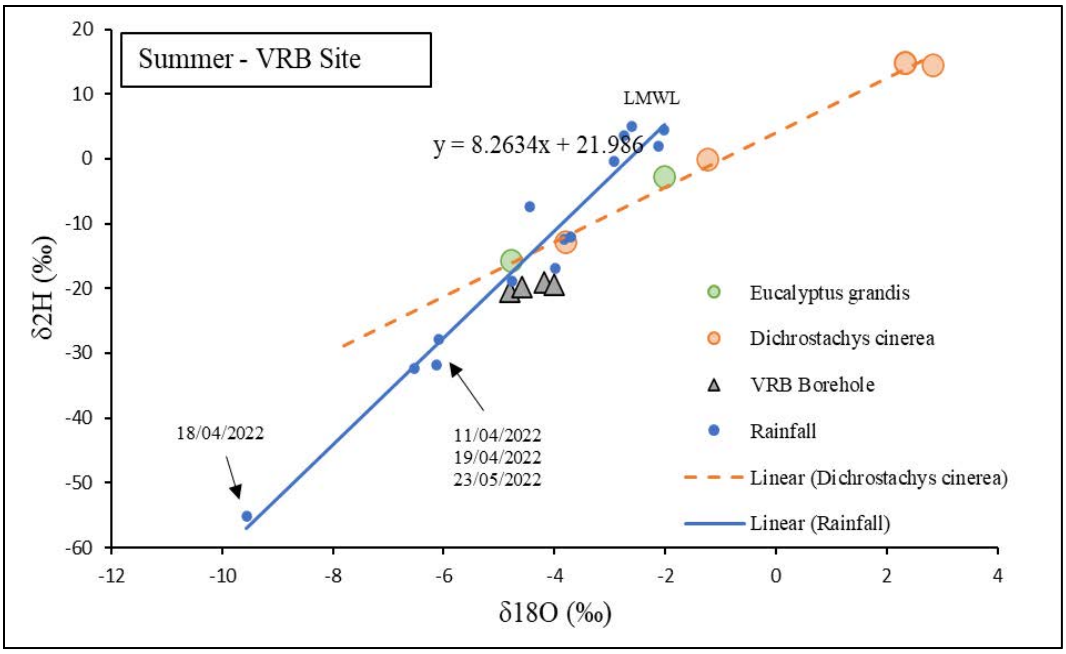


Figure 7-27 Summer months plant water source partitioning at the VRB Site, Lake Sibaya, for Dichrostachys cinerea and Eucalyptus grandis. Sampling period spanning October 2021 till May 2022

There were some rainfall events (11/04/2022, 18/04/2022 and 19/04/2022) that resulted in significantly depleted rainfall sample signatures (Figure 7-27). All the plant water samples plotted above and very close to the groundwater (borehole samples), however, this was caused by the distortion due to the few highly depleted rainfalls samples. The plant water sample did plot toward the LMWL (including the samples which suffered evaporative enrichment), therefore indicating predominant rainfall, i.e. soil moisture, contribution, despite the existing distortion. Due to evaporative enrichment in the *D. cinerea* samples, the displacement had to be corrected by projecting the samples back to the source waters with a trend line, based on Craig-Gordon 1965 evaporation slope.

Figure 7-28 illustrates the winter sampling data for *Eucalyptus grandis* and *Dichrostachys cinerea* during the month of August 2022, at the VRB site. Both the *E. grandis* and *D. cinerea* plotted above the groundwater samples for winter samples (Figure 7-28). Furthermore, the plant water samples made a cluster within the deep soil moisture isotopic signature range of -5 to -10 δ^2H and -2 to -4 $\delta^{18}O$. The winter plant water samples indicated more clearly the source water of the plants, i.e. deep soil moisture, without the sampled waters having undergone evaporative enrichment.

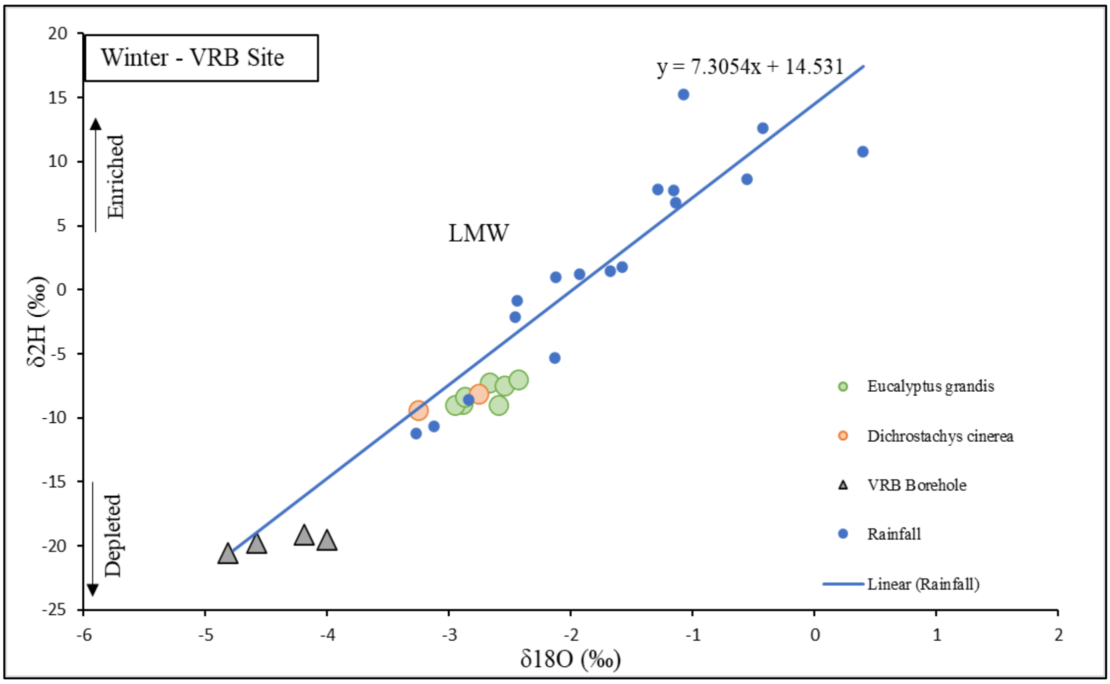


Figure 7-28 Winter month (August 2022) plant water source partitioning at the VRB Site, Lake Sibaya, for Dichrostachys cinerea and Eucalyptus grandis

Figure 7-29 illustrates the plant water sources of *E. grandis* and *D. cinerea* during summer at the MCW site. The summer samples underwent evaporative enrichment, and, therefore, their trend lines were used to project them back to their source waters and correct the observed displacements. The extreme rainfall events that occurred during the summer month of April 2022 (11/04/2022, 18/04/2022 and 19/04/2022) had an evident influence in both the *E. grandis* and *D. cinerea* isotope trend line signatures and thus the determination of their water sources.

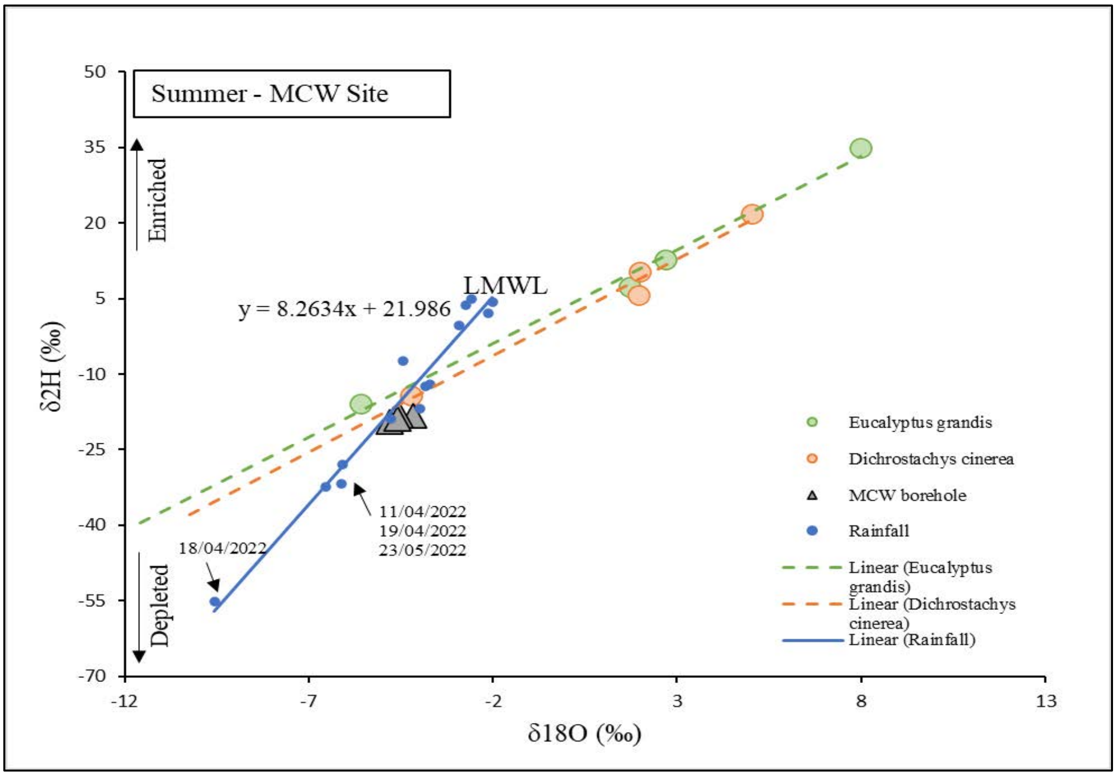


Figure 7-29 Summer months plant water source partitioning at the MCW Site, Lake Sibaya, for D. cinerea and E. grandis. The sampling period spanned from October 2021 to May 2022

Both trend lines project towards a depleted water source (-10 to -25 δ^2H and -2 to -6 δ^{18}O), and more so towards the groundwater samples. However, similar to the summer plot in Figure 7-27, the heavy rainfall events that resulted in depleted rainfall samples are possible sources of water for the plant samples and not necessarily the groundwater. Therefore, these results are inconclusive as to the source waters of the plant samples.

Plant water source results based on the winter sampling data at the MCW site Figure 7-30 were similar to the winter graph in the VBR site (Figure 7-28), the plant samples for both *D. cinerea* and *E. grandis* plotted within the more depleted portion (0 to -10 δ^2H and -1 to -3 δ^{18}O) of the rainfall samples which indicated deeper soil moisture as the source water. The plant samples that were displaced towards the left side of the LMWL were exposed to sunlight for the entire day and not affected by shade.

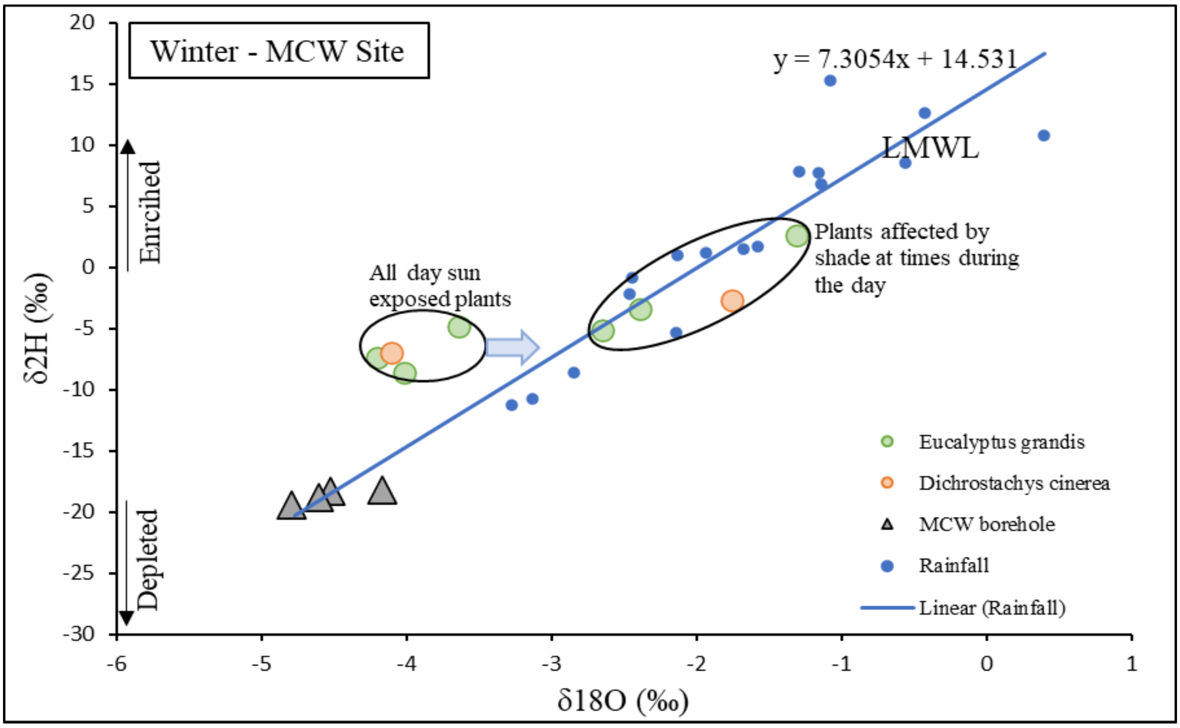


Figure 7-30 Winter month (August 2022) plant water source partitioning at the MCW Site, Lake Sibaya, for Dichrostachys cinerea and Eucalyptus grandis

The samples that were exposed to the sun for an extended period of time could have undergone isotopic exchange with the saturated environment in the transparent bag (Cernusak et al., 2022), unlike the samples that plotted along the LMWL.

There was insufficient data to provide a stand-alone analysis for the plant water sources for *Syzygium cordatum* and *Dichrostachys cinerea* during the summer (October 2021 to May 2022) and winter (August 2022) months at the SG site (Figure 7-31). For the winter samples Figure 7-31), although evaporative enrichment resulted in the need to project some of the samples closer to the source waters, there was a clear distinction in the water sources of the two species. *S. cordatum* seemed to obtain water from the shallower and less depleted soil moisture layers (0 to -5 δ^2H and -1 to -2.5 δ^{18}O). However, results for *D. cinerea* indicate that these plants obtain water from deeper and more depleted soil moisture layers (-5 to -10 δ^2H and -1.5 to -4 δ^{18}O), after projection to source water (Figure 7-31).

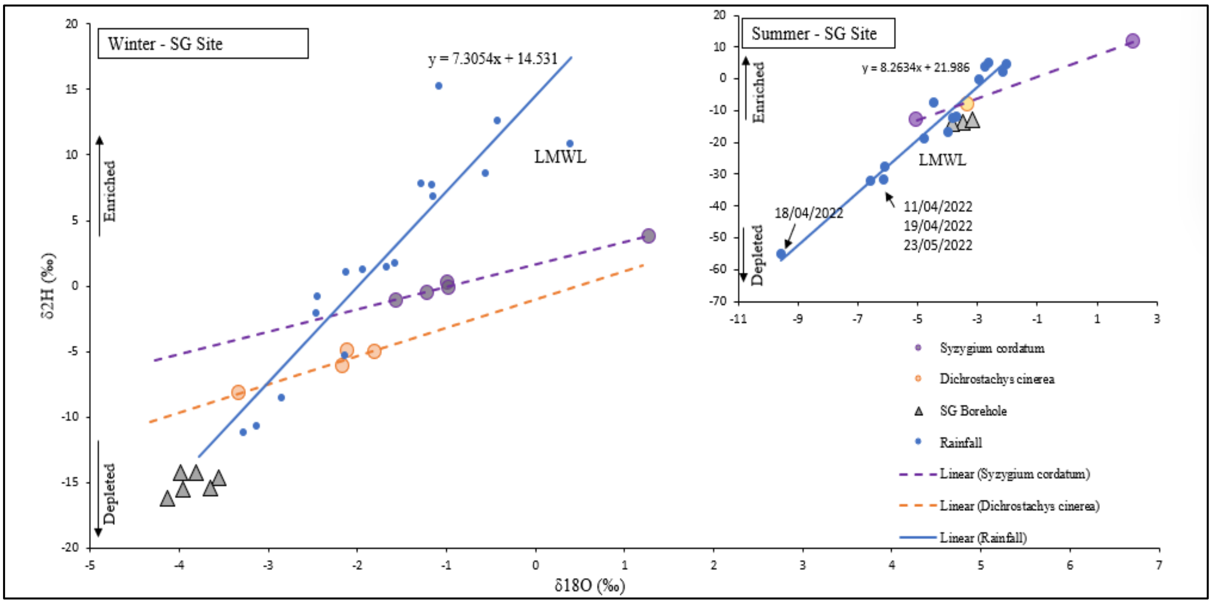


Figure 7-31 Winter and summer months plant water source partitioning at the SG Site, Lake Sibaya, for Syzygium cordatum and Dichrostachys cinerea

Results indicate, however, that the species may be utilising soil moisture (at varying depths) as their source water and not groundwater. In the summer months graphs, the plant water isotopic signatures ranged from -15 to 12 δ^2H and -5 to 3 δ^{18}O, due to isotopic enrichment that displaced the *S. cordatum* samples. However, there was a slight indication of rainfall, i.e. soil moisture, predominance as a source water. Due to insufficient plant water samples and the distortion caused by the heavily depleted rainfall samples, the plant source waters for the summer period were inconclusive.

7.3 DISCUSSION

The Lake Sibaya groundwater catchment, within quaternary catchment W70A has undergoing a substantial hydrological change over the last two decades. Surrounding wetlands have run dry and the area volume and water level of Lake Sibaya have declined significantly. The absence of surface water drainage feeding the lake as well as the low to moderate salinity of the lake (TDS<1000 mg/L) both imply the predominance of groundwater in the water balance for Lake Sibaya. Thus, groundwater modulates the water balance of Lake Sibaya and water availability in the region. The hydrological response of the lake to LULC change or regional climate forcing will thus depend largely on the response of the groundwater to these external drivers.

The Pitman and Hutchison (1975) model simulated a maximum lake level in the 1943-1944 period of 19,93 m AMSL. In March 1977, this level was surpassed, reaching 20,25 m AMSL, following several years of relatively frequent extreme rainfall events that led to the evacuation and abandonment of the Rhodes Hydrological Research Institute's, Lake Sibaya Research Station (Bruton, 1979b). To date, this record high stand has not been exceeded since this occurrence.

The minimum simulated level before 1973 was 16,20 m AMSL (0,48 m) in December 1935 (Pitman and Hutchison, 1975). This simulated low corresponds to the end of a long drought period. Historic station data from Manguzi (see the Pitman and Hutchison (1975) demonstrates that MCP region remained anomalously dry compared to the rest of the country where the drought had broken. A report from the Zululand Game Department (1937) confirms a serious drought in Northern Zululand in 1935, which highlights that the Mkuzi area, which neighbours the Lake Sibaya groundwater catchment, deteriorated badly. Rainfall for the region was less than that for 1934. The warden reported that water in the Mkuzi river "gave out" in September 1835 leaving Insumu pan as the only place with drinking water for game. It can thus be inferred that the record low lake level in December 1935 (16,20 m a.m.s.l) for Lake Sibaya simulated by Pitman and Hutchison (1975) is plausible.

The only subsequent incidence of the level receding to 16.20 m AMSL was in May 2011 after which a progressive decline continued. Unlike with the post 1935 scenario when the lake recovered, contemporary lake levels have not yet recovered above this.

To reveal the connection between rainfall and groundwater response necessitated a clear understanding of the groundwater recharge mechanism – the process of how the rainfall incident on the surface joins the groundwater. The finding from the isotope hydrology and groundwater level response to rainfall reveals that the aquifers respond only to exceptionally heavy rainfalls further confirm that the recent reduction in tropical storm and cyclonic activity (CHAPTER 5:) is a key driver of hydrological change in the region. These results, combined with those in CHAPTER 5: (which demonstrated a significantly lower number of extreme events over the last two decades) corroborate the importance of extreme rainfall events for groundwater recharge in this region as well as their frequency.

Historic rainfall data for Lake Sibaya (Pitman and Hutchison, 1975) as well as an assessment of historic rainfall events (Botes, 2014) indicate that heavy/extreme rainfall events have occurred in all months of the year. In addition to the tropical systems identified in CHAPTER 5: (1981 forward), pre-1981 tropical systems (extreme events) that likely have impacted on the rainfall in the Lake Sibaya study region include Severe Tropical Storm Claude (Dec 24th 1965-January 10th 1966); possibly Tropical Cyclone Helene (19th 28th March 1969); Very Intense Tropical Cyclone Danae (10th-29th January 1976); possibly Severe Tropical Storm Debra (22nd February-4th March 1991); interacting with an approaching cold front; possibly Intense Tropical Cyclone Leon-Eline (8th-29th February 2000); possibly Severe Tropical Storm Gloria (27th February-10th March 2000 (March rainfall at Mbazwana was 362 mm)); and an anomalous weather event that resulted in a Subtropical Depression on 11 June 2001.

Several major postulates can be drawn from the isotope hydrological and groundwater level data. Groundwater recharge of the main aquifers west of the lake takes place after the rain water has undergone open water evaporation, probably in wetlands and temporary flooded pools. This highlights the importance of wetlands within this system.

There is a strong correlation between the rainfall amount and its $\delta^{18}O$. When compared with the groundwater isotope signals, indications are that the minimum rainfall amount of rainfall to impact positively on recharging the aquifer is roughly 30 mm/day. The groundwater in the eastern dune cordon is also recharged from the lake, as shown by the continued rise in water levels in wells opposite the south basin in the absence of heavy rainfall events, and coinciding with the reconnection between the south basin and the main lake.

The amount weighed average isotopic composition of the rainfall water is relatively more enriched that the initial isotopic composition of the initial water that recharges the aquifers. Furthermore, there is a strong similarity between the isotopic composition of the groundwater (revealed from the intersection between LEL and LMWL) and the isotopic composition of the cyclonic rains of April 2021, with the implication that groundwater recharge takes place from selective heavy summer rains. The contribution to groundwater recharge in the small rain months of Oct, Nov and December is minimal.

There appear to be several groundwater flow systems feeding the lake. The ones coming from the west north and south west have been widely inferred in previous conceptual models. The flow originating from the north east coastal dune area around Mabibi that appears to joins the lake from east, as not been inferred previously.

Tropical storms are likely an important source of rainfall for groundwater recharge. The future of Lake Sibaya hydrology is tied to the regional climate. However, local LULC will also have an impact. One such feature of local importance is the land property (soil, microtopography) which allows the temporal accumulation of rainwaters in ponds. The effect of water ponding prior to recharge is reflected in the isotopic composition of groundwater which plot below the LMWL showing evaporation signal prior to recharge. Conversion of wetlands/pools to farm lands could alter the groundwater recharge processes.

The first preliminary water balance calculated from isotope balance equation reveals a lake whose water balance is dominated by groundwater inflow and evaporation. The isotope-based water balance estimation for Lake Sibaya can be used as an additional constraint to improve the numerical groundwater flow model developed for the region.

Attempts were made to determine where or not different tree species were obtaining their water from different sources (soil water versus groundwater). While interesting results emerged, given the various issues encountered and small samples sizes, results are inconclusive and, thus, could not be used to inform the ACRU model.

CHAPTER 8: MODELLING RECHARGE USING THE ACRU MODEL

By: ML Toucher

This chapter outlines the surface water modelling component towards addressing Aim 3: *Determine the relative impact of different vegetation units and climate on the hydrological response of the Lake Sibaya groundwater catchment;* as well as Aim 4*: Identify current as well as plausible future scenarios of climate and land use.*

8.1 INTRODUCTION TO THE ACRU AGROHYDROLOGICAL MODEL

The ACRU Agrohydrological model is a physical-conceptual, multi-purpose, multi-layered soil water budgeting, daily time step model (Schulze, 1995, Schulze and Pike, 2004, Warburton et al., 2012). It is physical in that it explicitly represents the catchment's physical characteristics and hydrological processes, and it is conceptual because significant processes and couplings are described as a system (Schulze, 1995). The model is not a parameter fitting or optimising model as physically estimated values are used. Its multi-level nature allows for multiple options or routines for computing outputs based on the available input data and the required outputs (Schulze, 1995, Warburton et al., 2012). The multi-purpose nature of this model allows for the simulations of many hydrological and terrestrial processes such as runoff, crop yield, reservoir yield, irrigation demand/supply, evaporation and land use (Schulze, 1995, 2000, Warburton et al., 2012). ACRU can be used as a lumped model, or as a distributed model in large catchments with complex soils and land uses, whereby the catchment is disintegrated into small catchments of similar properties (Schulze, 1995).

The ACRU model is sensitive to changes in land cover, land use and land management (Warburton et al., 2012). It has been used in several studies such as Jewitt et al. (2004), Kienzle and Schulze (1992, 1995), Tarboton and Schulze (1990) and Tarboton et al. (1992) to assess the impacts of reservoirs, afforestation and urbanisation on the streamflow. Gorgens and Van Wilgen (2004) used ACRU to estimate the water use of alien invasive plants and the subsequent impact on streamflow; while Haywood and Schulze (1990) assessed the catchment responses to sugarcane plantations under varying agricultural management practices. Warburton et al. (2010) confirmed the applicability of the ACRU model in the simulation of the hydrology of catchments under different land uses for different climatic regions.

The conceptualisation of the water budget in the ACRU model is shown in Figure 8-1. Precipitation, which is the driver of the hydrological cycle, is the major input component of the system (Figure 8-1). A certain percentage of this precipitation is initially abstracted as either stormflow or interception, and the remaining water is infiltrated into the topsoil (A horizon). Once field capacity is reached, the water further percolates into the subsoil (B horizon) as saturated drainage. If the subsoil then becomes saturated, water continues to percolate further down the soil profile into the intermediate zone and until it finally reaches the groundwater and contributes to runoff as baseflow. Unsaturated soil water distribution, both up and down the soil profile, may also occur. No lateral flow of water in the subsoil is accounted for.

The total evaporation component includes the evaporation of water from intercepted surfaces and from the soil, and includes transpiration by plants extracting soil water from the root zone (Figure 8-1). Potential reference total evaporation, which can be estimated using the A-pan reference evaporation, is incorporated into the model to estimate the actual total evaporation. The model provides the option to separate the calculation of the actual total evaporation into soil evaporation and plant transpiration, using various equations (Schulze, 1995), which are based on a vegetation cover factor. There are two soil-based parameters required as input to the ACRU model to define the soil moisture content of a given soil. These include the permanent wilting point (WP) representing the lower range of plant available water (PAW), and the field capacity (FC) representing the upper range of the PAW (Schulze, 1995).

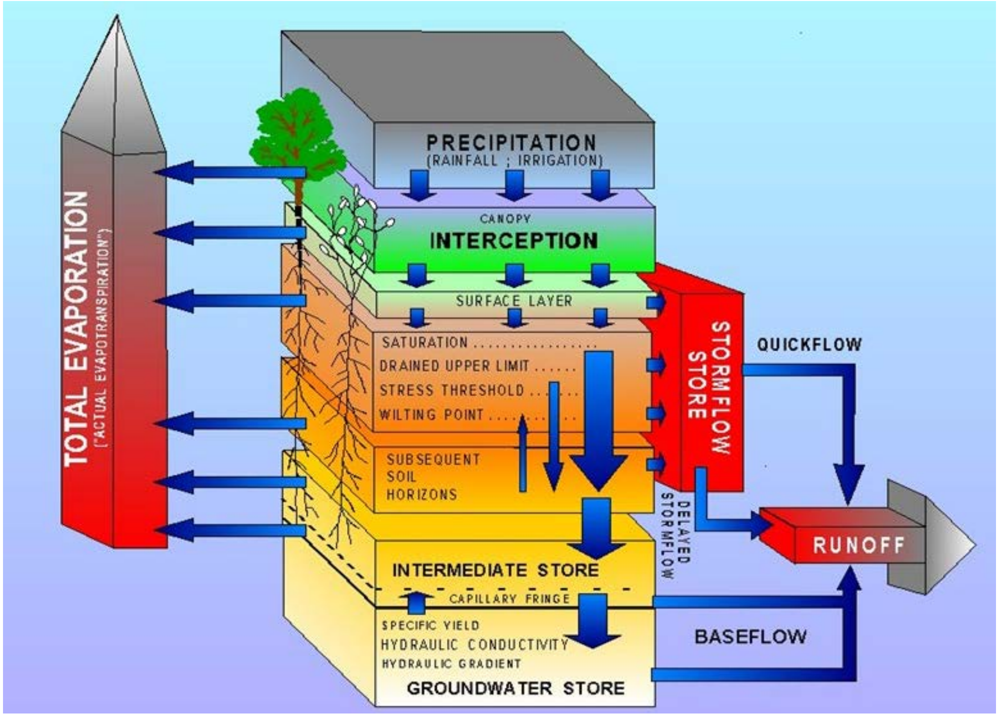


Figure 8-1 Representation of the water budget in the ACRU model (Schulze, 1995; Schulze and Smithers, 2004)

While the generation of simulated runoff depends on the antecedent soil moisture status and the rainfall intensity, the generation of runoff requires that the soil moisture deficit be satisfied. The antecedent soil moisture deficit is thus simulated at a daily time-step in ACRU to assess the stormflow generated following each individual rainfall event. A certain proportion of generated stormflow does not reach the weir at the outlet of the catchment on the same day as the rainfall event. Stormflow is, therefore, separated into various stormflow components in the ACRU model. These include (a) quickflow, which is the proportion of stormflow that is generated and reaches the outlet on the same day as the rainfall event; and (b) delayed flow, which is the proportion of stormflow that reaches the outlet, contributing to streamflow, several days after the rainfall event (Schulze, 1995). Ultimately, the ACRU model uses the catchment information, e.g. land cover information, referred to in this section as the inputs, in combination with various methods and equations, to simulate the streamflow (and other output variables such as sediment yield, crop yield, evaporation, peak discharge, rainfall and soil moisture) and hence, the hydrological response from a particular catchment.

The LULC affects the hydrological processes in various ways (Bulcock and Jewitt, 2012), thus the structure of the ACRU model demonstrates high sensitivity to climate and to land cover/use changes (Warburton et al., 2010). Landcover and water use properties, required for hydrological model input estimations, are conceptualised by grouping the natural vegetation processes into three major plant-related groups. This grouping is based on the properties of the biomass and its characteristics above-ground, below-ground, and on the ground surface (Schulze, 1995), as well as how these properties influence the uptake and distribution of rainwater. Before grouping the natural vegetation processes according to those related to the above-ground, below-ground, and on the ground vegetation properties, it is necessary to recognise the land cover-related attributes that characterise each group. These attributes inherently determine how the hydrological response of a catchment is affected by land cover changes, as well as how a hydrological model simulates these hydrological responses.

The above-ground attributes include the biomass, which is determined by the vegetation type and by the season of year and is dependent on climatic related factors, such as water availability, heat units, and frost duration (Schulze et al., 2007). The biomass properties primarily determine the potential transpiration rates, i.e. the water use of the vegetation, and the canopy interception losses and, hence, for purposes of hydrological modelling, are usually expressed as a leaf area index or a water use, i.e. crop, coefficient. The plant structure, which is another above-ground attribute, has an important role to play in the erodibility of rainfall, in terms of the fall height of the raindrops and the relative terminal velocities (Schulze et al., 2007). The structure of the vegetation also determines the degree of shading of the soil surface by the vegetation. Another important above-ground related attribute is the physiological factors of the vegetation, which determine the level of available soil water at which plant water stress sets in (Schulze et al., 2007)

The ground-surface attributes include (a) the infiltration properties of the soil, which in turn is a controlling factor of the initial abstractions of rainfall before the generation of stormflow; and (b) the presence and amount of litter and/or mulch, which has the potential to reduce and/or prevent soil erosion and soil water evaporation losses (Schulze et al., 2007). The below-ground-related attributes include two root-specific attributes that both contribute to determining the patterns of soil water uptake by the vegetation. Firstly, the seasonal variation of the effective rooting depth and distribution in the different soil horizons and, secondly, the degree of root colonisation within the soil horizons (Kienzle and Schulze, 1992; Schulze and Smithers, 2004). The onset of plant water stress is also considered to be a below-ground attribute related to vegetation. Within ACRU, this is typically considered to be when the fraction of plant available water of a soil horizon at which total evaporation is assumed to drop below maximum evaporation due to the drying of the soil. With natural vegetation, this fraction is assumed to be 0.4 (Schulze, 1995).

In respect to hydrological modelling, it is the water uptake function of roots that needs to be accounted for. This process of water uptake is affected by factors such as root growth, distribution, colonisation, extension, the differences in the water potentials between plant and soil, the hydraulic conductivity of the soil, and the availability of water in the soil. Thus, it is not a simple matter to attempt to model water uptake and, in ACRU assumptions, simplifications and generalisations have been made to simulate root water uptake. In ACRU, soil water extraction by roots is considered to occur simultaneously from both soil horizons in proportion to the assumed active rooting mass distributions in each horizon. The monthly fraction of active root mass in the A-horizon is required as an input, and using this fraction the B-horizon root mass is computed within the model. The fraction of roots in each horizon must account for the effect of genetic and environmental factors on transpiration, factors such as dormancy, senescence, regrowth, growth rates, and impeding soil layers. When the vegetation is stressed, the fraction of roots largely determines the differential rates of drying of the two soil horizons. It is important to note, that, in the conceptualisation of ACRU, if the parameter describing the fraction of active roots in the A-horizon is ascribed to 1, this designates senescence or no active water uptake by roots, essentially meaning that no transpiration is occurring only soil water evaporation (Schulze, 1995). A routine has been included in ACRU to allow for plant water uptake by the roots to occur from the soil horizon that is not stressed.

According to previous research efforts (Schulze and Smithers, 2004), the most important above-ground, below-ground and on-the-ground land cover-related model input variables include (a) the water use coefficient (Kcm) and interception loss (Il), which are both above-ground related variables; (b) the coefficient of initial abstractions (C) and soil surface cover by litter (Cs%), which are both on-the-ground related variables; and (c) the root distribution (Ra), which is a below-ground related variable. Where recorded data are not available for a certain land cover, vegetation and water use input parameters used in ACRU may be derived from other measured variables, extensive literature review or where necessary, expert knowledge.

The ACRU agrohydrological model was developed for application specifically in the Southern African region, and has been used extensively. Thus, the input data required is largely readily available in national level databases. However, these applications have primarily been surface-water modelling applications. The intermediate or shallow groundwater option in the model has been used to a limited extent. Thus, a key aspect of this project was to undertake a sensitivity analysis to better understand which input variables the groundwater recharge output from the ACRU model is sensitive to.

A strength of hydrological modelling is that, once a model is satisfactorily configured, it allows for scenarios of change to be explored and the impacts of these scenarios to be modelled. For the purposes of this study, scenarios of both land cover and land use change were of interest under different scenarios of future climate change, as well as the combination thereof. The ACRU model configuration is first described with the inclusion of the input data for the scenario runs, followed by the results of the sensitivity study and then the scenario-based model output.

8.2 CONFIGURATION OF THE ACRU AGROHYDROLOGICAL MODEL AND INPUT DATA

8.2.1 Spatial Scope and Scale of the Surface Water Modelling

Typically, when configuring the ACRU model, a hydrological catchment with a defined watershed will be modelled. The catchment will be delineated into sub-catchments that reflect the altitude, topography, soils properties, land cover, water management (water input and abstractions), and location of gauging stations. These sub-catchments are then considered as relatively homogenous hydrological response units. In this project, with the need to loosely couple the ACRU and the MODFLOW model, a different approach has been undertaken. The MODFLOW model is configured as a grid thus, as surface water flows were not of concern (only downwards water movement through the soil profile), the ACRU model was also configured in a grid. The grid scale used in the ACRU model was 1 km x 1 km. The flat nature of the area and the lack of large rivers further allowed for this approach to be considered. The grid matches the modelling domain of the MODFLOW model (Figure 8-2).

The Lake Sibaya groundwater catchment area was the primary “response variable” area to determine the impact of different LULC and future climate storylines on the water resource. The groundwater modelling domain, however, interacts with surrounding groundwater catchments, thus an extended modelling domain was configured. The surface hydrological model provided inputs to the groundwater model and was run for the groundwater catchment under consideration in this project (Figure 8-2). The coupled surface-groundwater catchment thus covers most of the W70A quaternary catchment, except for the northerly portion, and extends further west.

Figure 8-2 Scope of the modelling domain indicated in yellow and the extent of quaternary catchment W70A by the black line

8.2.2 Climatological Data

The hydro-climatological requirements of the ACRU model are continuous daily rainfall and daily reference evaporation (A-pan equivalent), with the latter computed from daily minimum and maximum temperature if not provided explicitly. Historically, the study area has been sparsely monitored with very limited operational weather stations within and adjacent to the study area. In the recent past, NRF-SAEON has installed several automatic weather stations in the area as well as additional rain gauges to supplement monitoring. However, as these stations have short record lengths, they cannot be used in the ACRU model and could only assist in infilling data. Thus, historical climatological data was sourced from the South African Weather Service (SAWS), Agricultural Research Council (ARC) and Ezemvelo KZN Wildlife (EKZNW). Additionally, rainfall data for prior to 1999 was extracted from the daily rainfall database for South Africa (Lynch, 2004), using the Daily Rainfall Extraction Utility (Kunz, 2004) for any stations that fell within or near the study area.

The observed historical climate data that was sourced had long period of missing data and was spatially sparse. The only temperature record that covered the time-period of the study fell outside the area of interest. Therefore, alternative sources of climate data were explored.

The gridded ERA5 rainfall and temperature products were used for the historical climate period from 1959 to 2020. ERA5 is a reanalysis climate data set produced using climate observations and model forecasts by the Copernicus Climate Change Service (C3S) at the European Centre for Medium-Range Weather Forecasts (ECMWF). While the temporal resolution is hourly, however, for the purposes of this project, daily totals of rainfall were used, as were the daily maximum and minimum temperature for the period 1959 to 2020. The spatial resolution of the product is a 30 km x 30 km grid. It must be noted that the data for the period 1959 to 1979 is a preliminary dataset that has been produced and it has been found that it suffers from excessively intense tropical cyclones. For each HRU grid, the closest ERA5 gridded daily rainfall and minimum and maximum temperature were assigned.

As the hydrological modelling is highly sensitive to the rainfall input, significant time was invested into the error and quality checking of the available observed rainfall records. The data, as obtained from the source, was used, but cross checked with other stations and data extracted from the South African daily rainfall database (Lynch, 2004).

A representative rainfall station was chosen for each of the HRUs (grids) based on

- The mean annual precipitation (MAP) of the rainfall station in relation to the HRU MAP;
- The altitude of the rainfall station in relation to the HRU altitude;
- The rainfall station’s location in respect of the HRU; and
- Comparison of the HRU median monthly rainfalls to those of the station.

Once the driver stations were allocated, the median monthly rainfall values for each grid, based on the record period for which complete historical rainfall existed (1959 to 1999), were obtained for both the driver rainfall station and the ERA5 data. To generate monthly correction factors the driver rainfall station median monthly values were divided by the ERA5 median monthly values. This produced one correction factor for each month which was then applied to the daily rainfalls in the corresponding months for the full period of interest.

As daily A-pan records were not available, the Hargreaves and Samani (1985) daily A-pan equivalent reference evaporation equation, which is an option in the ACRU model and only requires daily maximum and minimum temperatures as inputs, was used to estimate daily values. Bezuidenhout (2005) found that the Hargreaves and Samani (1985) equation mimicked the daily values of reference evaporation well for South Africa. The ERA5 daily maximum and minimum temperatures were used as input. The temperature records from the ERA5 reanalysis product and global climate models have a higher-level confidence then the rainfall, thus the temperature records were used directly.

With the historical climate data (the period 1959 to 2020) being finalised, the next step was to determine the climate projections to be used to simulate potential scenarios of change to 2050. The project aimed to provide the communities and decision makers plausible climate storylines of a wet and a drier future climate. Given the uncertainty surrounding the potential climate changes in the Northern KZN area, particularly in terms of the impacts of global warming on tropical cyclones, this approach of storylines (scenarios) of plausible wet and dry futures was deemed preferable to projections. Further discussion on this is provided in Section 5.4. For the purposes of the hydrological modelling, a short description of the climate scenarios used and how these were used in the hydrological model is provided here.

The future climate scenarios were drawn from models that formed part of the 6th Coupled Model Inter-comparison Project (CMIP6). As the ACRU model required daily rainfall and maximum and minimum temperature data, not all models in the CMIP6 suite could be considered. Not all CMIP6 models have those variables, and not all CMIP6 models are daily. The CMIP6 models are output at a 1.5º x 1.5º grid resolution. Most of the study area is covered by one grid cell. Given the coastal effects and the potential bias in using one grid cell, two grid cells were chosen and the climate variables averaged. A wet storyline and a dry storyline were selected based on the summer (October-March) as the wettest or driest respectively in the mid-century (Figure 8-3). Again, it must be noted these are simply plausible storylines of the future and they are not the wettest or driest projections for the future as those models did not have either the variables or temporal resolution needed for the hydrological modelling. The climate data was extracted for the time-period 1979 to 2100.

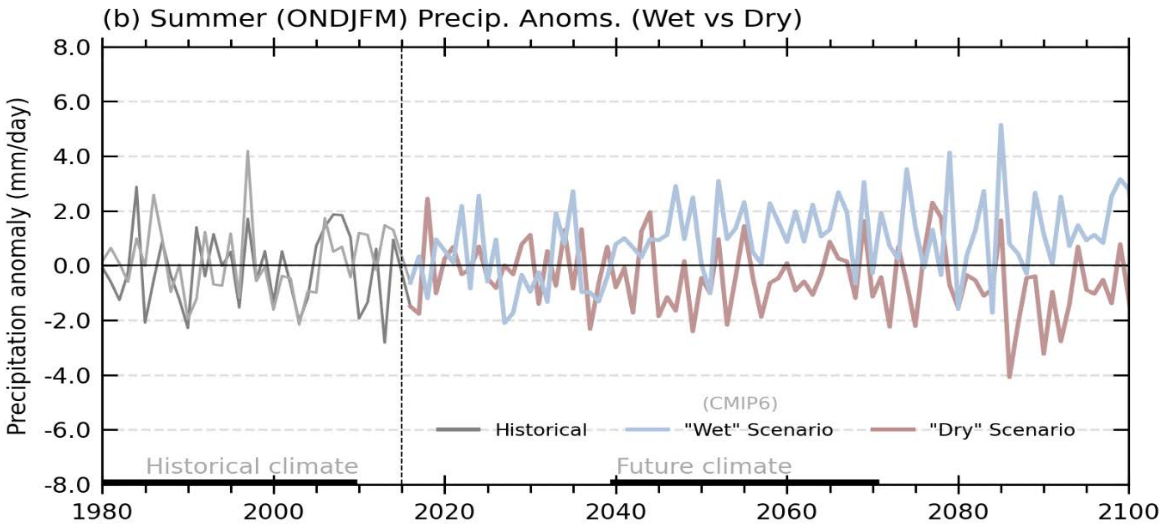


Figure 8-3 Graphical representation of the two CMIP6 models selected inform the two future scenarios storylines

The outputs from global climate models (GCMs) are useful for many applications; for understanding climate characteristics; and for the characterisation of plausible climate futures. However, all climate model predictions differ because of the different approaches to the way the fluxes are parameterised in the model and the underlying structure of the model. Thus, in short, there are biases in the outputs of all global climate models. As noted in CHAPTER 5: climate models over Southern Africa have large uncertainties and rainfall biases (Dieppois et al., 2015, Lazenby et al., 2016, Munday and Washington, 2017, 2018, Barimalala et al., 2022). Given these biases, the climate model data must be corrected before use in a hydrological model or before interpreting the output. For the purposes of this study a bias correction approach was used. Although bias correction is considered a simple approach, Shrestha et al. (2017) argues that it is sufficient at a monthly resolution.

The method that was followed to bias correct the storylines was guided by the ACRU and MODFLOW models being loosely coupled, the recharge output of ACRU being the input to the MODFLOW model, and the need to optimise the number of MODFLOW runs (particularly in consideration of the LULC and climate storyline combination scenarios). Therefore, the approach taken was to run the ACRU model using the daily rainfall and minimum and maximum temperature from the following sources and periods indicated, wet storyline given as an example:

- ERA5 data for 1959 to 2020
- CMIP6 wet storyline for 1991 to 2020 (present)
- CMIP6 wet storyline for 2021 to 2050
- CMIP6 wet storyline for 2031 to 2060
- CMIP6 wet storyline for 2041 to 2070

The recharge output from each of the above ACRU model runs was obtained. The percentage difference or change between the recharge from the CMIP6 present and the three future scenarios were determined. These percentage change factors were applied to 10-year increments of the ERA5 data (1991-2000; 2001-2010; and 2011-2020) to create a future wet recharge storyline. This was joined to the ERA5 data from 1959 to 2020 to create a continuous recharge record for input into MODFLOW from 1959-2050 representing the wet storyline. Figure 8-4 provides a visual illustration of the method. The same methodology was followed for the dry storyline. The reason for using the 30-year periods of the future climate data for the change factors was to emphasis the wetness or dryness of the respective storylines in a record that only spanned to 2050. Limitations of this method, however, are that the nuances in the pattern of the changes in the rainfall from the CMIP6 projections are not captured, and the bias corrected record is strongly influenced by the ERA5 period to which these correction factors are applied.

Box 1: Example of bias in the CMIP6 rainfall data

The mean annual rainfall (MAP) for the CMIP6 dry storyline 1991 to 2020 period was twice the MAP for the ERA5 1991 to 2020, period while the CMIP6 wet storyline was 2.3 times greater the ERA5 MAP for the same period.

For hydrological modelling, it is not only the amount of rainfall that affects the simulated streamflow or, in this case recharge, it is also the distribution of rainfall such as the number of raindays, the sequence of dry-wet days, and the distribution of rainfall between the months.

Not only is the volume of rainfall from the CMIP6 storylines biased but also the distribution of the rainfall. For example, for the period 1979 to 2021 there were 6 787 days in the ERA5 data with no rainfall. However, for the CMIP6 dry storyline there were only 2 610 days without rainfall and for the CMIP6 wet storyline only 919 days with no rainfall. Thus, both CMIP6 storylines had significantly more raindays than the best estimate of observed rainfall patterns.

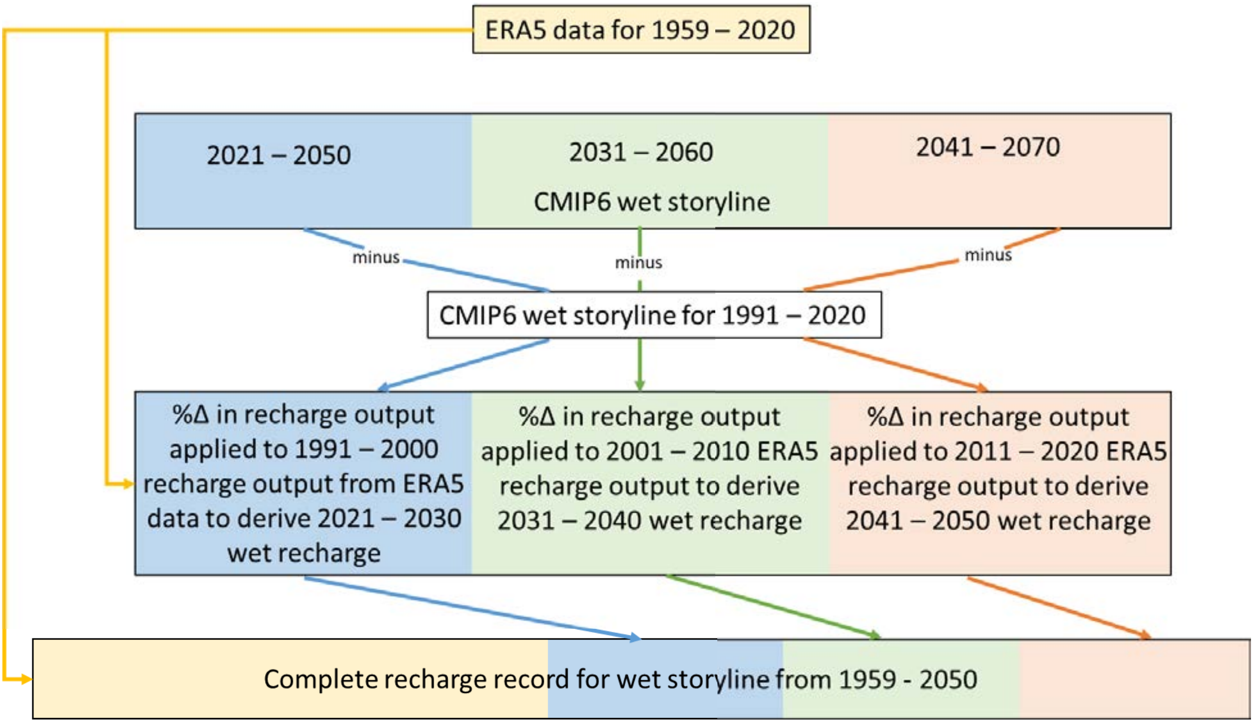


Figure 8-4 Visual representation of the bias correction undertaken to create a continuous recharge dataset for input to MODFLOW using the future climate inputs

Using this methodology, a continuous recharge time series for the period 1959 to 2050 was supplied to the MODFLOW modelling team for a wet and dry future storyline. The MODFLOW model also requires monthly rainfall and monthly lake evaporation data for the lake package. These were determined using the same bias correction methodology above applied to the rainfall record for a representative HRU grid falling over Lake Sibaya and the reference potential evaporation for that same grid cell. A representative HRU grid was selected due to the varied scales of the climate information, thereby deriving a continuous rainfall and reference potential evaporation record for the period 1959 to 2050 for the representative HRU grid for both a wet and dry storyline.

For the crop modelling purposes, the monthly bias corrected maximum and minimum temperature records were used, as well as bias corrected reference A-Pan evaporation. A comparison of the ERA5 temperature records for the nine ERA5 grids that cover the study area against the NRF-SAEON Vasi automatic weather station was undertaken for the three-year period of overlapping records (Box 2). The grid that best represented the observed temperature data was selected and the monthly maximums and minimums for the past and bias corrected values to 2050 were supplied to the crop modelling team. The crop modelling made use of the monthly bias corrected rainfall record supplied for the MODFLOW lake package.

Due to the bias in the CMIP6 future storylines and that the CMIP6 bias corrected runs were strongly influenced by the ERA5 period to which the corrections were applied (see CHAPTER 10: section 10.5.1), an alternative wet and dry future climate scenario were considered. The method used was to select a relatively wet period in the past and a relatively dry period, and to these periods apply a percentage change. The ERA5 rainfall data assigned to the HRU grids and corrected by the monthly correction factor was used. The identified wet period was 1971 to 2000 during which the high rainfalls associated with the March 1977 flood fell (cf. CHAPTER 6:). A 10% increase was applied to the rainfall for each HRU grid cell to create a plausible wet future scenario. The identified dry period was 1991 to 2020 during which the low rainfall occurred dropping the lake level to a record low of 16.20 m AMSL in

May 2011 (cf. CHAPTER 6:). A 10% decrease to the rainfall for each HRU grid cell was applied to create a plausible dry future scenario. To ensure consistency between the temperature and rainfall records, the ERA5 temperature data for the selected periods was used with 1°C added to each daily maximum and minimum temperature record to account for the expected warming. For the MODFLOW lake package and crop modelling, the percentage adjusted rainfall from the same representative grid cell as applied to the CMIP6 storylines was used. Similarly, the adjusted mean monthly temperature for the same grid cell was supplied to the crop modelling team.

To summarise, the future climate scenarios considered were the CMIP6 wet and dry future scenarios (bias corrected GCM output) and the ERA5 wet and dry future scenarios (percentage adjusted ERA5 historical data).

Box 2: Comparison of ERA5 temperature and *in situ* temperature data

No long term, high quality daily temperature records exist for the Maputaland Coastal plain. Thus, the team opted to use the ERA5 daily temperature data for this project. However, NRF-SAEON has installed three automatic weather stations (AWS) in the MCP area. Given the sensitivity of the crop modelling to temperature a comparison between the nine ERA5 temperature grids and the closest NRF-SAEON AWS to the agricultural areas, namely the Vasi AWS, was undertaken for the overlapping record period from June 2018 to December 2021. The crop model requires monthly means of maximum and minimum temperature; therefore, this was the first comparison undertaken.

There was a cluster of ERA5 grids that were similar to the Vasi AWS monthly maximums and minimums (Figure A and B). These were the ERA5 grids that were more inland and not covering the lake, whereas the coastal grids, e.g. Grid 8 and 9, were different to the Vasi AWS data with more moderate maximums and minimums. To make a final decision as to which ERA5 grid to use, the number of days with temperatures above 40°C, 35°C and 30°C were determined and compared (Figure C). The ERA Grid1 was decided on as the best representative temperature grid to use in the crop modelling.

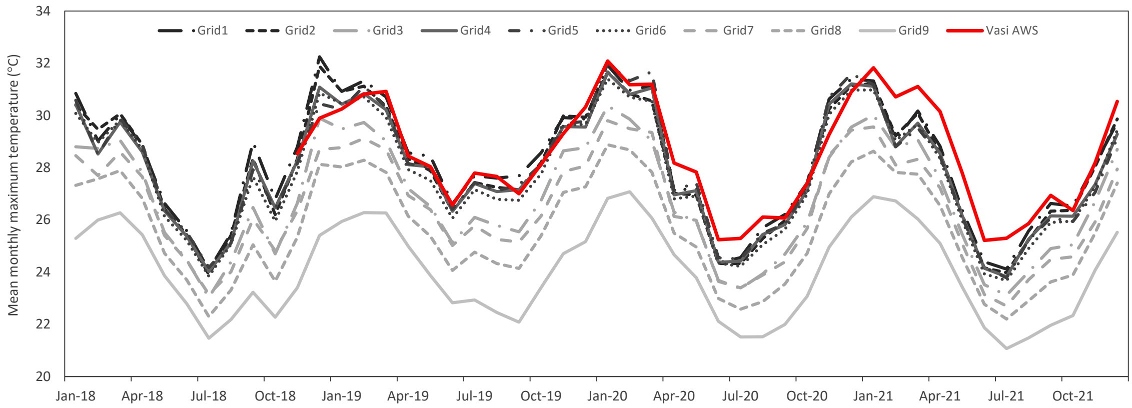


Figure A: Comparison of monthly mean **maximum** temperature data for the nine ERA5 temperature grids and the Vasi AWS for the period January 2018-December 2021

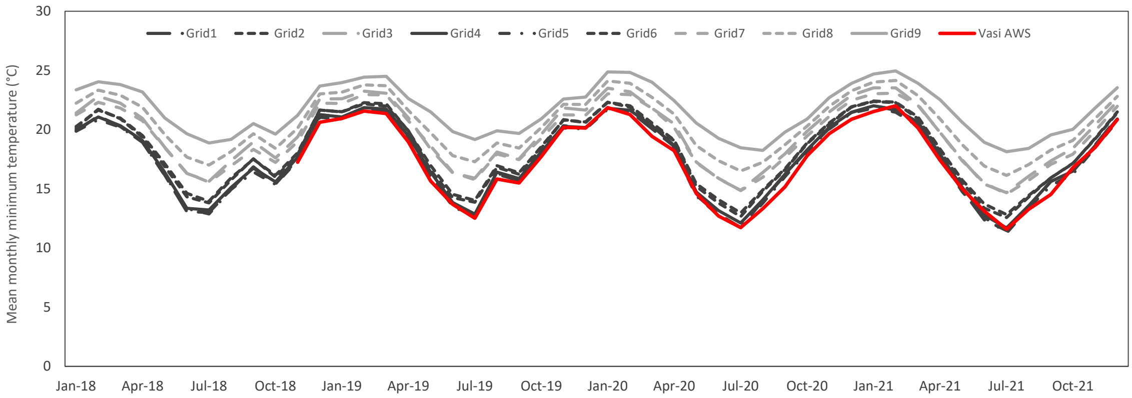


Figure B: Comparison of monthly mean **minimum** temperature data for the nine ERA5 temperature grids and the Vasi AWS for the period January 2018-December 2021

Box 2: Continued

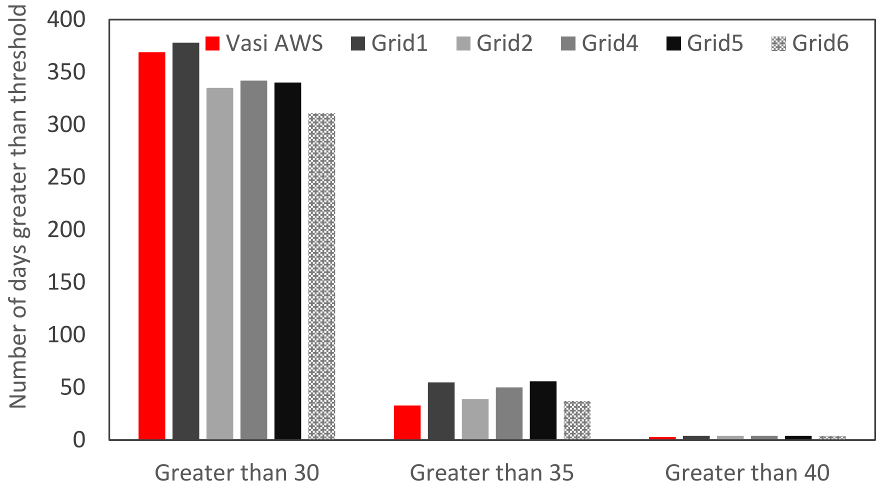


Figure C: Comparison of the number of days above the threshold temperatures of 30°C, 35°C and 40°C for the subset of ERA5 temperature grids and the Vasi AWS

8.2.3 Soils

The ACRU model is based on a daily multi-layer soil water budget and operates with surface layer characteristics and a topsoil and subsoil layer. Infiltration of rainfall, rooting development and soil water extraction takes place through the evaporation and transpiration processes. Other subsurface processes in the form of capillary movement and saturated drainage are also accounted for in the model (Schulze, 1995). Thus, information is required on the thickness of the topsoil and subsoil, as well as on soil water content at the soil's lower limit, i.e. permanent wilting point; its drained upper limit, i.e. field capacity; and saturation for both the topsoil and subsoil. Furthermore, the model requires information on the fraction of "saturated" soil water (above drained upper limit) to be redistributed daily from the topsoil to the subsoil, and from the subsoil into the intermediate/groundwater store (Schulze, 1995). Values for these variables were obtained for each of the HRUs from the electronic data accompanying the *South African Atlas of Climatology and Agrohydrology* (Schulze et al., 2008).

The soils information in the *South African Atlas of Climatology and Agrohydrology* (Schulze et al., 2008) was derived from the Land Type Inventories. The Land Type Inventories provide the soil form with series codes and their respective percentages making up a land type, as well as depth ranges of the soil profile. Through a decision support system these are converted to qualitative values needed as input for the ACRU model with a set of working rules, equations, and inferential values (Schulze, 2007).

The soil depths extracted from the soil's information in the *South African Atlas of Climatology and Agrohydrology* for the study area had a maximum depth of 0.3 m for the A-horizon and 0.88 m for the B-horizon. Based on information available, the depth of the A-horizon is likely 2 m while the B-horizon is 12 m deep and both constitute unconsolidated sandy material (Smithers et al., 2017). During the sensitivity study, model runs with varying soil depths were considered.

8.2.4 Streamflow Response Variables

In the ACRU model, streamflow response variables are used to govern the portion of generated stormflow exiting a catchment on a particular day, as well as the portion of baseflow that originates from the groundwater store, which contributes to streamflow. Typically, for South African situations, it is assumed that 30% of the total stormflow generated in a HRU would exit the same day as the rainfall event which generated the stormflow (Schulze et al., 2004). This variable is, however, influenced by the size, steepness, and land use of the HRU or sub-catchment. A small and/or steep and/or urbanised sub-catchment would respond more rapidly, thus the percentage of the total stormflow generated in a sub-catchment that would exit on the same day will be higher (Schulze et al., 2004). The study area, in this case, was flat and the modelled grid size small. Furthermore, there were no large, dense urban areas. As recharge to groundwater was the primary output of concern not streamflow, the sensitivity of groundwater recharge to the input value of the portion of generated stormflow exiting a catchment on a particular day was assessed. Based on the lack of sensitivity of the groundwater recharge output to this variable (cf. 8.4.2), the suggested value of 30% of the total stormflow generated in a HRU exiting on the same day as the rainfall event which generated the stormflow was used.

On any particular day, it is assumed that 0.9% of the groundwater store will become baseflow. This value has been found to be representative of large parts of Southern Africa (Schulze et al., 2004), and given the lack of sensitivity to this variable the representative value was deemed adequate. The thickness of the soil profile from which stormflow generation occurs is set to the thickness of the topsoil. The above streamflow response variables have been based largely on experiences in simulations on small and large research and operational catchments in climatic regimes ranging from semi-arid to sub-humid.

The coefficient of initial abstraction is a variable in ACRU which is used to estimate the rainfall abstracted by soil surface interception, detention surface storage, and initial infiltration before stormflow commences (Schulze, 1995). This value varies from month-to-month and differs, *inter alia*, according to land use, soil surface conditions, and typical seasonal rainfall intensity characteristics (Schulze, 2004). Impervious areas are hydrologically important and are represented in the urbanised land use units by inputting the fraction of the HRU that is impervious according to the typical South African values developed by Schulze and Tarboton (1995). Regarding impervious areas, the model distinguishes between adjunct impervious areas which are connected directly to rivers or stormwater systems and disjunct impervious areas, i.e. those not connected directly to rivers or stormwater systems. The fraction of the HRU which is specified as an adjunct impervious area, contributes directly to the streamflow on the same day as the rainfall event occurred. On the other hand, the runoff generated from the fraction of the HRU specified as disjunct impervious, contributes directly to the soil water budget and runoff responses of the pervious portion of the HRU under consideration. Disjunct impervious areas due to rock formations or natural features were the only considered impervious areas in this study.

8.2.5 Shallow Groundwater Routine Consideration

The ACRU model has a subroutine which can be turned on to simulate water uptake by tap roots, capillary rise, groundwater recharge, groundwater fluxes, and water table fluctuation (Kienzle and Schulze, 1992). The simulation of the water budget in the model is extended to incorporate an intermediate zone and capillary fringe if this subroutine is switched on. Conceptually, the water percolates through the B-horizon and enters the intermediate zone. For this zone, the simulation of the soil water content is based on the user input soil physical parameters, i.e. its texture, porosity, field capacity and wilting point, and a cascading “tank-type” model. The capillary fringe is conceptualised to be above the groundwater table, with the height based on a function of soil texture. It is assumed that the lower 10% of the capillary fringe is saturated, with the soil water content of the rest of the fringe being a linear decline to the soil water content of the intermediate zone. Water in the capillary fringe can be utilised by roots, and is then drawn upwards from the water table to the plant's roots.

Any water percolating downwards through the intermediate zone becomes part of the groundwater. This is governed by the specific yield of the aquifer, where the amount of water that can drain under gravity after saturation of the intermediate zone is the difference between porosity and field capacity.

This subroutine can only be used when the model is running in lumped mode, which implies that the different land uses and rainfall regimes could only be accounted for by configuring multiple model menus and running individually. Further, and more relevant, is that, under natural conditions, the water content of the intermediate zone is considered to be constantly at field capacity. Whereas, with deep rooted vegetation, which can make use of water from the capillary fringe, the intermediate zone must be filled entirely beyond field capacity before any recharge can occur. This Implies that only a very high rainfall amount would fill the entire intermediate zone and allow for recharge.

8.2.6 Land Use-Land Cover

As the LULC play a significant role in partitioning rainfall into the components of interception, plant and soil water evaporation, infiltration, runoff, and recharge, variables relating to the vegetation and its water use are required for hydrological modelling applications. In terms of the ACRU model, the following vegetation input parameters are required:

- Crop coefficient (K_c)
- Canopy interception loss input as a monthly interception loss (mm.rainday^{-1}) by the vegetation (VEGINT);
- The seasonal variation of the fraction of active roots (ROOTA) in the different soil horizons;
- The initial abstractions of rainfall before the generation of stormflow represented through the coefficient of initial abstraction (COIAM);
- The presence and amount of litter and/or mulch represented as percentage surface cover, (PCSUCO);
- The degree of root colonisation (COLON) within the soil horizons; and
- The fraction of plant available water at which plant stress occurs (CONST).

In terms of sensitivity, the hydrological response is most sensitive to changes in the K_c, thus the determination of this parameter has been given priority.

To represent land use in the ACRU model, three land use-specific components are considered, viz. canopy interception losses, evaporation from vegetated surfaces, and evaporation from the soil surface, with the latter two influenced by soil water extraction processes by plant roots from the two soil horizons (Schulze, 1995). Canopy interception losses per rain day were set using the interception loss variable for each month of the year determined for each land use considered (VEGINT) from a database of vegetation parameters (Schulze, 1995; Smithers and Schulze, 2004). The crop water use coefficient (K_c), determined for each land use considered from field-based measurements or the ACRU database of vegetation parameters, was used to estimate vegetation water use. The K_c values used are provided in CHAPTER 10: Table 10-2 To model the soil water extraction from both soil horizons, the fraction of active roots in the topsoil horizon (ROOTA) for each month of the year is required. These monthly values were also determined from a database of vegetation parameters (Schulze, 1995; Smithers and Schulze, 2004). In ACRU, evaporation losses from the soil surface are controlled largely by the percentage of litter covering the soil surface (PCSUCO), thus monthly values for each land use considered were input. The rainfall abstracted by canopy and surface litter interception, surface detention storage and initial infiltration before stormflow commences, i.e. the initial abstractions, is estimated in ACRU by the product of soil water content and a coefficient of initial abstraction (COIAM), with this value varying from month-to-month according to typical rainfall intensity and differing according to the land use (Schulze, 2004). The monthly COIAM values for each land use were determined from a database of vegetation parameters (Schulze, 1995; Smithers and Schulze, 2004).

As the historical climate data obtained was from 1959-2020, the historical land use used in the model needed to correspond. The land use in the study area has changed over this period, with the most significant change from a hydrological perspective being the increase in the commercial afforestation areas. Thus, the decision was made to run the ACRU model in dynamic mode. Dynamic mode allows for the monthly vegetation parameters per HRU to vary with time. The land use of each HRU was determined for the 1990, 2014, 2018 and 2020 time slices. For modelling purposes, the land uses were grouped into eight classes (Table 8-1). These land use classes were the significant groupings in the study area and were able to be accounted for in the model with the land use parameters.

Table 8-1 Land use classes accounted for in the ACRU model configuration and the areas of these land use classes per time slice considered

Land use class	Area (km^2)			
	1990	2014	2018	2020
Forest	247	286	328	372
Thicket, woodland and shrubland	1 134	1 074	1 086	1 042
Plantation	200	275	329	372
Grassland	512	454	378	313
Water (surface and wetland)	892	668	568	490
Bare ground	4	4	4	6
Cultivated	1	16	17	19
Developed	533	746	813	909

For each of these classes, the monthly K_c, VEGINT, ROOTA, PCSUCO and COIAM values were determined. These values were held constant but the areas of each land use type varied over the time slices. To note, a HRU was designated to the predominate land use class for that 1 km x 1 km grid cell.

Using this historical land use as a base, various scenarios of land use change were run through the model. For each scenario of land use change, the soils and streamflow parameters were held constant. Only the representation of the vegetation was changed in certain grids by varying the monthly K_c, VEGINT, ROOTA, PCSUCO and COIAM to represent the land use change of that scenario. Grid cells where no land use change occurred in the scenario were held constant at the 2020 parameters. Further information on the scenarios and the vegetation parameters used is provided in Sections 4.4.3 and 10.5.

8.2.7 Accounting for Irrigation

The ACRU agrohydrological model has an irrigation routine incorporated into it. The routine accounts for the major components of the irrigation water budget, such as atmospheric demand, total evaporation, available soil water, and rooting characteristics. The irrigation water budget in ACRU operates separately to the dryland soil water budget. The same principles of recharge and baseflow apply to both the dryland and irrigated areas, with water draining out the bottom of a soil horizon store when its soil water content exceeds the drained upper limit. A portion of the baseflow store is released downstream each day depending on a user input baseflow release coefficient, which, as described above, was set at 0.9%. However, within the irrigated area only one soil horizon is considered. Thus, the soil depth (soil water store) is shallower (smaller). In the irrigated area, because of the one soil layer, water moves through the soil into the store quicker with less opportunity for transpiration, i.e. no transpiration from B-horizon is accounted for. Additionally, the baseflow component from the irrigated area is only summed to dryland area downstream. Given the gridded approach used in this study, where the deep percolation to groundwater is being used, it was not possible to make use of the irrigation routine due to the irrigation water routine only considering one soil horizon and the contributions of baseflow and quickflow only from irrigation area being summed, not for the percolation variables. Added to this, a further constraint was that the options for the supply of irrigation water in ACRU include river, dam, and unlimited supply. The irrigation water in the study area is solely from groundwater abstractions.

8.3 DERIVING CROP COEFFICIENTS FROM FIELD BASED ESTIMATES OF EVAPOTRANSPIRATION FOR ACRU

Within ACRU total evaporation is driven by maximum potential evaporation (E_m), the forcing function of which is, in turn, a reference evaporation (E_r). The estimations of total evaporation in ACRU allow for the computation of the water balance, estimation of water availability, and water requirements (crop water requirements). The daily American Class A-Pan equivalent is used as the reference total evaporation in ACRU. The ACRU model contains several equations that can be used to estimate reference potential total evaporation, or total evaporation can be estimated from A-pan data, depending on the information available (Schulze, 1995). The evaporation from the soil surface and plant tissue within ACRU is computed using a meteorologically derived reference evaporation and a crop coefficient (K_c) which represent the vegetation water use. For each vegetation type, ACRU requires an input monthly K_c value. Crop coefficients provide a means to estimate the land cover's potential ET rate relative to the ET from a reference crop, expressed as:

$$K_c = \frac{ET_c}{ET_o} \tag{8-1}$$

Where,

- K_c = the crop coefficient (dimensionless)
- ET_c = crop (or vegetation) evapotranspiration ($mm.d^{-1}$)
- *ETo* = reference crop evapotranspiration ($mm.d^{-1}$)

ET_c refers to the crop ET under non-stress conditions, where the crop is well managed and watered (referred to as standard conditions). *ETo* refers to the ET from a reference surface, which is a short grass (0.12 m), under non-stress conditions. Through the use of a reference crop ET, the evaporative demand can be determined independent of crop development and management and can be compared across locations. A reference surface also provides a benchmark against which the ET from other surfaces can be compared (Allen et al., 1998).

ETo is only affected by climatic parameters, thus it can be calculated from meteorological data. The accepted and recommended method for determining *ETo* is the FAO Penman-Monteith method (Allen et al., 1998). The reasons for this include that the method closely approximates grass *ETo* at the location evaluated; is physically based; and it explicitly incorporates both physiological and aerodynamic parameters. The crop ET differs from the *ETo* as the surface from which the ET is occurring differs in terms of its ground cover, canopy properties, and aerodynamic resistance. By using the K_c approach, these differences between the reference surface and crop are accounted for. *ETo*, thus, represents the climatic demand, while K_c varies with vegetation characteristics and to a limited extent climate. This allows for the standard (those derived from non-stressed conditions) K_c values to be transferable between locations (Liu and Luo, 2010; Kar et al., 2007). K_c can be considered a surrogate for the vegetation height, albedo, canopy resistance, and the evaporation from the soil. To be able to determine K_c for a vegetation type, estimates of actual crop ET are required as well as climatic data to be able to calculate *ETo*. To better represent the land covers of the study area, NRF-SAEON undertook the monitoring of the actual ET over three land covers. Monitoring of ET, although highly valuable, is not an easy undertaking and numerous challenges were encountered.

8.3.1 Actual Crop Evapotranspiration Data

Total evaporation and energy balance components are monitored for three vegetation types – a grassland, eucalyptus, and macadamia sites. These systems were in place prior to the project, but the use of the data from these systems to derive K_c will be specific to this project. A summary of the equipment at each site, data length, and status are provided with images included for the vegetation to be visualised.

The ET above a grazed grassland in the study area is measured using an Eddy Covariance (ECo) system (Figure 8-5). The ECo system measures the water and energy balance components. The ECo system consists of an integrated 3-D sonic anemometer and open-path gas analyser for H_2O and CO_2 fluxes (IRGASON, Campbell Inc, Logan, United States of America) connected to an electronics panel (EC100, Campbell) and run off a Campbell datalogger (CR6) programmed with the EasyFlux-DL program which applied the necessary ECo corrections. The system was mounted on a lattice mast initially at 3 m, but has since been raised to 6 m to capture a greater footprint. The energy balance sensors consisted of a four-component net radiometer (CNR4 Kipp and Zonen, Delft, The Netherlands); soil heat flux sensors (HFP01-L, Hukseflux, Delft, The Netherlands); averaging soil thermocouple probes (TCAV-L, Campbell); water conductivity sensor (CS616, Campbell); and a relative humidity and air temperature sensor (CS215, Campbell). Rainfall is also monitored.

The system was installed in October 2020. Although the IRGASON has failed at times, the associated climatological measurements continued, which allowed for the data to be patched. Data collection from this system is ongoing, however for the purposes of this project, data for the period November 2020 to January 2023 was used to derive the K_c values.

Figure 8-5 The grassland site where the Eddy Covariance system is installed

A second, identical ECo system was installed over a young macadamia site (Figure 8-6) to measure the ET and energy balance components. This system was installed in December 2019. This site had numerous problems including power failures; failure of the four-component radiation sensor; problems with the soil heat flux measurements; and significant vandalism of the system in February 2022, which meant that the system had be removed. The system was not reinstalled again. The factor of most concern for this site was the lack of growth of the macadamia trees. The macadamia trees are grown by TMM, and they are responsible for the management of the crop. The intention of TMM was to irrigate the trees. However, several challenges, which included the theft and vandalism of pumps and transformers, have resulted in the trees not being irrigated. In addition, the trees were damaged in their early growth stage when on one day the temperature rose above 40^{o}C. Thus, the growth of the trees has been severely limited due to water stress. The measurements taken at this site are, therefore, not representative of an established macadamia stand, but rather of the initial establishment or of a disturbed (ploughed) area left to return to grass. Given this, the ET data could not be used to derive representative K_c values. Therefore, K_c values that were available in the ACRU-associated database of vegetation parameters (Schulze, 1995; Smithers and Schulze, 2004) for macadamias in the Sabie area were compared against those obtained by Taylor and Gush (2014) for a macadamia orchard in Mpumalanga. The K_c values are provided in Table 10-2 in CHAPTER 10:

Figure 8-6: The macadamia site where the ECo system is installed (the inset shows the condition of the trees)

The last site where ET measurements were taken is over a stand of *Eucalyptus urophylla* grown commercially by TMM (Figure 8-7). ET at this site is estimated using the shortened energy balance equation and the Surface Renewal (SR) method. The SR method is a cheaper alternative to ECo and uses high-frequency air temperature measurements and the structure function theory (van Atta, 1977) to estimate sensible heat flux (H). Through the use of the surface energy balance, latent energy flux (LE) can be estimated as a residual once net radiation (Rn) and soil heat flux (G) are accounted for. The SR system consists of two fine-wire thermocouples placed at 1.0 m (primary) and 1.5 m (secondary) above the top of the canopy (and moved as the trees grow), which are used for high-frequency (10-Hz) air temperature measurements. A net radiometer (NR2-lite, Kipp and Zonen, Delft, The Netherlands) was positioned 6 m above the ground and extended 1.5 m out from the tripod on a cross-arm, and measured net radiation (Rn). Two soil heat flux plates (HFP01-L, Hukseflux, Delft, The Netherlands) were installed 0.08 m below the soil surface and 1 m apart. Alongside these plates, four soil temperature averaging probes were installed, two placed 0.06 m and the other two placed 0.02 m below the soil surface and above each soil heat flux plate. Between the soil heat flux plates, a soil water reflectometer was installed at 0.025 m below the soil surface (CS655, Campbell Scientific Inc, Logan, United States of America). A further three soil water reflectometers were installed down the soil profile at 0.2, 0.4 and 0.6 m. These components were used to estimate soil heat flux (G). The sensors mentioned above were coupled to a Campbell datalogger (CR1000X).

The system was installed in October 2020 over newly planted seedlings (Figure 8-7). There are data gaps due to power issues and broken fine wires. A key aspect with the SR system is that it requires a calibration against an ECo system. One calibration of the SR system against an ECo system was undertaken. From the calibration, an α is calculated. The α was calculated from the slope of the linear regression between the H estimated by the SR system (x) and H estimated by the ECo system (y) for stable and unstable conditions. Only the unstable conditions are of interest as ET predominantly occurs when conditions are unstable. The α was calculated for unstable conditions (Table 8-2) for both the 0.4- and 0.8-s lags and for both fine wire heights respectively. Following the second calibration, another α value will be determined and these α values will be used to estimate the final H from the SR method from which the actual ET can be determined over the full record length. Tree heights and diameters have been measured monthly at this site to provide ancillary data.

The eucalyptus trees over which the ET was monitored were from seedlings to approximately 2 m tall. Given the large area under commercial trees in the study area, with the varied species and ages varying, a more broadly representative K_c value was deemed to be more appropriate than a site-specific, species-specific tree from seedling. These values were based on the most recent WRC report by Clulow et al. (2023).

Table 8-2 The α determined for 0.4- and 0.8-s lags at both fine wire heights for unstable conditions.

Lag (s)	Unstable α	
	Height 1	Height 2
0.4	1.204	1.791
0.8	1.413	2.049
Average	1.3085	1.92

Figure 8-7: The SR system installed on a lattice mast in a E. urophylla *compartment*

A land cover that was raised as a concern, and that the project therefore attempted to address, was bush encroachment. To be able to obtain the vegetation input parameters to represent this adequately, a partial SR system was installed (Figure 8-8) in a bush encroached site (using co funding). Additional sensors were required before all components of the energy balance could be measured. Procurement delays affected the arrival of these sensors. While waiting for the sensors to arrive, the site was vandalised twice. Due to the risks involved, a decision was taken to relocate the site. Unfortunately, delays in obtaining permissions for the new location, and the procurement of sensors, the measurement records were both too late and too short to be of use in this project. Measurement of ET over a bush encroached area will continue under the NRF-SAEON banner, and an identified recommendation from this project will be to further investigate the water use of the woody species common in bush encroached areas using the data from this site.

Figure 8-8: Installation of a Surface Renewal system in a bush encroached site in the Maputaland Coastal plain area

8.3.2 Monthly Crop Coefficients Derived to Represent the Grassland Land Cover

The ET record from the Maputaland coastal plain grassland ECo site is now longer than three years and monitoring is ongoing. The ET record is highly valuable given its length and location. Due to the timing of the hydrological modelling in the project, the ET record from November 2020 to January 2023 was used. A seasonal pattern in the partitioning of the energy balance components has emerged. During the summer months, the latent energy flux (LE) component of the energy balance is dominant, while the sensible heat flux (H) component accounts for a large percentage of net radiation in the late winter months when total evaporation is low (Figure 8-9). The soil heat flux (G) appears to vary between 12% and 15% of net radiation. The daily total evaporation data is presented in Figure 8-10. Mimicking the pattern in the partitioning of the energy balance components, a clear seasonal pattern in the daily total evaporation has emerged with winter evaporation which averages at 1.5 mm per day while total evaporation values in summer generally exceed 3 mm per day (Figure 8-10). Evapotranspiration values were, on average, higher in the 2022 wet season due to higher rainfall in this year compared to 2020 and 2021. Challenges have been experienced during the monitoring period due to equipment failure, however, these gaps in data can be patched as the net radiation data continued to be recorded. To patch the records, the crop coefficients determined from the good quality data was used.

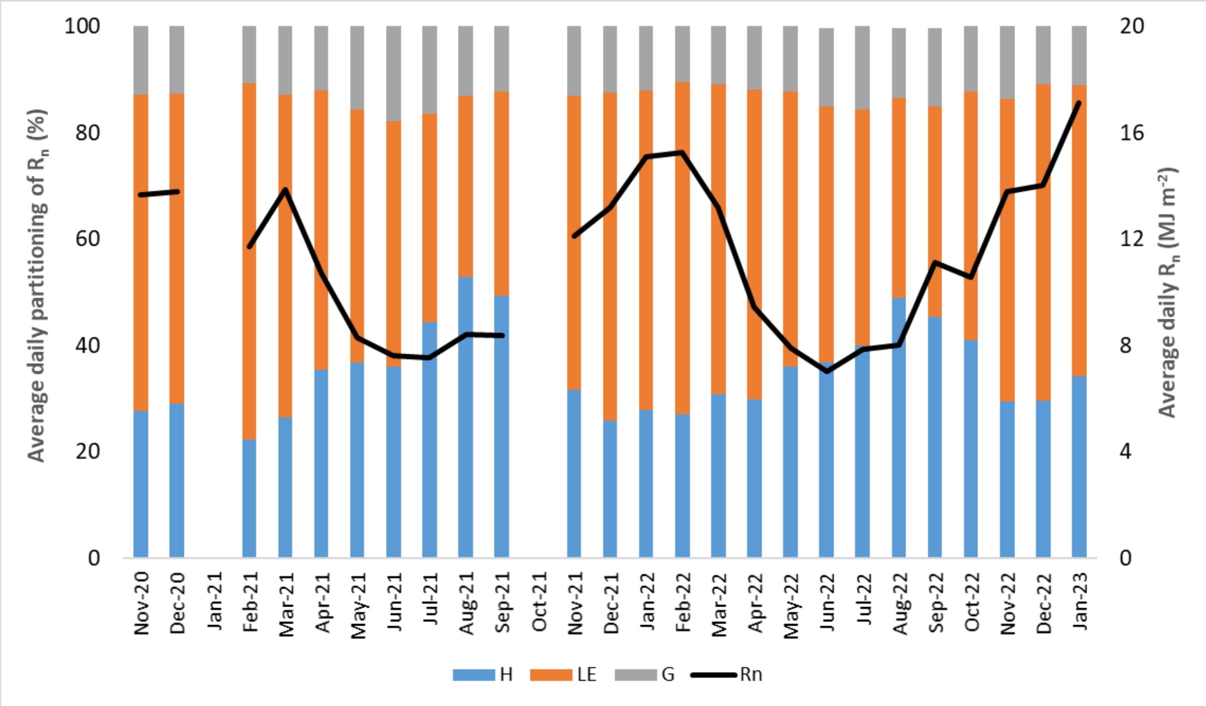


Figure 8-9 The average daily net radiation (Rn) and the average daily partitioning of net radiation (Rn) between the components of sensible heat flux (H), latent energy flux (LE) and soil heat flux (G) over the grazed grassland site in the Maputaland Coastal Plain

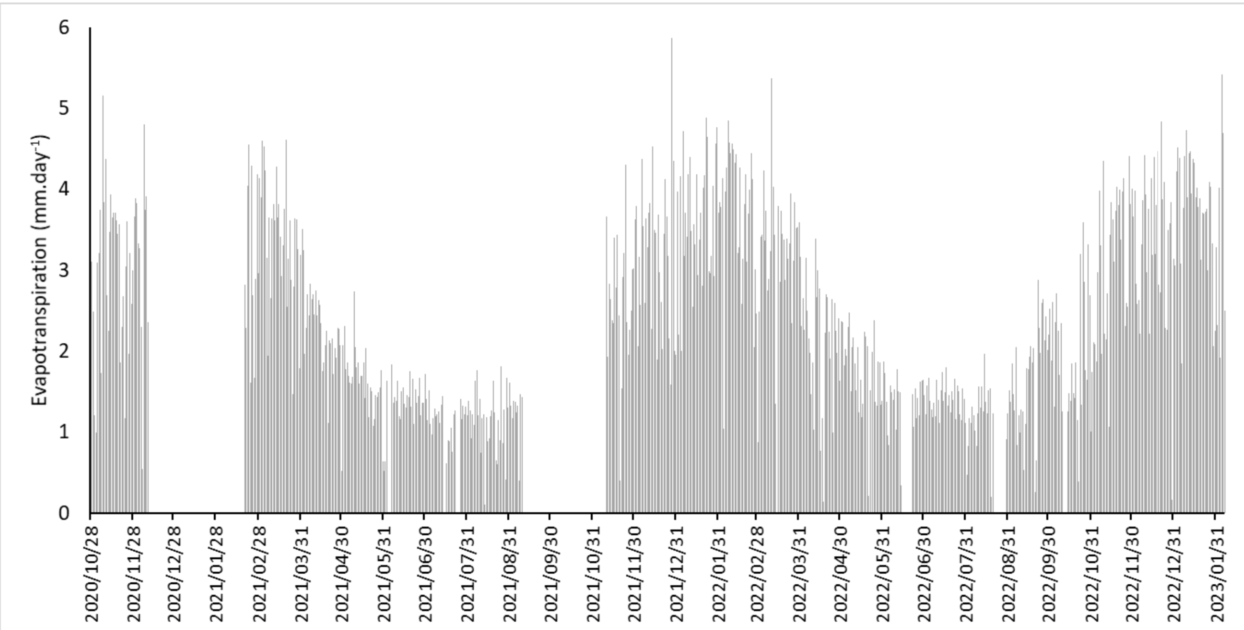


Figure 8-10: Daily total evaporation values measured using an Eddy Covariance system over a grazed grassland in the Maputaland Coastal Plain from November 2020 to January 2022

The FAO Penman Montieth reference potential evaporation was calculated using the climatological data from the grassland ECo system. Subsequently, the monthly K_c values that were derived with Equation

8-1. The K_c values follow a seasonal trend (Figure 8-11) with K_c values tend towards 0.2 in the late winter months in 2021 and 0.3 in the late 2022 winter months. A K_c value of 0.2 implies no transpiration as the vegetation has senesced or is dormant and only soil water evaporation has occurred, with a K_c of 0.3 that implies very low ET. A K_c value of 1 or greater implies that that actual ET is greater than the potential evaporation. Values of K_c greater than 1 would be expected for tall, dense vegetation. Thus, the K_c value of 0.96 for January 2022 can be considered high. The K_c values for 2022 are generally higher due to the wetter conditions in that year compared to previous years, thus a greater availability of water for actual ET while potential would have remained relatively constant to previous years. ACRU requires month-by-month K_c values. As these values need to representative, it would be preferable to have more than multiple years of data from which to derive the K_c values. To determine the month-by month values, the K_c values for months where there was more than one K_c value were averaged, whereas, when only one value was available for a month, that K_c value was taken to represent that month. The trend in the K_c values is as expected and the values are comparable with K_c values determined for other grassland areas. Further it must be noted that these are non-standard K_c values as the grass surface was not well watered, thus they may have been stressed at times.

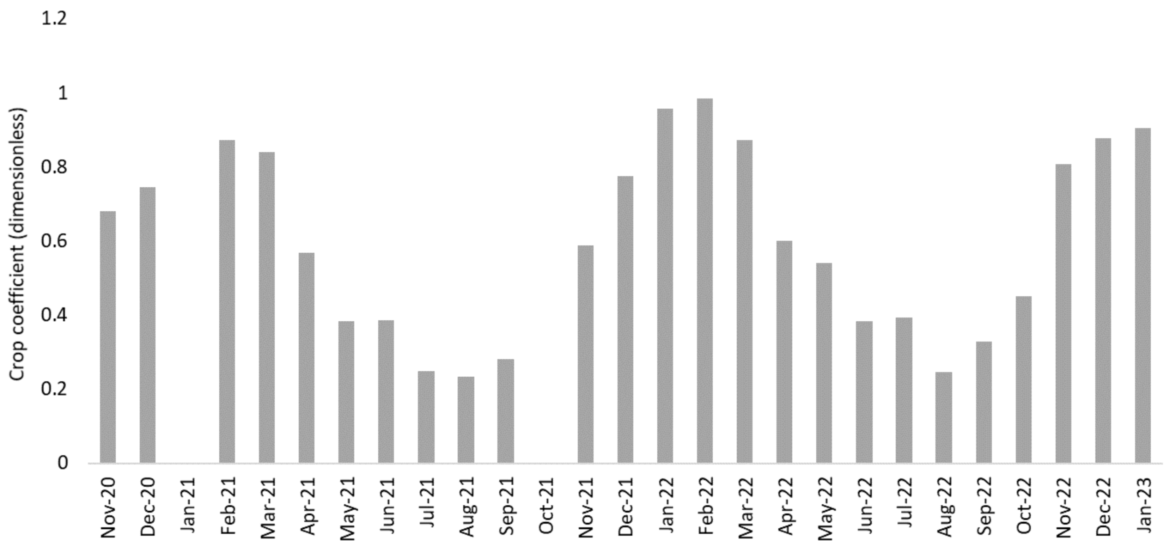


Figure 8-11 Time series of FAO Penman Monteith reference potential evaporation related crop coefficients derived for the grassland site

Table 8-3 Month-by-month FAO Penman-Monteith reference potential evaporation related crop coefficients for the grazed grassland site

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.93	0.87	0.84	0.57	0.38	0.38	0.32	0.24	0.30	0.48	0.69	0.80

8.3.3 Monthly Crop Coefficients Derived to Represent Marula (*Sclerocarya Birrea*) Trees

A crop suggested as an alternative to commercial trees by the communities in the workshops was indigenous Marula trees. No vegetation parameters were available for Marula trees in the ACRU parameter databases. Further, monitoring ET over Marula was beyond the scope of the project thus an alternative source of information needed to be found. Fortuitously, the WRC report titled *Water use and yield of selected indigenous fruit tree species in South Africa* (Ntshidi et al., 2022) was finalised in August 2022. Ntshidi et al. (2022) identified Marula as one of the indigenous fruit trees of interest and monitored the transpiration of Marula at a deep sandy site in northern Zululand, KZN, for a two-year period. Their findings indicated that the transpiration of Marula trees at the site was approximately 2 160 l/tree per annum, with a peak transpiration of 19 l/day measured. Further, it was found that trees were dormant for approximately four months during the winter period and the transpiration was strongly influenced by rainfall. With the use of a mean crown diameter of 8.53 m, e.g. Ceperley et al. (2012), the transpiration values were converted to a depth of transpiration. Ntshidi et al. (2022), alongside the transpiration values, provided the *ETo* values. Thus, the K_c values were estimated using Eq. 7.1 from the transpiration (converted to a mm value) and the *ETo* values. The K_c values used are provided in Table 10-2, CHAPTER 10:.

8.4 ACRU SENSITIVITY STUDY

As mentioned above, the application of ACRU has been focused primarily on surface water modelling and the streamflow output from the model. Thus, as an initial step in this project, a sensitivity study was undertaken to determine which input variables the recharge output was most sensitive to. In terms of hydrological modelling, sensitivity is a measure of the effect of changes in model input, or model structure, on model output (Schulze, 1992). Analysis of the sensitivity of the ACRU model to changes in model input is a useful tool to identify the input parameters that have minimal effect on the model output, and those variables to which the output is highly sensitive.

8.4.1 Methodology Followed

The ACRU model configuration as described above was used as the baseline or benchmark scenario with the rainfall adjustments switched off, and with the national scale and default input parameters where applicable. The model was run for the period 1960-1999 for the sensitivity analysis. Based on previous sensitivity studies, the following input parameters were investigated:

- Portion of generated stormflow exiting a catchment on a particular day;
- Percentage of groundwater store that becomes baseflow on a particular day;
- Total soil depth, as well as depth of the A-horizon and depth of the B-horizon;
- K_c; and
- ROOTA.

Further to these, the rainfall was also considered. A rule of thumb for streamflow responses is that a 10% change in rainfall will result in a 30% change in streamflow, thus percentage changes in rainfall were considered to determine if the same rule of thumb held for recharge values.

The input parameters for which the sensitivity was tested were considered individually. The model input parameters were held constant and the input parameter of concern, i.e. crop coefficient, was adjusted in 10% increments (c.f. Table 8-4 for a list of scenarios undertaken). The mean annual recharge for the full simulation period was then compared to the mean annual recharge generated from the baseline scenario. The percentage adjustments varied between parameters based on the alignment with acceptable ranges for the variables. For example, no decreases in the soil depths were considered as the soil depth determined from the national databases were considered shallow.

Table 8-4 Percentage adjustments for the various input variables

Input Variable	+ 100%	+ 50%	+ 20%	+ 10%	- 10%	- 20%	- 50%	- 100%
Total soil depth								
A-Horizon soil depth								
B-Horizon soil depth								
Portion of generated stormflow exiting a catchment on a particular day								
Percentage of groundwater store that becomes baseflow on a particular day								
Crop coefficient (K_c)								
Fraction of active roots in the A-horizon (ROOTA)								

To categorise the sensitivity of the parameter, the following ranking from Schulze (1995) was used:

- **Extremely sensitive:** The percentage change in output is more than twice that of the input parameter being tested, i.e. the change in recharge is greater than 20% for a 10% change in input parameter.
- **Highly sensitive:** The percentage change in output is more than that of the input parameter being tested but less than twice, i.e. the change in recharge is between 10% and 20% for a 10% change in input parameter.
- **Moderately sensitive:** The percentage change in output is less than that of the input parameter being tested, but by more than 50% of the input change, i.e. the change in recharge is between 10 and 5%, for a 10% change in input parameter.
- **Slightly sensitive:** The percentage change in output is between 10-50% of the change in the input parameter being tested, i.e. the change in recharge is between 5% and 1%, for a 10% change in input parameter.
- **Insensitive:** A less than 1% change in output to a 10% change in input.

8.4.2 Results from ACRU Sensitivity Analysis

The adjustment of the portion of generated stormflow that exited a catchment on a particular day generated no change in the recharge values for any of the HRUs in the ACRU model configuration. Similarly, the adjustment of the percentage of groundwater store that becomes baseflow on a particular day resulted in no change in the recharge values output by the model.

However, changes in the recharge output were noted for the other input variables tested (Table 8-4). The rule of thumb of a 10% change in rainfall resulting in a 30% change in streamflow held for recharge as well, with a 10% change in rainfall increasing recharge by approximately 30% (Figure 8-12). Thus, the recharge values can be considered to be extremely sensitive to rainfall input. Considering the lack of climatological observations and rain gauges in the study area, this is of concern. The uncertainties in the rainfall records for the area are going to be reflected and amplified in the recharge output from the ACRU model.

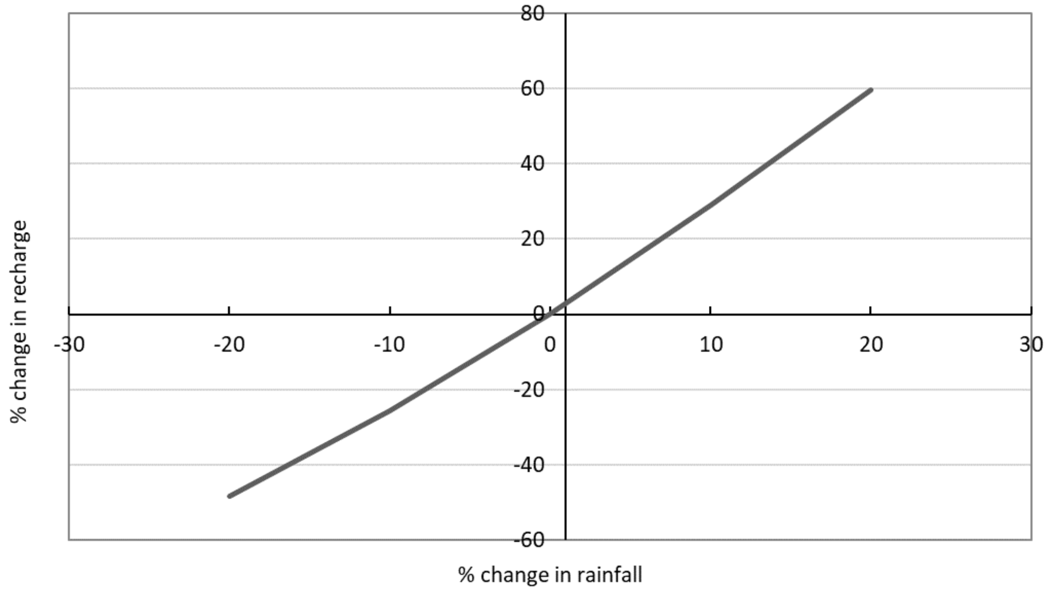


Figure 8-12 Percentage change in the mean annual recharge output (1960-1999) due to changes in the daily rainfall input

Only increases in the soil depth were considered as the soil's information in the *South African Atlas of Climatology and Agrohydrology* was used in the baseline runs. This extracted soils data was shallower than anticipated for the area with A-horizon depths averaging 0.3 m and B-horizon depths 0.88 m. Increases to the A-horizon and B-horizon depth were considered separately, followed by increases in both to result in a deeper total soil depth. The soil-related parameters of field capacity, wilting point, and porosity were held constant. The recharge output was moderately sensitive to an increase in the A-horizon depth, with a 20% increase in soil depth resulting in a 10% increase in recharge. The recharge output was also moderately sensitive to an increase in the B-horizon soil depth, however, for an increase in soil depth of the B-horizon there was a decrease in recharge (Figure 8-13).

The increase in recharge with an increase in A-horizon soil depth is due to a lower generation of stormflow, a generally wetter soil profile, and, thus, more percolation to the B-horizon and, from there, more recharge. Whereas, with the deeper B-horizon, the stormflow volumes are not altered and there is a great "reservoir" to fill before recharge can occur. An increase in the total soil depth did not have a significant effect on recharge initially, however, a run with a 2 m A-horizon and 12 m deep B-horizon decreased recharge substantially.

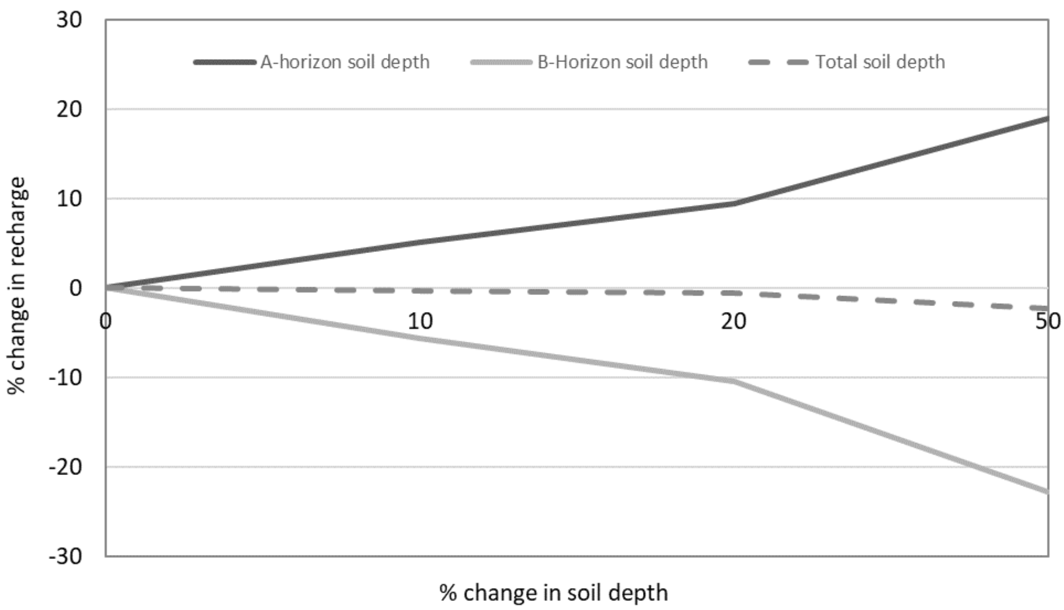


Figure 8-13 Percentage change in the mean annual recharge output (1960-1999) due to changes in the A-horizon, B-horizon, and total soil depth input

The sensitivity of streamflow output to the K_c has been shown in previous studies. The K_c is the variable that determines, together with the soil water content and rooting depth, the transpiration of the vegetation. Overall, at a catchment scale, increasing K_c resulted in a decrease in recharge but levelling off as the K_c became greater (Figure 8-13). The sensitivity of recharge to an increase in K_c was initially moderate and with greater percentage increases, became slightly sensitive whereas recharge is highly sensitive to a decrease in K_c. With a decrease in the K_c there is an increase in recharge. The reason for this is that with an increase in the K_c, the modelled vegetation tends towards a big biomass vegetation type that transpires at or near potential ET demand. However, this is constrained by plant available water in the soil which explains the levelling off of the response. With more transpiration, the soil water contents are lower and there is less recharge. On the other hand, a reduction in the K_c is towards a landscape with less transpiration and hence higher soil water contents and more recharge.

The sensitivity of recharge to a change in the ROOTA was also considered. Within ACRU, the conceptualisation of the root activity is such that if the input value for ROOTA is 100%, it is assumed that no active transpiration occurs and the vegetation has senesced. Thus, with an increase in the ROOTA, the value tends towards 100% which results in an increase in recharge due to less transpiration occurring. Therefore, recharge is highly sensitive to an increase in ROOTA. Within ACRU, the conceptualisation is that the percentage of roots in the B-horizon is 1 – ROOTA.

In conclusion, the uncertainty in the recharge output is going to be driven predominantly from the uncertainty that exists in the rainfall records for the area and the sparsity of those rainfall records in a highly spatially variable rainfall region. Further to this, the vegetation K_c parameters, ROOTA parameters, and soil depth parameters will need careful attention. The uncertainties introduced due to the K_c parameters can be minimised through the use of available ET data from the study area to determine the K_c values.

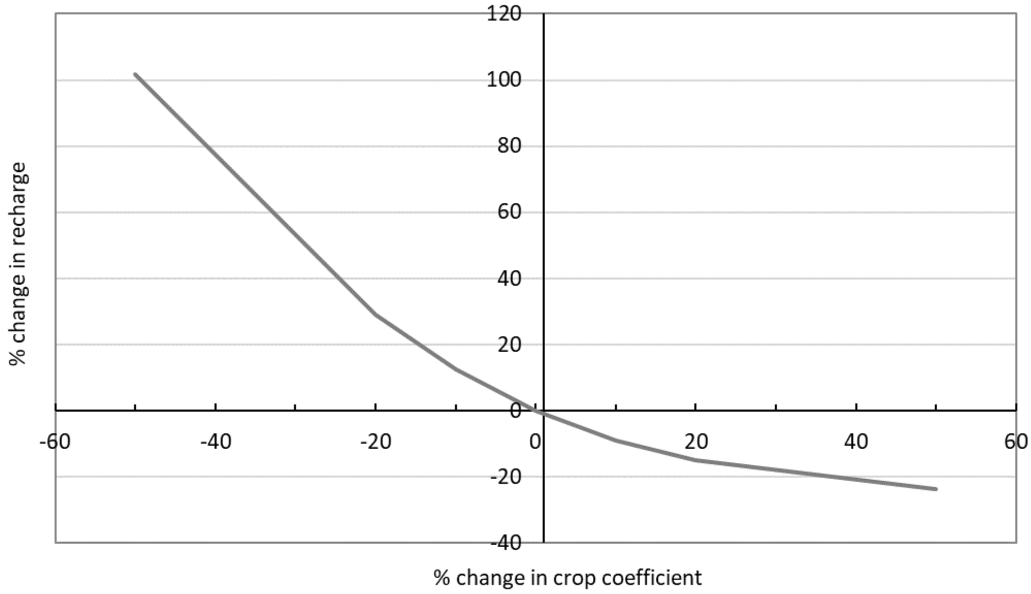


Figure 8-14 Percentage change in the mean annual recharge output (1960-1999) due to changes in the Crop Coefficient (K_c) monthly input parameters

8.5 VALIDATION OF ACRU MODEL RESULTS

Quaternary catchment W70A is a groundwater dominated system, with Lake Sibaya fed by rainfall and groundwater recharge. As ACRU is a surface water model which is typically confirmed against streamflow, a different approach to the validation of the model output needed to be adopted for this study. Thus, the approach taken to was to confirm that the simulated ET was in the range of the expected ET based on available measurements. Further, the annual pattern of ET was considered. The model was configured as described above for 3 394 hydrological response units (HRU, each 1 km x 1 km) that covered the groundwater extent. Each HRU was assigned a land cover, soil parameters, and climate driver. The ERA5 climate data was used. For each HRU a daily time step of output was obtained, that included ET, recharge, and rainfall. The daily time step output was aggregated to monthly, and the statistics over the simulation period (1959 to 2020) were obtained.

Prior to describing the results obtained, a few key points are noted.

1. The rainfall from the ERA5 product for the period 1959 to 2020 was used in the modelling exercise. As highlighted in Section 8.2.2, the ERA5 rainfall is approximately 11% lower than the rainfall available for the rainfall gauges in the study area for the period 1979 to 1999 (a period for which confidence in the gauge data exists). As noted in the sensitivity analysis, a 10% change in rainfall will alter the recharge by approximately 30% thus with an 11% underestimation of the rainfall, recharge will be approximately 33% underestimated.
2. The rainfall over the study area is variable over the groundwater extent, ranging from over 1 000 $mm.a^{-1}$ along the coast to 487 $mm.a^{-1}$ in the inland south-west areas (Figure 8-15). As shown in the sensitivity analysis, recharge is highly sensitive to rainfall. Therefore, by modelling at the 1 km grid scale, as done in this study, the variability of rainfall together with the land cover and soils variation is captured. Previously, one estimate of recharge per land cover was made, these estimates did not account for variable rainfall across the study area.

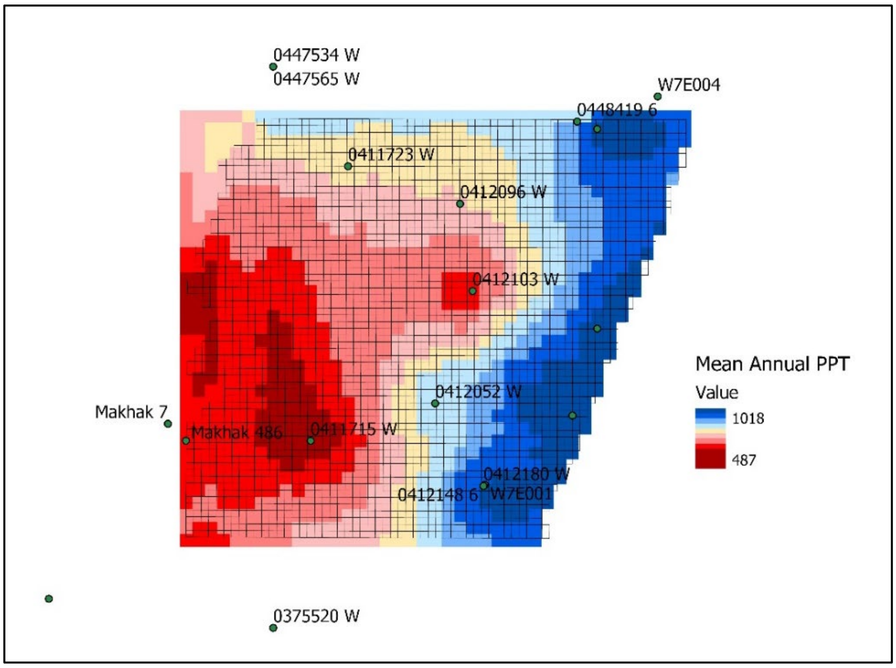


Figure 8-15 Mean annual rainfall over the Groundwater grid

The mean annual actual ET obtained for each of the HRUs grouped according to land cover were considered (Figure 8-16). According to Smithers et al. (2017), the mean annual ET for commercial trees in the MCP area is approximately 1 300 mm.a^{-1}. The ET obtained for the HRU's with commercial plantation forestry ranged from 953 mm.a^{-1} to 629 mm.a^{-1}. This ET is lower than what was described by Smithers et al. (2017), but, given that the ERA5 rainfall is 11% lower, a lower ET was anticipated. Similarly, the ET for the grass HRUs (mean of 416 mm.a^{-1}; range from 521 to 292 mm.a^{-1}) was lower than the approximate 528 mm.a^{-1} ET measured over a grassland in the study area. The range in ET within a land cover is representative of the range of rainfall across the study area.

The pattern of ET through the year mimicked the pattern expected, with lower ET values in the drier winter months and higher ET values in the wetter summer months. Further, as expected with the commercial trees being evergreen while the grass died back in winter, the ET from the commercial trees was far greater than the grass in the winter months, but similar in the summer months. As noted in the rainfall comparison, the months with the greatest underestimation in rainfall were January and February. These are also the months where the simulated ET for the high-water use land covers, such as commercial plantation forestry, was not as great as expected.

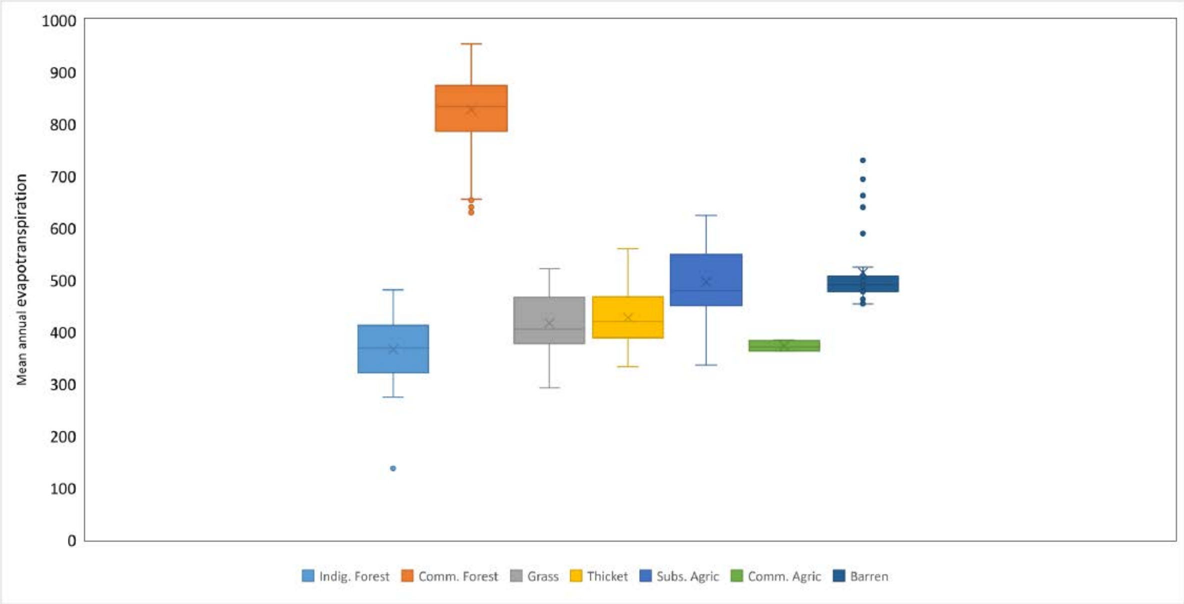


Figure 8-16 Box and whisker plots of the mean annual ET for the land covers considered

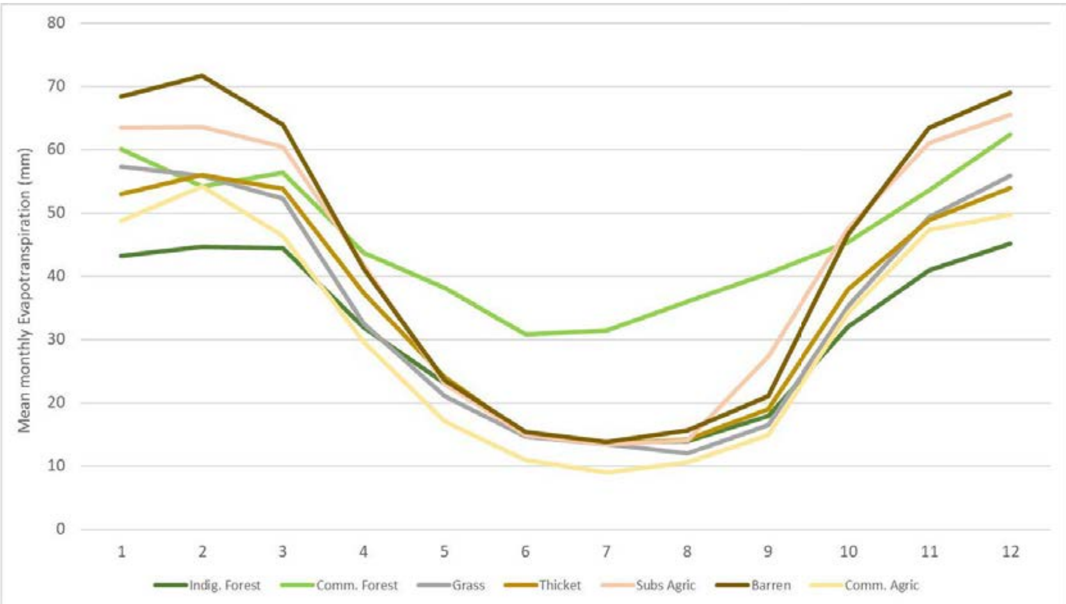


Figure 8-17 Mean monthly ET for the land cover classes

8.6 COMPARISON OF OBSERVED AND ERA5 RAINFALL

Given the sensitivity to rainfall of the recharge simulated by the ACRU model, a comparison between the observed historical and ERA5 rainfall product was undertaken. As described above, the observed rainfall data for stations in the study area was obtained from the Lynch (2004) dataset. The rainfall data for the stations included in this dataset has been patched for the period 1950 to 1999 as described in Lynch (2004). The ERA5 product is a 30 km^2 gridded rainfall product derived from a combination of historic observations with modelling and data assimilation systems. It must be noted at this point that the ERA5 product is spatially representative of a grid cell, whereas the observed data is point-based rainfall data. While this is a fundamental difference, however, understanding the differences between the two will assist in model output interpretation and comparison to previous studies results.

The comparison was undertaken for the period 1979 to 1999 as this was common to both datasets and covered the period of ERA5 for which the confidence was higher. From the comparison, the ERA5 product underestimates the monthly rainfall particularly in the wet summer months of January, February, and March (Figure 8-18). To look at the spatial variability, a box-and-whisker plot for each month covering the 3 394 grids was derived (Figure 8-19). The underestimation of the ERA5 product in January, February and June is particularly evident with both the mean and the spread of variation. In January, March, May, July, and September, the ERA5 mean is low compared to the observed rainfall, however in April, August, and October, the means are comparable. The variability of the rainfall across the grids in many months is comparable. At the annual time step, the underestimation by ERA5 was also evident. Averaged over the grids for the study area, the ERA5 product underestimates annual rainfall by 90 mm, which is an 11% underestimation. Based on the sensitivity results this will result, in the recharge being underestimated by approximately 30%.

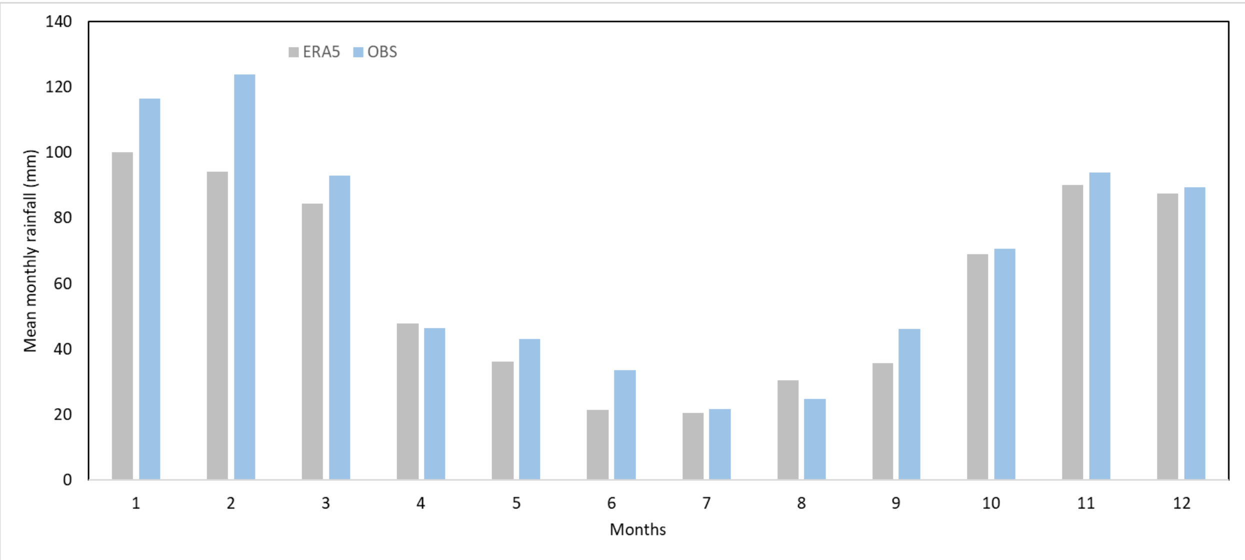


Figure 8-18 Averaged mean monthly rainfall for the ERA5 product and observed rainfall across all grids in the study area

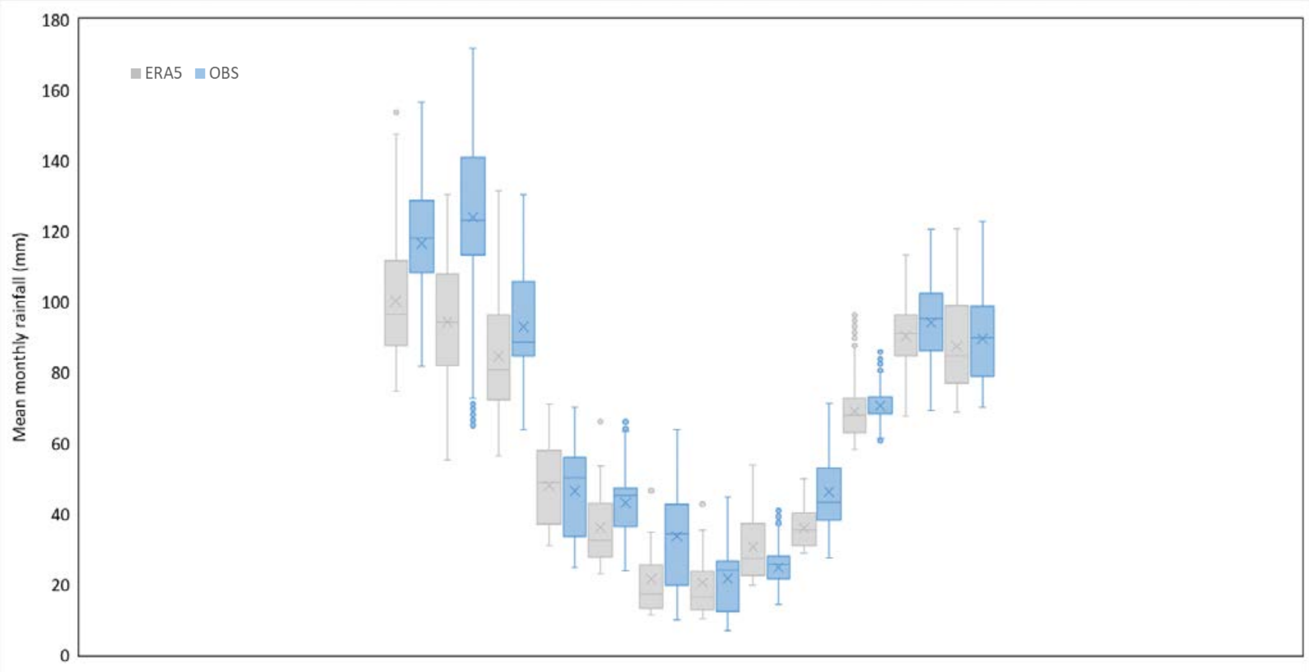


Figure 8-19 Box-and-whisker plots of the ERA5 and observation rainfall for each month for the grids falling across the study area

8.7 ACRU OUTPUT: RECHARGE RESULTS

The ACRU model was run with dynamic land use for the period 1959 to 2020 as the initial, baseline model simulation. The ACRU model outputs a range of variables, however the primary output variable of interest for this project is the saturated drainage from the B-Horizon to the groundwater zone. The model simulates the drainage daily per grid cell. However, to match the temporal resolution of the MODFLOW model, the daily output was summed to a monthly total per grid cell. Additionally, the monthly and annual means per grid cell were extracted from the output data.

The spatial pattern of the recharge reflects the rainfall pattern as well as the land uses present in the area (Figure 8-20). The recharge is highest to the south of Lake Sibaya along the coast, reaching over 400 mm per annum on average. The commercial plantation forestry areas to the north of Lake Sibaya on average do not experience recharge from the B-horizon to the groundwater zone. Most of the recharge occurs in the summer months (Oct to Mar), with large areas receiving little to no recharge during the winter months of April to September (Figure 8-20).

Given the influence of land use on the recharge, the pattern of recharge across the different land use categories was considered. The mean annual recharge per land use type for the period 1959-2020 was plotted as a box-and-whisker plot to show the mean and variability of the recharge per land use type (Figure 8-21). The areas of barren land and commercial agriculture were small; thus, these were not included in the analysis. The variability in the recharge across all land use types was large (Figure 8-21), likely due to the variability in the rainfall across the study area also having a strong influence. The grassland land use type experienced the highest mean annual recharge as well as having the largest variability in recharge. The commercial plantation forestry land use had the lowest mean annual recharge. The thicket recharge was also relatively low; this is attributable to the high crop coefficients and canopy rainfall interception by the vegetation together with a low percentage ground cover. The mean monthly recharge values per land use type reflected a similar pattern (Figure 8-22), and illustrated that February was the month of highest recharge across all land use types.

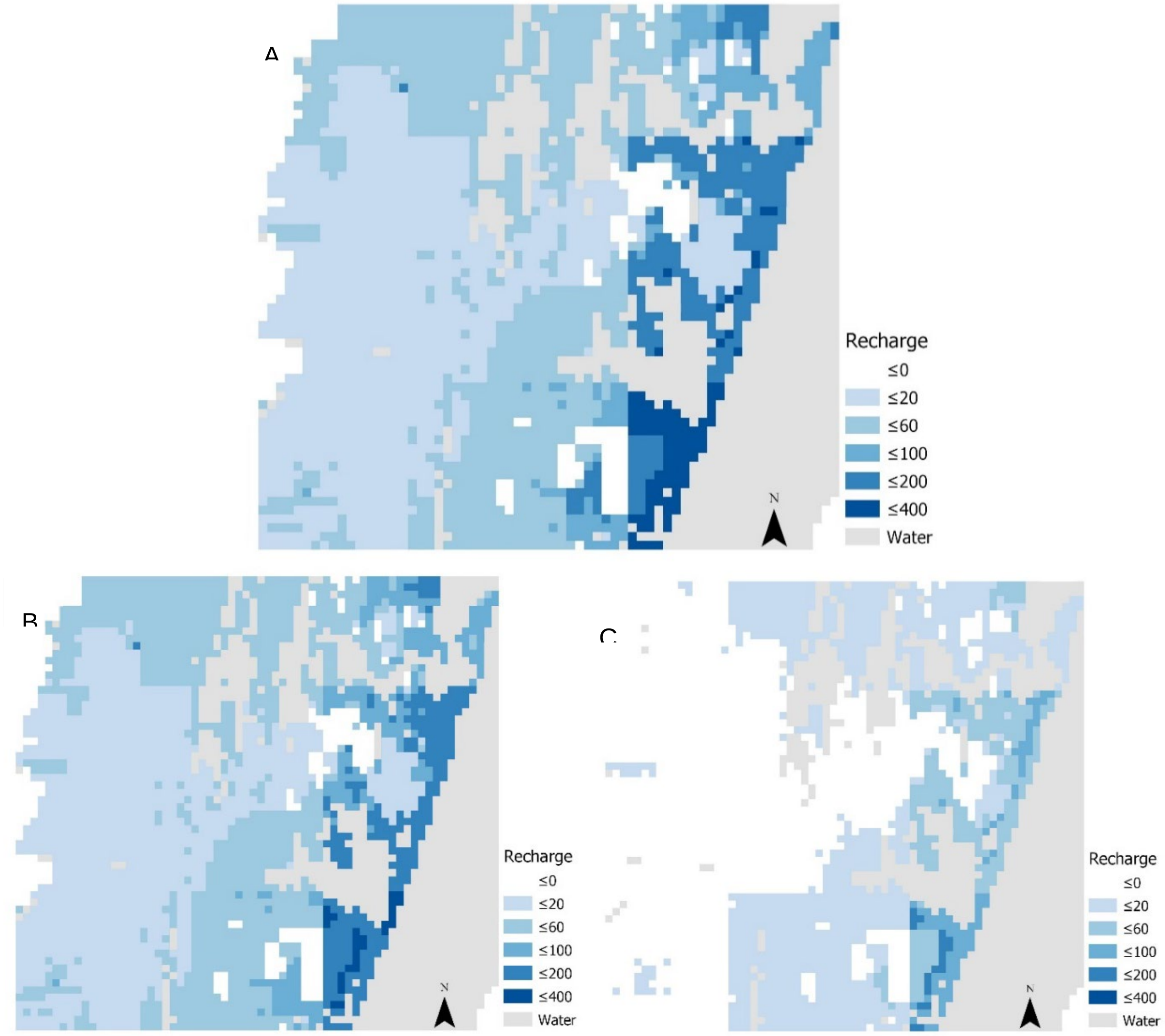


Figure 8-20 (A) Mean annual, (B) mean summer and (C) mean winter recharge under the dynamic land use from 1959-2020 for the study area

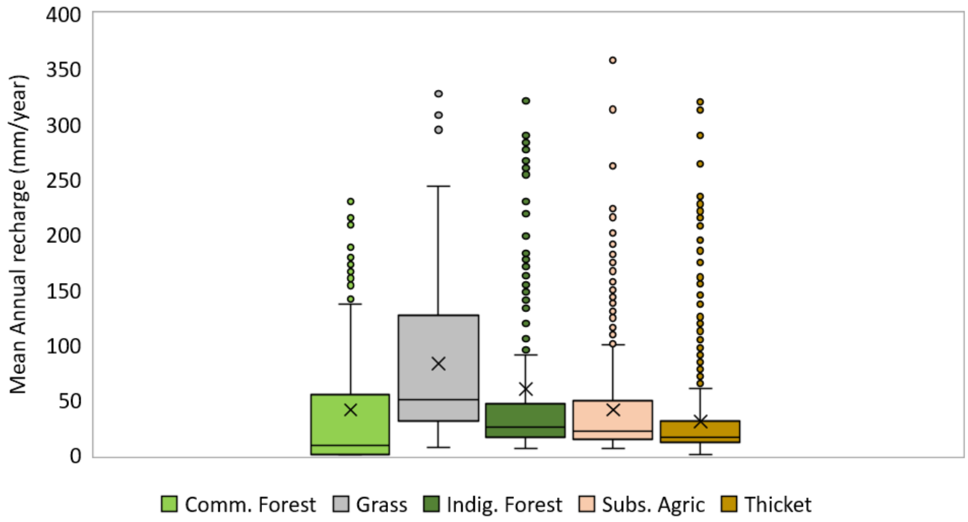


Figure 8-21 Mean annual recharge averaged per land use type for the period 1959-2020

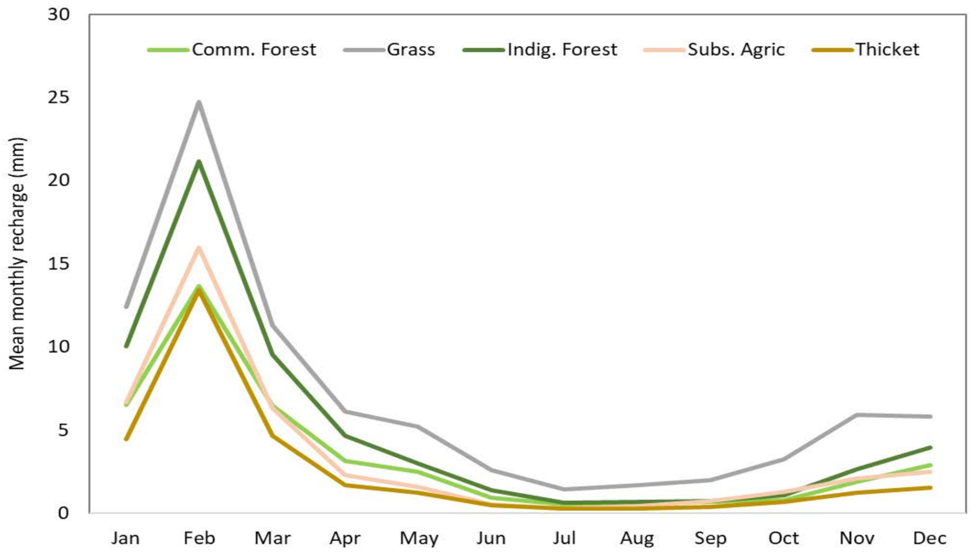


Figure 8-22 Mean monthly recharge averaged per land use type for the period 1959-2020

8.8 UNDERTAKING SCENARIO MODELLING IN THE ACRU MODEL

Various land use change scenarios were undertaken for present climate conditions as well as future climate storylines. How these scenarios were determined and the background to them is described in Section 4.4.3. This section describes how these scenarios were parameterised in the ACRU model.

The primary model configuration and output was that obtained using the dynamic land use (1990, 2014, 2018 and 2020) for the climate period 1959 to 2020. This scenario is referred to as the Status Quo (SQ) scenario (Scenario 0), i.e. the best representation of the current state of the hydrological model domain that we could reasonably model.

Scenario 1: No commercial plantation forestry

A land use of concern in the MCP area is the commercial afforestation. The commercial afforestation has increased over time and, having been declared a Streamflow Reduction Activity under the National Water Act of 1998, the negative impacts of commercial afforestation on water are understood. To determine the influence of commercial afforestation on recharge over time, the scenario considered was no afforestation. All HRU grids which were parameterised as commercial trees across the four land cover time slices (1990, 2014, 2018 and 2020) were parameterised as grassland. The same vegetation parameters as used for the grassland grids in the SQ scenario were used. Only the vegetation parameters were altered. The soils, climate, and streamflow response variables were held constant.

Following the historical simulation, this scenario was also undertaken for the future CMIP6 and ERA5 wet and dry storylines.

Scenario 2: Dynamic land use to 2020, with 50% of the grassland area encroached upon with woody vegetation (**Bush Encroachment**) from 2021-2050 and all other vegetation classes being held constant.

- 50% of the grass HRU grids within the Area of interest (AOI) become encroached
- The AOI (as described in detail in Section 4.4.3) is a 10 km buffer area around the Lake Sibaya recharge zone.
- Undertaken into the future for the CMIP6 and ERA5 wet and dry storylines.

Scenario 3: Dynamic land use to 2020, with 50% of the forestry area being replaced by **Dryland Crop** area as an alternative from 2021-2050 and all other vegetation classes being held constant.

- 50% of the forestry HRU grids within the AOI were converted to Dryland Crops.
- The four crops considered were maize, ground nuts, vegetables (modelled as Brassicas) and cassava.
- Undertaken into the future for the CMIP6 and ERA5 wet and dry storylines.

Scenario 4: Dynamic land use to 2020, with conversion of commercial afforestation to **Dryland Agroforestry** from 2021-2050 and all other vegetation classes being held constant.

- 50% of the forestry HRU grids within the AOI were converted to Dryland Agroforestry plantations.
- Undertaken into the future for the CMIP6 and ERA5 wet and dry storylines
- Note that enhanced transpiration for wet canopies was turned off for the agroforestry grids.

Scenario 5: Dynamic land use to 2020, with 50% of the forestry area being replaced with **Dryland Macadamia** from 2021 to 2050 and all other vegetation classes being held constant.

- 50% of the forestry HRU grids within the AOI were converted to Dryland Macadamia trees.
- Undertaken into the future for the CMIP6 and ERA5 wet and dry storylines.
- Note that enhanced transpiration for wet canopies was turned off for the macadamia grids.

Scenario 6: Dynamic land use to 2020, with 50% of commercial plantation forestry area being replaced with **Dryland Marula** trees from 2021-2050 and all other vegetation classes being held constant.

- 50% of the forestry HRU grids within the AOI were converted to Dryland Marula.
- Undertaken into the future for the CMIP6 and ERA5 wet and dry storylines.
- Note that enhanced transpiration for wet canopies was turned off for the Marula grids.

8.9 ACRU OUTPUT: SCENARIO RESULTS

The first set of scenarios (scenario 0) undertaken was to maintain the use the model configuration for the historical period with dynamic land use (where land cover changes in 1990, 2014, 2018 and 2020 were accounted for) and simulate into the future under both the CMIP6 and ERA5 dry and wet storylines holding the land use into the future as the land use in 2020 (Figure 8-23). The results are presented as a percentage change in the recharge simulated between (i) the historical CMIP6 past and CMIP6 future for the respective wet and dry storylines, and (ii) the ERA5 historical past and the ERA5 future for the respective wet and dry percentage adjustments. Note that for the recharge input to MODFLOW, these percentage changes were applied to the recharge simulated under the dynamic land use and used to extend the record for 30 years. Where commercial afforestation is present in 2020, the recharge is zero or very small (white areas in Figure 8-23) over the 1959 to 2020 period. Moving into the future, there are changes in these areas that appear large. However, as the changes are expressed as a percentage the small changes in recharge in these areas result in large percentages that are misleading, e.g. the darkest red in both the dry scenarios.

Across both the CMIP6 and ERA5 future storylines, the western side of the study area where the mean annual recharge was less than 20 mm for the period 1959 to 2020 is the area with greatest changes (Figure 8-23). Similar to the forestry area, this is deceptive as a small change in a low recharge will be a high percentage. Across the study area, the changes in recharge in the future under the CMIP6 storylines are relatively small, with the dry storyline having greater changes. The changes in recharge under the ERA5 storylines are marked, with the greatest changes occurring under the wet storyline.

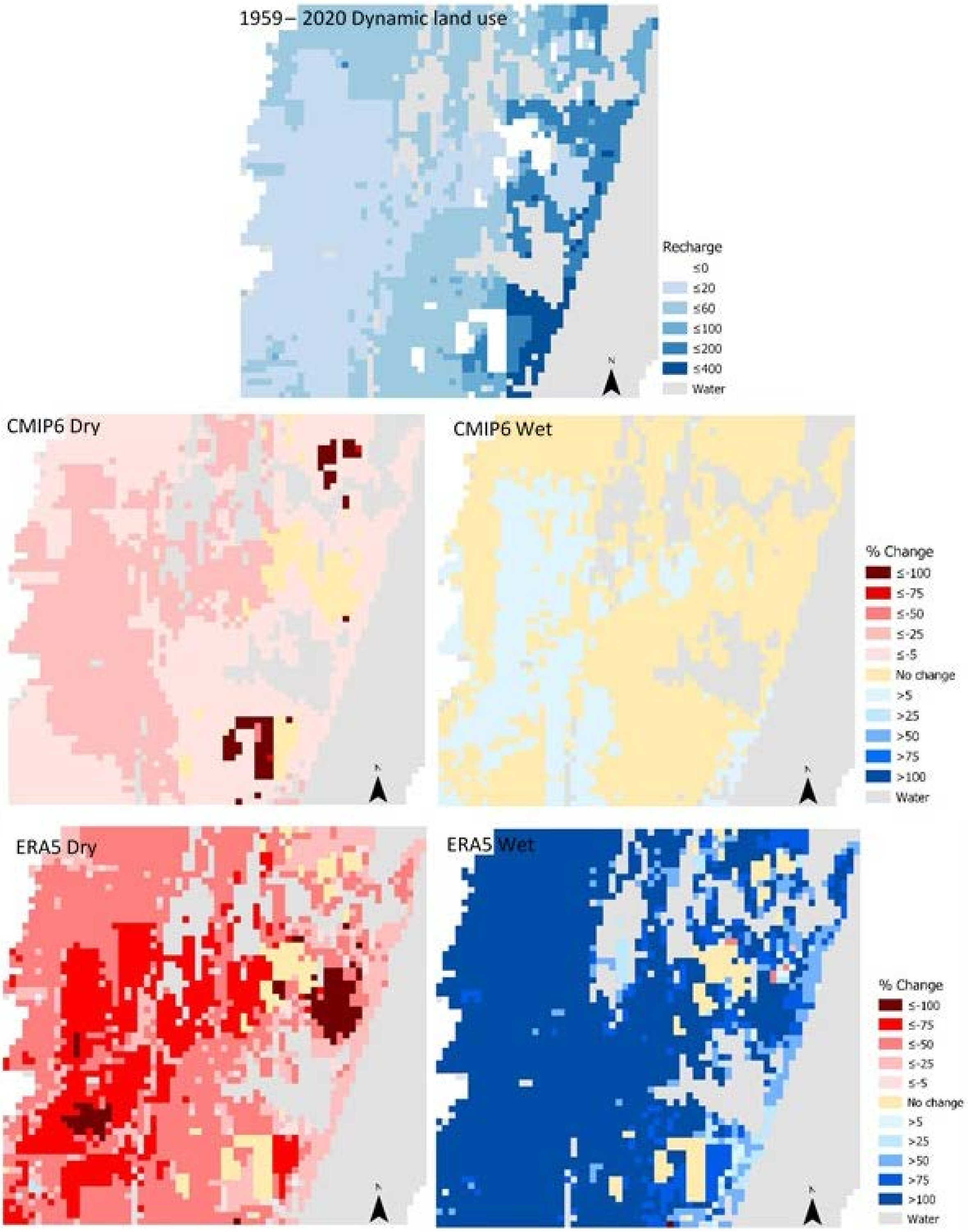


Figure 8-23 Percentage change in mean annual recharge under the SQ scenario (land use held constant as at 2020) for a future dry (left) and wet (right) storyline under both CMIP6 (middle) and ERA5 (bottom). Mean annual recharge (mm) under the 1959-2020 dynamic land use shown to contextualise the recharge changes.

Scenario 1: No commercial plantation forestry

The first land cover change scenario that was undertaken was to convert all commercial afforestation to grassland from the start of the model simulation. Thus, the model was run holding all other land uses constant except for the commercial afforestation which was converted to grassland for the period 1959 to 2020.

The simulated mean annual recharge is higher when no forestry is present in the area (Figure 8-24). For example, the forestry areas north of Lake Sibaya which experienced no mean annual recharge under the dynamic land use scenario (Figure 8-24), now experience more than 200 mm of recharge on average per year (Figure 8-24). Similarly, the mean summer recharge for the area is greater. The most marked change is the increase in the winter mean recharge for the area.

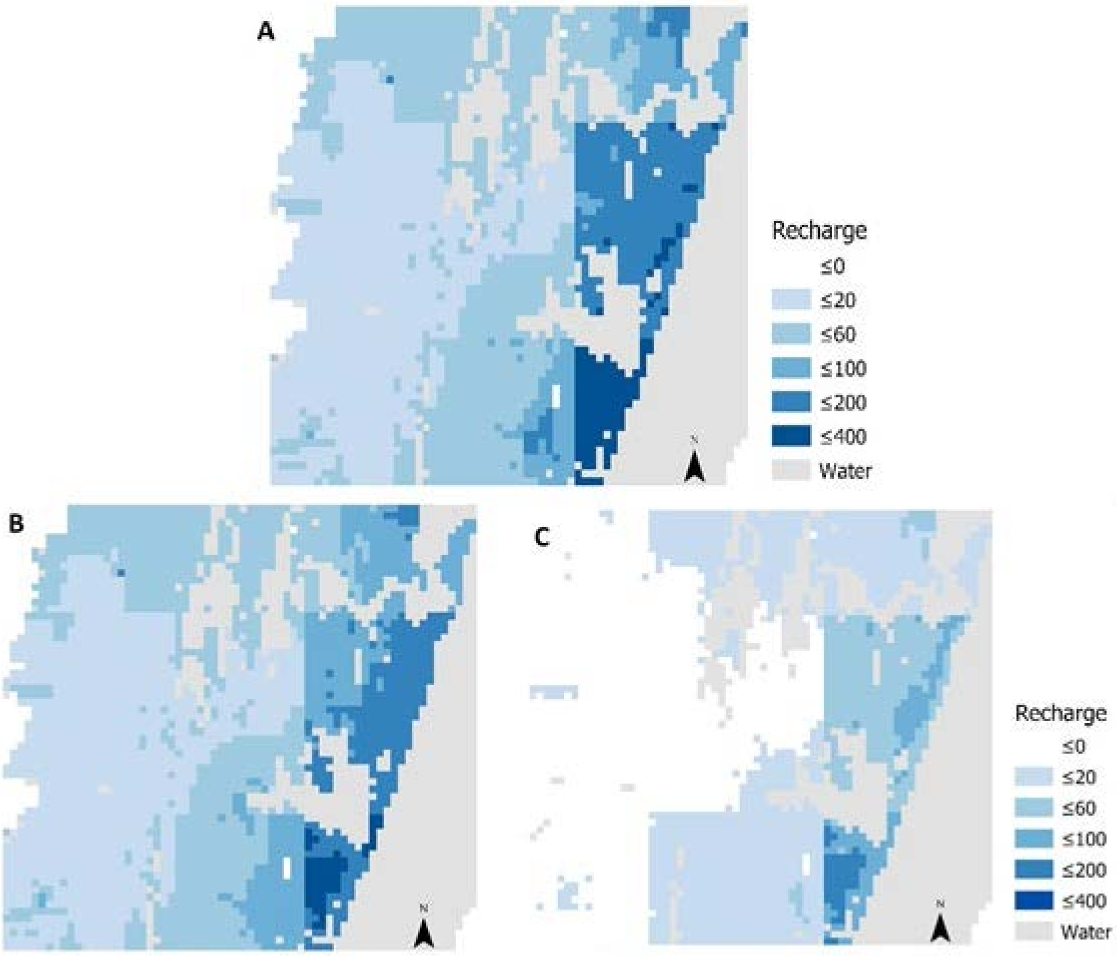


Figure 8-24 (A) Mean annual, (B) mean summer and (C) mean winter recharge under the no forestry scenario from 1959-2020 for the study area

The no forestry scenario was run under both the CMIP6 and ERA5 dry and wet future storylines with the relative percentage change between the recharge under the past and future being calculated (Figure 8-24). Across most of the study area, between a 5% and 25% decline in recharge is projected under the CMIP6 dry future storyline, in the currently low recharge areas to the west of the study area, the projected decline in recharge is 25-50%. These areas however currently experience a mean annual recharge of less than 20 mm; thus, a small volume change is a large percentage. Under the wet storyline, the majority of the area will have no change in recharge, with only the currently low recharge areas to the west of the study area projected to increase in recharge by 5-25% in the future (Figure 8-24). The ERA5 future storylines indicate a different picture, with decreases over the western area greater than 75%. While under the ERA5 wet future storyline, the increases in recharge are greater than 100% across the majority of the study area.

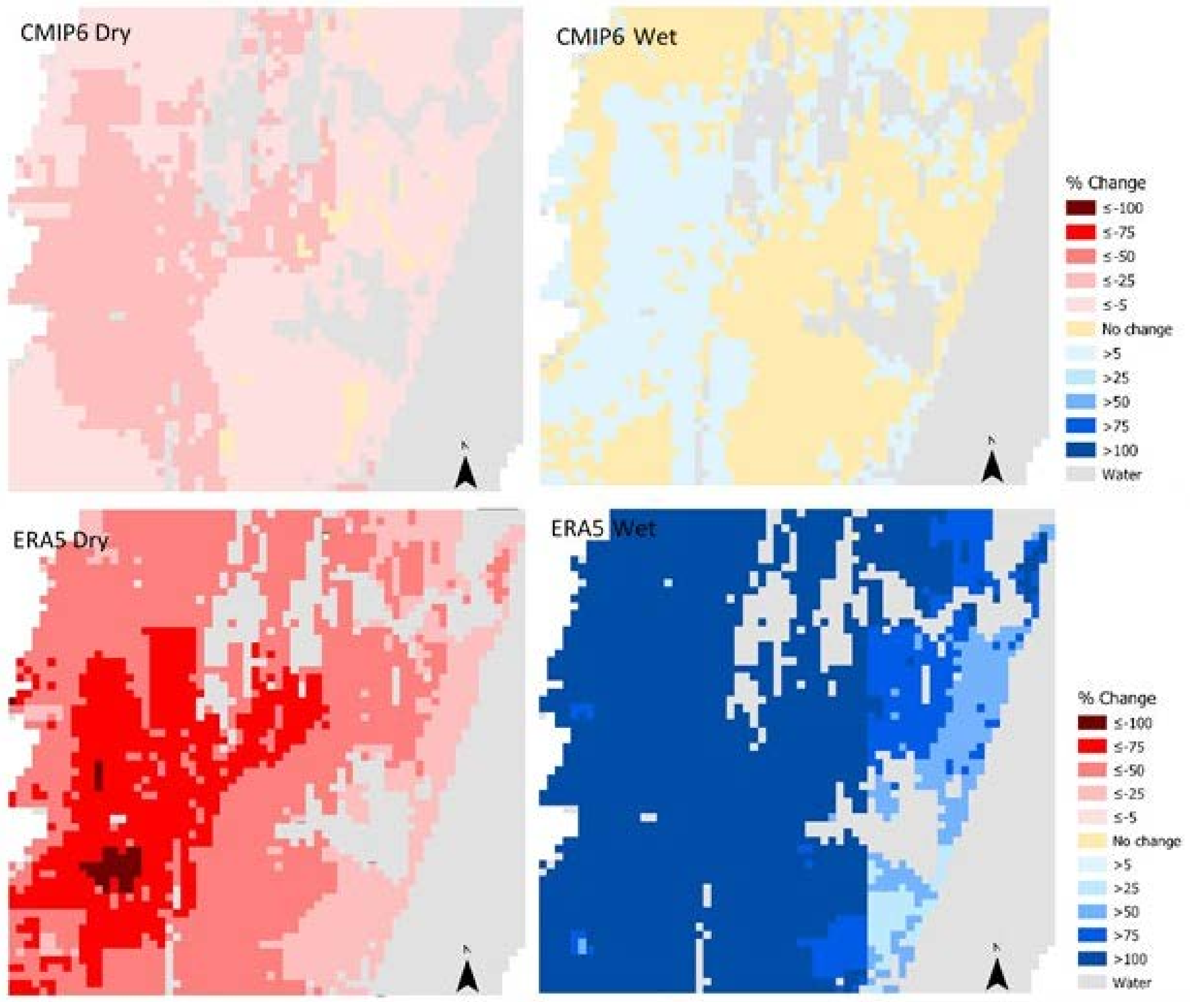


Figure 8-25 Percentage change in mean annual recharge under the no forestry scenario for a future dry (left) and wet (right) storyline under both CMIP6 (middle) and ERA5 (bottom).

Scenario 2: 50% of the grassland area becomes encroached with woody species (bush encroachment)

The second land cover scenario to be considered was that 50% of the grassland area becomes encroached with woody species into the future (Bush Encroachment). The land cover to 2020 was the dynamic land cover, and after that the land cover change scenario was implemented under both the CMIP6 and ERA5 dry and wet future storylines. The impact on recharge into the future under the CMIP6 storylines was similar to that of the dynamic land use scenario. Under the CMIP6 dry storyline most of the study area experiences between a 5% and 25% reduction in recharge, while the western part of the study area sees a reduction in recharge of between 25% and 50% (Figure 8-26). The areas that show large reductions in recharge are those areas with no to little recharge, thus any change reflects as a large percentage. Under the CMIP6 wetter storyline, the majority of the study area sees no change in recharge, except for the western pasts which show between a 5% and 25% increase in recharge (Figure 8-26). Under the ERA5 storylines the changes in recharge are greater, particularly under the wet storyline with changes in recharge across the majority of the study area being greater than 100%. The impacts of the land use change scenario, conversion to woody species (bush encroachment), becomes evident under the ERA5 storylines. The areas indicated in the black circles were areas of commercial plantation forestry that were converted to woody species (bush encroachment). In these areas, the changes in recharge are particularly marked. Under commercial afforestation, no to little recharge was experienced in these areas. Thus, any changes in the future storylines appear as a large percentage but are in small volume changes in recharge.

Scenario 3: Conversion of 50% of the forestry area within the area of interest to Dryland Crop area

The third land cover scenario to be considered was that 50% of the commercial plantation forestry area is converted to Dryland Crops into the future. The land cover to 2020 was the dynamic land cover and, after that, the LULC scenario was implemented under both the CMIP6 and ERA5 dry and wet future storylines. The crops considered were maize, cassava, ground nuts and vegetables. The areas of commercial afforestation that were changed to Dryland Crops show an increase in recharge across both the ERA5 and CMIP6 future scenarios (Figure 8-27). The changes appear to be large, however, as the areas experienced no to little recharge in the dynamic scenario; the changes will be a large percentage but a small volume. Despite the volume of recharge being small, it is still an indication of a positive impact on recharge due to the land use change. Again, the under the ERA5 future storylines, the changes in recharge due to the changes in the rainfall are greater than those under the CMIP6 storylines. In the MODFLOW model, irrigation of these crops and the influence on the water table will be considered in addition to the dryland scenario.

Scenario 4: Conversion of 50% of the forestry area within the area of interest to Dryland Agroforestry

The fourth land cover change scenario to be considered was the conversion of 50% of the commercial plantation forestry area to dryland agroforestry. The land cover was considered to be the dynamic land cover until 2020, after which 50% of the commercial plantation forestry in the area of interest was converted to agroforestry under both the CMIP6 and ERA5 dry and wet future storylines. The areas under commercial afforestation that were changed to agroforestry show an increase in recharge (Figure 8-28) under the CMIP6 dry and wet storylines. These are percentage changes and, thus, appear large due to the recharge volumes being small. The ERA5 dry storyline shows a decrease in the recharge under the agroforestry scenario relative to the commercial plantation forestry that was previously in those areas, while the ERA5 wet storyline shows an increase (Figure 8-28). As the volumes of recharge in these areas are so small, any change appears as a large percentage. Thus, the dry nature of the scenario would have caused the reduction of the small volume of recharge by a small amount and it would still appear to be a large percentage.

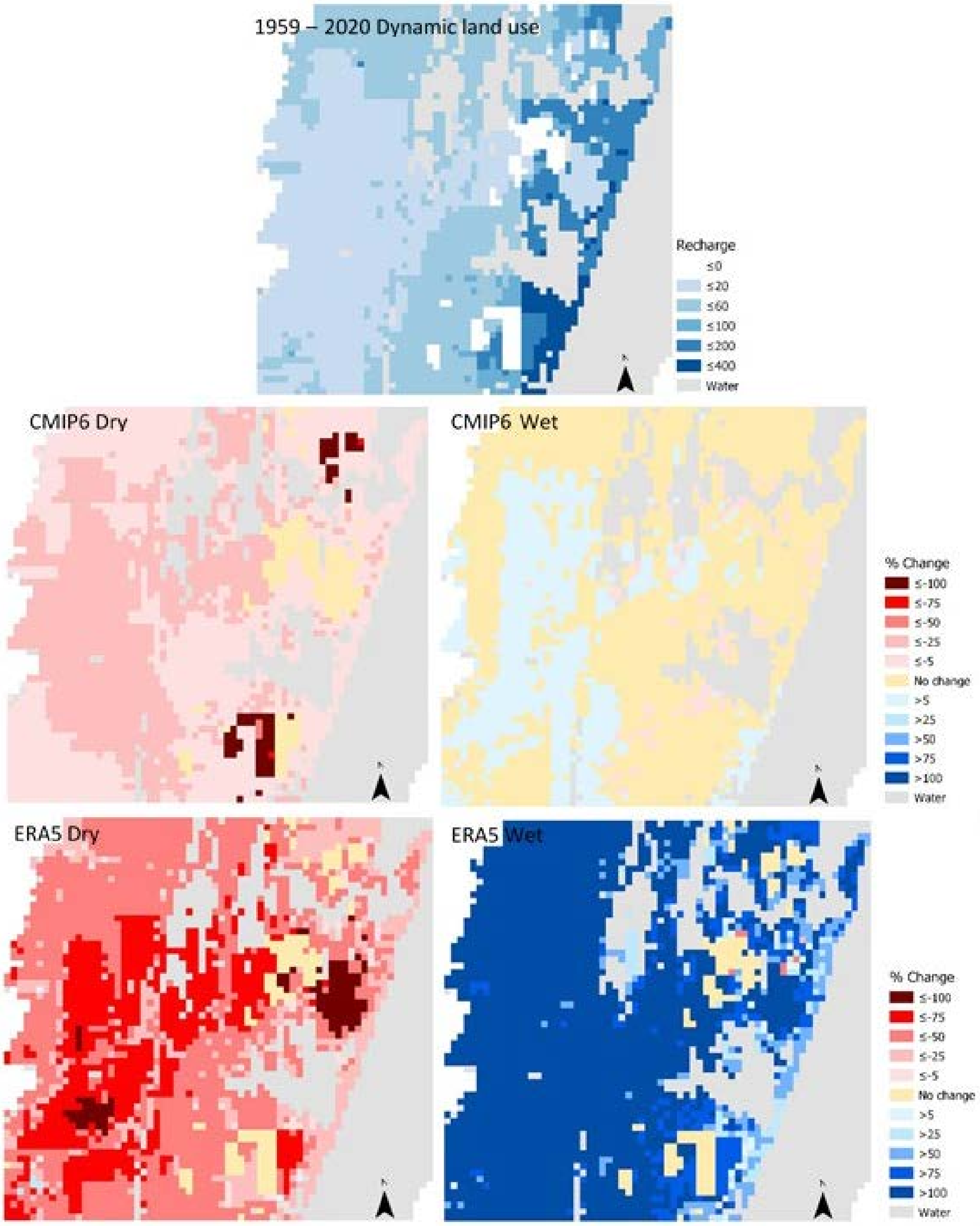


Figure 8-26 Percentage change in mean annual recharge under the bush encroachment scenario for a future dry (left) and wet (right) storyline under both CMIP6 (middle) and ERA5 (bottom). Mean annual recharge (mm) under the 1959-2020 dynamic land use shown to contextualise the recharge changes.

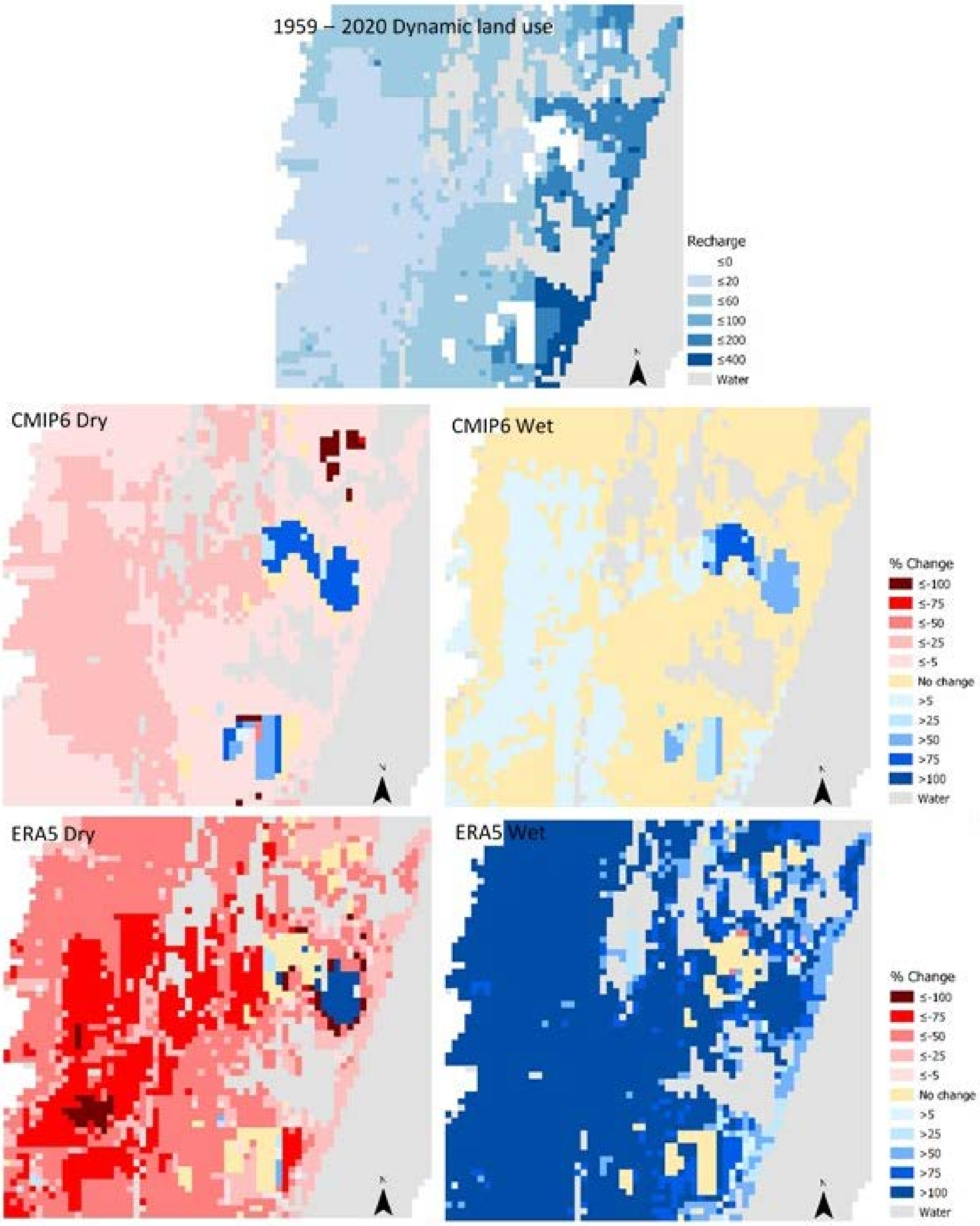


Figure 8-27 Percentage change in mean annual recharge under the Dryland Cropping scenario for a future dry (left) and wet (right) storyline under both CMIP6 (middle) and ERA5 (bottom). Mean annual recharge (mm) under the 1959-2020 dynamic land use shown to contextualise the recharge changes

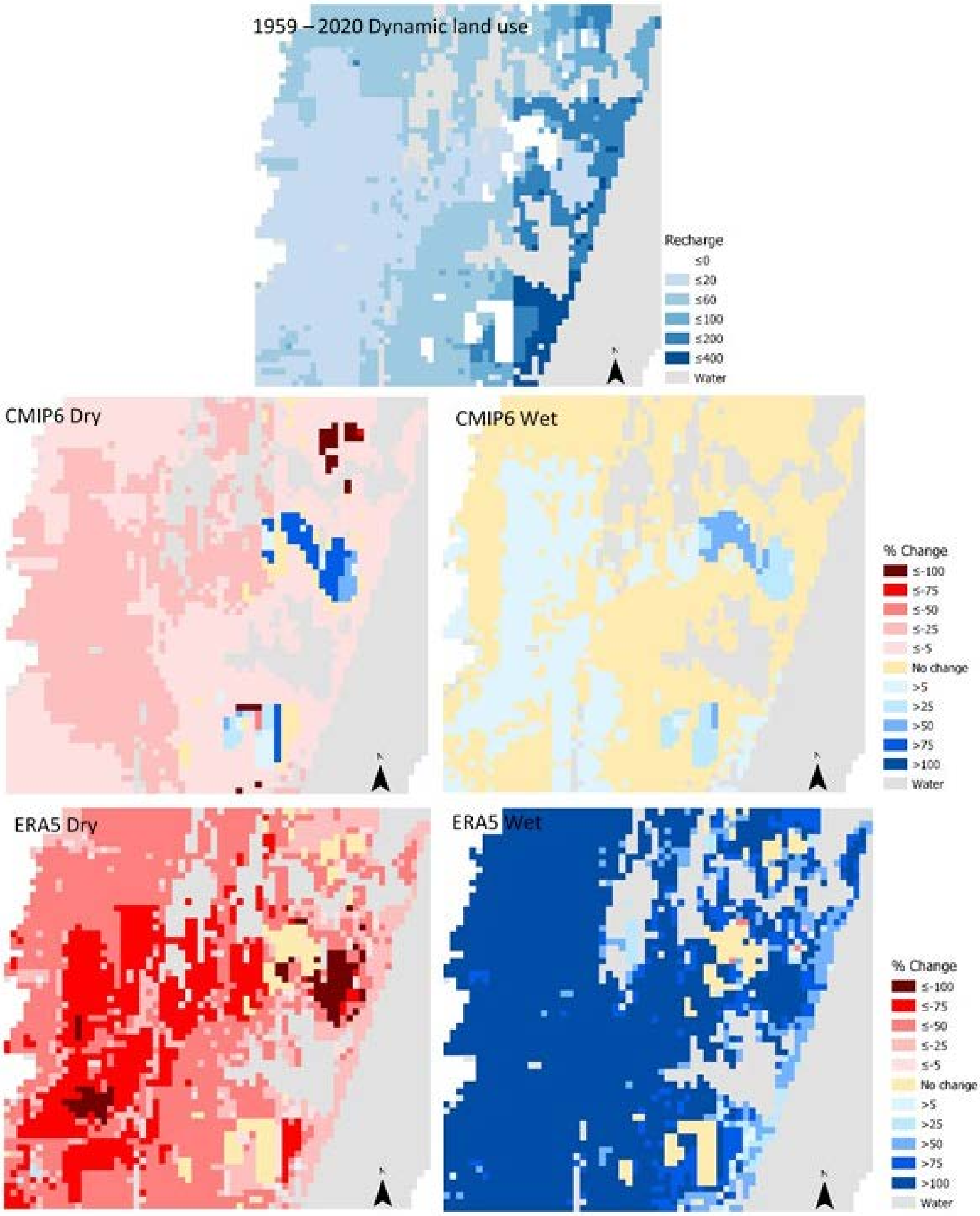


Figure 8-28 Percentage change in mean annual recharge under the dryland agroforestry scenario for a future dry (left) and wet (right) storyline under both CMIP6 (middle) and ERA5 (bottom). Mean annual recharge (mm) under the 1959-2020 dynamic land use shown to contextualise the recharge changes

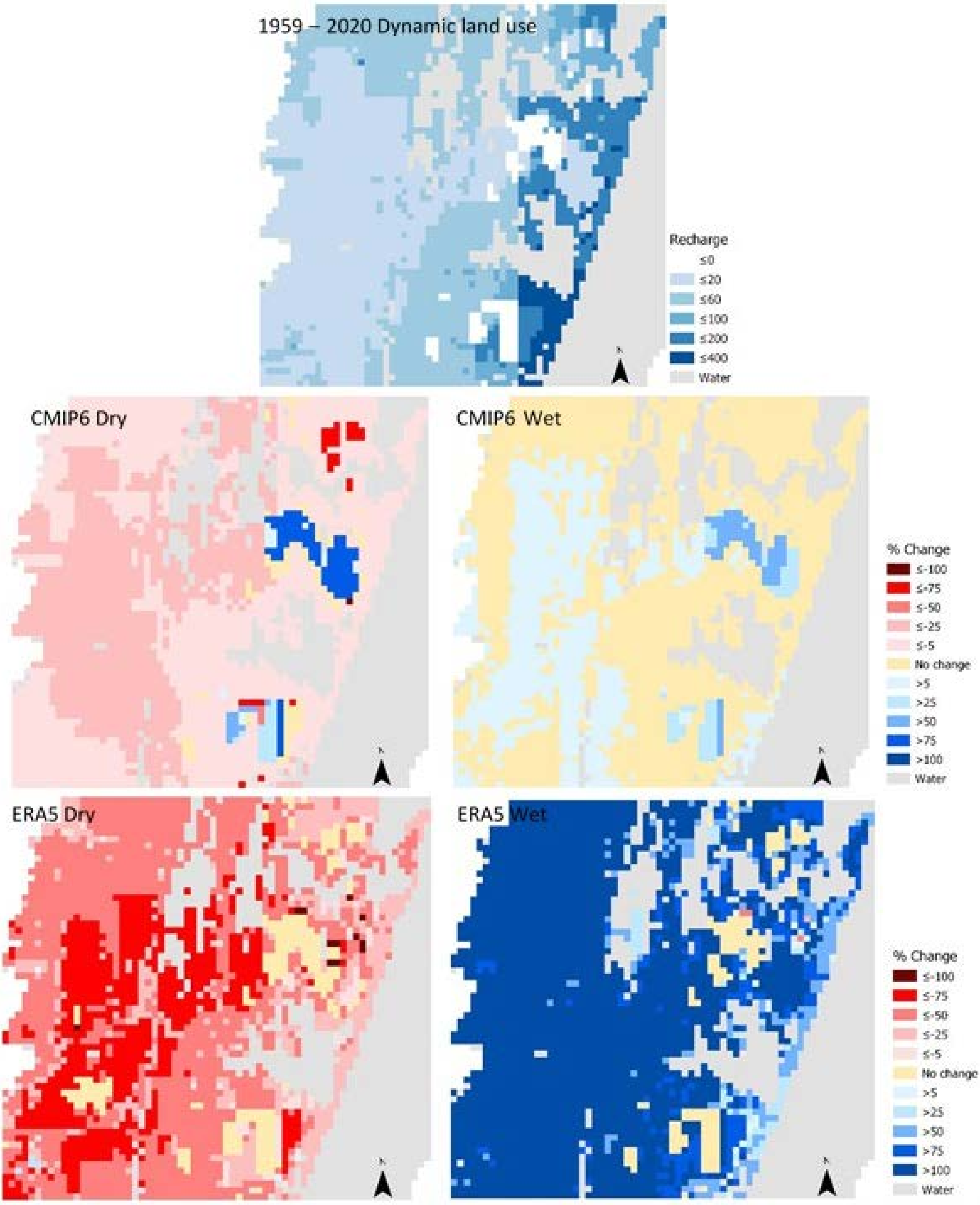


Figure 8-29 Percentage change in mean annual recharge under the Dryland Macadamia scenario for a future dry (left) and wet (right) storyline under both CMIP6 (middle) and ERA5 (bottom). Mean annual recharge (mm) under the 1959-2020 dynamic land use shown to contextualise the recharge changes

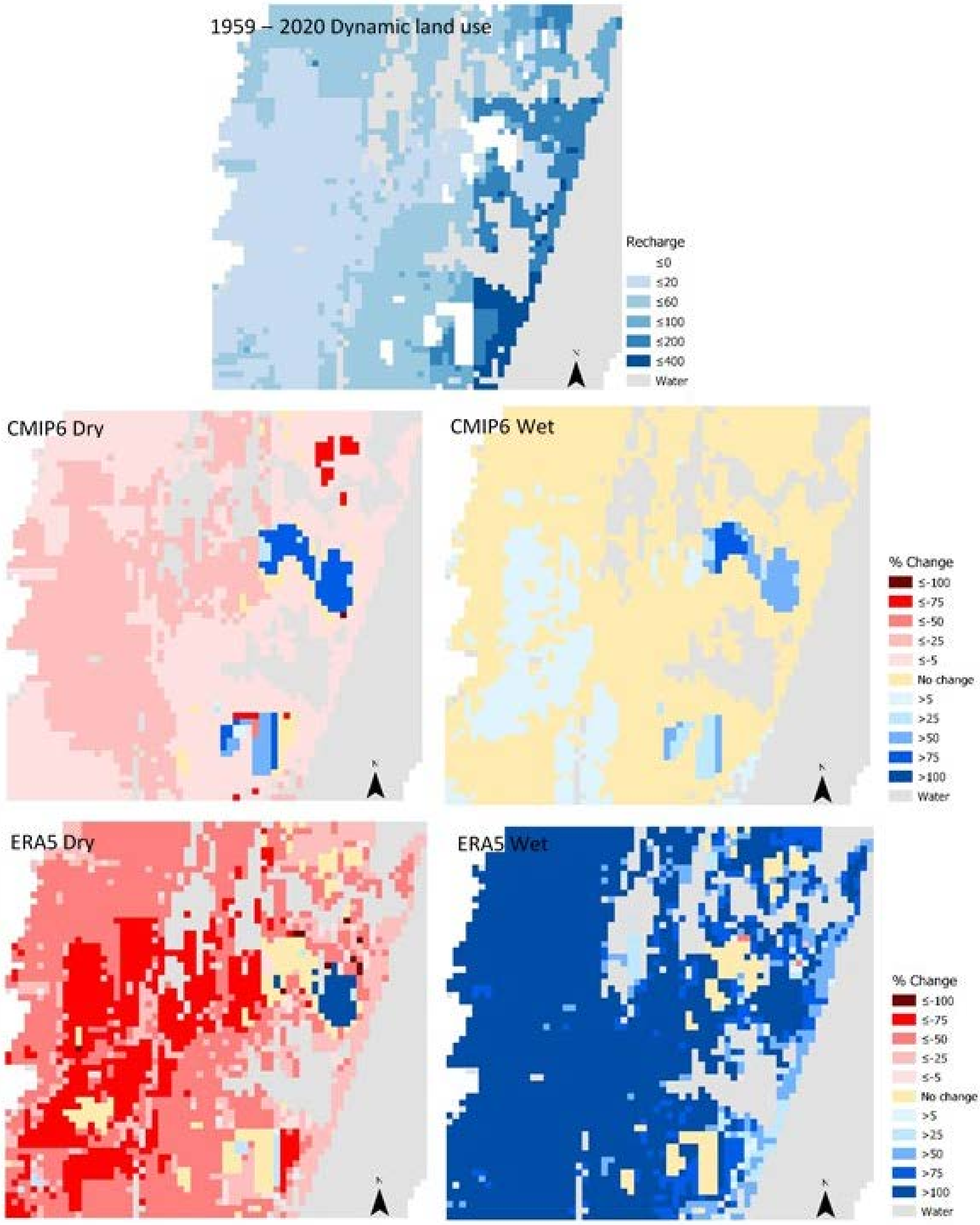


Figure 8-30 Percentage change in mean annual recharge under the dryland Marula scenario for a future dry (left) and wet (right) storyline under both CMIP6 (middle) and ERA5 (bottom). Mean annual recharge (mm) under the 1959-2020 dynamic land use shown to contextualise the recharge changes

Scenario 5: Conversion of 50% of the forestry area within the area of interest to Dryland Macadamia

The fifth land cover change scenario to be considered was the conversion of 50% of the commercial plantation forestry area to Dryland Macadamia. The land cover was considered to be the dynamic land cover until 2020, after which 50% of the commercial plantation forestry in the area of interest was converted to Dryland Macadamia under both the CMIP6 and ERA5 dry and wet future storylines. The patterns of change in recharge under Dryland Macadamia are similar to those under dryland agroforestry. Under the CMIP6 storylines and ERA5 wet storyline, the areas converted from commercial plantation forestry to Dryland Macadamia show an increase in recharge (Figure 8-29) whereas, under the ERA5 dry storyline, there is a decrease in recharge. These percentage changes in recharge are large, but the volume changes will be small. The relevant aspect to note is that a change in the recharge results from the land use change. Irrigation of the macadamia will be accounted for in the MODFLOW model in addition to this dryland scenario.

Scenario 6: Conversion of 50% of the forestry area within the area of interest to Dryland Marula

The sixth land cover change scenario to be considered was the conversion of 50% of the commercial plantation forestry area to Dryland Marula as requested by the stakeholders. The land cover was considered to be the dynamic land cover until 2020, after which 50% of the commercial plantation forestry in the area of interest was converted to Dryland Marula under both the CMIP6 and ERA5 dry and wet future storylines. The pattern of change in recharge under the CMIP6 storylines and ERA5 wet storyline was similar to the pattern under the macadamia scenario with increases in recharge being evident (Figure 8-30). The difference came under the ERA5 dry scenario where increases in recharge under the Marula were evident (Figure 8-30). Again, note that these percentages are large but the volume changes will be small as the recharge in these areas is small. Irrigation of the Marula will be accounted for in the MODFLOW model in addition to this dryland scenario.

8.10 DISCUSSION OF ACRU MODELLING COMPONENT

The ACRU agrohydrological model was developed using data from the Cathedral Peak Research catchments starting back in the 1970s (Schulze, 1995). The strength of the model is that it is a daily, distributed model that has a multi-layered soil water budget which makes it sensitive to climate and land use changes. This projects study site (sandy and groundwater driven) has vastly different characteristics to the Drakensberg area where the data the ACRU model was originally developed stems from the many other sites where the ACRU model has been extensively tested and verified, as well as further developed. Further to this, a different approach to the model runs were taken in this project. The ACRU model was configured in a “grid” set up rather than a catchment configuration with the reason being that the streamflow components were not of interest; only the point based vertical movements of water through the soil profile to the groundwater store were. Configuration of the model in a grid had advantages and disadvantages. The first significant advantage was that the loose coupling with MODFLOW was better facilitated through the spatial scale of the recharge data supplied to MODFLOW that accounted for the variability of the climate and land use over the study area. The second advantage was that use of the grid approach was more aligned with the gridded climate data used from ERA5 and CMIP6. The significant disadvantage that became evident was that the shallow groundwater routine could not be used due to the way the model was configured. However, the sensitivity analysis showed the high sensitivity of recharge to rainfall. Being able to account for the spatial variability of the rainfall (ranging from less than 500 mm in the west to over 1 000 mm per year along the coast) across the study area was considered to outweigh this disadvantage. Further, the spatial variability of the land uses, as well as scenario-based changes in land use, could also be relatively easily considered. Another disadvantage was that the irrigation routine could not be used. However, the grid-based setup was not the only reason; the source of the irrigation water was also a factor.

As with all models, the accuracy and quality of the ACRU model simulation is only as good as the input data. In this project there were a number of concerns and problems related to the input data available. The most significant concern was the rainfall data given the sensitivity of the recharge to this. The sensitivity study showed that an error of 10% in the rainfall meant that the recharge changed by 30%.

The ERA5 rainfall averaged across the study area was 11% less than the area averaged observed rainfall. However, the most significant underestimations of rainfall were for the high rainfall months of January and February (Figure 8-18) when the recharge events would likely have occurred. These underestimations in the ERA5 rainfall would have had significant impacts on the modelling accuracy and would have been perpetuated through to the future climate scenarios given the methods used. However, although the absolute values would have been an underestimate, the relative differences between scenarios are valid. As the length of the observed rainfall records being undertaken by NRF-SAEON increases, the records will become of use in modelling.

CHAPTER 9: MODELLING HYDROLOGICAL OUTCOMES USING THE MODFLOW GROUNDWATER MODEL

By MH Maseko, ML Toucher, S. Janse van Rensburg, and B. Kelbe

This chapter outlines the groundwater modelling component towards addressing Aim 3: *Determine the relative impact of different vegetation units and climate on the hydrological response of the Lake Sibaya groundwater catchment*.

9.1 INTRODUCING MODFLOW

Groundwater modelling involves using computational methods to depict real-world underground water systems (Kumar, 2002, Merz, 2012). Models can be enhanced, through the use of new information and data, to provide a more accurate representation of reality (Baalousha, 2009). The United States Geological Survey (USGS) modular finite-difference flow model (MODFLOW) was selected to model the groundwater component of the MCP for this study.

MODFLOW is a finite-difference, three-dimensional, transient, and modular groundwater flow model, that employs the finite difference method to simulate flow in porous media (Mehl and Hill, 2007, Harbaugh et al., 2000, Hariharan and Shankar, 2017). It is particularly suitable for block-centred methods as it effectively handles finite difference boundaries (Kelbe et al., 2010, Weitz, 2016). The modular structure allows for easy process enhancements and model comprehension (Harbaugh et al., 2000). MODFLOW is the preferred choice for modelling groundwater-driven systems as it is open-source software and has user-friendly and affordable graphical user interfaces (GUIs) (Kumar, 2002, Hariharan and Shankar, 2017, Diaz et al., 2020) such as Groundwater Vistas, Visual MODFLOW, and Processing MODFLOW (Kumar, 2012, Hariharan and Shankar, 2017; Kiptum et al., 2017). For this study, the GUI used was the Environmental Simulations Incorporation (ESI).

The key advantages of MODFLOW include that it is open-source software; it is continuously developed; it has global applicability; it features standardised data formats for easy exchange; and has extensive support facilities (Kumar, 2019). However, the model has limitations, such as the inability to use the same code in transient problems involving rewetting/drying cells. Additional packages can be added to address such issues, but this requires additional expertise and associated data (Kumar, 2019).

9.2 INTRODUCING PEST

As with most hydrological models, MODFLOW needs to be calibrated. MODFLOW primarily employs the Parameter Estimation (PEST) package for automated parameter calibration. PEST is a non-linear inverse parameter optimisation and estimation code, available as open-source software (Kumar, 2002; Weitz, 2016). It facilitates the analysis of parameter predictions, uncertainties, and estimations independently of the model (Doherty and Hunt, 2010; Weitz, 2016).

During calibration, PEST controls the model over a period, adjusting parameters to minimise discrepancies between laboratory or field measurements and model outputs based on the weighted least squares statistic (Kumar, 2002). The PEST automated calibration technique can be utilised in two ways – by manually adding zones into the model for calibration using the piecewise method, or) the incorporation of pilot points to be used for calibration (Rumbaugh and Rumbaugh, 2020b).

The main advantage of PEST is that it provides quantitative insights and expanded possibilities through numerical algorithms. However, a drawback is that user expert knowledge is not incorporated (Weitz, 2016). PEST has been extensively applied in automated calibration across various fields, including surface water and groundwater hydrology, mining, mechanical engineering, geotechnical, and geophysical studies (Kumar, 2012).

In this study, PEST served as the primary calibration technique for the updated groundwater model, with a trial-and-error approach applied to specific hydraulic parameters showing high residual errors. Further elaboration on this process is provided in section 9.5.5.

9.3 IDENTIFIED LIMITATIONS FROM PREVIOUS STUDIES

An existing MODFLOW model configuration, based on MODFLOW 2000 and MODFLOW 2005, facilitated through the Groundwater Vistas user interface, was iteratively developed for the Lake Sibaya groundwater catchment over time by Kelbe (2019; 2020). The initial MODFLOW configuration developed by Kelbe (2019) was a two-layer model configuration, subsequently updated to a three-layer model (Kelbe, 2020). The primary limitations of the MODFLOW configuration done by Kelbe (2020) was the scarcity of observed groundwater and streamflow data, as well as groundwater and lake abstraction data (Weitz, 2016; Kelbe, 2019, and 2020). Another constraint was the absence of spatially and temporally representative land use data for the region (Kelbe, 2020; Johnson, 2021), which led to a lack of dynamic recharge data based on LULC change across the model domain. Kelbe (2020) simply simulated three categories of plantations being varied over time within the Lake Sibaya groundwater catchment. Weitz (2016) represented changes in land uses through scenarios that involved a change in one land use per scenario. As with Kelbe's (2019, 2020) MODFLOW simulations, the recharge data required as input for this study will be obtained from the ACRU model with improvements made as detailed in Chapter 7.

The following sections detail the refinements made to the MODFLOW configuration of Kelbe (2020) to provide an improved groundwater simulation in this project. Subsequently, the results from the baseline simulation are provided to set the scene for the future scenario results provided in CHAPTER 10:.

9.4 METHODS

The Construction or update of a groundwater model requires careful conceptualisation of the groundwater system, with consideration to available information and the systems response to various stressors. This conceptualisation must align with the modelling objectives. Data collection and model conceptualisation occur simultaneously, which then inform the design and construction of the numerical model (Merz, 2012). In this study, limitations and uncertainties identified in previous numerical modelling studies for Lake Sibaya were addressed through the improvement of the conceptualisation of the groundwater system by Kelbe (2020) using additional monitoring data obtained before and during this study. A brief outline of the conceptualisation of the model components by Kelbe (2020) is provided. Thereafter, improvements to the numerical model are detailed. Sensitivity tests on the numerical model were then performed as a pre-requisite for model calibration.

Initially the focus was on the past to present (1959 to 2020) baseline simulation (presented in this chapter). Thereafter the model was used to simulate future scenarios (See CHAPTER 4: and CHAPTER 10:) which stretched the model capabilities beyond what has previously been done for the study area, both in terms of the improvements attempted as well as the extreme hydrological futures simulated. As with any modelling, several iterations were conducted. The information provided in this chapter is the result of several iterations, testing performance under both past to present and future scenarios. The provisional future scenarios provided an opportunity to identify certain aspects that were then addressed to enhance model performance.

9.4.1 Overview of the MODFLOW Model Configuration by Kelbe (2020)

Kelbe's (2020) groundwater model is the most recent model developed for the Lake Sibaya system. Due to this project's time constraints, Aim 3 was devised to focus on the update an existing groundwater model for the area. Thus, this component of the project will focus on the improvement of limitations experienced when developing Kelbe's (2020) model and use of the improved model to assess historical vegetation and climate changes in the region. Upon a satisfactory update to the model, the revised model will be used for future scenario simulations to address the remaining aims of this project.

9.4.1.1 Hydro-geological domain

The hydrogeological domain is an essential component of a conceptual model for the investigation of current and potential future stresses on the groundwater system (Merz, 2012). The domain should consider the spatial extent of various processes that govern the behaviour of the studied groundwater system (Merz, 2012). This study used the conceptual model domain (Figure 9.1) defined by Kelbe (2019, 2020). This conceptualisation is based on an unconsolidated aquifer system which encompasses both the Lake Sibaya internal and external drainage boundaries, thus considering the potential impact of surrounding areas. The external boundary of the model domain was defined by the ocean to the east, the Pongola River to the west, the Mkuze River to the south, and the Maputo River and Kosi Bay to the north (Figure 9-1). These water bodies fall within the groundwater catchments (indicated by grey lines in Figure 9-1) that influence the extent and dynamic nature of the Lake Sibaya groundwater catchment.

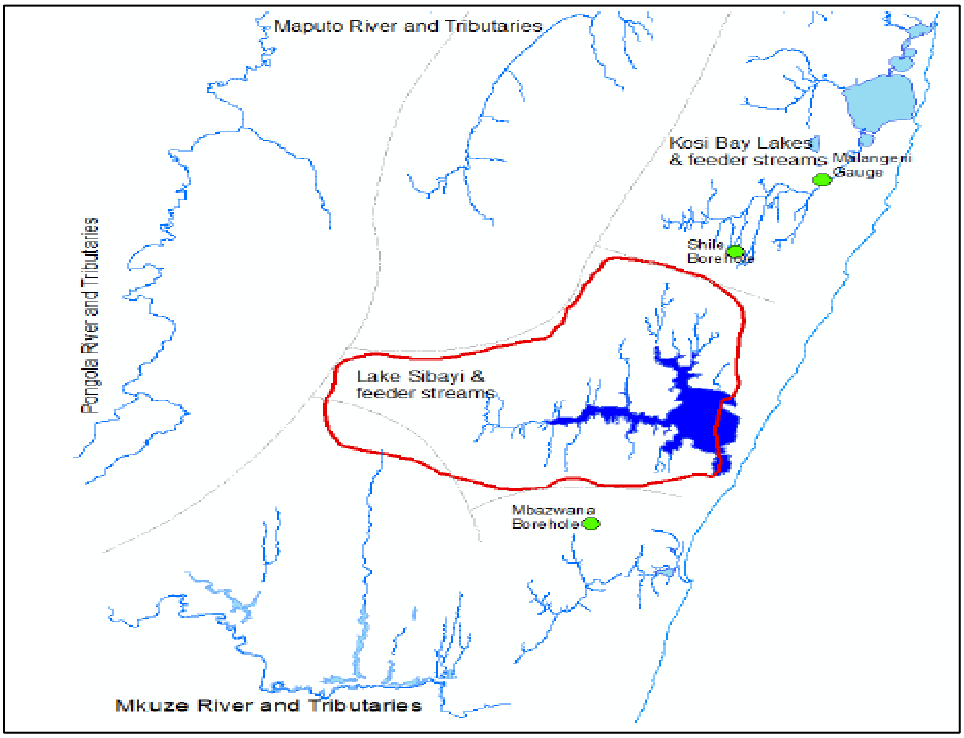


Figure 9-1 Full extent of the model domain, including external and internal boundaries within the domain. The light grey lines delineate groundwater ridges estimated from the simulated groundwater elevation and light blue lines indicate drainage boundaries (Kelbe, 2019, 2020)

In the development of a conceptual model, the degree of influence and availability of data for the water bodies in the respective catchments must be considered as this will determine whether the water bodies can be specified as either constant head or variable head within the numerical model. In Kelbe's (2019, 2020) numerical model, the ocean boundary, and the aforementioned rivers, due to a lack of water level data, were designated as constant head boundaries. The monitored lake and streams within the Lake Sibaya groundwater catchment (enclosed in a red polygon in Figure 9-1) were set as variable head boundaries. The Malangeni/Siyadla stream, which flows into Kosi Bay Lake north of Lake Sibaya and is monitored by NRF-SAEON, was also set as a variable head boundary (Figure 9-1).

With a focus on the Lake Sibaya catchment, Miller (2001) determined that the streams and lake beds are dominated by organic-rich dark-grey mud (Gyttja) and very-fine to medium-grained quartz sand. The infiltration rates of the organic-rich mud generally fall in the lower ranges, with hydraulic properties that hinder water flow between the beds of water bodies and the underlying aquifer. However, the very-fine to medium-grained sand, more prevalent in the lake bed, possesses higher hydraulic properties than those of the surrounding aquifer (KwaMbonambi Formation) (Bate et al., 2016; Weitz, 2016; Kelbe, 2019, 2020). Therefore, the groundwater exchange between the lake-aquifer and stream-aquifer systems alternates between aquifer-controlled in sand-dominant areas and being stream or lake bed-controlled in mud-dominated areas (Kelbe, 2019). The hydraulic properties for both of these soil types were refined by Kelbe (2019, 2020) based on field observations and results from a similar system, Lake St Lucia (Kelbe, 2009). Additionally, a geological map of the study region by Porat and Botha (2008) guided hydraulic property distributions for the soils in the study area. Kelbe (2019, 2020) used the geological map mainly for the streams, whereas a homogenous area comprising the hydraulic properties of medium-grained quartz sand was used to represent the sediments of the lake. A homogenous lake bed was used by Kelbe (2019) as the lake package in MODFLOW is unable to simulate varying sediment types across the lake basin (Kelbe, 2019). These spatial conceptualisations and the associated properties of the sediments are a potential source error.

Limited hydraulic conductivity information is available for the different aquifers in the study area, hence an isotropic zonal approach was used. In the three-layered model by Kelbe (2020), the starting point for the hydrological properties ("Hydraulic Conductivity" and "Storage|Sy|Porosity") was the geological map by Porat and Botha (2008). For the second and third layers, the initial hydraulic properties were assumed from regional literature and modified during the calibration process with reference to water level targets in the model. Kelbe (2020) configured the model to calculate leakance (interlayer conductivity) between parallel aquifers using vertical hydraulic conductivity (Kz – hydraulic conductivity in the z/vertical direction) values. The isotropic configuration of the zones (areas in the model delineated based on homogeneous hydraulic properties), meant that for parameters such as hydraulic conductivity, Kz equalled Kx (horizontal – east to west) and Ky (horizontal – north to south). Therefore, the leakance between layers depends on the Kz in both connected layers. (Communication 2021). The lack of data to inform these variables leads to great uncertainty that needs to be considered when model performance is assessed.

9.4.1.2 Hydro-stratigraphy

Kelbe (2019, 2020) defined the hydro-stratigraphy for a three-layer groundwater model using information published by several authors. The hydrogeological information used by Kelbe (2019, 2020) to delineate the hydro-stratigraphy was initially obtained from surface elevation data (which represents the KwaMbonambi Formation, Layer 1, as in Figure 2-4 in CHAPTER 2:) based on a Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model (DEM). The top elevation of the Cretaceous Formation, which is also the bedrock of the primary aquifer (Uloa Formation) (Layer 3, see Figure 2-4), was derived from various sources of published data and fieldwork investigations. Remnants of the data used for Layer 1 and 3 was used to estimate the thickness of Layer 2, made-up predominantly of the Isipingo Formation (Figure 2-4). This elevation data was also combined with historical drill logs based on the assumption that drilling would take place until the Uloa Formation, just above the Cretaceous layer, after which no further drilling was possible due to the undesirable physical and chemical properties of the Cretaceous layer (Communication 2021).

A gradient of 1º to 3º across the top of the Cretaceous layer, from the east to west of the model domain was used as in previous studies (Worthington, 1978; Bate et al., 2016; Weitz, 2016). The depth of the different model layers was largely conceptual, except for the depth of the 3rd layer (Cretaceous bedrock) due to the availability of various drilling logs to inform this. The conceptualisation of the hydro-stratigraphy and associated hydrological properties has great uncertainty given the lack of data to inform it.

9.4.1.3 Bathymetric survey

Several bathymetric maps have been developed for Lake Sibaya (Hill, 1979; Miller, 1994; Miller, 2001; Muggleton, 2018). In 2018 Muggleton re-surveyed Lake Sibaya, and provided an updated bathymetric data that includes recent changes in the lake's morphology. During the 2018 survey, Muggelton found a discrepancy in the measured benchmark height by Miller (2001). A height of 19.745 m AMSL was measured by Muggleton (2018), as opposed to the 18.82 m AMSL measured by Miller (2001). Thus, a correction of +0.075 m was applied to Millers (2001) data to tie it in with Muggleton's (2018). Muggleton (2018) developed a DEM using his survey data. This DEM informed Kelbe's (2019, 2020) conceptual and numerical models.

Based on the NRF-SAEON DWS survey undertaken in 2021 (cf. Chapter 6), a recommendation was made that a correction of -0.492 be made to Muggleton's (2018) survey data. However, it was not possible to explore modifications to the DEM based on NRF-SAEON-DWS survey data due to the possible implications to other model parameters and project time constraints; thus, Muggleton's (2018) DEM as it stood was used in this study (Figure 9-2).

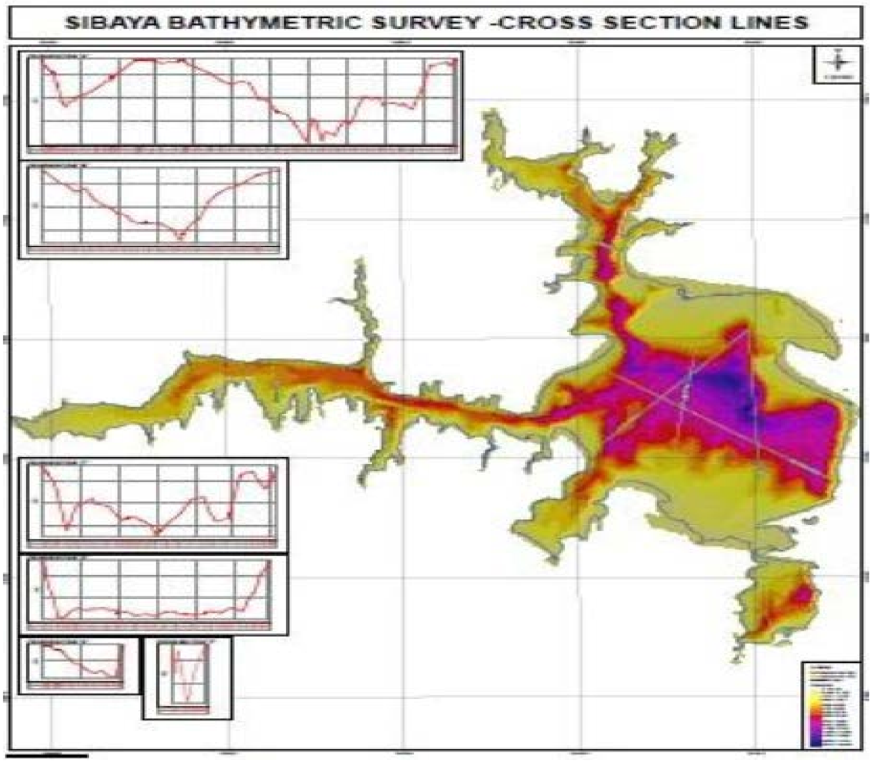


Figure 9-2: Bathymetric DEM for Lake Sibaya (Muggelton, 2018)

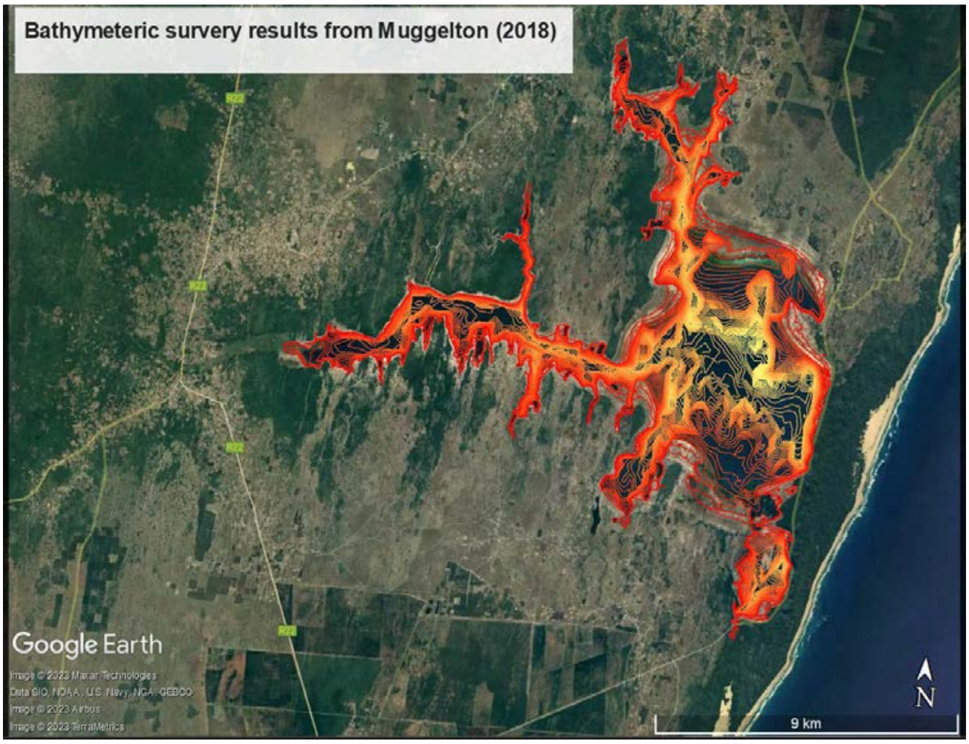


Figure 9-3 Actual contours from Muggelton (2018) bathymetry survey

9.4.1.4 Conceptual groundwater model diagram

The conceptual links between the MODFLOW packages and ACRU output data used in this study are illustrated in Figure 9-4. Surface hydrological processes, i.e. infiltration, ET, and soil water balance, were accounted for in the ACRU model. The recharge simulated by ACRU was used as input to MODFLOW. The LAK3 and STR packages previously used by Weitz (2016) and Kelbe (2019, 2020) were also used in this study. The LAK3 package was used to configure direct streamflow into and out of the lake (Figure 9-5), and the STR package was used to configure flow and seepage towards and outwards from the lake (Figure 9-4).

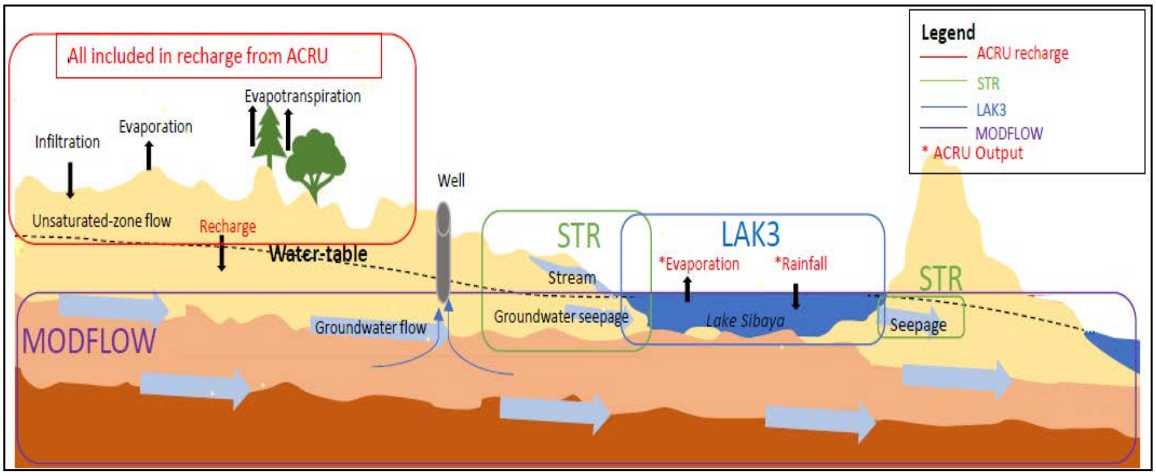


Figure 9-4: Conceptualization of the MODFLOW packages and ACRU output data used in the current Lake Sibaya groundwater model

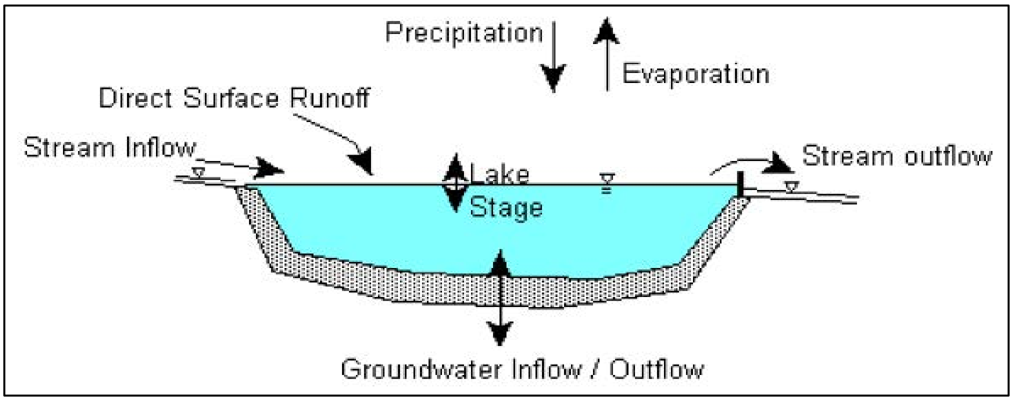


Figure 9-5: Components of the water balance included in the MODFLOW LAK3 package (Kelbe, 2020)

Kelbe (2019) used the RIV package to incorporate external rivers simulated as head-dependant boundaries, the STR1 package was used to configure internal streams/rivers flowing into Lake Kosi Bay and Lake Sibaya as specific head-dependent boundaries. Using the STR1 package, Mannings approach was utilised to simulate transient flow rates (Prudic et al., 2004). Kelbe (2020) improved on that by converting from a two-layer to a three-layer groundwater model and upgrading from a LAK1 package to a LAK3 package that allowed for modelling the separation of the lake into the Main and south basin. This enabled the lake basins to be simulated as compartments that separated after the lake had split (Kelbe, 2019). The LAK3 package requires rainfall and evaporation data which was provided by the ACRU model. Kelbe (2020) only incorporated the Mseleni river flowing into Lake Sibaya and the Malangeni river flowing into Lake Kosi Bay. The STR package was also used for groundwater direct flux simulations through the bed of the lake and shoreline (seepage to the ocean) (Weitz, 2016, Kelbe, 2019, 2020).

9.4.2 Groundwater Model Components and Improvements for MODFLOW

Significant effort was put into the identification and addressing opportunities to improve the existing groundwater model. The following sections detail the modifications and improved input data used.

9.4.2.1 Gridded climate data

An important component to consider when integrating across different models is data consistency. ACRU used gridded climatological data, both historical and future, as input to simulate recharge values used in MODFLOW. As mentioned, the LAK3 package required rainfall and evaporation data. Thus, for consistency, the gridded rainfall over the lake used by ACRU needed to be used as input into the LAK3 package as well. As no observed lake evaporation data exists, the reference potential evaporation simulated by ACRU for the lake was used. Details related to the historical and future climatological data used are provided in CHAPTER 8:.

9.4.2.2 Streamflow (stream discharge)

All streams flowing into Lake Sibaya are considered to be groundwater discharge/seepage areas (Weitz, 2016; Smithers *et al*., 2017; Kelbe, 2019; Kelbe, 2020). In the models by Kelbe (2019, 2020), the Malangeni stream, flowing into Lake Kosi Bay, was one of the streams with a relatively continuous streamflow record. A single rough streamflow measurement was available for the Mseleni stream. The Malangeni and Mseleni streams were under-simulated during model calibration (Kelbe, 2019; 2020). Extending the Malangeni streamflow measurements and conducting additional measurements for the Mseleni stream were key to the improvement of the model. Three additional streams flowing into the main basin of Lake Sibaya were selected for additional periodic *in situ* measurements of streamflow. The streams sampled were:

- Mseleni River/Stream,
- Northern Arm Stream (flowing from the Kumzingwane River),
- Western Arm South Bank Stream, and
- The Unknown Lake Stream (south west basin, main lake).

Additionally, the Malangeni/Siyadla stream which is not within the Lake Sibaya groundwater catchment but which flows into Lake Kosi Bay was monitored. Streamflow monitoring was undertaken using the velocity plank method primarily. At times a digital flow meter was available which was used to provide comparisons of streamflow data.

9.4.2.2.1 Velocity plank method

The velocity plank, formally known as the Transparent Velocity Head Rod (TVHR), is a simple, inexpensive, citizen science tool that allows stream velocity measurements to be taken and converted into discharge rates (Graham and Taylor, 2018). For each stream, a point along the length of the stream was located as close as possible to the mouth of the lake. At this location, a cross-section comprised of measured intervals marked by survey pegs, was constructed (Figure 9-6 left). Velocity plank water level measurements of the upstream, downstream, and side of the plank were taken at each interval (Figure 9-6 right), starting at the bank on one side and ending on the bank at the other side.

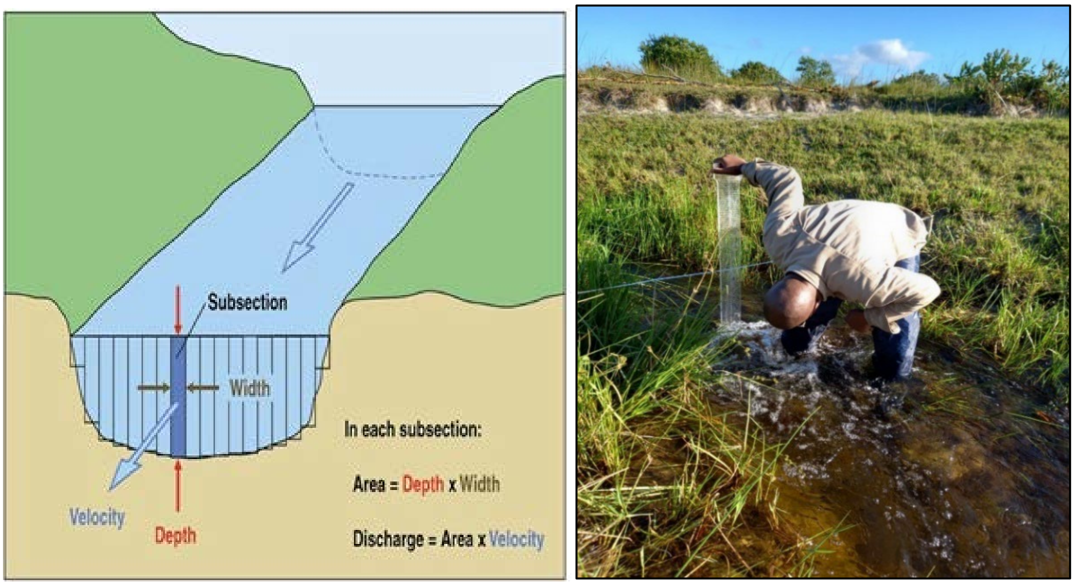


Figure 9-6 A conceptual diagram for general determination of streamflow (USGS, 2023) (left), and conducting velocity plank measurements in the Unknown Lake Stream (right)

9.4.2.2.2 Digital flow meter method

When possible, at the cross-section constructed for the velocity plank measurements, an electromagnetic OTT MF Pro Flow meter was used to take comparison measurements. The stream discharge measurements obtained using the MF Pro were intended to provide confidence in the precision of the velocity plank stream discharge measurements. In some of the streams the streamflow needed to be channelised to create a stream head conducive for the operation of the OTT MF Pro Flow meter. Figure 9-7 shows the channelisation of the northern arm stream to obtain a flow depth that allows the use of the flow meter.

Figure 9-7 Conducting streamflow measurements using the OTT MF Pro Flow meter

9.5 COMPARISON OF STREAMFLOW MEASUREMENTS FROM DIFFERENT METHODS

Streamflow measurements taken using methods described above for the streams that flow into the northern arm (Northern Arm Stream) and into the south bank of the main basin from the Unknown Lake (Unknown Lake Stream), are provided in Table 9-1. These are the only streams where both measurement methods were applied.

The discharges obtained from both methods were very comparable for the Northern Arm stream (Table 9-1). However, for the Unknown Lake stream, only the first measurement was comparable. Mixed results were obtained for the rest of the Unknown lake stream measurements which were caused by high turbidity in the stream, induced by a rough stream bed. The comparable flows in the Northern Arm stream were likely due to a smooth stream bed. In addition, channelising the flow in the Northern Arm stream to enable the use of the flow meter during low flows, also provided a smooth bed and prevented turbidity. The comparable results obtained between the two methods increased the confidence in the flow plank (TVHR) measurements used in the model.

Table 9-1 Flow measurements obtained from the TVHR velocity plank and the OTT MF Pro Flow Meter

Stream	Date	Velocity Plank (m^3/s)	Velocity Plank (m^3/day)	Flow Meter (m^3/s)	Flow Meter (m^3/day)
Northern Arm	08/03/2022	0.01	939.3	0.01	777.6
	25/05/2022	0.06	5 463.4	0.05	4 233.6
	12/08/2022	0.04	3 419.4	0.03	2 764.8
Unknown Lake	24/05/2022	0.17	14 408.9	0.11	9 590.4
	12/08/2022	0.12	10 063.7	0.03	2 851.2
	18/05/2022	0.20	17 141.8	0.05	4 147.2

9.5.1 Improving Aquifer Storage Target Inaccuracies

Another important component to the model is groundwater level measurements. When documenting the initial boreholes drilled in the area, the absence of a Global Positioning System (GPS) meant borehole coordinates were not recorded correctly and in some cases were several kilometres out. These inaccurate coordinates were used by Kelbe (2019) when the model was configured. In addition, as the boreholes were overlain on the SRTM DEM data, the errors in the DEM data further amplified the errors in the elevation of these boreholes used in the model. Furthermore, similar elevation errors have been observed in newer boreholes, however, a GPS was used to provide correct coordinate data for these boreholes. This points to the need for an improved, fine scale DEM for the area.

To reduce the impact of these errors during model calibration, low weights were assigned to boreholes that had these errors. Boreholes surveyed by NRF-SAEON and DWS were given a higher weight for them to have a greater influence in the calibration of the model.

9.5.2 Borehole and Abstraction Well Data

Boreholes are added as groundwater level targets into the model. These target levels do not serve the function of abstraction from or injection of water into an aquifer. Attribute information required when adding targets included co-ordinate and borehole depth information, as well as groundwater level measurements. Information for most of the boreholes in the model was obtained from the Groundwater Resource Information Project (GRIP) data. Additional data was available from JG Afrika's hydro census and the National Groundwater Archive (NGA). Boreholes from the GRIP, JG Afrika and NGA located within our model domain's spatial extent were reviewed and those that were previously omitted, were added to the model. Transient data, particularly from NRF-SAEON monitored boreholes, was appended to applicable borehole data.

In the groundwater model, wells refer to boreholes that either abstract water out of or inject water into an aquifer. The wells included in the model by Kelbe (2020) were used in the updated model without modifications. An additional two wells obtained from the hydro census data were added to the model. Attribute information for the two wells is given in Table 9-2.

Table 9-2 Attribute information for the two wells incorporated into the model (JG Afrika hydro census data)

Date	Hydrocensus_ID	Latitude	Longitude	yield m^3/day	BH_depth m_below ground	Altitude m_msl	Layer	WL_m_msl
2010/05/10	2732BCR0003	-27.402	32.556	2.4	62	77	2	77
1998/05/12	2732ADG4725	-27.432	32.374	10	64	87	2	49

An error was observed in the attribute information of the first well whereby the altitude and water level were a similar value (Table 9-2). This implies wetland conditions which is contrary to where the well is located based on its coordinate information. As a solution, water level measurements were removed from the attribute information of wells identified as having this issue when the previous model was reviewed. Water level information is not a required input for wells.

9.5.3 Lake Abstractions, Lake Water Level Data and Lake Water Balance

The main source of lake abstraction information was from the Water Use Authorization and Registration Management System (WARMS) which provides allocation volumes and not actual abstraction volumes. However, due to the lack of reliable continuous data, the WARMS allocation values provided the most reliable quantification of lake water abstractions until recent times (2016 to 2018) where pump meter readings were used (see Appendix C).

The revised verified Lake Sibaya water level record, developed as part of this project, was used (c.f. CHAPTER 6:).

A conceptual lake water balance was derived neither in the studies by Kelbe (2019, 2020), nor in this study. However, an isotopic lake water balance based on the isotope study that was conducted simultaneously with the modelling study (c.f. CHAPTER 7:) will be compared to the model simulated lake water balance.

9.5.4 Recharge Values

In the groundwater model, surface processes are accounted for through recharge data. Changes to LULC and the use of spatially varied rainfall and temperature data were the primary changes made to improve the recharge data. Kelbe (2019, 2020) used a land use type map provided by JG Afrika to define land use zones and only varied areas of commercial plantation forestry as scenarios of change. Seventeen homogenous zones covering the entire model domain were used, however, land use variations were constrained within the Lake Sibaya groundwater catchment. Point weather data mainly from the Mbazwana weather station was used. This study used land use data from SANLC maps for four time slices which were adapted to represent actual changes in LULC over time as described in CHAPTER 4:. Gridded satellite rainfall and temperature data, detailed in CHAPTER 8:, was used. The dynamic gridded approach accounted for changes across the entire model domain (3 394 grids cells of 1 km x 1 km resolution) contrary to Kelbe (2020).

In this study, recharge data was provided as percolation from the second soil horizon. For Kelbe's (2019, 2020) model recharge as moisture percolation from the capillary fringe was used. Deep percolation into the capillary fringe was simulated using the ACRU shallow groundwater subroutine which was not possible in this study due to the constraining effect on ACRU by the gridded approach.

9.5.5 Auto-Sensitivity and Model Calibration Process

Model calibration is used to obtain simulated water levels that are comparable to observed levels. Groundwater Vistas (GV) supports MODFLOW model calibrations in three ways: a) through the calculation of flux, concentration, drawdown, or head calibration statistics; b) sensitivity analysis of automated parameters; and c) through use of the least squares non-linear PEST technique for model automated calibrations (Rumbaugh and Rumbaugh, 2020b). PEST was used as the primary calibration technique for the previous as well as the updated model, followed by trial-and-error calibrations on specific parameters. These calibrations were preceded by auto-sensitivity tests to determine which parameters should be prioritised during calibrations.

9.5.5.1 Sensitivity analysis

To exclude insensitive parameters from the calibration process, a sensitivity analysis must be performed on aquifer hydraulic properties and recharge parameters (Bate et al., 2016). In this study recharge was excluded from this analysis, as well as model calibrations, as it was assumed to be the best representation of actual recharge that occurred in the area when obtained from ACRU. This was also the case in the model by Kelbe (2020). In this study, auto-sensitivity runs revealed that the following parameters showed significant sensitivity to parameter multipliers:

- Kx and Ky – Horizontal hydraulic conductivity (horizontal K in x-direction; Ky scaled based on horizontal anisotropy, hence Kx=Ky);

- Kz – Vertical hydraulic conductivity;
- Ss – Specific storage; and
- Sy – Specific yield.

Each of the three model layers were subdivided into two homogenous zones to allow for efficient testing of parameter sensitivity. One zone was around the groundwater catchment of Lake Sibaya, while the second zone covered the rest of the model domain. The auto-sensitivity results for the horizontal and vertical hydraulic conductivities are presented in Figure 9-8.

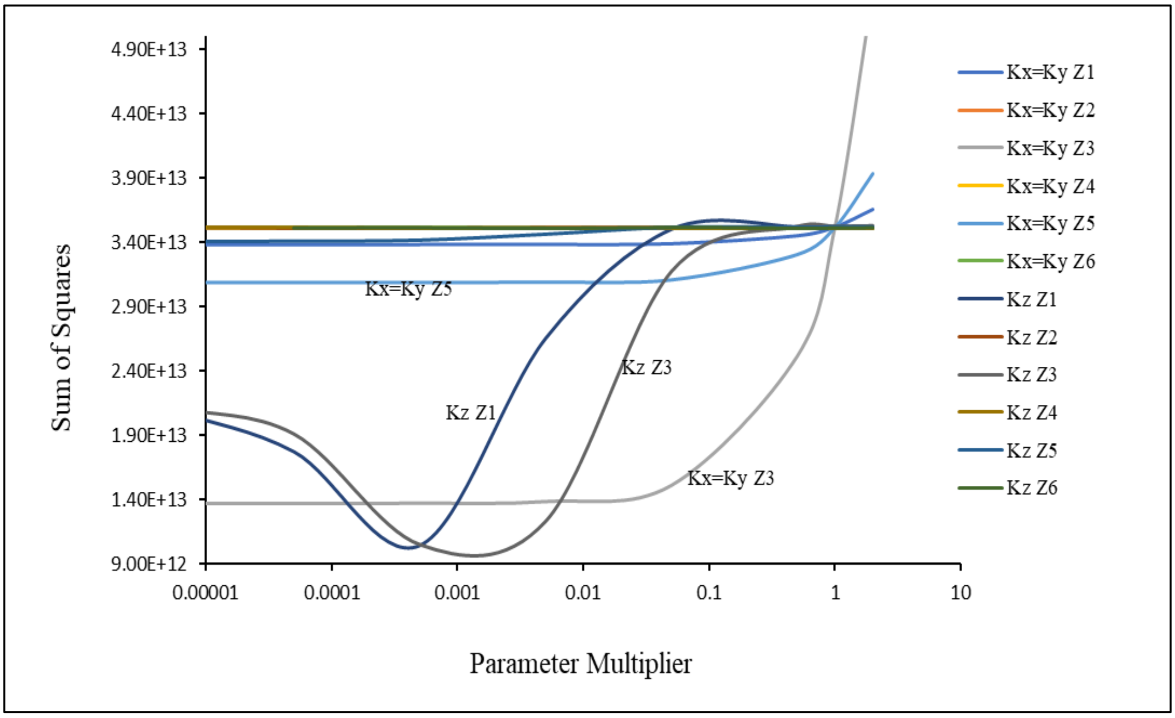


Figure 9-8 Auto-sensitivity runs for horizontal (Kx=Ky) and vertical (Kz) hydraulic conductivity in the three groundwater model layers

Zones labelled Z1, Z3, and Z5 (Figure 9-8) refer to zones around Lake Sibaya in each of the three layers, respectively. Zones Z2, Z4, and Z6 cover the rest of the model domain in each of the respective layers. Most of the zones, except for Z2 and Z4, exhibited sensitivity to changes in both the horizontal and vertical hydraulic conductivity. The highest sensitivity was observed for Kz Z1, Kz Z3, and Kx=Ky Z3, which emphasised the importance of including these parameters in model calibration. These results indicated that zones within the Lake Sibaya groundwater catchment had the greatest sensitivity to hydraulic conductivity changes while zones outside of the catchment had minimal sensitivity.

The second set of parameters that were analysed included the storage and specific yield parameters (Figure 9-9). Similar to the hydraulic conductivity auto-sensitivity tests, zones within the Lake Sibaya groundwater catchment (Z1, Z3 and Z5) showed the greatest sensitivity to changes in storage and specific yield. Zones outside of the catchment (Z2, Z4, Z6) indicated a lower sensitivity to changes in these parameters.

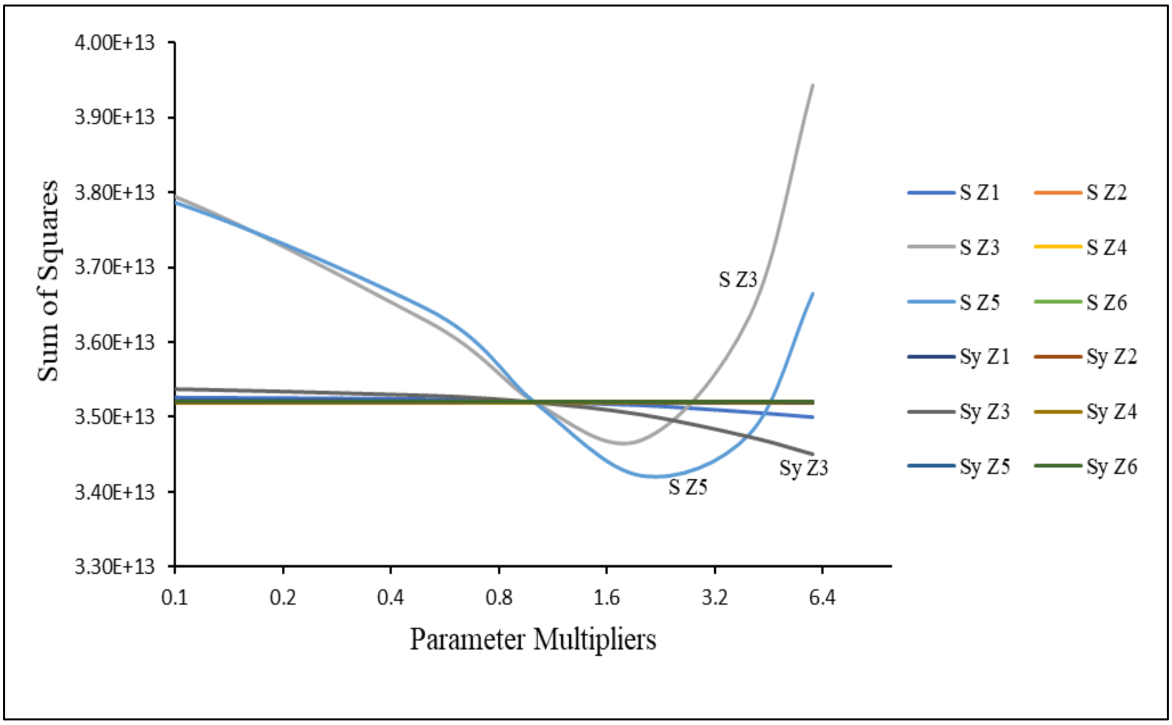


Figure 9-9 Auto-sensitivity runs for specific storage (S) and specific yield (Sy) in the three different groundwater model layers

9.5.5.2 Model calibrations

Model calibration is defined as the process whereby parameter values are adjusted until the predicted/simulated values are similar to the historical observed values. This is carried out to ensure that the model is a good representation of the system being modelled (Merz, 2012). As mentioned previously, the PEST method was used as the primary calibration technique followed by a trial-and-error method.

9.5.5.3 Model calibration: PEST

PEST calibrations, were initially run for Kx=Ky, Kz, S and Sy parameters in user-defined zones in the model. The parameters in the updated model used the same zones from the model by Kelbe (2020). During the PEST calibration, the model determined the initial residual sum of squares error (RMSE) and derived a suitable λ value through numerous iterations, to be applied to the model parameters in an attempt to reduce the RMSE value. When a suitable λ value was obtained, PEST would run the model and apply the λ value to one zone per parameter in each run. This process would be repeated until PEST reached a "switch" whereby it would continue this process, however, there would be a minimal reduction in the RMSE value. Therefore, when the model PEST reached a switch, the calibration would be stopped. In the end, the calibration did 1 000+ runs over one to two days. This approach was also used to calibrate stream conductance values.

9.5.5.4 Trial-and-error calibration

Targets that showed high residual errors after automated calibration using PEST were manually calibrated by either modifying the weighting of that target or changing the model layer within which the target is located. The aim was to reduce the residual error for a target while maintaining realistic parameter values. In particular, Zone 18 located on the northern side of the lake, had an unrealistic Sy value that resulted in spikes in the preliminary future scenario lake simulations. Manually calibrating this zone revealed other areas in the model where zones were incorrectly assigned. These calibration issues were addressed and a SQ model was finalised.

9.6 RESULTS

Throughout this section, the term “previous model” is used to denote the original groundwater model by Kelbe (2020) before any updates were applied during this project. The term “updated/revised model” is used to denote the updated model from which the SQ model simulation was obtained, that was then used as a basis for future scenario simulations.

9.6.1 Recharge Data

To achieve some of the aims of this project, an existing groundwater model was enhanced by incorporating updated recharge data as the primary input. For recharge data comparisons, specific recharge zones from the previous model were selected and matched to the corresponding grid cells in the updated model (refer to Figure 9-10). There was a spatial output variation between the two models, whereby zones in the previous model covered large areas and the updated model used a 1 km x 1 km recharge grid. Additionally, temporal disparities existed in the datasets, which necessitated the use of two horizontal axes in the recharge comparison graphs (see Figure 9-11). Stress periods in the model represent the time increments utilised. The previous model adopted a break-point approach to aggregate similar climatic periods, while the updated model used stress periods that corresponded to months. Conversion of stress periods back to dates in the previous model posed challenges due to unavailable underlying data.

Recharge comparison graphs focused on forestry and grassland land uses. Zones 15 and 16, over the Manzengwenya plantation, were chosen for forestry, and zone 5, north of the Mbazwana plantation, was chosen for grassland. Grid cells (labelled 'Cell #') located in these zones were selected for the comparison (Figure 9-10).

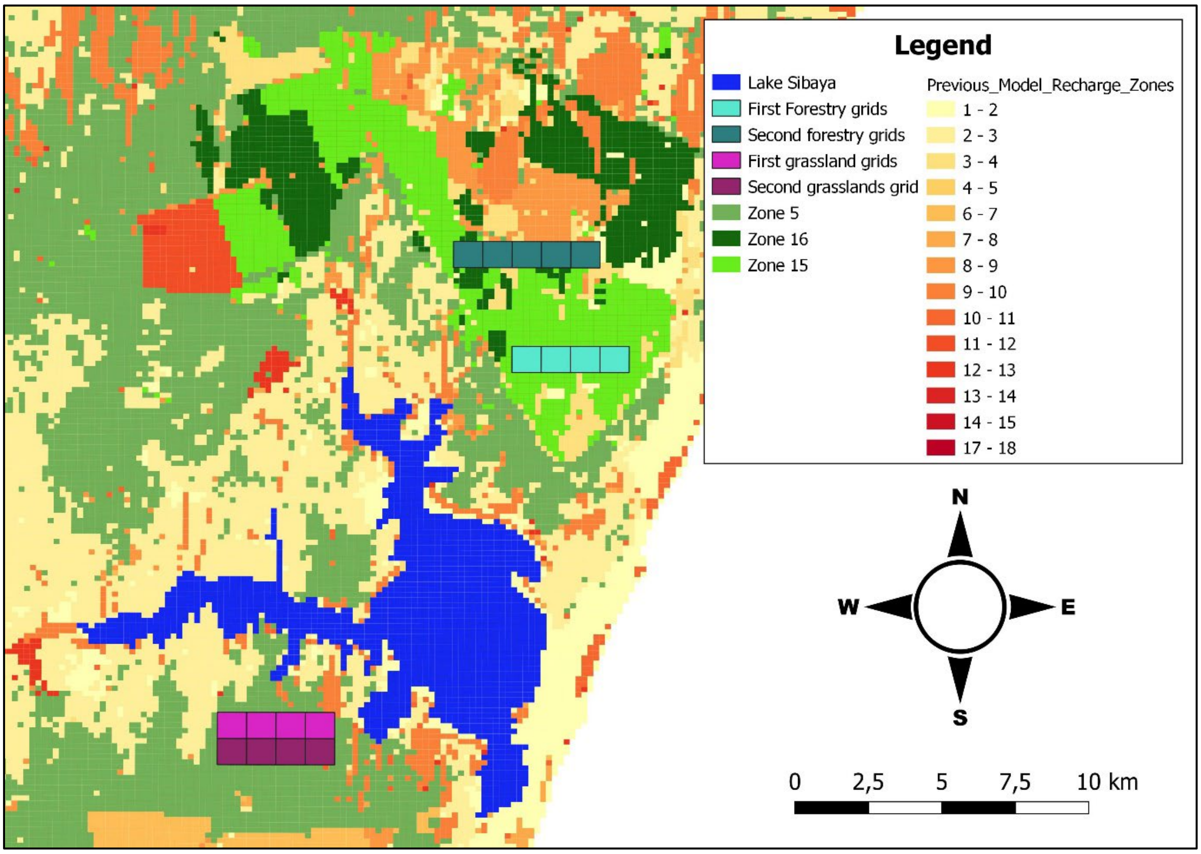


Figure 9-10 Location of zone 15 and 16 over the Manzengwenya plantation and zone 5 north of the Mbazwana plantation. In addition, grid cells 1812 to 1815 over zone 15, grid cells 1589 to 1593 over zone 16, grid cells 2541 to 2544 and grid cells 2594 to 2597 over zone 5

The recharge over the forestry plantations (zones 15) for the SQ period of 1959 to 2021, in the previous model, was consistently higher in magnitude and frequency compared to the updated model's grid cells (Figure 9-11). After May 1992, recharge in Zone 15 began to have a declining trend as well as increasingly negative recharge values until stabilising at -0.001 m/day in 2015. The grid cells had too few recharge events to provide a trend (Figure 9-11). Both Zone 15 and the grid cells had a maximum recharge of approximately 0.007 m/day, and a minimum of -0.0025 and 0 m/day, respectively, before 1992, with Zone 15 peaking in 1988. The grid cells peaked after 1975, followed by two more events and no further recharge until the end of the time series. During recharge events, the grid cells overlapped one another with grid cell 1 815 having the highest recharge values during those events. Limited recharge due to forestry is exceedingly evident from the grid cells. Although forestry began in the 1950s, more recharge before the expansion of forestry in the 1990s was expected.

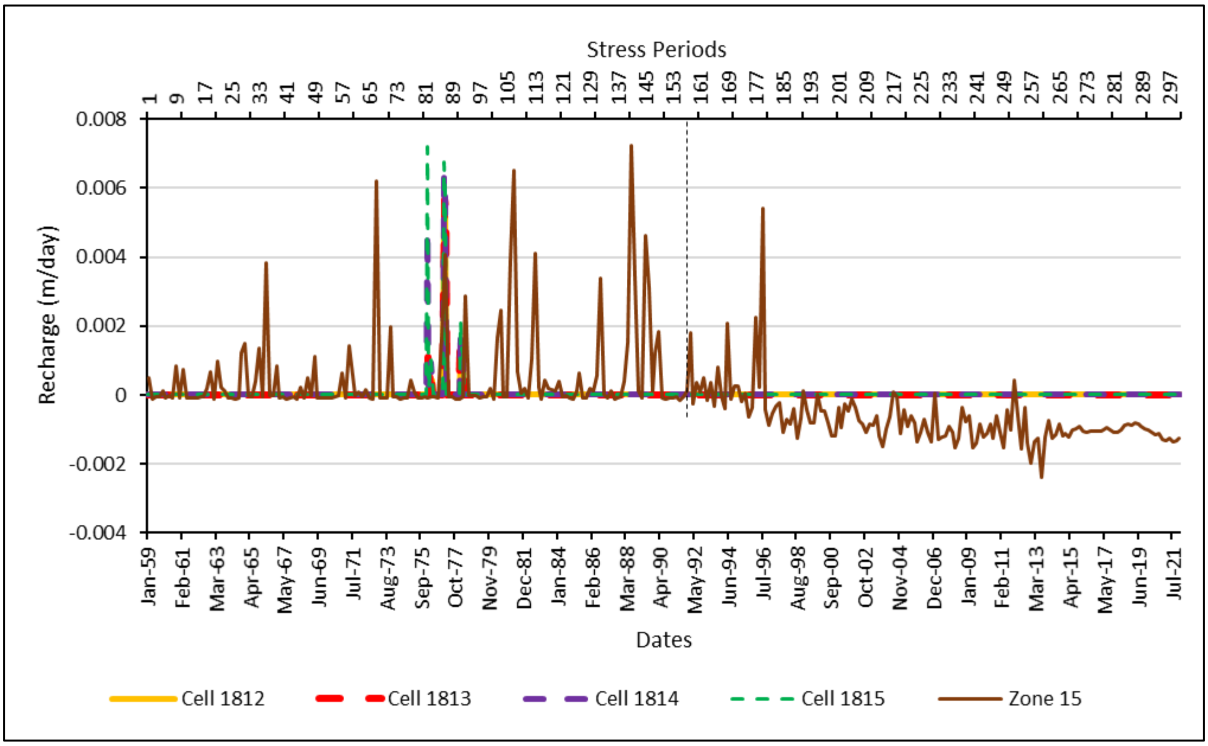


Figure 9-11 Recharge comparisons over the Manzengwenya forestry plantation land use in the previous groundwater model (Zone 15) against the updated model (cell 1812 to 1815), over the same land use area

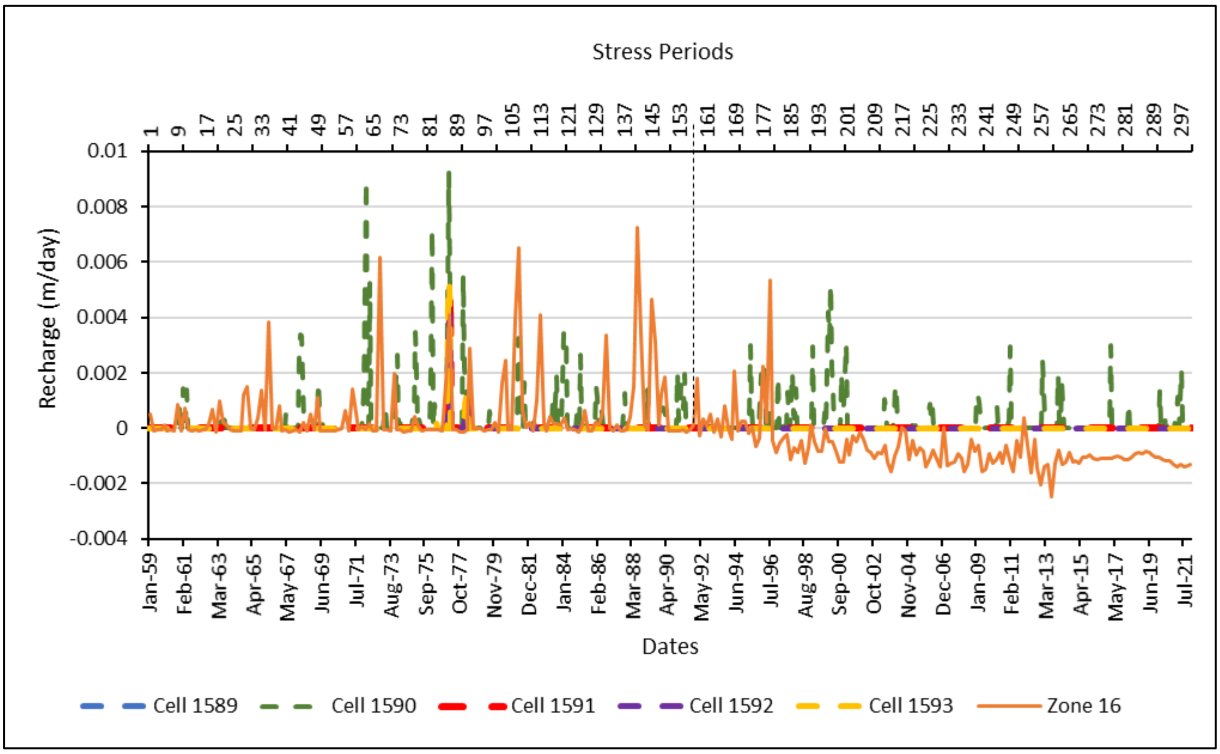


Figure 9-12 Recharge comparisons over the Manzengwenya forestry plantation land use in the previous groundwater model (Zone 16) against the updated model (cell 1589 to 1593), over the same land use area

Recharge in Zone 16 (Figure 9-12) mirrored the trend of that in Zone 15 (Figure 9-11). Most of the grid cells, however, experienced a single recharge event in 1977. Grid cell 1 590 exhibited anomalous recharge by having more frequent recharge events throughout the SQ period compared to other cells as well as Zone 16, with a maximum recharge of 0.0092 m/day compared to 0.007 m /day in zone 16. Negative recharge values from zones 15 and 16 indicate root water uptake from the capillary fringe by forestry plantations, thus indicating the removal of recharge from the system.

Recharge from grid cells appeared significantly more frequent and with a greater magnitude compared to Zone 5 (Figure 9-10 and Figure 9-13). As with the forestry land use comparisons, zone 5 reached peak recharge in 1988 at 0.0076 m/day. However, zone 5 did not experience negative recharge until later in the time series but rather extended periods of low recharge below 0.002 m/day from 1991 onwards, with only two events surpassing this magnitude. Grid cells in the grassland area peaked in 1972 and again in 1977, both at 0.0094 m/day. After 1991, recharge remained frequent but only reached a maximum of 0.005 m/day, with no clear trend of continuously decreasing recharge, unlike in Zone 5.

Greater recharge rates over grassland land use compared to forestry, was expected. What was interesting to observe was the difference in recharge magnitudes between the grids and the zones. The grids had significantly limited recharge over forestry compared to the zones while also having significantly greater recharge over grasslands compared to the zones. This illustrates how different the two sets of recharge datasets provided to the models are.

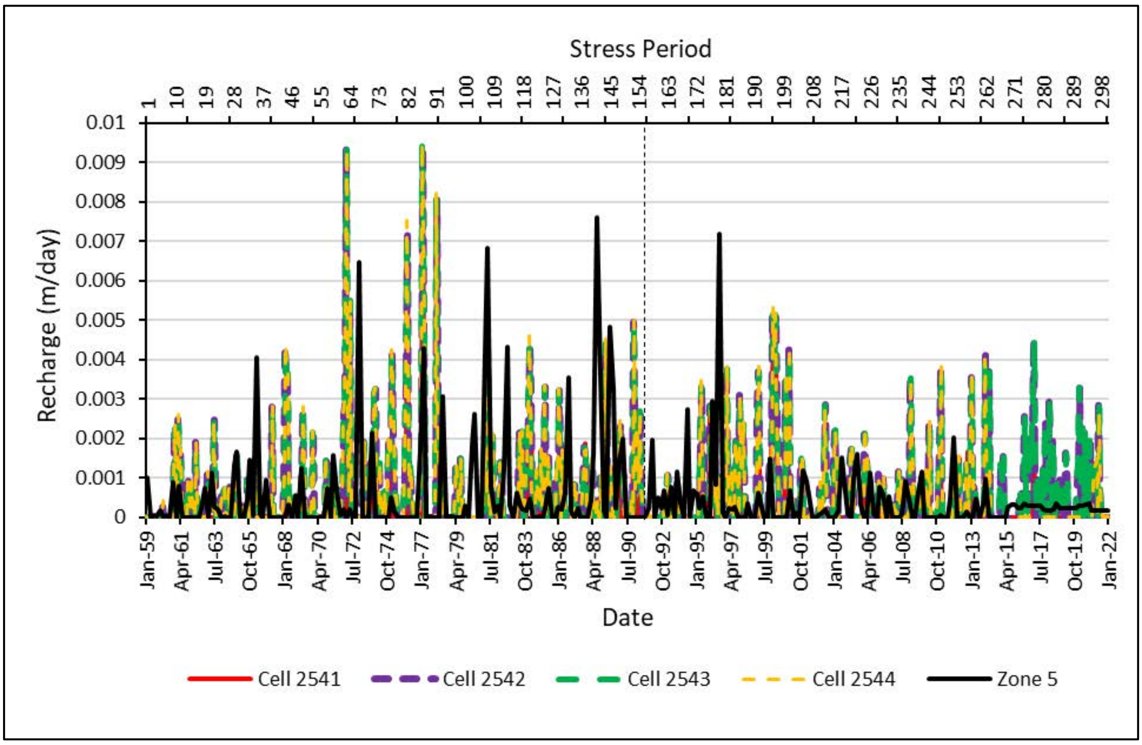


Figure 9-13 Recharge comparisons over grassland landcover with the previous model represented by zone 5 (black line) and the updated model by grid cells

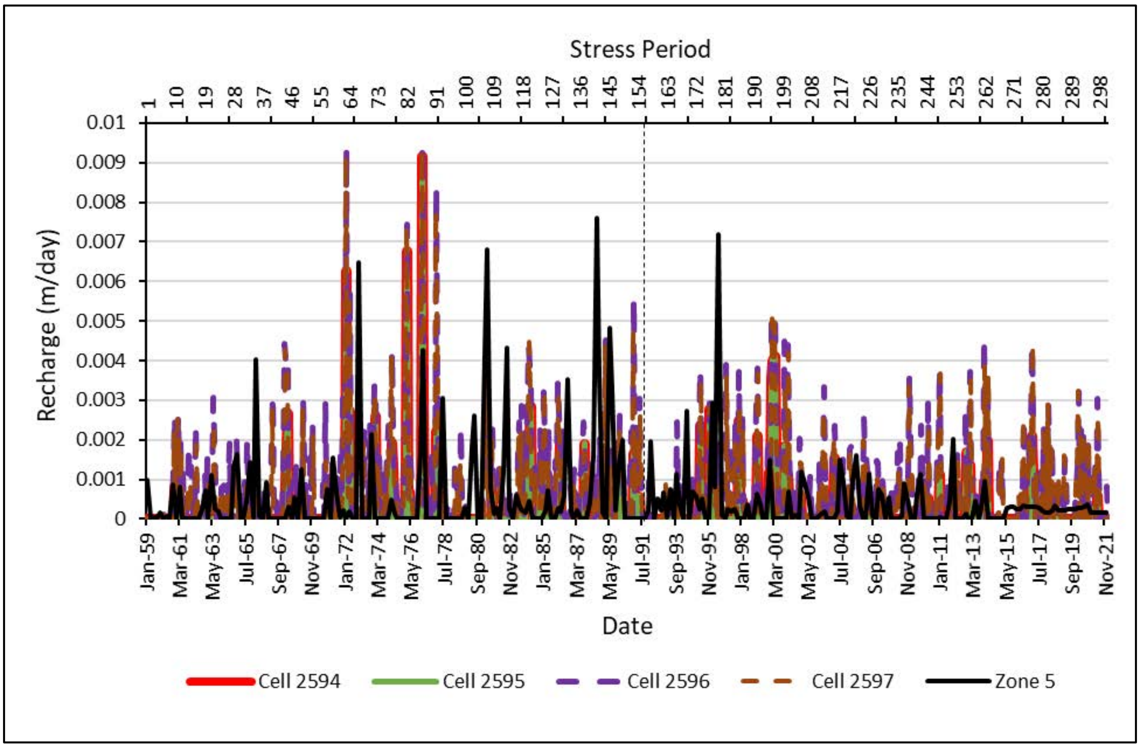


Figure 9-14 Recharge comparisons over grassland landcover with the previous model represented by zone 5 (black line) and the updated model by grid cells

9.6.2 Groundwater Model Calibration

This section outlines the calibration results of the updated model in comparison to the previous model. For the PEST calibration of the updated model, only borehole groundwater levels (head targets in the model) and streamflow measurements were utilised. A trial-and-error iterative calibration approach was later used to address errors revealed by future scenario simulations, which resulted in corrections to the base model. Calibration statistics from both models, calculated with user-defined weightings assigned to the model targets, are presented in Table 9-3.

The updated model demonstrated a comparable calibration performance to the previous model, with a minor RMS error difference of 0.07 between the two (Table 9-3). The RMS error, measured in metres, indicates an almost three-meter error relative to all simulations in the model. The negative residual mean in the updated model suggests an overall under-simulation in the model when all simulations are considered.

The scaled statistics, derived from dividing the residual mean statistics by the range of observations, offer a more meaningful indicator of calibration performance. With the scaled residuals, particularly Scaled RMS, being close to 0, the calibration statistics signify effective model calibration while also considering the model's complexity and size. In addition, there was a close match between the two models' scaled statistics. At the extremes, the updated model exhibits a higher minimum residual (indicating a greater under-simulation for some targets) and a higher maximum residual (indicating a greater over-simulation for some targets) compared to the previous groundwater model. The greater range in min and max values aligns with the higher residual statistics observed in the updated model, considering the updated model's additional 6 043 observations. Thus, it can be stated that the updated model had a better calibration.

Table 9-3 Calibration statistics from the updated and previous groundwater model

	Previous Groundwater Model	Updated Groundwater Model
Residual mean	0.19	-1.30
Residual Standard Dev.	2.86	2.64
Absolute Residual Mean	1.38	2.18
Residual Sum of Squares	6.15e+05	7.09e+05
RMS Error	2.87	2.94
Minimum Residual	-32.32	-53.66
Maximum Residual	18.74	32.60
Range of Observations	117.98	119.00
Scaled Res. Std. Dev.	0.024	0.022
Scaled Abs. Mean	0.012	0.018
Scaled RMS	0.024	0.025
Number of Observations	74 931	81 974

The observed versus simulated head target calibration results from the previous groundwater model are shown in Figure 9-15. The black line running diagonally across the graph represents the 1:1 line (or line of best fit). Both models consist of three layers, but there is a distinction: the previous model only had targets in the first (red) and third (blue) layers, whereas the updated model has targets in all three layers (Figure 9-16). The majority of head targets simulated in the previous model closely aligned with the line of best fit (1:1) (Figure 9-15). This indicated a close agreement between the simulated and observed values. Layer 1, however, simulated some targets to have similar values despite varying observed values. This discrepancy suggests that the configuration of Layer 1 may not accurately represent geohydrological processes.

The updated groundwater model used similar zones for hydraulic parameters as the previous model. These hydraulic parameters within these zones were calibrated and plotted (Figure 9-16). The lack of streamflow data meant that the previous model could not calibrate stream conductance, contrary to this study which was able to incorporate stream conductance into the calibration.

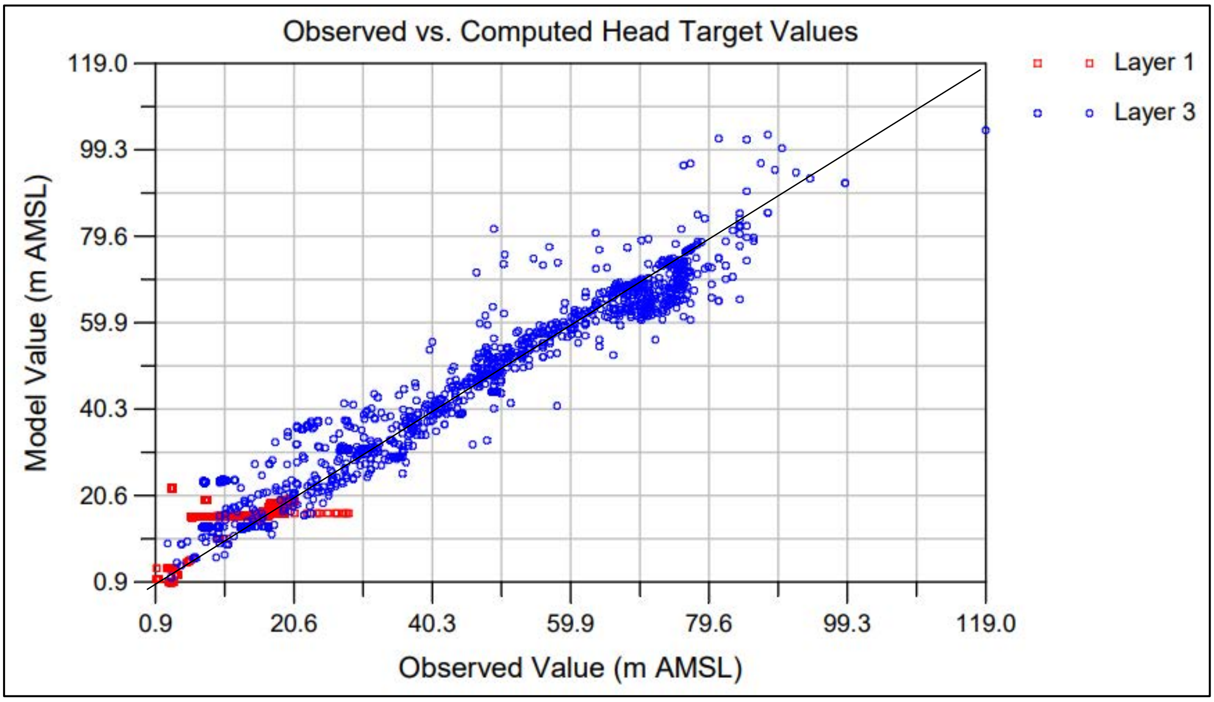


Figure 9-15 Observed versus computed head target values based on a zonal calibration approach in the previous groundwater model

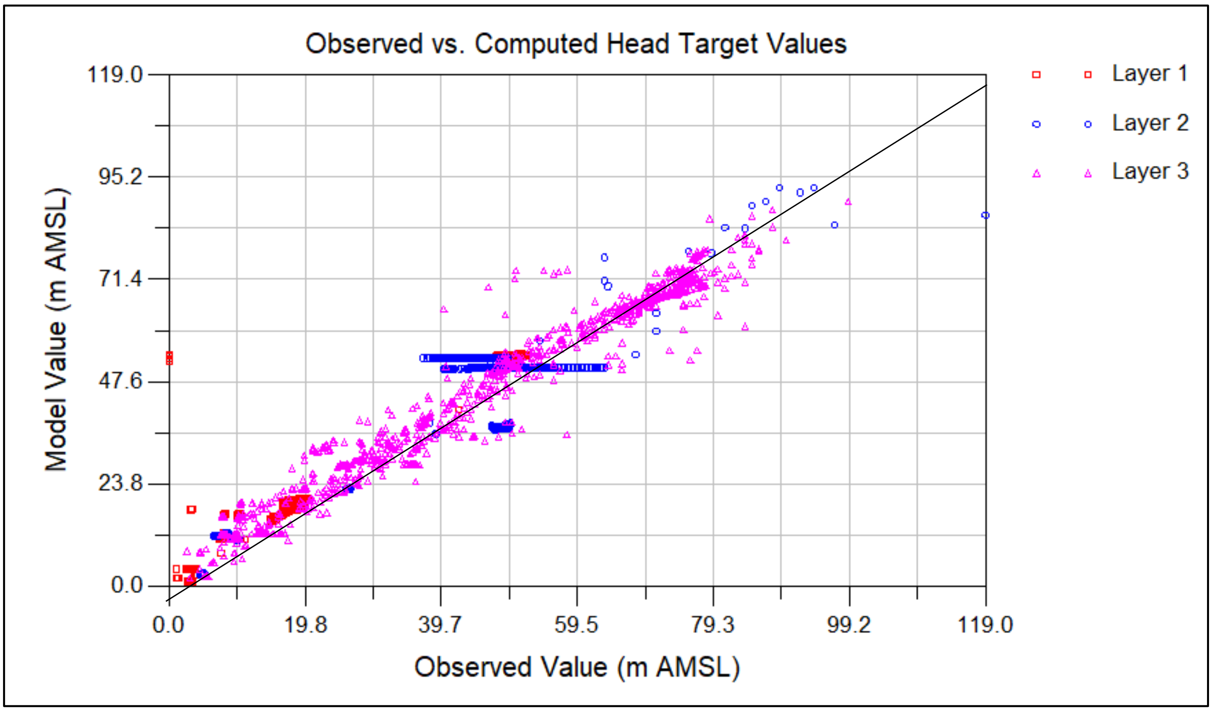


Figure 9-16 Observed versus computed head target values based on pre-defined piece-wise homogenous zonal calibration setup in the updated groundwater model

Targets are represented for the first (red), second (blue), and third (pink) layers of the model (Figure 9-16). These results showed a slight improvement compared to the previous model. Fewer targets in the updated model were simulated further away from the line of best fit, despite having a greater number of targets. Target simulations in the first and third layers were notably good. However, outliers such as two model values simulated in the 50 m AMSL range with observed values of 0.0 m a.m.s.l, were observed in layer 1. Another outlier was a target with a simulated value of 79.3 m AMSL at an observed value of 119.0 m AMSL in Layer 2. A similar issue to that observed in Layer 1 of the previous model (Figure 9-15) was experienced in Layer 2 in the updated model, whereby some targets were simulated with constant head values despite varying observed values The first and third layers of the updated model had a better calibration along the 1:1 line compared to the previous model (Figure 9-15) in similar layers.

More targets are being simulated more accurately in the updated model compared to the previous model. However, the issue of similar simulated targets with varying observed values indicates a problem within the model configuration. Nonetheless, the updated model's calibration is satisfactory.

9.6.3 Groundwater Level Simulations

The groundwater model relies heavily on groundwater level measurements for calibration, which allows it to optimise model parameters to simulate measured water levels accurately. After model calibration, the subsequent step involves time series comparisons to assess how well the updated model simulates groundwater levels and stream fluxes compared to the previous model. A comparison of simulated groundwater levels for the SIBO2 borehole between the updated and previous model's relative to observed values is provided in Figure 9-17.

The SIBO2 borehole (depth of 35 m) is located south of the lake's main basin. The observed values exhibit increments in groundwater levels from 2019 to 2023. These increments are due to extreme high rainfall events. The updated model used modelled gridded climate data while the previous model used observed point data that ended in 2020. Thus, the simulated groundwater levels from January 2020 onwards could not be compared to observed values. Despite this limitation, a comparison between the two model simulations was possible which revealed that both models simulated a gradual decline in groundwater levels. Early in the time series, the model simulations up to 1986 both exhibited overlaps, after which the previous model consistently simulated higher levels (1 m at most) than the updated model until the end of the simulation. However, the updated model's simulation displayed increased variability in groundwater levels, characteristic of observed levels, in contrast to the smooth trend from the previous model.

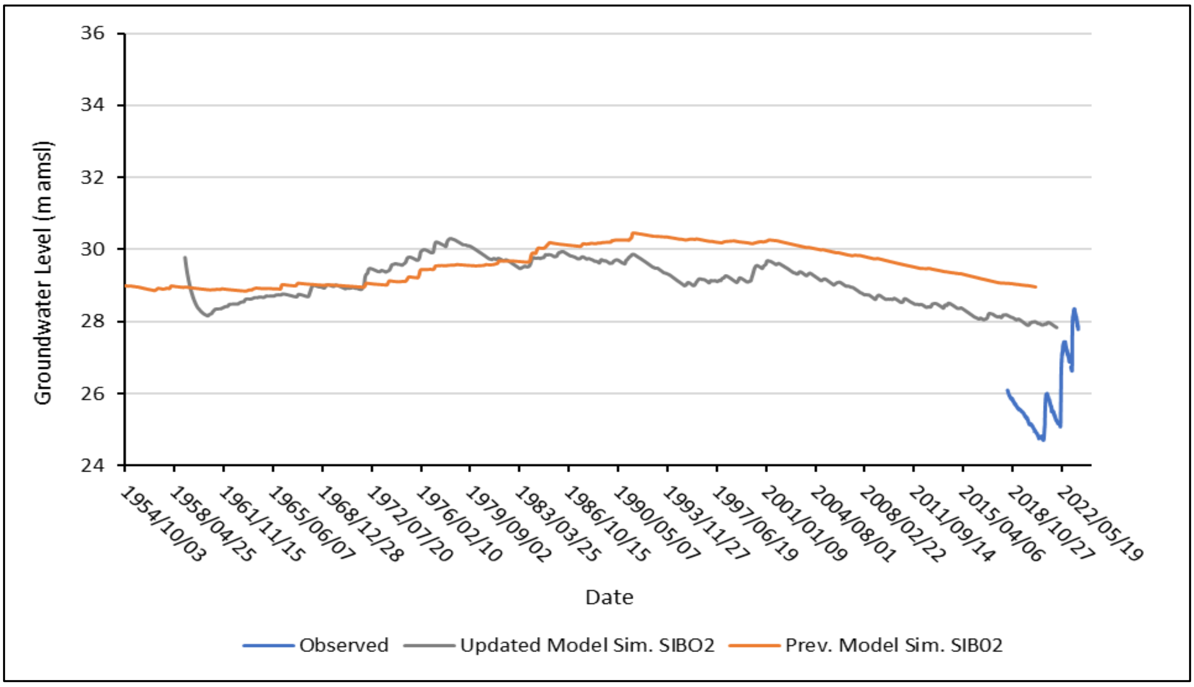


Figure 9-17 Groundwater level simulated in the updated and previous groundwater models against observed levels at the SIBO2 deep borehole (35 m depth), on the southern side of the main basin

Simulated groundwater levels in the SGO shallow and deep boreholes, from the eastern side of the south basin, are shown in Figure 9-18. Additionally, simulated groundwater levels for the Sibaya East borehole, located on the north eastern side of the main basin, are provided. The previous groundwater model configured these boreholes as steady-state and, thus, could not provide transient simulations. The Sibaya East borehole has observed and simulated water levels approximately 4 m higher than the SGO1 boreholes. This may be attributed to geohydrological conditions in their different locations. Furthermore, the Sibaya East borehole was placed in the first layer of the model while the SGO boreholes were placed in the second and third layers. The Sibaya East borehole simulated levels exhibit less variability in water levels compared to the SGO borehole simulations, which show greater peaks and dips while following a similar trend as Sibaya East. The Sibaya East borehole over-simulates groundwater levels by less than a metre compared to observed values, while the SGO boreholes range in their over-simulations from less than 1 m to up to 2 m.

The close simulation of groundwater levels to observed levels indicates a good simulation. Additionally, the increased variability in water levels in the SGO boreholes indicates a greater responsiveness of groundwater levels to changes in precipitation and land use in the southern side the South Basin compared to the north-eastern side.

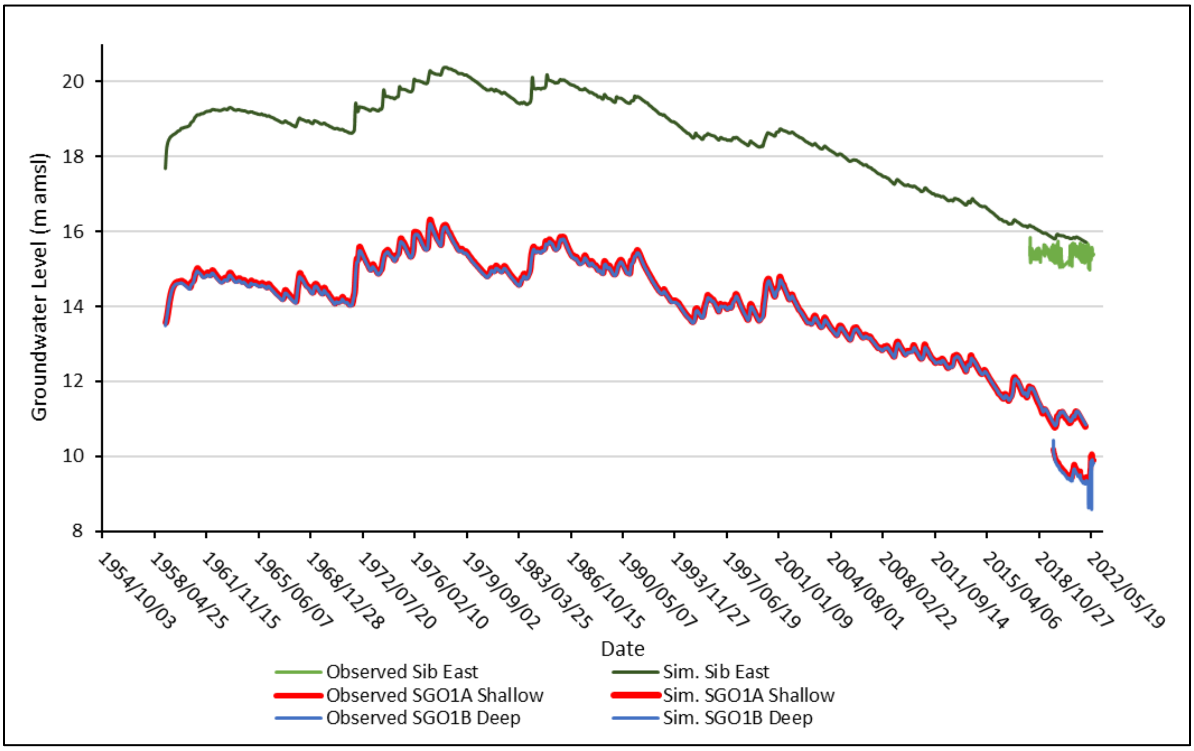


Figure 9-18 Groundwater level simulations from the updated groundwater model against observed levels from boreholes on the south side of the south basin (SGO boreholes, depth of 21 m for shallow BH and 52.8 m for deep BH) and eastern side of the main basin (Sibaya East borehole, 1.36 m depth), along the lake edge

9.6.4 Streamflow Simulations

As mentioned earlier, stream conductance was utilised during calibrations to enhance streamflow simulations. Simulated stream flows (m^3/day) for the Mseleni stream, a major inflow into Lake Sibaya, are illustrated in Figure 9-19. A comparison between the updated and the previous model simulations relative to observed data is provided (Figure 9-19). The use of a logarithmic scale on the y-axis accommodated significant flux changes in the stream. The updated model exhibited a closer agreement with observed flows towards the end of the simulation. Notably, the model captured a dip in flux levels in December 2021, albeit slightly delayed compared to the observed flows. However, the short length of observed data prevents conclusions to be made on the model simulations compared to observed values. Comparing the model simulations of the previous and updated models, both initially had overlapping flux simulations until the 1980s, after which they diverge, with the previous model showing higher flux simulations. Additionally, before 1986, most spikes in stream fluxes occurred simultaneously between the two models, although with lower magnitudes in the previous model. For the remainder of the time series, spikes did not usually occur synchronously. Despite these variations, both models exhibited a similar trend in flows throughout their simulations.

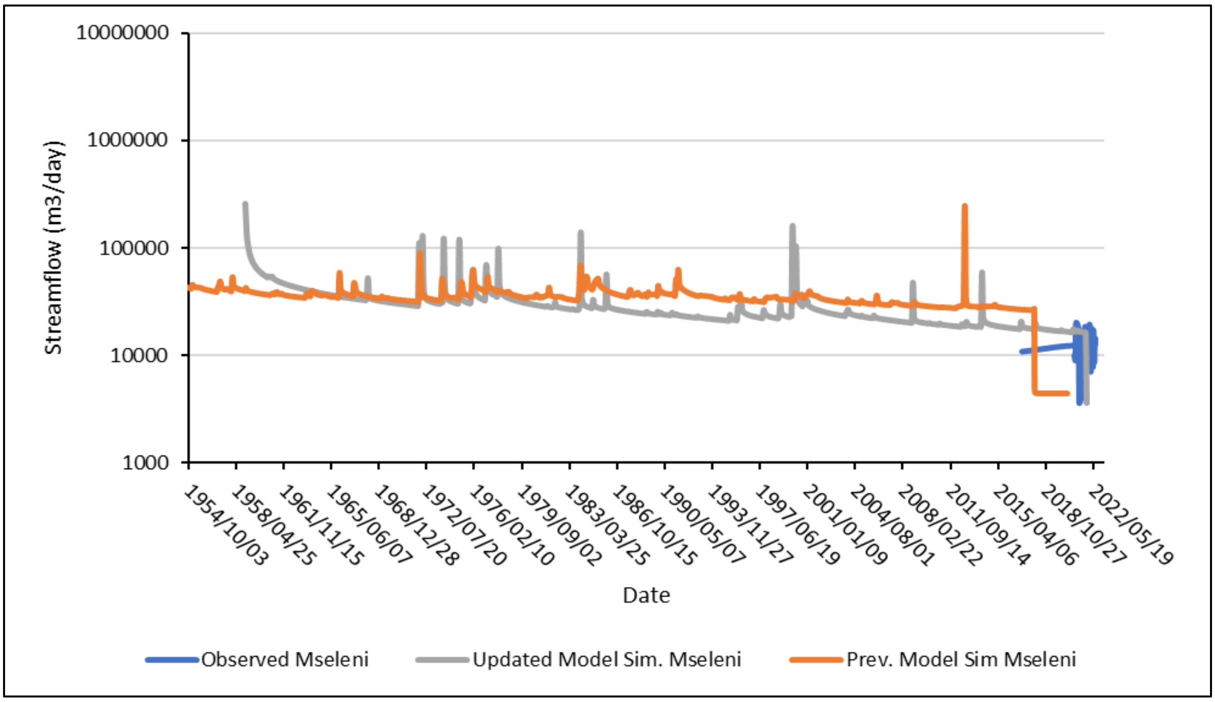


Figure 9-19 Mseleni streamflow rates (m^3/day) simulated using the updated as well as the previous groundwater model, against observed streamflow data

Simulated streamflow in the Malangeni stream, which flows into Lake Kosi Bay, compared to observed flows is provided in Figure 9-20. The Malangeni stream is located in the Kosi Bay Lake groundwater catchment north of Lake Sibaya. Compared to the Mseleni stream with observed fluxes typically around 10 000 m^3/day (Figure 9-19), the Malangeni stream exhibits higher fluxes, around 50 000 m^3/day and occasionally exceeding 100 000 m^3/day (Figure 9-20). This highlights a substantial difference in stream sizes and fluxes.

Both models over-simulated the Malangeni stream fluxes compared to observed flows by approximately one order of magnitude. The peak in observed flows aligned with a spike in the updated model simulation, although this was the only comparable aspect. Due to the limited observed data record, no definitive conclusions can be drawn. In contrast to the Mseleni stream (Figure 9-19), the updated model's Malangeni stream simulation was consistently higher than the previous model. Despite this, both models demonstrated a similar overall trend and mostly concurrent periods of spikes or high flow events, with the updated model exhibiting greater magnitudes during these periods.

Comparisons of streamflow simulations revealed a close agreement between the previous and updated model's simulation, however, were inconclusive when compared to observed data. This was primarily due to the short record of available streamflow data to validate the model performance.

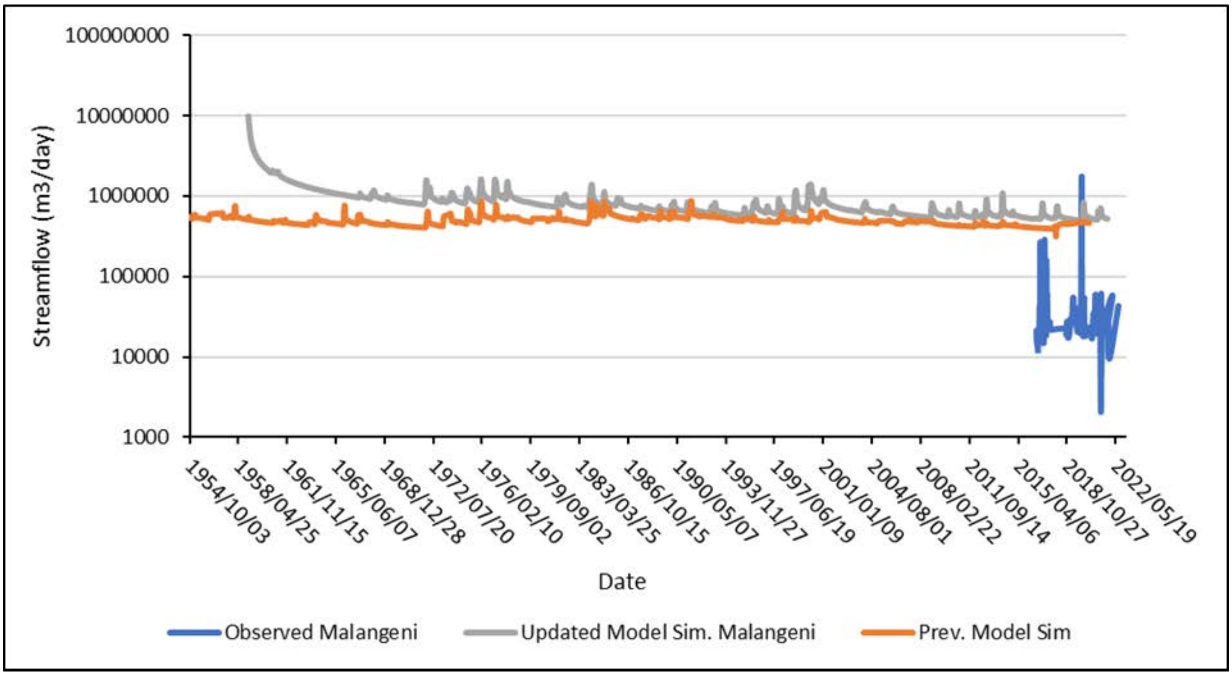


Figure 9-20 Malangeni streamflow rate (m^3/day) simulated using the updated as well as the previous groundwater model, against the current set of observed streamflow data

9.6.5 Groundwater Flow Direction and Contours

The groundwater flow direction map was constructed using groundwater information from the first and second layers of the model with which the lake intersects. Each stress period produces a map, e.g. Figure 8-24, which provides comprehensive groundwater data for the entire model domain. This information encompasses both groundwater flow direction and contours. The overlain data from the first and second layers facilitates the visualisation of continuous groundwater flow in instances where parts of the first layer have become dry.

Groundwater contours that illustrate flow gradient as well as groundwater flow directions are depicted for both model layers. Denser groundwater contours and directional arrows indicate a high hydraulic gradient. The black line delineates the groundwater catchment of Lake Sibaya, in reference to the contours and groundwater flow directions.

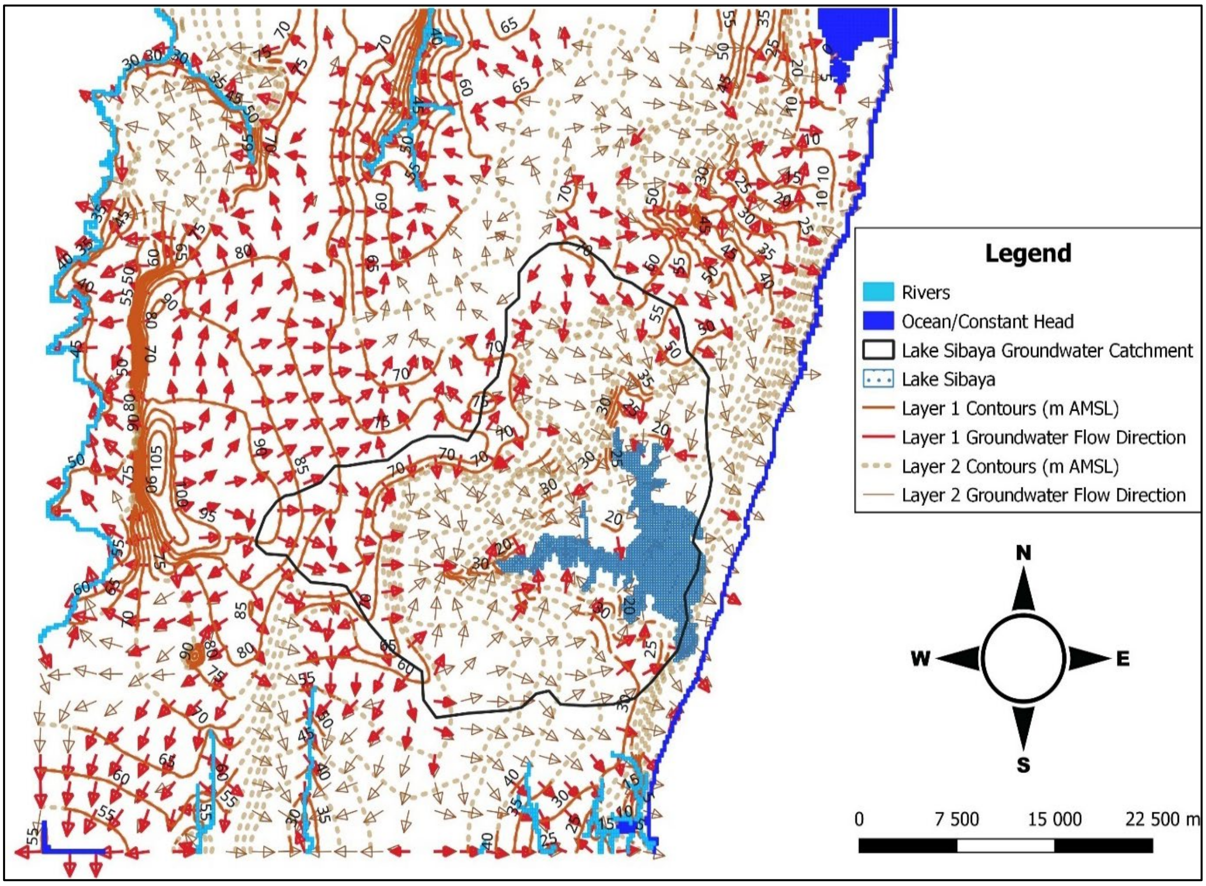


Figure 9-21 Groundwater flow direction map for the model domain, with groundwater information from the first and second layers of the groundwater model for 21 December 2020 as an example.

The ocean is delineated by a dark blue line on the eastern side and the Pongola River is represented by a light blue line on the western side (Figure 9-21). The groundwater catchment of Lake Sibaya is subjective, as devised by Kelbe (2019; 2020) (Figure 9-21), who relied solely on information from the first layer. The map reveals a water table depth within the marked groundwater catchment of Lake Sibaya which ranges from 20 m AMSL (towards the lake) to 70 m AMSL (towards the extremities). Based on the contour lines, the water table in much of the area around Lake Sibaya is within the second layer (dotted brown line), with some parts near the lake shores having water in the first layer (solid brown line). A trough appears to exist on the western and northern sides of the lake, where the water table at the catchment boundary shifts from the first layer to the second layer and then back to the first layer closer to the lake. Additionally, a dense hydraulic gradient within the Lake Sibaya groundwater catchment, particularly for the western and northern sides, was observed.

Groundwater flow directions and contours across the entire model domain agree with catchments of neighbouring water bodies, including rivers. This supports the understanding that neighbouring catchments potentially influence the extent of the Lake Sibaya groundwater catchment, while also indicating a spatially extensive and well-configured model.

9.6.6 Lake Water Balance

A water balance provides an indication of the volume (or flux) of water that enters and leaves a water body. This section outlines the water balance components for the two basins of Lake Sibaya. The basins were configured as two separate lakes connected through various fluxes, however, the widely documented lake separation was not configured for this study. Figure 9-22, which presents a monthly averaged water balance for the main basin, displays average flow rates over the years 1959 to 2020 and 1959 to 2021 for the previous and updated models, respectively.

In the main basin water balance, the updated model (blue columns) shows a net influx of precipitation, while the previous model (green columns) shows a considerable net loss due to evaporation. Additionally, it was observed that surface water inflows had significant influence on the water balance of both the updated and previous groundwater models. The updated model had a net groundwater outflow of 171 572 m^3/month, whereas the previous model shows a net groundwater influx of 863 832 m^3/month.

Both models experienced a net influx of surface water, with only the updated model having withdrawals from the main basin. These withdrawals had a negligible impact on the water balance. The updated model also demonstrates a significantly higher “Lake-Inflx”, which indicates a water flux between two connected lake basins, and results in a substantial loss of water from the main basin to the south basin. The difference in “Lake-Inflx” between the updated and previous models was 4 213 701 m^3/month. This loss occurs through lake water flow and seepage into the south basin.

In summary, the updated model simulates a net loss of 236 724 m^3/month from the system whereas the previous model simulated a net loss of 158 017 m^3/month, over the entire model simulation. These losses suggest a historical long-term decline in lake levels for Lake Sibaya.

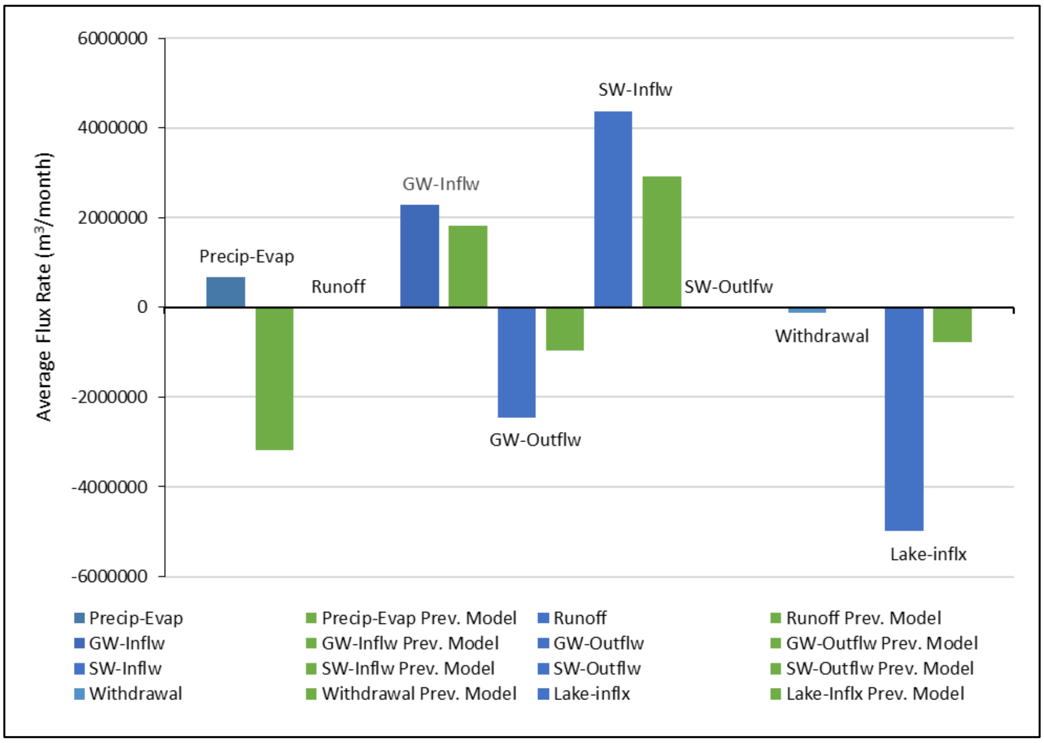


Figure 9-22 Monthly averaged lake water balance for the main basin over the period 1959 till 2020 and 2021 for the previous and updated models, respectively

The water balance for the south basin as averaged monthly flow rates from 1959 to 2020 for the previous model and 1959 to 2021 for the updated model, is shown in Figure 9-23. As with Figure 9-22, blue columns represent the updated model's water balance values and the green represents the previous models. Groundwater outflow, which represents lake water seeping towards the ocean, was the predominant contributor to water loss in the south basin for both models. Evaporation and withdrawal losses were significant for the previous model compared to losses from other parameters, whereas these were negligible in the updated model. Similar to the losses experienced in the main basin (Figure 9-22), the south basin experienced a net loss of 12 144 m³/month in the updated model and a net loss of 8 004.6 m³/month in the previous model.

In both models, a significant flow (Lake-Inflx) from the main to the south basin coupled with groundwater inflow, as well as rainfall for the previous model, have been instrumental in maintaining water in the south basin. However, this substantial inflow is primarily released from the south basin as groundwater outflow (seepage to the ocean) in both models as supported by the close match in magnitude of the 'Lake-Inflx' in the south basin to groundwater outflow. The difference in flux volumes between the two models can be linked to the difference in recharge amounts provided to both models (Section 9.6.1).

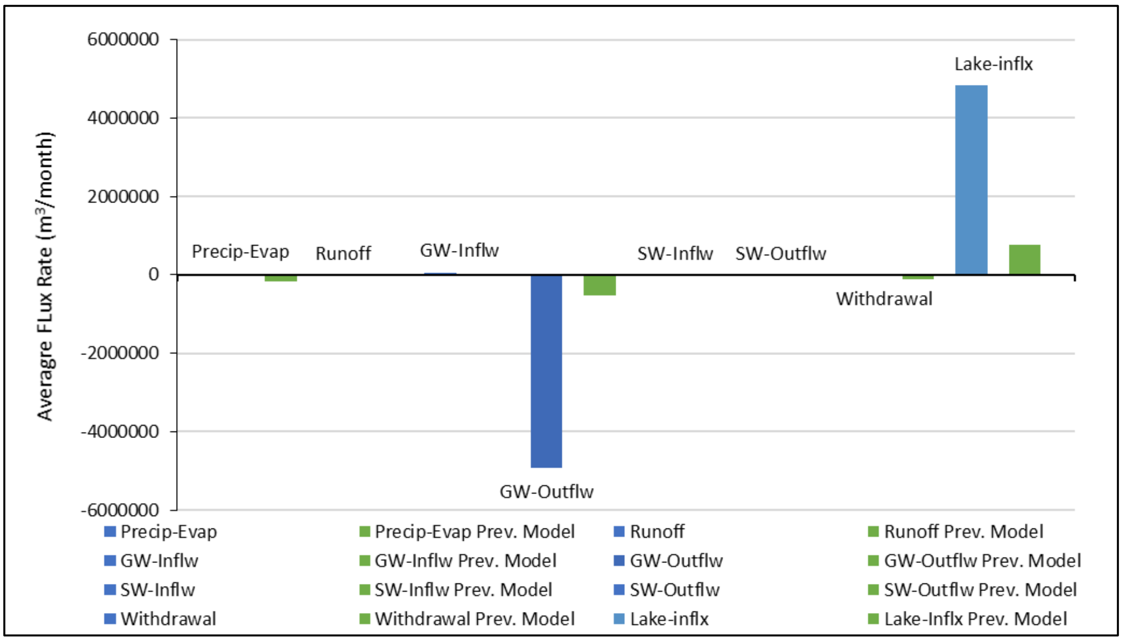


Figure 9-23 Monthly averaged lake water balance for the south basin from the year 1959 to 2020 and 2021 for the updated and previous models, respectively

9.6.7 Lake Simulations

Observed lake levels were not used in the calibration of any of the models; instead, they were used for model validation, to assess if the models could simulate lake levels close to those observed. Lake Sibaya water levels (Figure 9-24) are considered a proxy for trends in groundwater levels for the area due to the fundamental connection of these systems. Thus, lake level simulations serve as a representation of the overall state of water resources in the Lake Sibaya groundwater catchment. Figure 9-24 provides a comparison of observed lake levels from January 1966 to August 2022 against simulated levels from January 1959 to December 2020 and 2021 for the previous and updated models, respectively.

Both model simulations agree with the observed lake level trends throughout the entire simulation period. However, over-simulations were evident from 1959 to 1977, where both models tended to overestimate lake levels by 1 m (previous model) or 1.5 m (updated model) (Figure 8-27). After 1977, both models closely matched the observed levels. The updated model effectively replicated the initial high and low periods, but struggled to accurately simulate the peak in lake levels in 2001. The previous model initially under-simulated lake levels, in alignment with low flows, but subsequently transitioned to over-simulating lake levels in alignment with high flow periods. This transient analysis up to the early 2000s indicates the dynamic nature of the updated model's lake simulation, closely tracking observed lake levels. In contrast, the previous model exhibited less variability and shifted between under and over-simulations. From the early 2000s, as lake levels began to decline, both models exhibited improved alignment with observed levels. However, the updated model provided a closer simulation while it also incorporated the minor fluctuations of the system during this period, whereas the previous model mostly provided a smooth trend.

Overall, the updated model provided a stronger simulation and the consistent declining trend seen in both models aligns with the overall loss identified in the water balance (Figure 9-22 and Figure 9-23), affirming the acceptability of the model configuration.

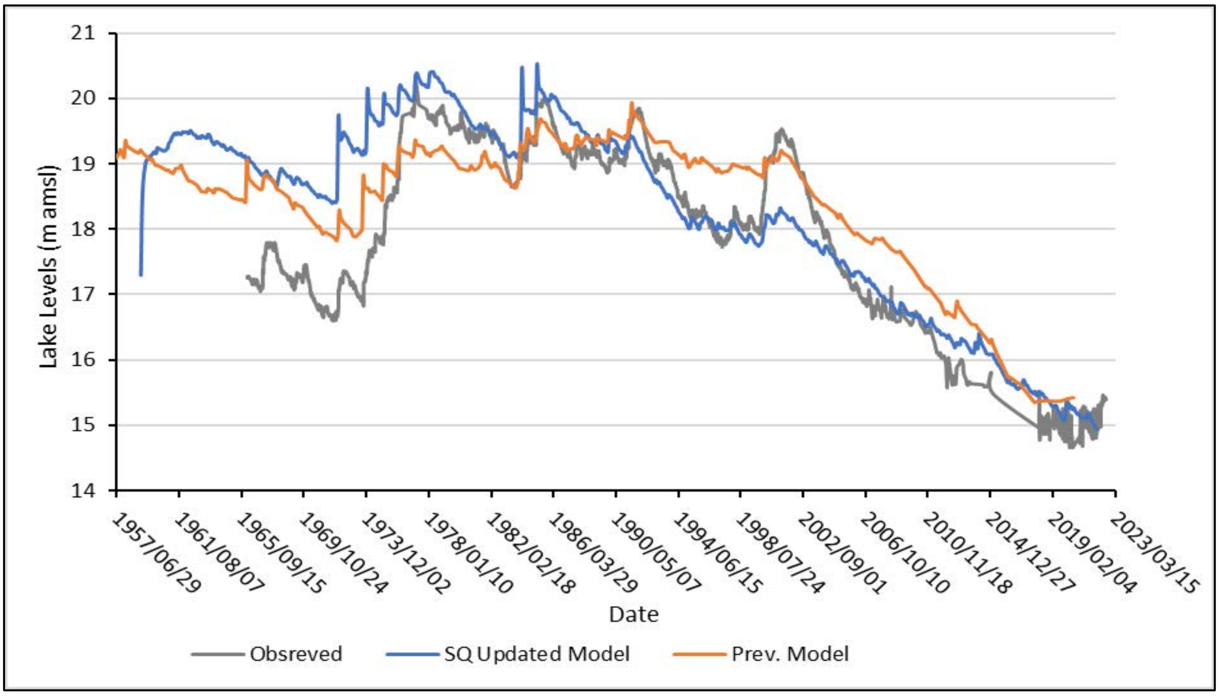


Figure 9-24 Observed lake levels against simulated levels from the previous and updated models

9.7 DISCUSSION

In line with Aim 3 of this project, this chapter focused on modelling the groundwater dynamics of the Lake Sibaya region through the use of an updated version of an existing model. This was done to explore the influence of changes in vegetation and climate on the hydrological response of the Lake Sibaya system. The updated and improvement method of previously developed groundwater models is widely adopted, as demonstrated by organizations such as the USGS (USGS, 2023) and Golder Associates Africa (Golder Associated, 2016).

To assess the relative impacts of historical changes in vegetation and climate, "corrected" LULC data from SANLC and satellite-derived climate data was used, as the best available spatial data for the region, to generate recharge data. Analysis of recharge comparison graphs (Figure 9-11 to Figure 9-14) revealed significantly higher recharge rates in grassland areas compared to forestry areas. These results are consistent with findings by Allen and Chapman (2001) that indicated that forestry activities reduce recharge. Moreover, the updated model received substantially greater recharge over grassland areas compared to the previous model, while the reverse was observed for forestry land use. Furthermore, the previous model experienced increasingly negative rates after 1992, which links to water extraction from the capillary fringe due to forestry activities. Although the ACRU model used in the previous study could account for this phenomenon, it was not feasible in the study due to limitations associated with the gridded setup. Additionally, anomalous recharge observed in grid cell 1 590 (Figure 9-12) may be attributed to one of the peatlands (Vasi peatlands), given their proximity to the plantations.

Following a satisfactory calibration of the groundwater model, with slight improvements in statistics compared to the previous model, a common issue identified in both models was the presence of a horizontal line of targets (borehole simulations). This suggests ineffective model simulations, particularly in the first layer of the previous model and the second layer of the updated model. Possible causes include inaccuracies in borehole locations and layer assignments, potentially stemming from errors in coordinate data due to absence of GPS and vertical elevation data relative to metres AMSL due to inaccurate SRTM data (Section 9.5.1). Another consideration, raised by the isotope study in CHAPTER 7:, was the likelihood of a single-layer aquifer, indicated by the absence of significant isotopic differences between the supposed three layers. Comparing model calibrations, Mylopoulos et al. (2007) developed and calibrated a multi-layered groundwater model for an area facing water resource declines, which achieved results of 2.8 m RMSE, comparable to this study's 2.9 m RMSE. Their study suggests that deviations of head targets (that simulate groundwater levels) from the line of best fit may signal a need for a more detailed grid in those areas, possibly due to prevailing high hydraulic gradients. This suggestion warrants further investigation in the model used here during future studies.

The short record of observed groundwater level and streamflow measurements posed a significant constraint in the previous groundwater models (Weiz, 2016; Kelbe, 2020), and persisted as a challenge in the updated groundwater model, evident from the groundwater (Figure 9-17 and Figure 9-18) and streamflow (Figure 9-19 and Figure 9-20) simulations. Unlike previous models, which mostly relied on single measurements for boreholes and streams, e.g. Mseleni stream, this project utilised an extended dataset, which facilitated improved model calibrations. However, analysis of simulation comparisons indicated that these observed records were still too short to guide conclusions on the model simulations.

Despite the challenges encountered in model simulations, this study, akin to previous works by Weitz (2016) and Kelbe (2019, 2020), employed Lake Sibaya water levels as the primary means of model validation. In the main basin's water balance (Figure 9-22), the updated model showed a net influx for precipitation, while the previous model experienced a net loss due to significant evaporation. Regarding this, Weitz's (2016) conceptual water balance agreed with the previous groundwater model and the isotope lake water balance in Chapter 7. The updated model indicated a water balance dominated by surface water inflow and groundwater outflow, either moving to the south basin or seeping into the ocean. In contrast, the previous model indicated a water balance dominated by surface water inflow and evaporation (Figure 9-22 and Figure 9-23). A different perspective, the isotope water balance (CHAPTER 7:), suggested a dominance of groundwater inflow and evaporation, which aligns with Weitz (2016).

Differences in dominant water balance parameters between the updated and previous groundwater models could be due to variations in recharge; precipitation over the lake; and parameter calibrations due to lack of observed data in the previous model. Overall, the Lake Sibaya water balance revealed a net loss of water from the system, mainly attributed to groundwater seepage into the ocean (Figure 9-22 and Figure 9-23). Due to the lack of a transient aspect, the isotope water balance could not provide such a conclusion. However, the modelled findings align with the examination of observed lake level in Figure 9-24, which illustrates historical declines in lake water levels.

Observed lake levels indicate progressively lower peaks until a continuous decline from the early 2000s onwards. The updated model effectively captured the variability in lake levels and closely simulated observed data. Earlier lake water levels exhibit large fluctuations, with a trend towards declining peaks from the 1970s to the late 1990s. The expansion of forestry activities, particularly in the 1990s, coupled with below-average rainfall from 2001 to 2011 and the 2015/2016 drought (Smithers et al., 2017); contributed to the sustained decline in lake levels since the early 2000s. Concerns have been raised with regard to the deterioration in the hydrological response of Lake Sibaya, particularly evident when compared to other lakes in the region that have recovered from the 2015/2016 drought while Lake Sibaya has not recovered. However, observed lake levels from 2019 to 2021 indicate a positive response to several heavy rainfall events.

In reflecting on Aim 3 of this project, the updated model was an improvement compared to the previous model. This was evident in the analysis of the lake water level time series (Figure 9-24), which serves as the primary model validation method due to the strong interconnectivity between surface and groundwater systems in the area. The utilisation of a groundwater/surface water system to validate or predict the other is an accepted practice, as seen in previous studies like Dogan et al. (2008), who employed artificial neural network (ANN) modelling using lake levels and climate data to predict groundwater levels in north-central Florida. This approach was feasible due to the interconnected nature of surface and groundwater systems in the area, supported by a sandy surficial aquifer. This aquifer serves as the uppermost water-bearing aquifer in the region and is hydraulically linked with lakes and streams across the basin (Dogan et al., 2008), mirroring the Lake Sibaya system (Weitz, 2016).

CHAPTER 10:RELATIVE IMPACTS OF FUTURE LAND USE-CLIMATE STORYLINES ON HYDROLOGICAL OUTCOMES: IMPLICATIONS FOR THE SYSTEMS MODEL

By: S. Janse van Rensburg, MH Maseko, P Gordijn, LN Gule, B Kelbe S. Maseko, and ML Toucher

This chapter contributes towards Aim 1: *The development of a system-wide resource economics model with appropriately scaled and integrated climatological, land cover and hydrological components of the region as a decision support tool to explore net effects of plausible future trajectories for quaternary catchment W70A with Lake Sibaya's groundwater catchment as the primary response variable.*

10.1 LEARNING BY DOING

This chapter outlines the hydrological outcomes of climate future storylines and various land use scenarios, along with endeavours to connect these outcomes to economic impacts.

After the configuration of the ACRU and MODFLOW models for the past-to-current period, the goal was to simulate the hydrological response of nine alternative future land uses under two future climate storylines (Table 10-1). These responses could then be assessed in relation to the SQ outcomes, where land use remained constant, and then linked to economic impacts. The SQ simulations under both climate storylines were thus prioritised as test cases.

Interim results revealed emergent issues such as prerequisites for running the groundwater simulations to facilitate alignment with the economic model, and limitations on some of the conceptual linkages initially proposed. The results from the hydrological and climate components also enriched the interpretation of the initial results and prompted the need for additional simulations. Furthermore, it became clear that, given the issues and insights encountered, the target of seven land uses under different climate futures was ambitious and prioritisation was required.

The components and results presented here allude to the iterative learning-by-doing activities, and emphasise how the identification of limitations has informed recommendations for future improvements. Given the iterative nature of the work, the structure is somewhat unconventional.

10.2 RETHINKING CLIMATE STORYLINES

The hydrological outcomes for the future SQ and Dryland Crop scenarios, combined with findings from the climate (CHAPTER 5:) and isotope (CHAPTER 7:, Section 7.2.3) studies, revealed the need to contextualise the results based on the CMIP6 climate storylines in relation to the frequency of extreme precipitation events. This led to additional analyses using high and low rainfall frequency periods as described in CHAPTER 8:, Section 8.2.2.

The original CMIP6 future climate datasets reflected slightly wetter and drier scenarios relative to each other, but both are characterised by a low frequency of extreme events as the bias corrections were applied to the ERA5 data set from 1991 to 2000. Additionally, a 10% underrepresentation of rainfall in the ERA5 data was identified, which results in a 30% underrepresentation of recharge into the groundwater system (CHAPTER 8:, Section 8.6). Consequently, these climate storylines could be considered as representative of "worst-case" wet and dry future storylines. With acknowledgment to the importance of extreme events demonstrated within this study, the alterative ERA5 Wet climate future was also simulated to represent a period with a high frequency of heavy rainfall events. Due to time constraints in the project and the time required for running both surface and groundwater hydrological models, not all LULC scenarios were simulated for all climate futures.

The relative precipitation results, comparing the CMIP6 bias corrected and ERA5 percentage adjusted future datasets, are shown in Figure 10-1 for an example HRU grid. The initial two bias corrected CMIP6 future climate storylines generally have lower precipitation compared to the percentage adjusted ERA5 wet period (Figure 10-1). The dry percentage ERA5 adjusted period was similar to that of the initial bias corrected CMIP6 dry storyline (Figure 10-1).

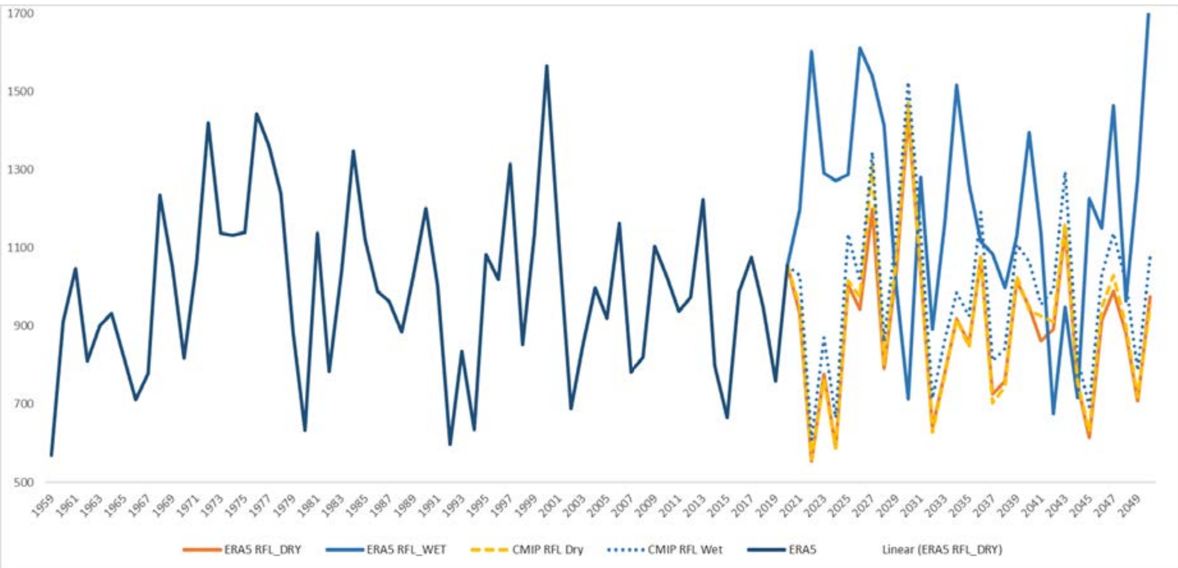


Figure 10-1 Graphical comparison of the four future rainfall storylines (2020 to 2050) in comparison to the past period (1959 to 2020)

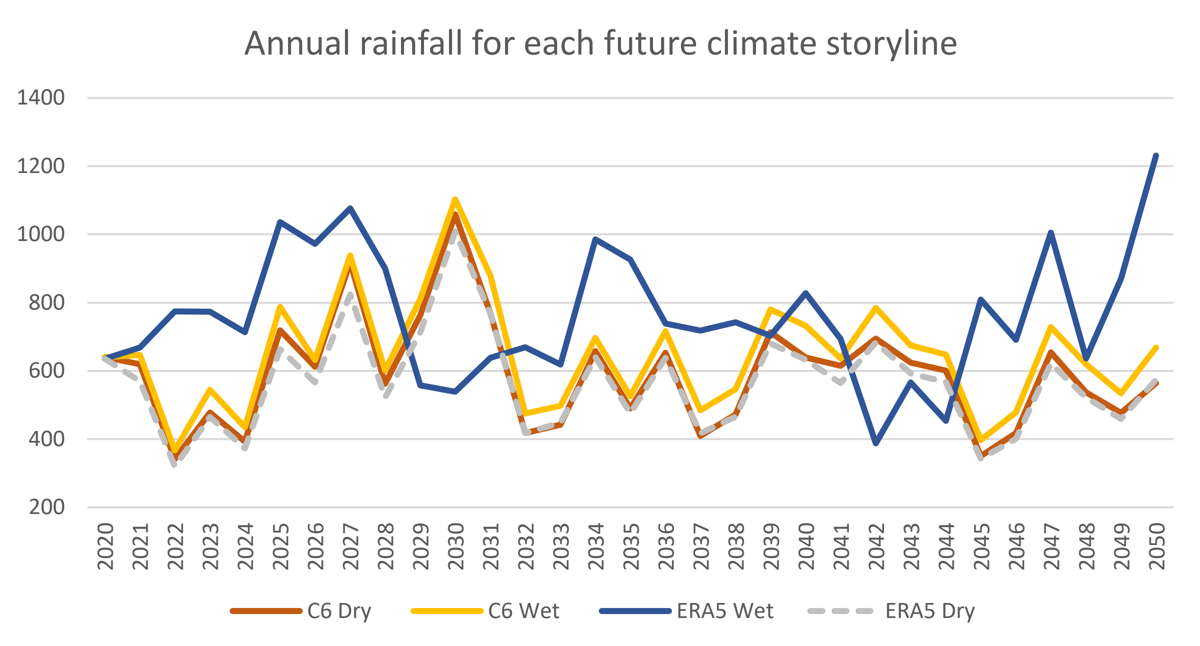


Figure 10-2 Graphical comparison of the four different rainfall storylines for the future period from 2020 to 2050

10.3 FUTURE SIMULATIONS

Initially, a maximum limit of 14 hydrological simulations was planned. Adding additional LULC scenarios pushed this to 18, using CMIP6 bias corrected climate future storylines. The additional ERA5 climate futures led to 36 modelling simulations all of which have been run through ACRU and most completed in MODFLOW. A sub set has been used in the systems economic model. For brevity, only those results most pertinent to illustrate key hydrological outcomes are presented (Table 10-1).

Table 10-1 List of all scenarios simulated by the hydrological models indicated in green Y

	Future scenarios (all past runs were based on the dynamic LULC change)	CMIP6 Bias correction, low frequency of extreme events		Different historic ERA5 periods +10%/- 10%	
		Warmer wetter	Warmer Drier	Warmer wetter	Warmer Drier
0	Status Quo	Y	Y	Y	Y
1	No Forestry	Y	Y	Y	N
2	50% loss of grassland to **Bush encroachment**	Y	Y	Y	N
3	50% Forestry block converted to **Dryland Crop**	X	Y	Y	N
4	50% Forestry block converted to **Irrigated crop**	Y	Y	Y	N
5	50% Forestry block converted to **Irrigated Macadamia**	Y	Y	Y (Not shown)	N
6	50% Forestry block converted to **Dryland Macadamia**	Y	Y	Yes (Not shown)	N

	Future scenarios (all past runs were based on the dynamic LULC change)	CMIP6 Bias correction, low frequency of extreme events		Different historic ERA5 periods +10%/- 10%	
		Warmer wetter	Warmer Drier	Warmer wetter	Warmer Drier
7	50% Forestry block converted to **Irrigated Marula**	Y	Y	No irrigation required	
8	50% Forestry block converted to **Dryland Marula**	Y	Y	Y (Not shown)	

10.4 INTEGRATING HYDROLOGICAL AND ECONOMIC OUTCOMES

A key challenge in the achievement of the aims of this project was to incorporate the hydrological consequences of significant land use changes into the economic model. Several conceptual ideas; were explored with varying degrees of success:

- **Ensure consistency of input data:** Sources of climate, rainfall, temperature and associated calculated variables as well as population growth rate data were consistent across models.
- **Develop numerical relationships linking hydrological outcomes with economic outcomes:** The most effective link found was through the water available for irrigation and how this impacted on crop/tree yield.
- **Set up target points within the MODFLOW model simulations to assess outcomes (groundwater level changes) in different positions and under different land uses in the area**: The idea was to try and work out the area of farmable wetland under different hydrological conditions. However, due to the low-resolution DEM data, this could not be achieved. As an alternative, a digitisation exercise was undertaken to provide a snapshot for illustrative purposes of wetland conditions, under the known hydrological conditions during the study period.
- **Develop a set of "rules" in relation to lake level stages that constrain or enable certain activities within the economic model**: These were initially developed prior to seeing the results. Based on the simulation results, this became a nonsensical approach and was not developed further. Instead, narrative storylines could address outcomes in relation to allocable water, based on the Reserve Determination and Resource Quality Objectives (RQOs) for the area as determined by the DWS. These aim to ensure human and ecological needs are prioritised.

10.4.1 Data Consistency and Numerical Relationships

10.4.1.1 Accounting for population growth

Throughout the project, it was crucial to maintain consistency between the components. The economic model factored in population growth. Consequently, the groundwater simulations needed to incorporate this growth for human water use abstraction. The average monthly population growth was derived from the economic model's input data. This monthly growth rate was then applied within the MODFLOW model by adjusting the lake abstraction to reflect the same percentage growth as in the economic model. Borehole water abstraction for human use was considered from the past-to-present based on available well abstraction data (Section 9.5.2) but does not account for non-registered private wells, of which there are many. However, changes in this abstraction due to population growth was not accounted for in future scenarios. Given the low human water use estimated from the HH surveys, the impact is likely to be minimal.

10.4.1.2 Irrigation: A key link to economic outcomes

Several scenarios incorporated irrigation to stimulated commercial-scale production, aligned with the aspirations expressed at the TC workshops. Irrigation scenarios included mixed crops (cultivation), macadamia, and Marula. It was necessary to determine irrigation requirements for each of these so that abstractions could be accounted for in the "irrigated" hydrological model simulations. However, the amount available for irrigation may be limited by the availability of water. While the economic model, in isolation, could assume optimal irrigation, preliminary hydrological outcomes suggested there might not be sufficient water available to achieve this. Therefore, a clear way to link hydrological outcomes with economic results emerged through the use of the availability of water for irrigation, based on MODFLOW results, to determine yield impacts and, consequently, economic outcomes.

This connection was established numerically within the economic model through damage functions (DFs) based on water availability for irrigation as determined from the MODFLOW model and temperature impacts.

To achieve the numerical links, once ACRU model outputs were available for the scenarios required, irrigation requirements were determined, based on crop water demand. Standard monthly crop coefficients (K_c) are used to calculate water demand. Accurate K_c values based on local conditions are practically non-existent and notoriously arduous to determine (Allen et al., 1998a). Various sources of information thus were consulted to decide on appropriate K_c values to work out irrigation need and DF (Allen et al., 1998a, Attarod et al., 2004, Taylor and Gush, 2014, Mashabatu et al., 2023, Ntshidi et al., 2023). These values differed slightly from those used by ACRU in some cases, as in ACRU, the K_c value represented an area and not a single crop or field, thus K_c values used to derive irrigation need and DFs could be more nuanced. While this use of DFs is conceptually sound (Roson and Sartori, 2016) it is important to note that a simplified version of DF calculations was used (see CHAPTER 11:) and that the K_c values, months for which they are applied, and methodology for the determination of irrigation needs were coarse. Sophisticated models, such as CROPWAT (Roja et al., 2020), should be used for fine scale assessments to inform these parameters in future iterations. The approach used for this project is outlined below.

Where common parameters were required for the irrigation calculations and the economic model, consistent sources were used, either derived from ACRU or calculated where necessary.

The procedure followed to determine crop water demand was FAO-56 (Allen et al., 1998b):

- The daily A-Pan reference potential evaporation as output from the ACRU model was converted to FAO Penman-Monteith reference potential evaporation (ET_0) by multiplying the A-pan values by 0.8. These values were then summed to monthly ET_0 totals.
- The monthly rainfall was summed and converted to effective rainfall (*Pe*) using:

$$Pe = PPT \leq 75\ PPT * 0.8; PPT * 0.6 \qquad \text{10-1}$$

- The crop coefficients (Kc) values used in the ACRU model to represent the various crops were used to determine irrigation requirements as well (Table 10-2).
- The actual crop ET (ETc) was calculated by multiplying Kc with ET0.

- The Pe was subtracted from the ETc to determine the "deficit crop water requirement" that the rainfall could not meet. The deficit was regarded as the irrigation demand on a monthly basis.
- This was done for both the "dry" warmer future and the "wetter" warmer future based on the CMIP6 future storylines.
- The Kc values were kept consistent within the economic model.
- These data were used to work out the precipitation deficit DF for dryland scenarios.

Table 10-2 Average monthly Crop Coefficients used to calculate Crop water need for irrigation as well as calculate DF

Month	Marula	Macadamia (ACRU)	Macadamia (Ntshidi et al., 2023)	Cassava	Ground nuts	Maize	Vegetables
Jan	0.5	0.65	0,68	0.8	0.6	1.0	0.5
Feb	0.6	0.65		0.8	0.5		0.5
March	0.5		0.21	0.6			0.5
April	0.4		0.59	0.3			0.7
May			0.44	0.3			0.7
June			0.37	0.3			0.0
July			0.32	0.3			0.5
August			0.50				0.5
Sep	0.3		0.73				0.5
Oct	0.4		0.72	0.3		0.4	0.7
Nov	0.5	0.30	0.69	0.5	0.3	0.8	0.7
Dec	0.5	0.60	0.68	0.6	0.6	1.1	0.2

The following steps were used to determine the total irrigation requirements for the irrigated scenarios:

- Irrigation requirements were only calculated for those months that each crop was "in the ground", or growing periods for trees, as reflected in Table 10-2.
- An area-based calculation was used to determine the irrigation need per crop based on the areas determined in CHAPTER 4:, Section 4.5.3 (

- Table 10-3)
- It was assumed that a total of 60% of each crop area would require irrigation, accounting for spacing and roads. The irrigation requirement calculated for Marula assumed that 40% of the area would be irrigated whereas 50% was used for macadamia, accounting for spacing, roads and inter tree distances.
- The total volume required for irrigation in mega litres (ML) was determine by multiplying the "deficit" crop water requirement" (mm) by 60% of the area in m^2. Since 1 mm per m^2 =1 litre, this was divided by 1 000 000 to get to ML.

Table 10-3 Total area and% area assumed for determining irrigations statistics per ha used in the calculations to determine irrigations

	Marula	Macadamia	Maize	Ground nuts	Cassava	Vegetables
Total area (ha)	15 500	15 500	7 600	3 900	3 100	900
Plants per ha (for yield)	200	3 000	50 000	150 000	10 000	35 000
% area irrigated	40%	50%	60%	60%	60%	60%

Once irrigation requirements had been determined, abstraction wells had to be "added" in the future MODFLOW simulations. These were required to account for the impact of irrigation abstractions in the simulations as well as assess if irrigation demand could actually be met. It was assumed that there was an investment availability for a total of 21 wells, each of which could produce up to 1 ML per day (Pers. Com Mark Schapers). The 21 wells were proportionally allocated across each traditional community area (Figure 9 3). All wells were set to be 50 m deep. Using the elevation of the wells, if the water level dropped below 45 m from the surface, irrigation was "stopped" which resulted in a deficit in relation to demand. The available water per month per scenario for those months that required irrigation was provided by MODFLOW.

Figure 10-3 Proportional allocation and positioning of irrigations fictitious wells

Since optimal irrigation requirements could not always be met, the precipitation DF was determined. This was calculated as follows:

- The total irrigation requirement per month was assessed against the available water from the 21 wells based on the MODFLOW results.

- Where there was a deficit, the available irrigation derived from MODFLOW was added to PPT and Pe was then recalculated on the basis of “irrigated PPT” and used to calculated the DF. Where requirements were met, the DF was 0. These outputs were provided to the economic modelling team. See CHAPTER 11: for further explanation of DF.

10.5 HYDROLOGICAL OUTCOMES OF FUTURE SCENARIOS

The groundwater and Lake Sibaya water level simulation over the historic period (1959 to 2021) was discussed in CHAPTER 9:. In this section, the results of future land use scenarios under three climate storylines are presented. Future scenario outcomes are illustrated as simulated water level trajectories for Lake Sibaya, which reflects groundwater trends for the study region. It is important to remember that the climate input data is associated with high uncertainties and should only be used as “what if” storylines. Focus on the assessment of the relative trends under different scenarios and understanding possible process explanations or modelling limitations is more valuable. Observed lake level records in the results extend to the end of 2023 whereas the simulated “future periods” start in 2021.

10.5.1 Status Quo LULC Scenarios

Figure 10-4 illustrates Lake Sibaya water level simulations for the SQ (SQ) LULC (holding 2020 LULC constant from 2020 to 2050) under alternative future climate storylines. This provides insight into the impact of the different climate future storylines, with all else held constant, and serves as the baseline against which subsequent LULC alternatives can be assessed.

Both CMIP6 bias corrected future climates storylines (C6Wet and C6Dry) under the SQ LULC resulted in a sustained declining lake level trend, with the C6Dry declining to a greater extent than the C6Wet (Figure 10-4). It was this initial result that prompted a review of the climate input data (see CHAPTER 8:, section 8.2.2). The bias corrected CMIP6 future storylines both reflect a period typified by a low frequency of extreme rainfall events and a generally below average rainfall, replicating the trends experienced from 1990 to 2020. Hence an additional set of climate futures storylines was simulated; one which used a period typified by a higher frequency of extreme rainfall events (1971 to 2000); ERA5 + 10% (ERA5Wet) and another which used the same period used to bias correct the CMIP6 projections (1991 to 2020); ERA5-10% (ERA5Dry) (see CHAPTER 8:, section 8.2.2).

Under the ERA5Wet, (high-frequency of extreme rainfall events climate storyline), the lake level simulation exhibits a recovery trend. Even in this extremely wet scenario, the lake level had not yet recovered to equivalent high stands in the historic observed record, before the start of the observed declining trend from 2001. However, it does come close to the simulated high for 2000/2001. The fluctuating dynamic lake levels in the ERA5Wet simulation are consistent with patterns seen in the observed record, and reflected the impact of extreme events. The ERA5Dry scenario shows the most extreme declining trend for the future period and is not considered a plausible representation of future climate. Consequently, simulation results from this climate scenario are not presented in subsequent analyses.

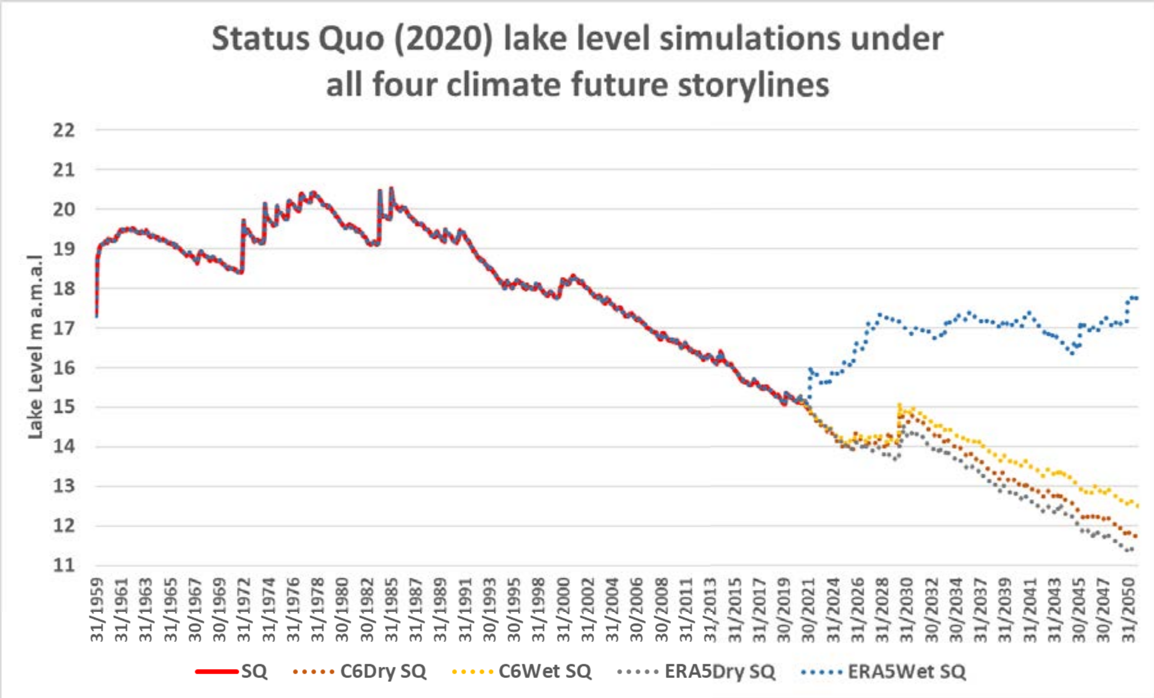


Figure 10-4 Status Quo future scenario simulation for warmer wetter and warmer drier climate, using two methods to determine future climate scenarios, with LULC held consisted from 2020 to 2050 using the 2020 land cover

10.5.2 No Forestry LULC Scenarios

A "No Forestry" LULC scenario was simulated to assess the relative impacts of forestry and climate over time. For this scenario, all forestry was replaced by grassland for the entire simulation period, with dynamic land cover change till 2020. The LULC for the future periods was based on the 2020 LULC, with all commercial plantation forestry (including "woodlots") changed to grassland.

Simulation results indicate that a 1.5 m drop in the lake level is due to commercial plantation forestry, and reflect its impact on the linked groundwater table (Figure 10-5). The dynamic LULC time slices used the 1990 LULC as a baseline for the pre-1990 period. There are indications of bush encroachment and forest expansion between the start of the simulation period (1959) and 1990 (Figure 10-6). Hence the pre-1990 simulation period likely underestimates the amount of grassland in the system. Grasslands have higher recharge rates then thicket and indigenous forest (see CHAPTER 8:, section 8.7). It is likely that with a more accurate vegetation land cover over the full simulation period, the simulated impact of the "No Forestry" LULC scenario on "current day" water levels would be more pronounced.

The declining trend observed in both the SQ and "No Forestry" LULC scenarios from 2000 to 2020 under the C6Wet (Figure 10-5) and C6Dry (Figure 10-7) climate future storylines provides evidence of the climate's impact on the groundwater system. This is consistent with results from CHAPTER 5: and CHAPTER 7:, as there were fewer extreme rainfall events, vital for groundwater recharge, over this period relative to the past.

Collectively these results demonstrate that commercial plantation forestry exacerbates the impact of below average rainfall in the region. Consequently, by 2020, the system was below the ecological reserve drought water level threshold (should not have more than five consecutive years < 16.5 AMSL), a situation that would have been avoided in the absence of commercial plantation forestry.

The "No Forestry" LULC scenarios for both the C6Wet and ERA5Wet climate storylines result in significantly higher lake levels relative to their matched SQ LULC scenarios (Figure 10-5). However, the trend between the "No Forestry" LULC C6Wet and ERA5Wet climate futures is divergent. The ERA5Wet climate future simulates a lake level recovery to match historic simulation high stands, whereas the C6Wet climate future simulates a declining trend, consistent with the C6Wet SQ. The latter again demonstrates the significant impact of below average rainfall on the system, regardless of land use. However, the current water crises would only have been experienced around the year 2050 had commercial plantation forestry not been initiated. The overall higher lake levels under the no forestry scenarios is a clear trend. The relatively long recovery time of the lake even under a high frequency wet scenario is noteworthy.

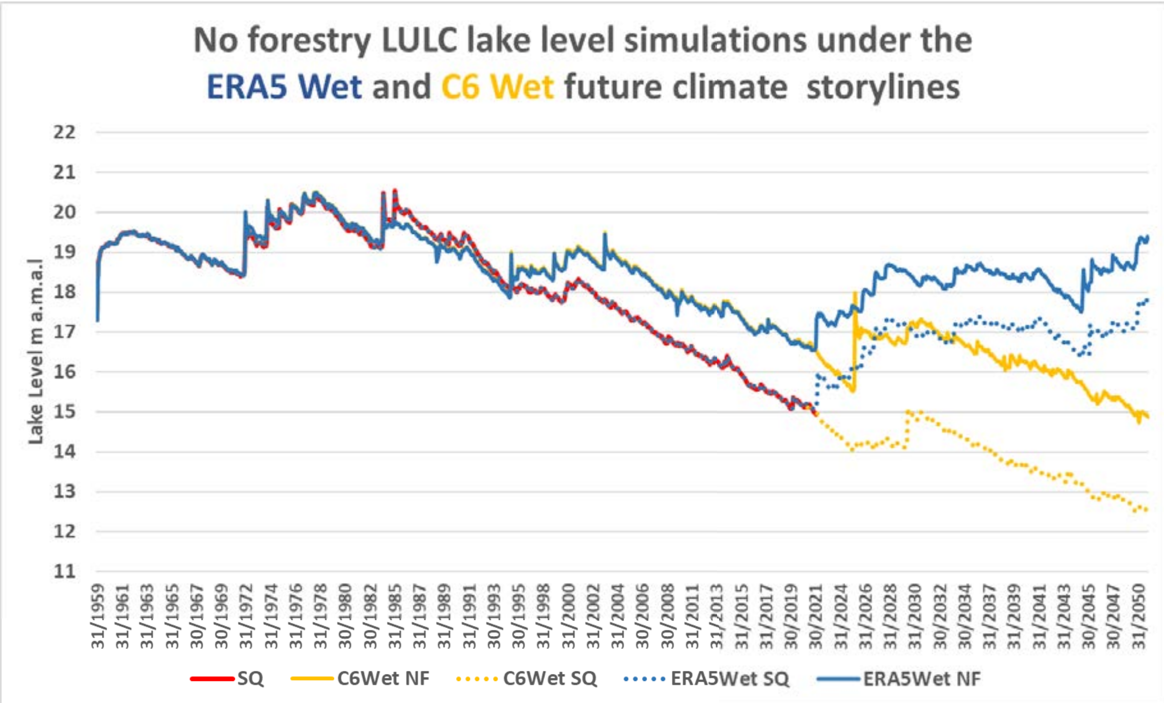


Figure 10-5 Comparison of past to present and future lake level trends for the No Forestry LULC scenario relative the SQ LULC, under CMIP6 bias correct wet and ERA5 +10% wet future climate storylines

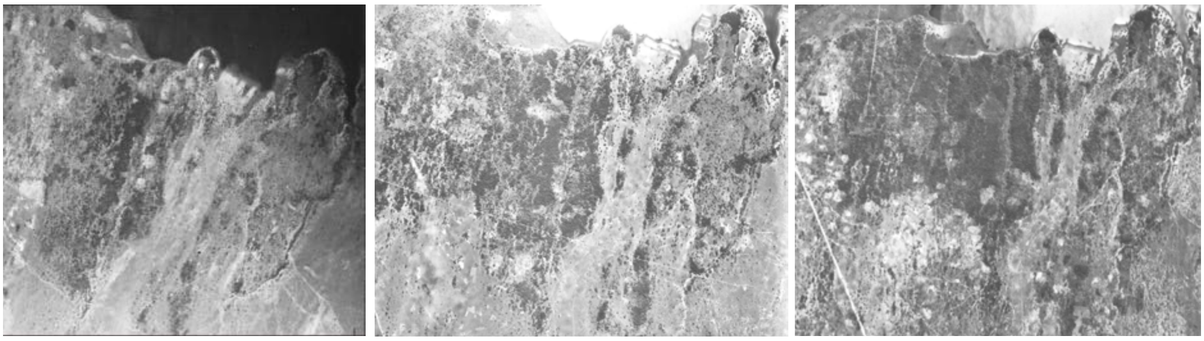


Figure 10-6 Aerial photos from 1942 (left) 1971 (middle) and 1990 (right) indicating evidence of LULC change prior to 1990. Portion of western arm, south of Mseleni, Lake Sibaya area

Under the C6Dry climate future storyline, if forestry had never been initiated, the system would have only reached the crisis levels experienced in 2018, by 2044 (Figure 10-7). There is a slightly greater difference (0.5 m) in the 2050 lake level No Forestry and SQ LULC scenarios between the C6Dry and C6Wet climate future storylines.

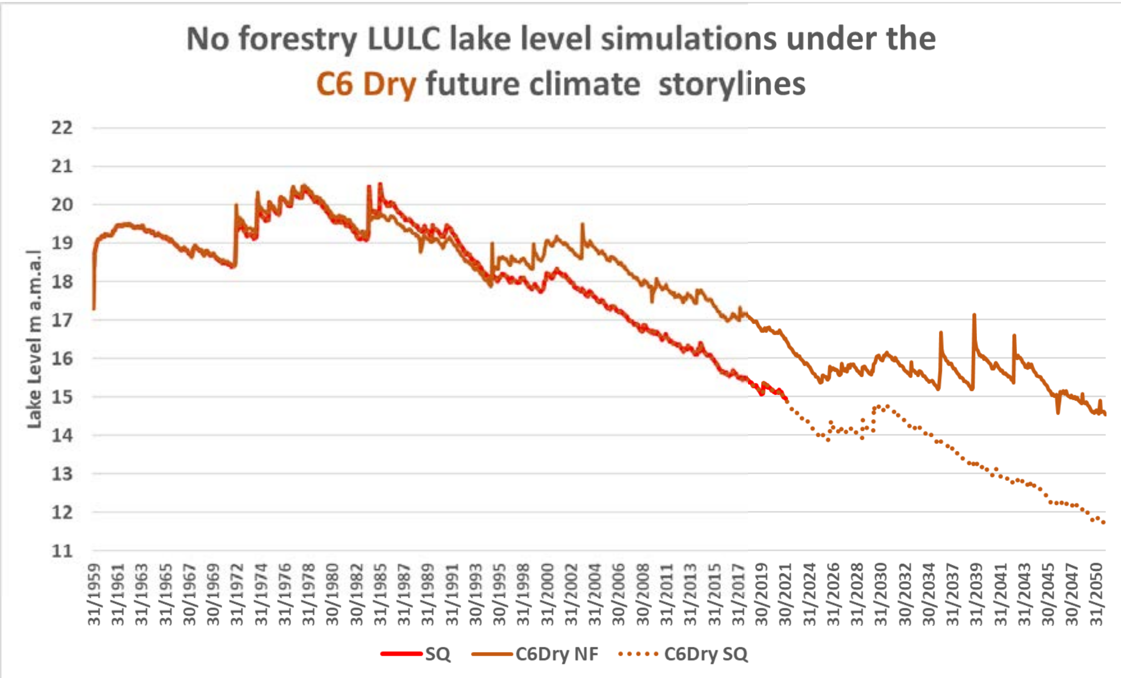


Figure 10-7 Comparison of the No Forestry LULC scenarios against the SQ LULC under the CMIP6 Dry future climate storyline

In the rest of the future scenario simulations, the data presented focus in on the 2015 to 2050 time period.

10.5.3 Bush Encroachment LULC Scenarios

Bush encroachment was raised as a concern in the initial TC workshops as well as in the 2023 workshops and knowledge exchange (see CHAPTER 13:). A dominant perception is that there has been a significant increase in indigenous woody species (bush encroachment) that replace grasslands. People suspect these increases may impact on groundwater. In response to community members' requests, the loss of grasslands to bush encroachment was thus considered.

Replacement of 50% of the grassland area within the AOI to bush encroachment (thicket) as of 2020 results in slightly lower lake levels relative to the SQ over time for the C6Wet and C6Dry future climate storylines (Figure 10-8). No consistent pattern is evident in the ERA5 wet scenario. In all cases the general trend matches that of the respective SQ trends.

As noted in the "No Forestry" LULC scenario section, the extent of grassland for the entire simulation period prior to 1990 is likely an underestimate. One recommendation for future simulations is to conduct a similar experiment to that of a No Forestry run, and reduce the thicket areas prior to 1990 based on improve vegetation cover for the whole model domain to see if there is a more conclusive impact. Estimates of actual ET over a bush encroached landscape will aid in the reduction of the uncertainty related to the K_c values used to represent thicket in the ACRU model. Current results suggest, however, that bush encroachment impact is insignificant compared to that of forestry, but produce the worse outcomes in conjunction with commercial plantation forestry.

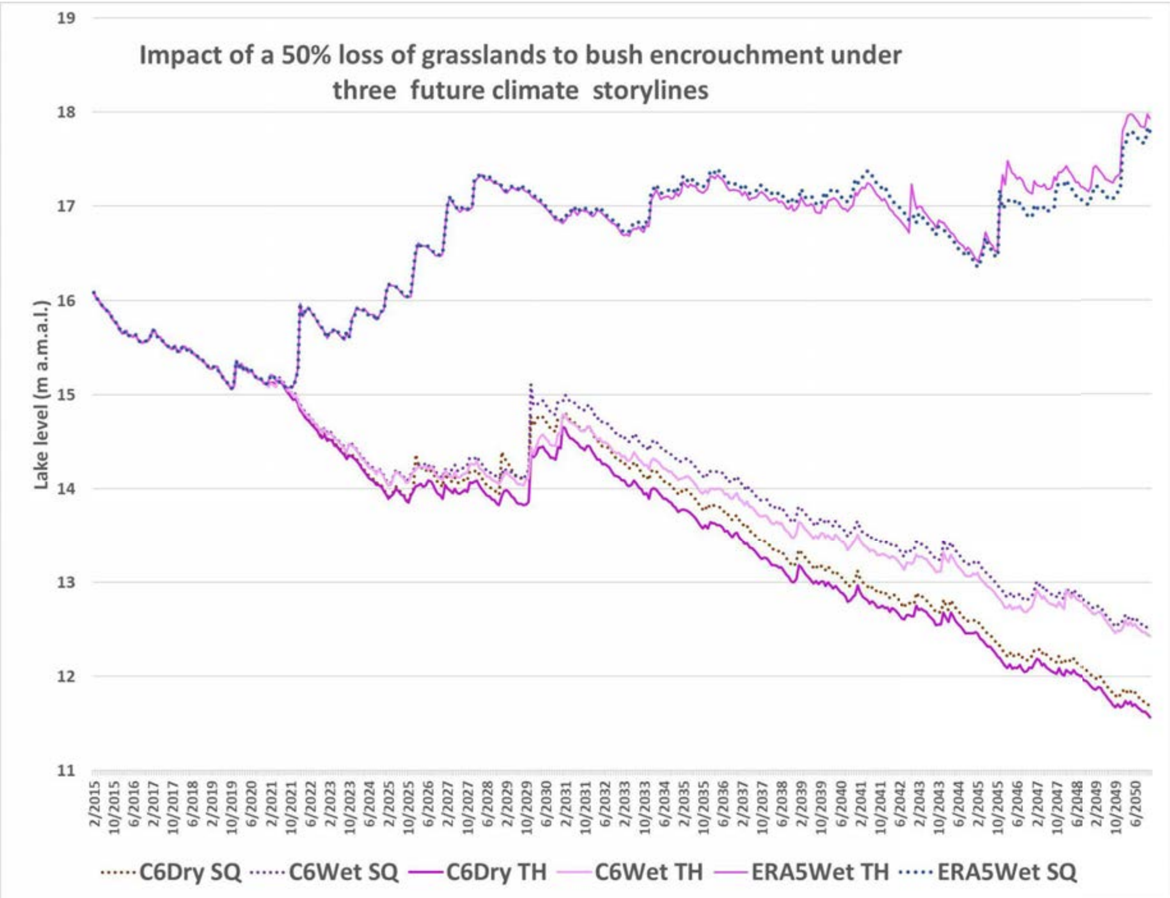


Figure 10-8 Comparison of 50% increase in bush encroachment (thicket) future scenario against SQ using for C6Wet, C6Dry and ERA5Wet future climate storylines

10.5.4 Dryland Crop LULC Scenarios

Figure 10-9 illustrates the future lake water levels for the Dryland Crop (rainfed) LULC scenario under CMIP6 wet and dry and ERA5Wet future climate storylines. In this scenario 50% (15 500 ha of 31 000 ha) of the commercial plantation forestry area was “converted” to Dryland Crop. The change area is within the formal forestry blocks and partitioned spatially in accordance with ownership as described within the TMM 2014 Business plan and described CHAPTER 4:.

The simulated lake level trends for Dryland Crop are consistent with their matched climate SQ scenarios (Figure 10-9). Replacement of 50% of the commercial plantation forestry with Dryland Crop from 2020 results in slightly higher lake levels relative to the SQ over time all future climate storylines. The extent to which the Dryland Crop LULC scenarios diverge from the SQ appears to increase towards the end of the simulation period, hinting at a lagged recovery trend relative to the SQ. The slightly higher lake levels for Dryland Crops are in contrast to the slightly lower levels in the bush encroachment scenario for both the C6 wet and dry futures (Figure 10-8). While consistent, the differences are slight but can be viewed in relative terms.

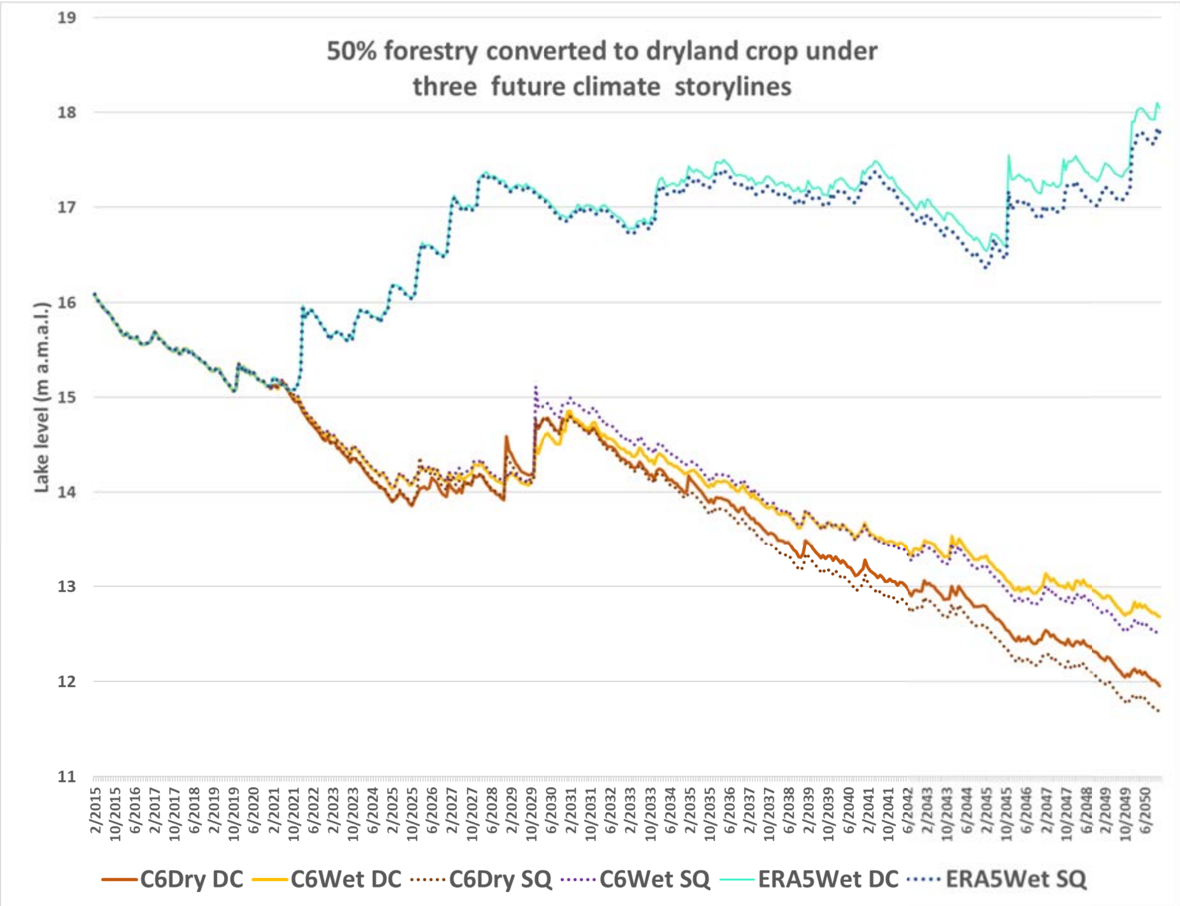


Figure 10-9 Dryland Crop scenario with 50% of the area of forestry within the AOI converted to cropland under for methods for determine climate future

10.5.5 Crop-Irrigated LULC Scenarios

Irrigated Crop scenarios were simulated to assess the impact of abstraction on the water table. Irrigation volumes were restricted by the number of wells (21); a maximum pumping rate (1 ML per day); and cessation when water levels dropped below 45 metres BGL. Likely due to these restrictions, there was no evident difference between the Irrigated-Crop and SQ LULC under the C6Dry climate future (Figure 10-10). Irrigation in the C6Wet future scenario resulted in noticeable but insubstantial drops in the water table compared to the C6Wet SQ, particularly evident during the period of increased water tables (2030 to 1931) (Figure 10-10). This suggests that, as the water table rises, more water becomes available for irrigation, and its removal leads to a decline. However, for both scenarios, water levels remain well below the required reserve, technically prohibiting irrigation under these circumstances.

In the ERA5 wet scenario there was no substantial difference between the SQ and the Irrigated Crop trends, however, at the end of the periods the water levels were slightly higher than the SQ. Under this climate future, despite irrigation, the water table continues to recover.

10.5.6 Macadamia – Dryland and Irrigated LULC Scenarios

The impact of converting 50% of the forestry area to Macadamia LULC scenarios was simulated for irrigated and dryland (rainfed) conditions under both C6 climate futures (Figure 10-11. The trends for the Macadamia LULC scenarios are consistent with the matched SQ climate futures. Rainfed Macadamia scenarios resulted in higher lake levels towards the end of the simulation period, relative to the SQ whereas the Irrigated scenarios resulted in lower lake levels especially in the C6Wet climate future. While the relative rate of decline towards the end of the simulation period is lower in the Dryland Macadamia under both future climates, these are insufficient to reverse the declining trend within the simulation period.

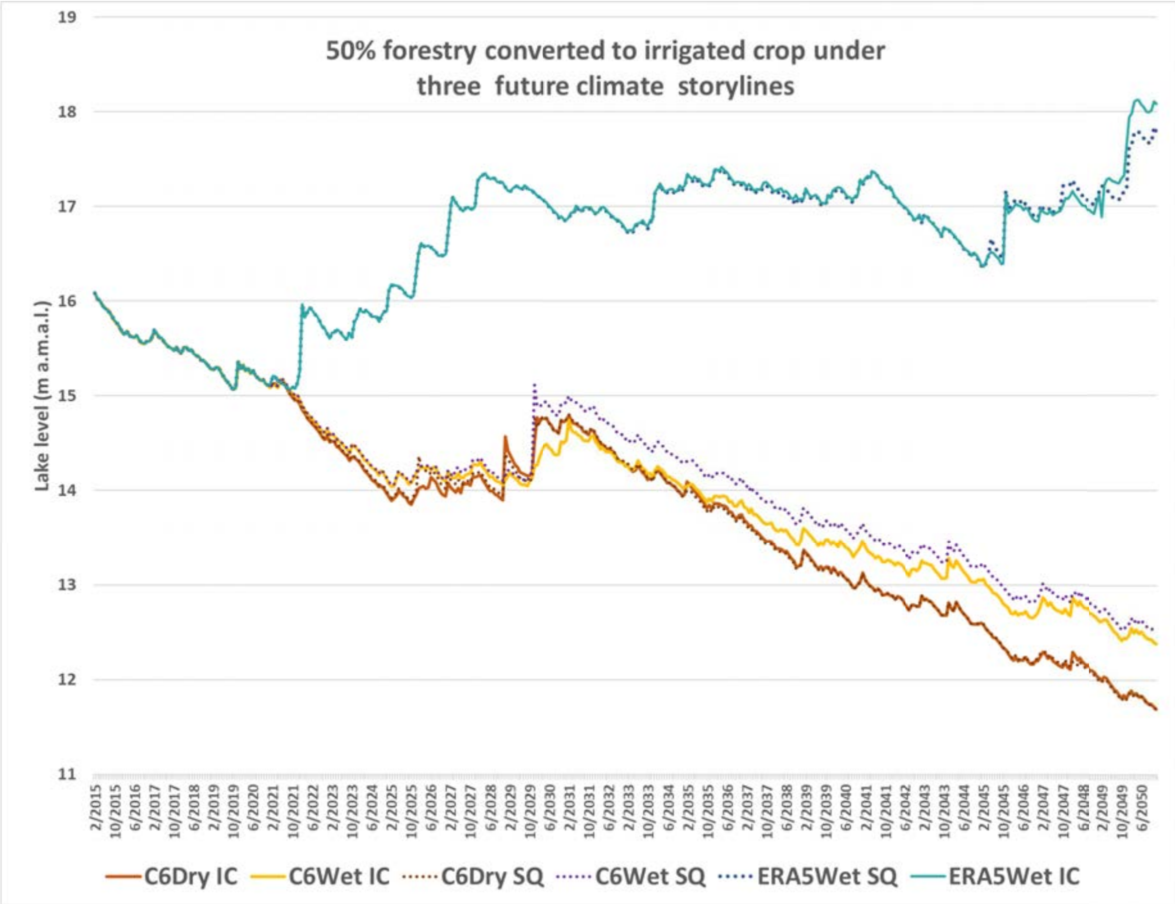


Figure 10-10 Comparison of Irrigated Crop LULC scenarios under the C6Wet and C6Dry climate future storylines

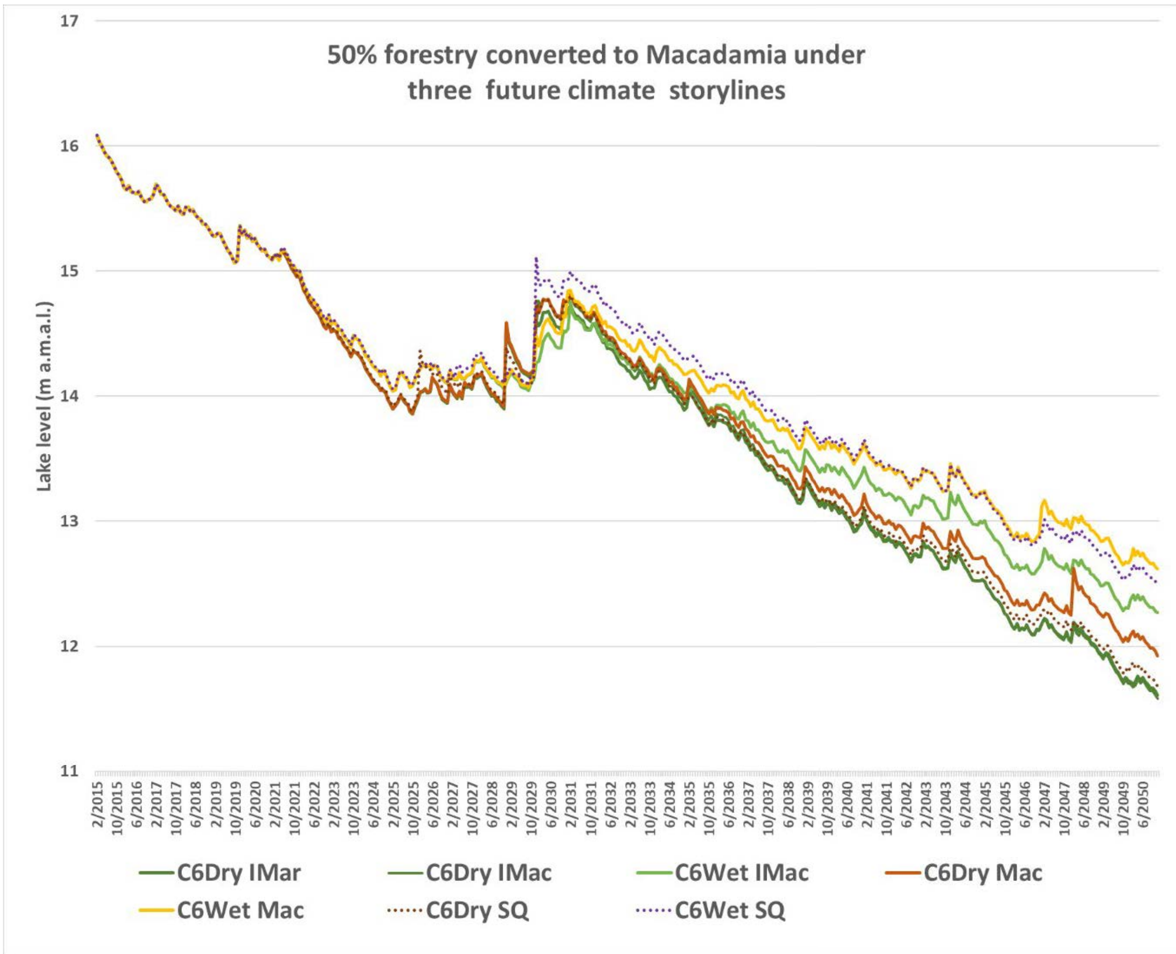


Figure 10-11 Comparison of Irrigated and Dryland Macadamia LULC scenarios under the C6Wet and C6Dry climate future storylines

10.5.7 Marula LULC Scenarios

Wild Marula is a source of food and income in the area. A novel suggestion from one TC group was to replace eucalyptus forestry with Marula plantations. Given that they grow naturally in the area and are a potentially high value crop, thus this scenario was also simulated. There was, however, very little data to parametrise the Marula vegetation and water use parameters required in the model with confidence. The Marula LULC scenario was simulated for irrigated and dryland (rainfed) conditions under both C6 climate futures.

The trends for the Marula LULC scenarios are consistent with the matched SQ climate futures. As with macadamia, Dryland Marula scenarios resulted in slightly higher lake levels towards the end of the simulation period, relative to the SQ scenarios whereas the irrigated scenario resulted in lower lake levels. While the relative rate of decline towards the end of the simulation period is lower in the Dryland Marula under both future climates, these are insufficient to reverse the declining trend within the simulation period. Marula is one of the most water efficient trees when compared to other indigenous fruit trees. Maximum water use of Marula is less than that of plantation species such as eucalyptus and pine (Gush et al., 2015; Ntshidi et al., 2022).

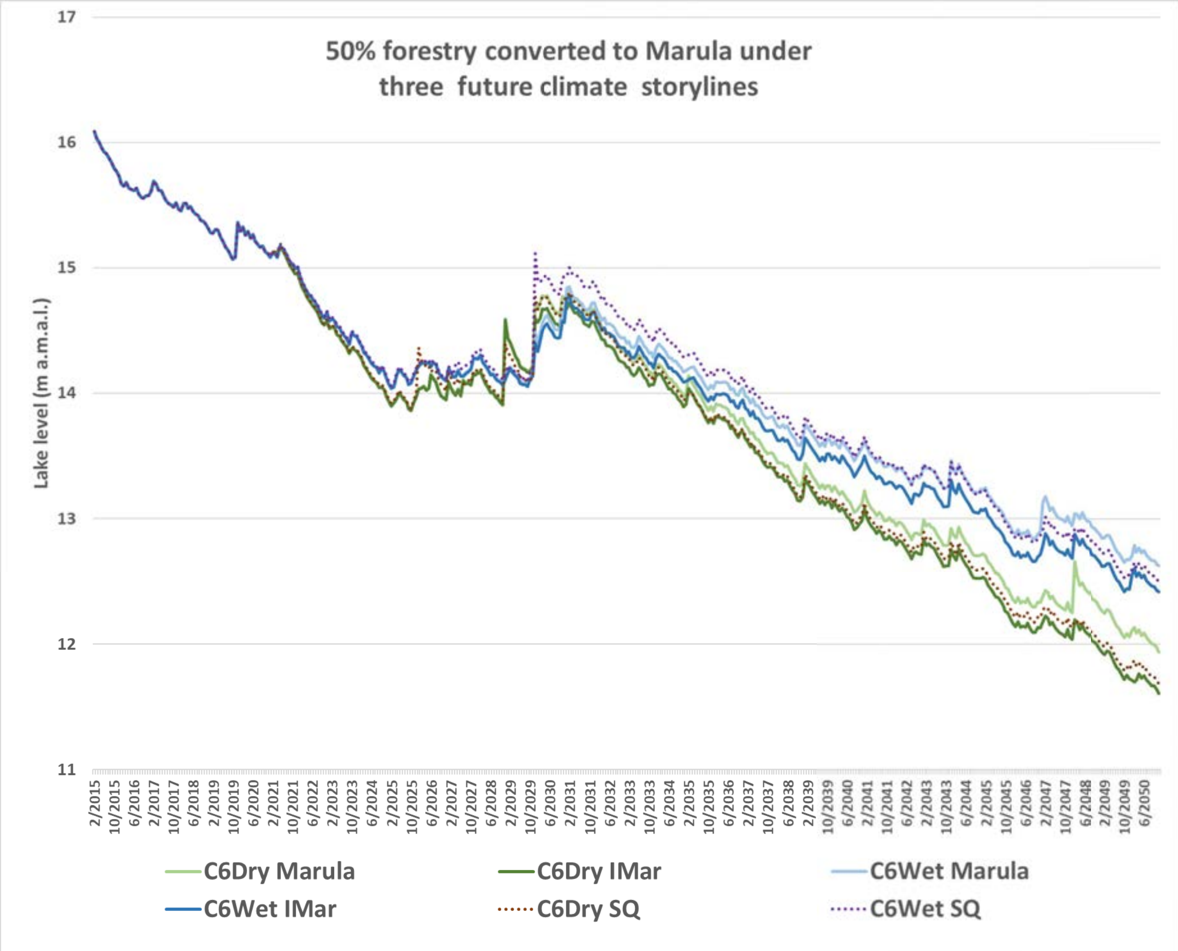


Figure 10-12 Comparison of Irrigated and Dryland Marula LULC scenarios under the C6Wet and C6Dry climate future storylines

10.5.8 Summary Comparisons

The scenario with the best overall results was the No Forestry LULC scenario under the ERA5Wet future. Following an extended drought period, typified by a low frequency of extreme rainfall events (1990 to 2020), the most rapid and best recovery of the groundwater system was under this scenario, where recovery to the level of historic simulated high stands was achieved by 2050. The No Forestry scenarios under the C6Wet and C6Dry futures, both typified by a lower frequency of extreme rainfall events, resulted in declining lake level trajectories, demonstrating the impact of climate on the system. However, crisis lake levels would only have been experienced in the 2040s. The difference between the SQ scenarios and the No Forestry scenarios represents the degree to which commercial plantation forestry has increased risk to vulnerable communities, leaving them more exposed to anticipated future climate knocks. This provides the motivation to alter current land use urgently.

Observable relative differences are evident in different LULC change scenarios regarding the rate and extent of lake level declines, however these were relatively small (Figure 10-13, Figure 10-14 and Figure 10-15). Bush encroachment under the C6Dry future storyline (Figure 10-13) had the most observable negative impact relative to all SQs and all other LULC scenarios. This was most evident in the early periods and become less significant in the later period, as the climate signature becomes more dominant.

Excluding the "No Forestry" scenario, a change of 50% of the current commercial plantation forestry area to a Dryland Crop LULC had the least negative impact on the water resource, relative to the all other LULC scenarios, under all climate futures (Figure 10-13, Figure 10-14 and Figure 10-15). The influence of changing to a Dryland Crop (removing 50% of the forestry) will take a long time to see an influence, however, it will have a positive influence on Lake Sibaya water levels over time. Irrigation had a negative impact relative to the SQ for the C6 future climates and was inconsistent in the ERA5Wet scenario.

The impact of climate in the future periods was evident in the sustained declining trend under both C6 climate futures, regardless of LULC change, in stark contrast to consistent recovery trends under all LULC scenarios under the ERA5Wet future climate storyline. These extremes represent, best-case and worst-case future climate storylines. Should there be a drying trend into the future, only a drastic land use change, i.e. extreme removal of commercial plantation forestry, will influence the lake level, otherwise rainfall will be the overriding factor. The next step would be to simulate a more plausible "mid-range" climate future storyline to ascertain if a radical change in land cover would improve the water situation sufficiently to compensate for the cumulative impact that commercial plantation forestry has had over time on the water table. Simulations where a larger proportion of forestry is removed may also be useful to test.

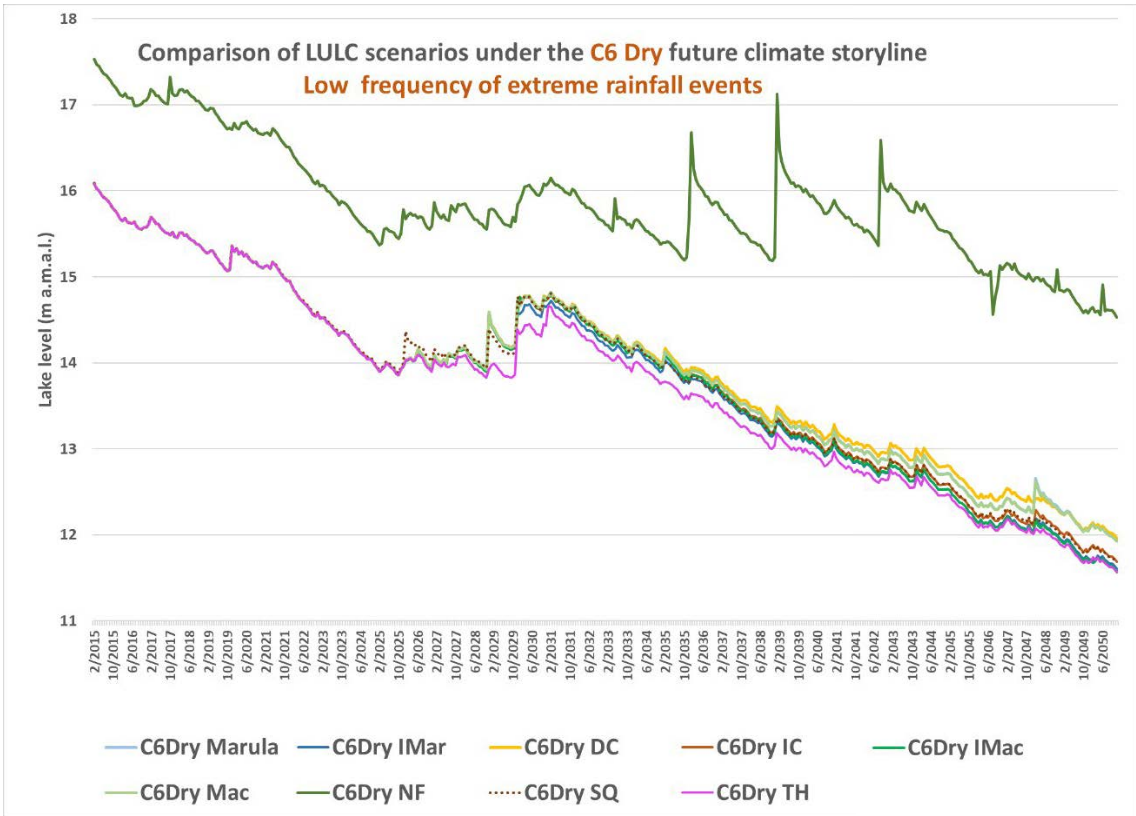


Figure 10-13 Comparison of all LULC scenarios under the C6Dry climate future storylines

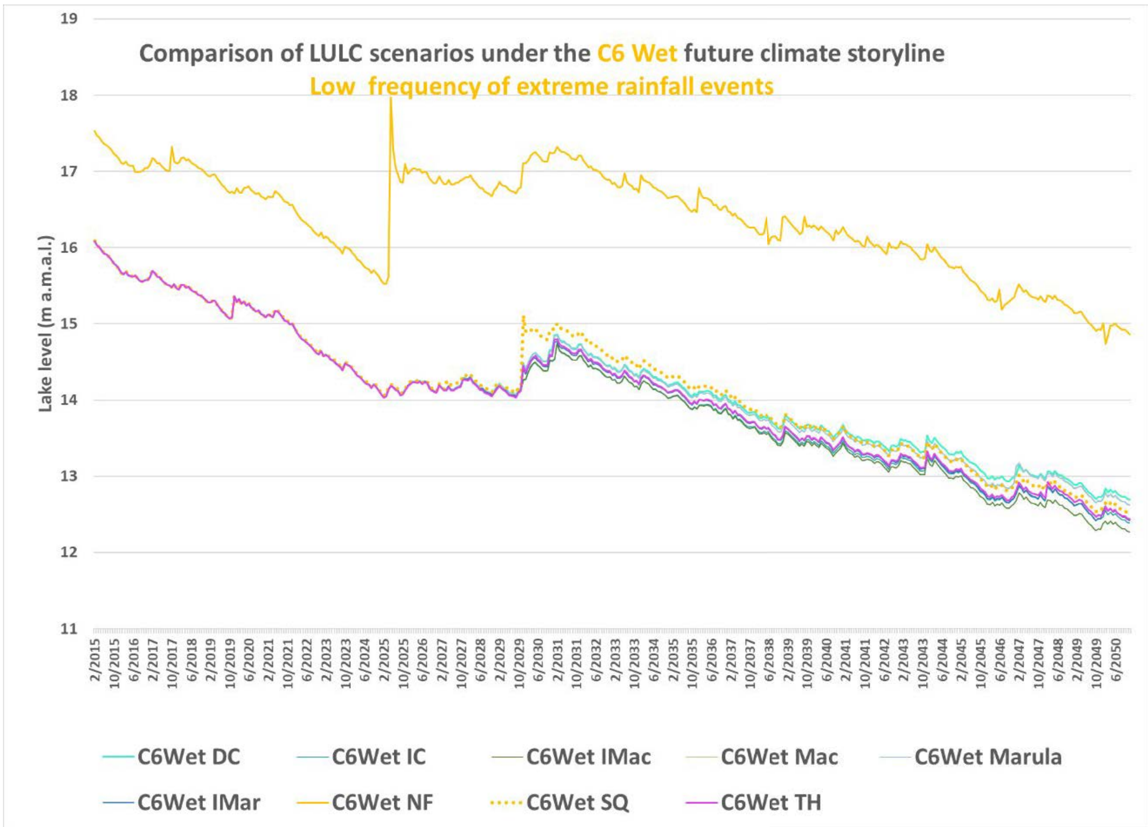


Figure 10-14 Comparison of all LULC scenarios under the C6Wet climate future storylines

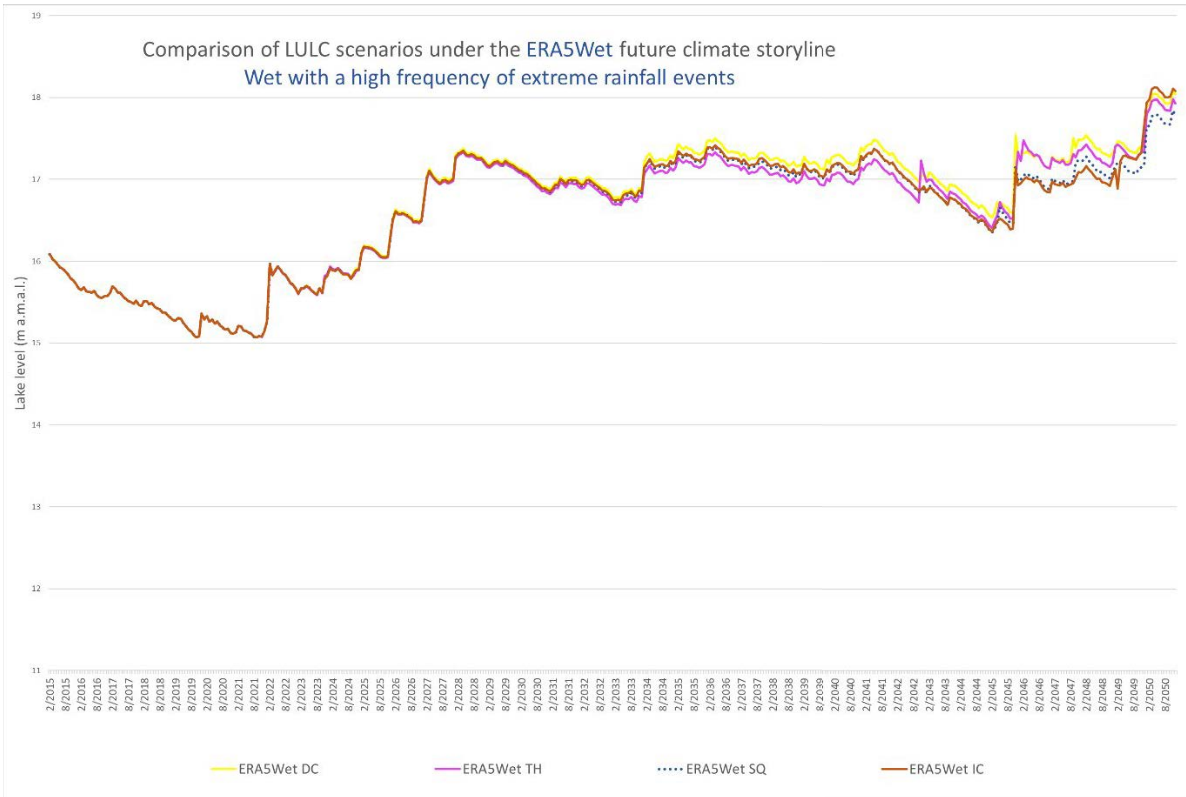


Figure 10-15 Comparison of all LULC scenarios under the ERA5Wet climate future storyline

10.6 RULES IN RELATION TO LAKE LEVEL: THE ECOLOGICAL RESERVE

DWS (2015) conducted a Reserve Determination for the Lake Sibaya catchment area, which recommended the lake should not fall below the Recommended Ecological Category for the whole lake; it should be maintained in a B/C condition. The recommended lake levels to achieve this were provided. Graham et al. (2020) revised the Reserve Determination, noting that the lake had exceed the recommendations and the levels set in the DWS report. They noted, given the extent of deterioration in the system due to declining lake levels, a major intervention would be required (removal of eucalyptus plantations) to ensure the recommended ecological state of the lake was restored. They, thus, revised the determination to an Alternative Ecological Category (AEC). The AEC was established as a worst-case scenario which would ensure that the lake stays in a C condition relative to the water levels specified in the DWS 2015 report. All the scenarios for the C6 future climates would breach these recommendations. Hence, under these climate futures for the economic model, while the net outcomes of irrigation scenarios can be assessed, these technically will not be permitted.

Table 10-4 Comparison of original DWS 2015 REC and the revised Graham et al. (2020)

DWS 2015: specification to maintain the lake in a B/C condition	Graham et al. (2020) revised AEC	2023 status
Reflect natural climate conditions, in particular five to six-year averages in rainfall, as well as shorter term (one year) rainfall conditions;	Reflect natural climate conditions, in particular five to six-year averages in rainfall, as well as shorter term (one year) rainfall conditions;	Not achieved since about 2010
Retain variability, including periods of high and low water levels;	Retain variability, including periods of high and low water levels;	Not achieved in the last 23 years
Maintain median water levels over a 30-year period between 17.39 and 18.48 m AMSL;	Maintain median water levels over a 30-year period should be between **16.89 and 17.98 m** AMSL.;	Unlikely to be achieved with 2000 as a starting period
Not have more than five consecutive years < 16.5 m AMSL (as a drought water level threshold); and	Not have more than five consecutive years < 16.5 m AMSL (as a drought water level threshold); and	Lake level has been below this level for over seven years
Have at least six years in a 30-year cycle > 19.2 m AMSL.	Have at least one year within a 30-year cycle > 19.2 m AMSL.	

When applications for additional abstraction for human use are considered, given the status of the lake at the time (approx. 15.2 m AMSL in the main basin and about 5 m in the south basin), Graham et al. (2020) recommended pumping should stop from the south basin and the Mbazwana well field should be used as the alternative. For the Mseleni abstraction plant, it was recommended that pumping should only be done to supplement the Mseleni well field.

10.7 IMPLICATIONS FOR WETLAND FARMING

A major concern for the region is the decline in status of its wetlands (Van Deventer et al., 2021). This is driven by changes in the water table as well as use by people. In the past, when the water table was much higher than it is currently, several wetlands outside of the protected area and further inland, would have been wet enough for farming, However, as the water table declined, these wetlands dried up and only wetlands close to or within the protected area were wet enough to farm. This led to the encroachment of wetland gardening into the protected area, including clearing of endangered swamp forest, which resulted in conflict between the community, conservation, and ecotourism businesses. Following recent heavy rains, however, a number of these planted wetlands became flooded, and the farmers lost their crops. This dynamic points to the sensitivity and risks associated with wetland farming and the possible knock-on consequences for people's livelihoods and the integrity of the wetlands. The peat in many of these wetlands took thousands of years to form and, once lost, is irreplaceable. The question is whether wetland degradation, which results from the decline in the water table, would have occurred if commercial plantation forestry had not been imposed in the region?

During work in the area, various places were noted that had clearly previously been farmed but were now degraded, with little or no organic matter left, and abandoned. This provided the idea to try and estimate the loss of these important wetland ecosystems due to the combined impacts of poor farming practices as well as the decline in the water table. There are methods for the wise use of wetlands to ensure that people can continuously benefit from them, while protecting their integrity. If there is a link between wetland degradation and economic impacts, this would strengthen the case for the promotion of wise use as well the diversification of income streams to improve adaptative capacity.

To assess the current condition of wetlands, a sub-area within the AOI was selected to digitise and categorise "farmed" wetland areas within 1 km of Lake Sibiya (Figure 10-16), using QGIS with the most current Google Earth image to map. The outcomes were then incorporated into the interpretation of results from HH surveys (CHAPTER 11:)

When the images were digitised, the condition of each polygon was estimated as one of the following categories – abandon green (meaning evidence of farming but not current and the area is still vegetated, so presumably still partially intact soils); abandon Unknown (evidence of farming but condition difficult to assess); dry degraded (areas where there is clear evidence of prior farming, but currently has no/little vegetation, with high degree of white sand exposed ("no" organic material left)); semi-degraded (in-between abandon green and dry degraded); and wetland cultivation (evidence of current cultivation (Figure 10-17).

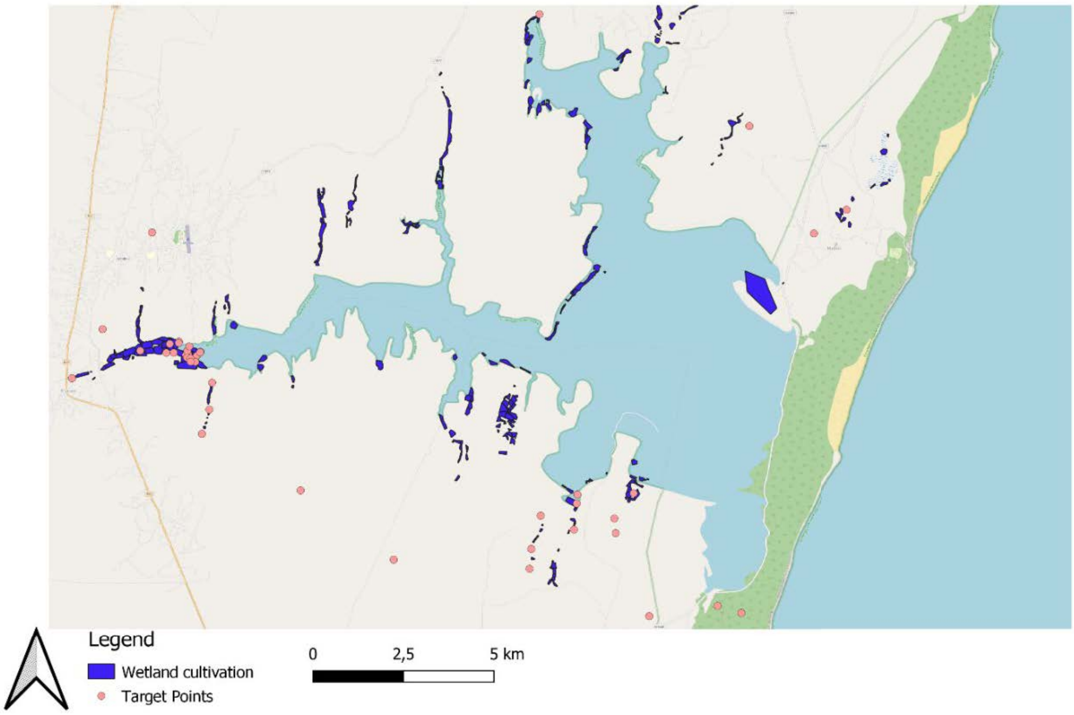


Figure 10-16 Areas around Lake Sibaya identified as wetlands either currently being farmed or previously farmed. Targeted points requested as outputs from the economic model are included for reference

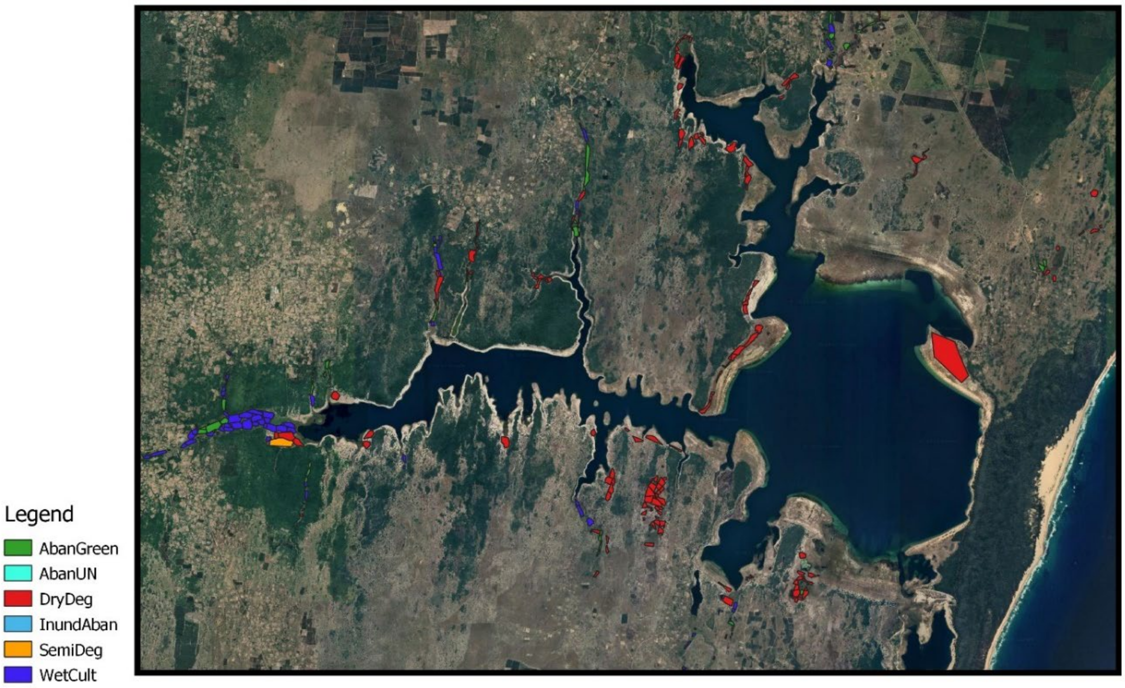


Figure 10-17 Areas of wetland cultivation according to the various categories used to estimate condition

The total area estimated as “wetland cultivation” (either now or in the past) is 418 ha. Of this total area, 59% was categorised as “dry” degraded which represents the area possibly permanently lost with respect to essential wetland function (Figure 10-18). The extent of area currently being farmed around the lake is estimated at 107 ha which is 26% to the total area mapped. Green abandoned areas account for 12% percent of the area and the combined remaining categories 3% of the total area. It should be noted uncultivated wetlands were not mapped because it is not possible to assess if “pristine” wetland identified would be suitable for farming from the imagery

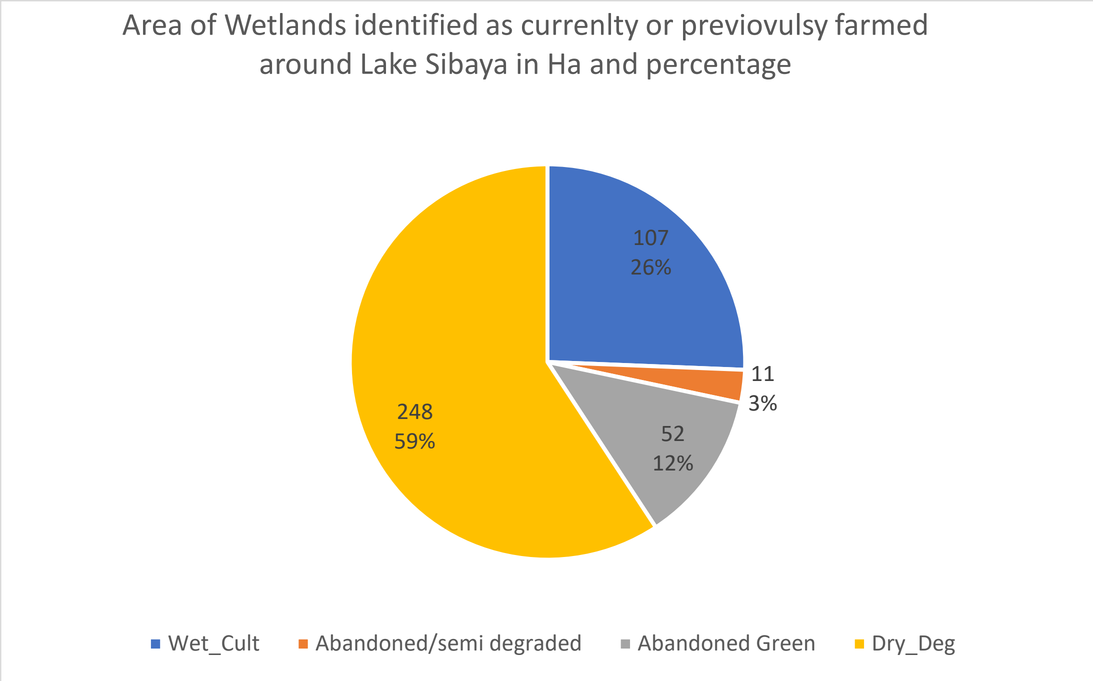


Figure 10-18 Estimated area of cultivated wetlands per category mapped around Lake Sibaya

The next step was to assess the implication of wetland degradation on household livelihoods as well as determine the economic and employment outcomes of the alternative LULC scenarios under the three future climate storylines.

CHAPTER 11: SYSTEMS MODEL: NET OUTCOMES OF FUTURE LAND USE-CLIMATE STORYLINES

By: S. Maseko, S. Janse van Rensburg, LN Gule, MH Maseko, N Mkhize and J Blignaut

This Chapter addressed Aim 5: *Estimate the net economy-wide impacts and consequences of several plausible trajectories of climate and compatible land use-land cover change for the quaternary catchment W70A region.* As well as Aim 1: *The development of a system-wide resource economics model with appropriately scaled and integrated climatological, land cover and hydrological components of the region as a decision support tool to explore net effects of plausible future trajectories for quaternary catchment W70A with Lake Sibaya's groundwater catchment as the primary response variable*.

11.1 INTRODUCTION

Studies that model the impacts of climate and land use changes on the economy separately, or those that are sector-specific, may fail to account for the "confounder" effects caused by the interplay between these factors (Dinar et al., 2012). Integrated assessments that consider water, land use, and climate change generally focus at national or regional scales and are insufficient to inform local decisions (Howells et al., 2013). Furthermore, the economic consequences of these physical impacts are comparatively poorly studied (Auffhammer, 2018). Given the integrated nature of social ecological systems, methodologies for understanding the interplay between climate change, productions systems, and economics are, However, under development, such as the translation of climate change impacts into to yield damage functions (DFs) with economic consequences (Roson and Sartori, 2016). The ULM within the MCP in KZN has experienced rapid land use change (increasing afforestation with eucalyptus) and prolonged drought, both of which are contributing to a decline in the water resource (detailed in CHAPTER 4:, CHAPTER 5:, CHAPTER 9: and CHAPTER 10:). An increase in water scarcity is likely to threaten food security and livelihoods that are dependent on aquatic ecosystems, an increased risk in an already vulnerable population that climate change shocks will only exacerbate. This project aimed to investigate the interplay between the climate, land use, water resources, and the ULM economy at the local scale, in response to a societal need for waterwise economic alternatives to eucalyptus plantations.

Previous studies in the study area demonstrated that the population exhibits a high dependence on food production and natural resources-based livelihoods, many of which are associated with aquatic ecosystems (Moll, 1972, Bruton, 1979a, Pooley, 1980, Cunningham, 1985, 1990; Mountain, 1990). More recently, tourism has been shown to complement natural resource-based livelihoods (Oldham et al., 2000). A dominant narrative in the region suggests that forestry is crucial for the economy, however, Oldham et al. (2000) demonstrated that ecotourism offered better returns and has greater potential for a positive impact in the area. The trade-offs in employment, economic security, and water security between forestry, other sectors, and natural resource livelihoods have not been quantified in this region, particularly in the context of climate change. Recent water yield determination studies demonstrate that radical land use change interventions are needed to ensure enough water for human use and ecosystem integrity, which supports natural resource-based livelihoods (Graham et al., 2021). Alternative land uses that improve economic and water security are, thus, required and should ideally be informed by a holistic analysis of the consequences associated with these choices.

Through engagements with TCs, water scarcity, unemployment, poor economic growth, and a number of concerns related to natural resource (ecosystem) integrity were identified as primary challenges in the area (CHAPTER 4:, Section 4.5.2). The lack of alternative economic activities is often cited in defence of plantations, despite an understanding of their high-water usage. Some companies actively promote forestry as the only economically feasible investment (SA Forestry, 2012) – a notion explored in this study. Others are more concerned about the negative impacts of forestry on other livelihoods. Contrasting views are often informally held in the absence of neutral discussion platforms within community structures, which may be characterised by varied power dynamics. Consequently, the achievement of a shared common goal of sustainable economic development that benefits all can be hindered (Aucamp, 2019). Participatory science and data driven information may provide a neutralising focus for the facilitation of debates and the shift of mindsets towards a more water sustainable future.

Climate and land use change impacts are often felt simultaneously through their impact on water availability. The variation in water availability may also influence sectorial and household outcomes and behaviour. These complex dynamics require an equally dynamic method to capture interactions and feedback. The System Dynamics approach, which is grounded on understanding interactions and suited for understanding complex systems over time, is thus ideal for the investigation of linkages between biophysical factors (climate and hydrological processes) and the ULM economy.

11.2 SYSTEM DYNAMICS

System dynamics is a technical tool and method to describe and model a dynamically, i.e. ever-changing, and complex, i.e. multi-varied, system (Pruyt, 2013). It is also a way of thinking. Consideration of a range of interactive processes, the information behind these processes, and the embedded thresholds in dynamic complex systems, system dynamics provides a framework to think through dynamically complex processes in a robust and structured manner. Doing so assists the researcher to seek the best way to bring a range of variables, of diverse units and dimensions, together. Yet, it does so by the distillation of a high degree of rigour and discipline as the model outcomes can easily be verified as the outcome and the system behaviour are linked to and caused by the system structure. If any anomaly is found through the application of a range of tests, among other structural tests, the basic architecture or the theory of the model is wrong and should be revised.

System dynamics was developed by Forester towards the end of the 1950s within the context of system engineering (Forrester, 1958, 1993, 1997). Since then, its application has mushroomed in a range of disciplines such as environmental economics (Vundla et al., 2016; Bester et al., 2019; Crookes et al., 2020). System dynamics have been used within the context of climate change (Arroyo M and Miguel, 2019; Sarindizaj and Zarghami, 2019), cropping or conservation agriculture (Smith, 2006) and animal husbandry (Godde et al., 2019; Blignaut et al., 2022). Moreover, system dynamics (SD) modelling has also been used in water resource management in Iran and Mexico; sustainable land use management in Sweden; and climate change adaptation and energy in South Africa (Luna-Reyes et al., 2013; Blanco et al., 2017; Gohari et al., 2017; Carnohan et al., 2021). It is, therefore, a well-accepted and broadly endorsed means of investigation, with broad application. This project aimed to integrate the impacts of climate, land use and hydrological processes on net outcomes through the use of a system dynamics approach to explore multiple future scenarios.

11.3 RESEARCH OBJECTIVES

The objective of this component of the study was to contribute to the assessment of the current and future well-being of the region in relation to four key challenges identified by the communities themselves: water security, employment, economic status, and natural resource integrity. Specifically, data on the socio-economic circumstances of households was gathered to assess the relative contribution of different employment and income sources as well as household water security, to determine the impact of commercial plantation forestry on current household status. Household challenges and land use preferences were also explored. A system dynamics approach was then used to build a model for the ULM region to explore the relative outcomes of alternative LULC scenarios under several future climate storylines.

This marks the initial attempt at developing a model for this region, specifically targeting intricate socioeconomic, climate and hydrological interactions. Hence, it focuses on providing a model structure, with the understanding that parameterization can be improved over time.

The model was informed by:

- Estimates of the economic value of different land uses and activities (sector and household-based) as well as general household dynamics (covered within this Chapter).
- Plausible climate and land use scenarios for the region (covered in CHAPTER 4:, CHAPTER 5:).
- Understanding the diversity in terms of land use and economic sectors (covered in CHAPTER 4: and this chapter).
- Outcomes of the loosely coupled ACRU-MODFLOW model which assessed the impact of future land use-climate scenarios on the water resource (Covered in CHAPTER 4:, CHAPTER 5:, CHAPTER 8:, and CHAPTER 10:).

11.4 METHODS

The four primary challenges distilled from community engagements as described in CHAPTER 4: were water, employment, economic status, and natural resources integrity. The alternative land use scenarios, informed by TC workshops, are listed in Table 10-1. The derivation of the datasets for the two future climate scenarios used for both the hydrological and economic models is detailed in CHAPTER 8: section 8.2.2. The intention was to assess the feasibility and net outcome of alternative future scenarios in relation to the key challenges identified, through the use of a system dynamics approach. To determine a measure against which outcomes could be compared, priority was given to the development of the model based on the SQ scenario, with no change in land use, under the two future climate storylines. Based in initial results from hydrological scenarios, additional system dynamics runs were prioritised to demonstrate the functionality of the model.

11.4.1 Data Sources

Despite the economic challenges in the area, there is a scarcity of existing economic research. Both primary and secondary sources were utilised to collect the necessary data for the assessment of the socioeconomic status of the region and as input data for the system model. Primary data sources encompassed information gathered through household and sector surveys. Secondary data was gathered by reviewing published and grey literature. The economic data provides a description of the baseline situation of the area's economy from both a household and business perspectives.

11.4.1.1 Household surveys

A HH survey approach is a well-reviewed and widely applied method in research, especially in the field of social sciences, for the collection of household socioeconomic information (Statistics South Africa, 2018). In this study, a HH survey was designed to generate baseline information on household economic activities; access to water; the impact of extreme dry and wet conditions on households; information on their coping strategies; and elicit households' preferences on land use futures (Appendix D). The NRF-SAEON Ethics Guidelines were adhered to in the development and application of these surveys.

The data was collected in the three communities involved in the study namely Mabasa to the west of the lake; Mbila/Zikhali on the south side; and Tembe on the northern side of the Lake Sibaya groundwater catchment.

The questionnaire was developed in four stages, namely, i) a desktop study to improve understanding of the area and identify which variables were important for this study; ii) consultation with key informants about the area to complement desktop information and direction of the study; iii) workshops with community leaders to further enhance the development of the questionnaire; and iv) piloting of a questionnaire in the area for two weeks and then refinement and training of enumerators.

The HH survey questionnaire had four main parts: Part 1, which focused mainly on perception, behaviour, and water supply; Part 2, which covered socioeconomic information with a focus on demographics as well as household livelihoods and also a section on households' food security; Part 3, which focused on climate change and included household perception of climate change, climate change impact on livelihoods, and coping strategies; and Part 4, which assessed the preferences of participants between four future land use climate scenarios relative to the key challenges identified through the TC workshops.

The survey data was collected between June 2022 and October 2022. All respondents approached were advised of what informed consent meant and were provided with a copy of the consent form (Appendix E). The interview only proceeded if consent was given and was stopped if so requested. Roughly equal numbers of households from all villages within the Lake Sibaya groundwater catchment were randomly selected. The target was to sample 100 household in each community area (300) sampled, however, with COVID-19 related start delays and logistical constraints, fewer households were sampled (223). Survey teams consisted of two project interviewers who worked independently, each with a guide appointed from the local community and a project team driver to transport the team to ensure that remote locations were also reached.

11.4.1.2 Sector surveys

A semi-structured questionnaire was developed for sector interviews (Appendix F). Representatives from different sectors who operated in the area, including tourism, conservation, and commercial plantation forestry, were approached with requests to be interviewed either online or in-person. Supplementary information was sourced from literature.

11.4.2 System Dynamics Modelling

The core justification to the use of the SD approach is that it has proven consistently to be adaptable to the assessment of climate, land use, and resource management research. It also allows flexibility, which ensures that the model structure fits the issue under investigation and study area. Here, the use of SD modelling was extended to assess the relationship between climate change scenarios and land use choices and their impact on employment and economic outcomes in the ULM, moderated by water availability and climate impacts.

The Vensim software was used to develop the model. Simulation plays a large part of SD models; the model runs for 27 years, which is equivalent to 324 monthly time steps from January 2024 to December 2050. The model entitled *ULM Lake Sibaya Catchment Model* (ULMCatchMOD), includes a qualitative component illustrated through the use of a causal loop diagram and a quantitative component with stock-and-flow diagrams (simulation). The scenarios do not change the model structure, only the value of certain variables change.

11.4.2.1 Causal loop diagram

Figure 11-1 shows the conceptual framework that illustrates the causal and feedback relationships between variables (processes, sectors) in ULM. Climate is an exogenous factor, and not influenced by other variables in the area. Hydrological processes, economic activities, household income, business revenue, and land use are assumed to be endogenous to the study area:

- **Climate:** The climate has a direct influence on hydrological processes and economic activities. For hydrological processes, precipitation is the primary driver of surface water and groundwater levels. Alongside this, the climate directly impacts crop productivity. It is important to note that the sensitivity of economic activities to climate or hydrological changes varies.
- **Hydrological processes and economic activities:** The feedback (blue dotted causal loop) between hydrological and economic activities is explained by water as an important input in production (directly or indirectly) whilst the same economic activities impact hydrological processes. For example, forest plantations exploit groundwater for growth which is well known to reduce groundwater recharge.

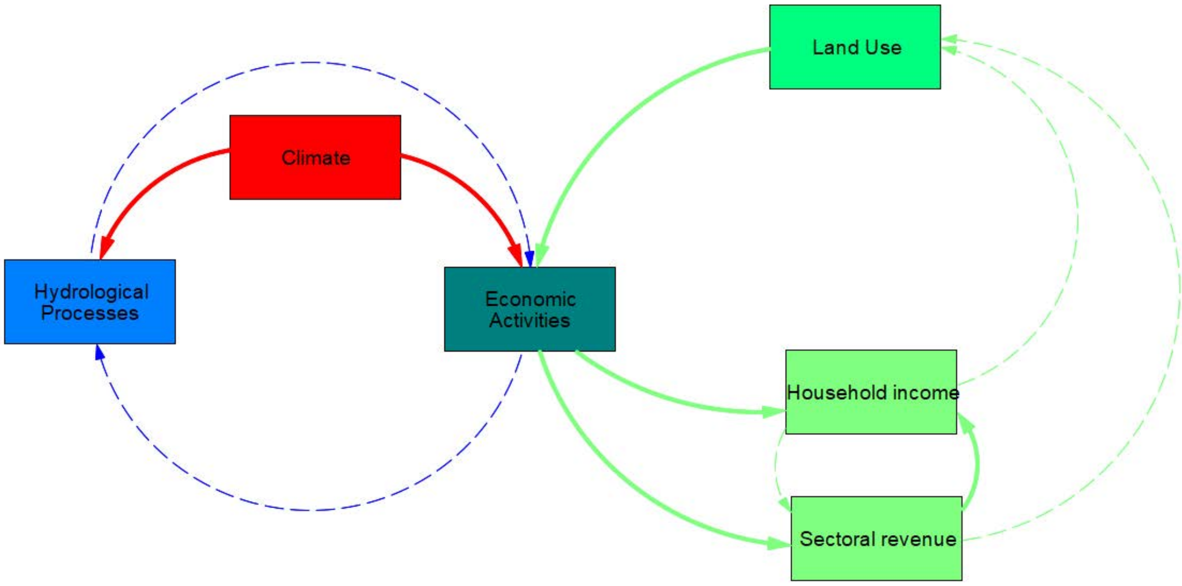


Figure 11-1 ULMCatchMOD conceptual model

- **Land use:** Land use distribution influences the nature of the ULM economy, i.e. the type of economic activities (See CHAPTER 4: for details).
- **Economic activities:** Economic activities generate income and revenue for households and businesses respectively as shown by the arrows from "economic activities to households" income and sectoral revenue. The potential number of employment opportunities was used to compare the different scenarios (land use). In an ideal economy, households would influence sectoral revenue, e.g. tourism, however, the main market is external. This may be due to the low socioeconomic status (little disposable income) to spend on tourism.

- **Household and sector:** One of the reasons commercial plantation forestry rapidly expanded over the years is the perception that local people have of it being the most economically viable industry in the area. Viability of land-based economic activities often attracts more investment which leads to expansion. This is illustrated by the green dotted arrows from household income and sector revenue to land use. However, the model is currently not set up to capture this dynamic, partly because feedback (coupling) to the hydrological model was not possible as the ACRU hydrological model cannot efficiently cater for "live time" dynamic LULC change. Every change in LULC currently requires a revised configuration and simulation within ACRU which, while possible, is time consuming. An exploration of alternative ways to achieve such coupling this is recommended as a future advancement, including the use of alternative surface hydrological models that can be used to determine recharge.

11.4.2.1.1 Stock and flow diagrams

The model consists of three sub-models: land use, household economy, and sector economy. Some of the exogenous variables used in the model are presented in the boundary table in (Appendix H). The model was built such that it can be replicated for the three tribal areas as well as for the whole system.

11.4.2.1.2 Land use land cover (LULC) sub-model

The land use sub-model aggregates and models the different LULC types; settlements, cultivation, conservation/ecotourism, forestry, and grasslands as seen in Figure 11-2. The blue solid arrows show the SQ land uses while the dotted dark arrows show the land use change scenarios modelled. (See Appendix I for the detailed model of land use). The conservation area was included but not modelled. The inclusion allows for future extension of the model. The sum of the LULC (Combined-LU) is equal to the area of interest (Max Size) at any given point in the simulation. Degraded areas, wetlands and the lake were omitted from the total size of the area. Each LULC class has a stock value in hectares (ha) which is the land size at any given time. The LULC area values are from 2020. Stock variables in the LULC sub-model include settlements, forest plantations, conservation, macadamia, dryland cultivation, wetland cultivation, thicket, grassland area, and the alternative LULC scenarios choices. Changes in the LULC stock values are driven by expansion (inflow) or decline (outflow) rates. Stocks are a key variable that can be used to explore alternative stock size of land use classes and how they impact the economy. For the purposes of this project, these were aligned to hydrological land use scenario runs. The components of the land use sub-model are explained below:

- **Settlements** – These consist of residential (household) and developed areas. They have two stocks: population and settlement area. The residential area is determined by multiplying the average residential area by the number of households. A population growth model was applied based on current growth rates. This can be used to project changes in the extent of residential area; as the population grows, available land would decrease, as more land is required for housing. However, monthly time set changes in the extent of the residential area could not be included efficiently into the ACRU hydrological model for the future LULC scenarios. Technically the economic model could be used to provide a feedback to the LULC grids imported into the ACRU model to inform the extent of change in the area of settlements, and, based on economic drivers, which LULC would be converted. It is recommended that how this could be achieved efficiently should be further explored to produce a more powerfully integrated economic-hodological feedback in future iterations. The water use required for the increasing populations was however accounted for in the MODFLOW model through increased abstraction, tied into the population growth rates used in the ULMCatchMod.

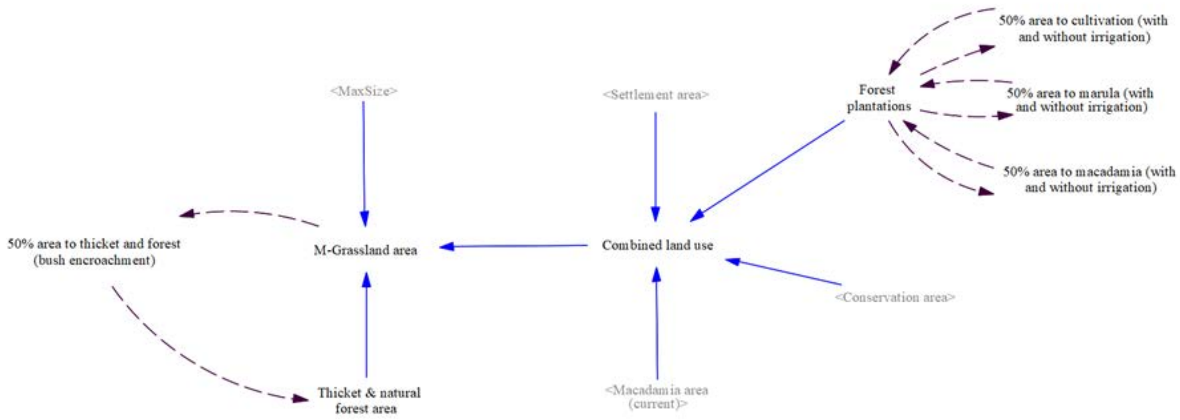


Figure 11-2 A Simplified LULC sub-model (Stocks). The blue solid arrows show the SQ LULCs, the dotted dark arrows show the different LULC scenarios modelled

- **Dryland Cultivation** – Cultivation areas consist of areas under household dry and wetland cultivation. They take place in different areas. Dryland cultivation in the model, which is often within household boundaries, does not influence land use change, but is influenced by the number of households involved in cultivation and the average area cultivated. Since wetland cultivation involves wetland use, it does not influence change since wetland areas were omitted in the LULC sub-model area. The household cultivation component can be used for the estimation of productivity (tons/value per hectare). Changes in the area under household cultivation area is calculated as the difference between the number of households involved in cultivation and the percentage of households that stop cultivating. For wetland cultivation, the cultivated area is influenced by changes in either groundwater or surface water. Although attempts were made to link these changes with hydrological dynamics, this was not possible due to poor resolution elevation data.

- **Forest Plantations** – Forest plantations consist of eucalyptus and pine trees. However, due to the insignificant area of pine, declining interest in this species, and that the hydrological model only estimated eucalyptus water use, the contribution of pine plantations to the economy was not modelled spatially but could be added in future iterations. The total area of forestry AOI of interest within the model included the formal forestry blocks and the small-scale commercial plantations. The 50% "change area" used for the scenarios was restricted to the area within formal forestry blocks but equated to 50% of the total combined formal and small-scale commercial plantation forestry area.

- **Macadamia** – The macadamia model consists of one stock which is the area under macadamia cultivation. Macadamia is only modelled as a commercial sector as an alternative to eucalyptus within the 50% change area.

- **Conservation** – The model includes subroutine for conservation areas, however, it is not explicitly modelled in this project as a land use change. The assumption is that the conservation area will not change but the amount/occupancy of tourism and associated activities and infrastructure can.

- **Grasslands** – The grassland area is the residual; the difference between total area size and stock values of the above-mentioned land use and thicket area at any given time.

11.4.2.2 Household economy sub-model

The household economy sub-model models how households in the study area generate income (Figure 11-3). These include service-based (salary, grants and remittances) and commodity-based (crop cultivation, livestock, crafting (reeds), traditional medicine and Lala Palm wine) income-generation activities. The model can track the monetary value of selected economic activities over time expressed as net present value (NPV). The value includes cash income and imputed income. For a household that produces maize and sells a portion of it, the value would be the total yield produced and not the value of portion sold. Damage functions were used to capture the effect of climate (precipitation and temperature) on yield (See section 11.4.2.3).

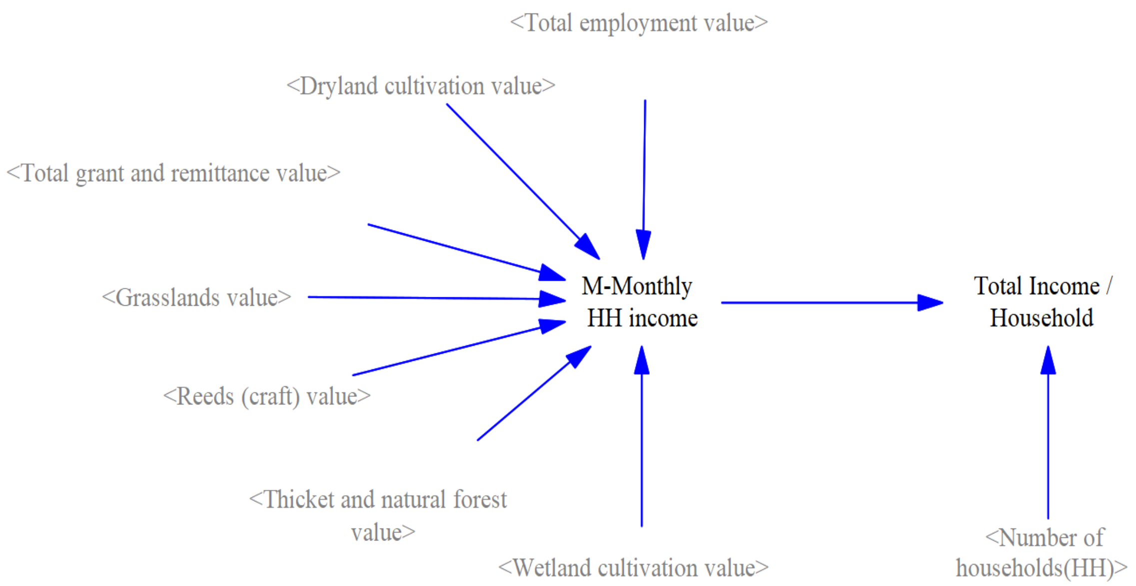


Figure 11-3 Household economic activities sub model

11.4.2.2.1 Employment, grant and remittances value

These economic activities are simulated to better understand whether there are disparities between genders. The model uses a linear relationship between the percentage of households that generate income from employment, grant, and remittance, and the average monthly household income. The value of employment (total salary) is linked to the population and the fraction of households in the different sectors. Such information is important in the study to estimate the percentage of the population employed in each industry and to understand the income generated by households from the sector. The same approach is used in grants and remittance components.

11.4.2.2.2 Household generated value

- **Dryland and Wetland cultivation:** This component simulates the economic returns of crops including groundnuts, maize, cassava, sweet potato, taro (Amadhumbe) and banana. The total value of crop production is influenced by the percentage of total households involved in cultivating specific crops; the average quantity of produce per household in tons; climate impact; and local prices (unit price). The value of household crop production was estimated and compared the value of the cultivation methods and the impact of climate on specific crops. Dryland cultivation benefits (value) in the model are also influenced by climate, while in the final structure the model will also link wetland cultivation to changes in lake and groundwater levels.

- **Livestock**: The value of livestock in the area was also simulated through the use of the number of livestock units per household involved in livestock farming, and livestock birth-rate and death rate. The stocking rate has a bearing on productivity, with over stocking leading to poor production and optimal stocking rates that result in optimum production. A change in the percentage of livestock sold per year to reflect different levels of commercialisation, enables the model to simulated the benefits from livestock as well as their productivity.
- **Resource Harvesting**: These include crafting (reeds), and medicinal and traditional beverages. They are modelled separately and, as with the methods for subsistence cultivation, the value of each industry is influenced by the percentage of total households involved and average household income per specific period.

11.4.2.3 Crop damage functions

An important integrator between the different project components was climate data. Damage functions are a method to explore the effects of physical impacts (temperature and rainfall) on economic outcomes (Roson and Sartori, 2016) and have been used to understand the relationship between changes in climatic conditions and economic outcomes (Hsiang et al., 2020; Nordhaus, 2017; Tol, 2002). The DF approach is used to express the magnitude of the impact on welfare by different levels of exposure to an external factor. Hence, a key link between the climate, hydrological component and economic component was the assessment of DFs based on the climatic data as well as available (deficit) water for irrigating (obtained from the groundwater model).

The following subsections explain the DF approach used to understand precipitation and temperature effects on crop yield dose-response relationships. The procedure is replicated for all of the crops, i.e. cassava, groundnuts, maize, and vegetables (based on cabbage) as well as Marula and macadamia scenarios.

11.4.2.3.1 Precipitation effect

While refined models now exist for accurate determinations of crop yields, the original FAO Cropwat model provided a valid simple methodology for first approximations for understanding the impact of water changes on crop yields (Steduto et al., 2012). This is suitable for rainfed production. The method assumes that water stress (ET) is closely related to the reduction in yields. This relationship is expressed in the water function formula (World Bank, 2022):

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y\left(1 - \frac{Pe}{ET_c}\right) \qquad \textit{11-1}$$

On the right-hand side, *Pe* and ET_c are the effective rainfall and crop water needs, respectively. K_y is the yield response factor that constitutes the reduction of ET to yield loss, which accounts for a unique crop specific response to a water deficit. The resultant estimates are equal to the deficit (yield loss) between maximum yields (Y_x) and actual yields (Y_a). When $Pe = ET_c$, crop water requirements are met and yield will be optimal. A deficit occurs when the $Pe < ET_c$ (FAO, 1978), resulting in a reduced actual yield. The model uses monthly Pe and ET_c values for the production period for each crop. The input data for *Pe*, ET_o, ET_c were obtained from the ACRU modelling team. A limitation to be noted is that the surface water modelling component had to be set up early in the project, including which months would be "active growing months", the outputs of which were provided for the economic model. Hence, these could not be changed within the economic model to ensure consistency. Through the survey results refinements to this were identified as a revision to consider after this project is concluded.

Step 1 Crop water need (*ET_c*), is the optimal amount of water needed in the crop's production cycle. It is the product of the monthly potential reference ET (ET_o) and crop coefficient (K_c). The ET_o values were generated using ACRU; and the K_c values used were those from the ACRU modelling component (see Section 8.3.1).

Step 2: Effective rainfall (*Pe*) is the quantity of rainfall water in the soil that crops can use. For rainfed crops, rainfall is the main input in production, and how much it rains determines how much water crops use. The monthly rainfall values (PPT) were obtained from the ACRU model for a representative HRU grid. P_e was calculated using:

- If monthly rainfall was greater than 80 mm, P_e = 0.8*PPT-25,
- If monthly rainfall was less than 80 mm, P_e = 0.6*PPT-10.

Step 3: Estimating the annual impact on crop yield (DY_t^c) using the seasonal ratio between *Pe* and ET_c. The *Pe* and ET_c ratio can also be done monthly, but since data available was based on seasonal K_y the former was used. Multiplication of the yield response factor (K_y), enables one to calculate the ET deficit. The result is the percentage change in crop yield relative to crop ET (percentage damage). The product of the damage percentage and the actual maximum crop yield is the actual yield lost. It is also possible to determine the actual yield. Two maximum yield variables (Y_t^c). Among households, the maximum yield is the long-term maximum yield households have produced; this is summed to generate data on traditional community area -–specific output. For commercial farming (scenarios), the maximum yield is calculated from the product of the official crop unit yield per hectare in South Africa.

Notes on K_y according to Marsal (2012)

- "K_y >1: crop response is very sensitive to water deficit with proportional larger yield reductions when water use is reduced because of stress.
- K_y <1: crop is more tolerant to water deficit, and recovers partially from stress, exhibiting less than proportional reductions in yield with reduced water use.
- K_y =1: yield reduction is directly proportional to reduced water use.

These methods were used for all rainfed (dryland) scenarios.

11.4.2.3.2 Links to hydrological results: Irrigation water availability

Hydrological results were integrated into the economic modelling by linking available water from "irrigation wells" to crop performance. For all irrigation scenarios, there was a limit of 21 wells that could pump up to 1 ML of water per day, provided the well did not drop below 45 m from the surface. The actual volume of water available in the wells under these constraints was then obtained from the groundwater model and used to adjust the DF, consequently impacting the yield.

For both irrigated and Dryland scenarios, the DF was calculated in relation to the summed Pe/ET_c values over the growing season, not the monthly values.

11.4.2.3.3 Temperature effect

Temperature is an essential factor in crop development. However, extreme temperatures, especially during temperature-sensitive stages, such as the flowering period, greatly affect productivity (Hatfield and Prueger, 2015). Crops have an optimum temperature range and maximum temperature threshold; information and data on crops' optimum, i.e. upper optimum, range was sourced from crop production literature. To isolate the effect of temperature, a linear relationship between temperature and productivity at temperature-specific thresholds for different crops based on findings from World Bank (2022) was used.

Step 4: T_t^m **is the average monthly maximum temperature during the flowering period in the crop production cycle.** The temperature impact is represented by **ϕ**. Temperatures (T_t^m) equal to or below the upper optimum have a non-negative effect on yield. Thus, there is no negative impact on yield.

$$T_t^m \leq \epsilon = 1 \qquad \textit{11-2}$$

Temperatures above the upper optimum (ϵ) but not greater than the maximum temperature threshold (θ) have a linear and negative effect on yield. The closer the mean maximum temperature is to the maximum threshold, the higher the risk of crop failure, which is zero yield. Temperatures closer to the maximum threshold have a higher negative impact.

$$\epsilon < T_t^m < \theta = \frac{\theta - T_t^m}{\theta - \epsilon} \qquad \textit{11-3}$$

Temperatures equal to or above the maximum temperature threshold over the flowering period are assumed to cause total crop failure, i.e. average monthly maximum temperature during the flowering period over the maximum threshold results in no yield.

$$T_t^m \geq \theta = 0 \qquad \textit{11-4}$$

11.4.2.3.4 Combined effect

Step 5: **Since the effects of precipitation and temperature interact, to determine their combined effect on crop yield, the product of the two is the estimated value as:**

$$Damages_t^c = (1 - (1 - DY_t^c) \times (1 - \phi)) \qquad \textit{11-5}$$

This way, a damage impact of zero percent from either factor does not influence the outcome. For example, if the temperature damage percent was 0 (no damage) and the precipitation damage was 0.5 (50%), their product would have zero impact, which is not practical. The 1s are therefore place holders. The calculated value is the combined damage, with zero being no damage and 1 being damage. It was assumed that a value of 1 and above 1 result in total crop failure.

Step 6: In the SD model, the actual crop yield is estimated using the combined damages determined by:

$$Actual\ crop\ yield = Y_t^c * (1 - Damages_t^c) \qquad \textit{11-6}$$

11.4.2.4 Sector economy sub-model

The sector economy sub-model focused on modelling the economic value of the formal industries identified for future scenarios, as guided by TC workshop outcomes. The sub-model evaluates the value of key sectors using the net income and net present value (NPV) for different future climate storylines. The NPV is an economic metric that examines both cash outflows (costs) and cash inflows (revenues) simultaneously. It is used to evaluate the profitability of an investment. In simpler terms, it is like asking: "Is the money I expect to make from this investment in the future worth more than the money I'm putting into it now?". The NPV estimates start with capital investments but, in this study, only seasonal (yearly) operational costs were used as outflows because specific investments for each land use would have led to less accurate results due to the lack of consistent capital per unit of land, and for this study it was important to demonstrate comparative outcomes. Figure 11-4 shows a simplified version of the formal ULM economy sub-routine. The solid blue arrows show the current formal economic sectors (SQ), with the dark dotted arrows illustrating the formal sectors that are modelled in the scenarios. The number of employment opportunities was also used as an outcome to assess the impact of the alternative land use-climate scenarios, one of the top four challenges identified by the communities.

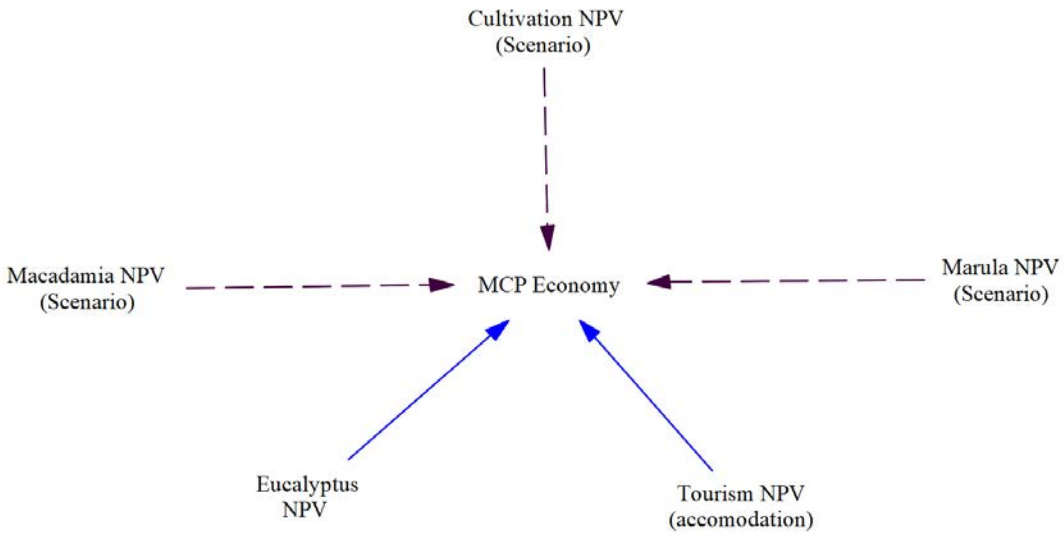


Figure 11-4 MCP Formal Economy sub model. The solid blue arrows show the current formal economic sectors (SQ), with the dark dotted arrows illustrating the formal sectors that are modelled in the scenarios

Eucalyptus, Marula, crop cultivation and macadamia value are influenced by the size of land, yield and the unit price (Rands per ton). The industries also provide employment opportunities for residents. Ecotourism, on the other hand, is influenced mainly by the number of overnight visits. Tourist values should also include recreational activities such as dining, diving, and fishing but, due to data constraints, have not been included. This limitation should be addressed in the future model refinement.

11.5 RESULTS

The results presented begin by contrasting the results from TC workshops with information gathered during HH surveys regarding challenges, economic activities, and preferences. Pertinent data from the HH surveys are also summarised. Sample results from the ULMCatchMOD simulations are then presented for demonstration purposes, with an assessment of the outcomes of a subset of alternative future climate and land use storylines in relative to employment and economic benefits.

11.5.1 Comparison of Perceptions from Tradition Council Workshop to Household Data

A significant amount of data was gathered from the HH surveys. Only pertinent information from the HH surveys which related to the perceptions gathered from the TC workshops are present. Where necessary, data were aggregated into "categories" for comparative purposes with results presented in

CHAPTER 4: Section 4.5. In addition, narratives gathered from HH surveys are summarised to provide evidence for the current local context.

11.5.1.1 Talking points/challenges

Participants of HH surveys were asked to identify up to three challenges (talking points) in their area (see Appendix A Table 2 for an unabridged list). Results from the household data matched with perceptions recorded during the TC workshops for the top two challenges in the region. Water insecurity was most frequently given as a key challenge. Unemployment/poverty was the second most cited challenge. Thereafter there is some differentiation from the council workshops outcomes. Lack of infrastructure was the third most frequently cited challenge overall, whereas the TCs recorded a higher number of natural resource challenges. However, "additional comment" narratives from the HH surveys allude to a pronounced impact on natural resources (see section 0 Table 11-6).

Table 11-1 A synthesis of all challenges identified by interviewees during HH surveys. Data aggregated, where appropriate, into categories similar to those used in the TC workshop summaries. Cells highlighted in blue were also identified and ranked important in TC workshops. Cells in yellow were also identified in TC workshops but not ranked important. Clear cells were household responses not identified in TC workshops.

Challenges aggregated to TC categories	Mabasa	%	Mbila/Zikhali	%	Tembe	%	Total	%
Water shortage	48	32.9	43	26.2	39	34.8	130	30.8
High unemployment	48	32.9	46	28.0	29	25.9	123	29.1
Lack infrastructure, roads, transport, services, shops, economic development	9	6.2	29	17.7	16	14.3	54	12.8
High crime rate	15	10.3	7	4.3	1	0.9	23	5.5
Lack of electricity	3	2.1	9	5.5	11	9.8	23	5.5
Network issues	3	2.1	11	6.7	0	0.0	14	3.3
Poor governance	7	4.8	1	0.6	5	4.5	13	3.1
Alcohol and drug abuse	2	1.4	6	3.7		0.0	8	1.9
High school drop outs, poor high school education, lack of schools, shortage skilled people	1	0.7	5	3.0	1	0.9	7	1.7
Poor livestock management	1	0.7	1	0.6	3	2.7	5	1.2
Teenage pregnancy	2	1.4		0.0	2	1.8	4	0.9
No RDP houses		0.0	1	0.6	1	0.9	2	0.5
Witchcraft	1	0.7	1	0.6	0	0.0	2	0.5
Poor sanitation (lack of toilets)	1	0.7		0.0	1	0.9	2	0.5
Livestock theft		0.0		0.0	2	1.8	2	0.5
Soil not good for cultivation		0.0	1	0.6		0.0	1	0.2
Poor family planning		0.0	1	0.6		0.0	1	0.2
Food is expensive		0.0	1	0.6		0.0	1	0.2
Isimangaliso conserving the area that the communities need for natural resources		0.0	1	0.6		0.0	1	0.2
Expansion of gum trees	1	0.7		0.0		0.0	1	0.2
Land disputes hindering development	1	0.7		0.0		0.0	1	0.2
Motor vehicle accidents	1	0.7		0.0		0.0	1	0.2
Lack of public infrastructure (stadiums)	1	0.7		0.0		0.0	1	0.2
Poor service delivery		0.0		0.0	1	0.9	1	0.2
Lack of market for products produced in the area like craft	1	0.7		0.0		0.0	1	0.2
Grand Total	146		164		112		422	

11.5.1.2 Relative importance on economic activities

At the TC workshops, the top five economic activities perceived as important for the area were crafts, eucalyptus forestry, crop farming, fishing, and livestock (Table 11-2). The HH survey results, however, demonstrate that pensions and grants are the commonest source of income in the region (Table 11-3). Cultivation was the second most common source of income, also identified in the TC workshops as important. Both the TC workshops and household data demonstrated the importance of crafts as a common and important source of income. Unlike the TC workshops, fishing and livestock farming did not feature as common income sources among the households surveyed. Employment from tourism and employment in general emerged within the top five most common sources of income for households (Table 11-4).

Table 11-2 Most important economic activities identified in TC workshops

Economic activities	Frequency	Ranking (Top 5)
Crafts and wood carving	8	8
Gum trees/timber	7	8
Crop farming (wetland and dryland)/selling vegetables	9	6
Fishing	8	5
Livestock (cattle and goat)	6	4

Table 11-3 Most common sources of income from HH surveys categorised into comparable categories as the TC workshops outcome (total number of responses from HH surveys)

Classes as per TC outcomes	Mabasa	Tembe	Mbila/Zikhali	Grand Total
Grant/pension/remittances	81	76	92	249
Crop farming (wet and dryland)/selling vegetables	26	9	21	56
Crafts and wood carving	3	21	30	54
Employment: Tourism	10	12	20	42
Employment: General	15	14	9	38

It should be noted that not all income sources provided by participants had income values. However, for those for which income values were available and an average could be calculated, it was then multiplied by the total frequency. Monetary values are thus only rough approximations.

The total number of income sources "counted" was 580, of these 25% were from direct employment. Using an average household size of 6.9, the average monthly household income was R5 286 (R766 per person). Grants/pensions/remittances provide the most monetary import. Notably, income from crafts and tourism far exceed that from the combined value of employment and ownership of eucalyptus farming (Table 11-4). The most profitable form of income seems to be from Government jobs, especially within the health sector, however this is from a small sample size of given salaries. During interviews anecdotes alluded to the view that the people employed in the health sector (other than cleaners) do not come from the area because the level of schooling and education within the region is too low to enable locals to excel in this sector.

Table 11-4 Actual frequencies of different economic activities recorded during HH surveys and associated estimated income

Classes as per TC outcomes	Mabasa	Tembe	Mbila/ Zikhali	Total number*	Total income per year from each source	Average per year per number*
Grant/Pension/Remittances	81	76	92	249	R 4,926,020	R 19,783
Crop farming (wet and dryland)/selling vegetables	26	9	21	56	R466 520	R8 331
Crafts and wood carving	3	21	30	54	R592 897	R10 980
Employment: Tourism	10	12	20	42	R1 722 080	R41 002
Employment: General	15	14	9	38	R367 852	R9 680
Employment: Government jobs	13	5	6	24	R2 451 000	R102 125
Employment Hospital/medical	14	2	2	18	R2 540 000	R141 111
Gum trees/timber	2	4	10	16	R155 967	R9 748
Livestock (cattle and goat)	7	3	4	14	R242 967	R17 355
Self employed	7	1	5	13	R230 400	R17 723
Construction/brick laying/builder/roads	3		8	11	R29 400	R2 673
Employment: Forestry	1	6	2	9	R180 720	R20 080
Selling medicinal plants/traditional medicine	7		2	9	R71 940	R7 993
Small business/entrepreneur /tuck shop/tavern /leasing	4	1	4	9	R152 000	R16 889
Transport/taxi driving/truck driver/driver	1		3	4		
Fishing	1	2	0	3		
Workshop/mechanic	1		2	3		
Herbalist/traditional healer	1		1	2		
Lala wine	1		1	2	R10 500	R5 250
NR: Harvesting	1		0	1	R2 700	R2 700
Pastor	0		1	1		
Selling cannabis	0	1	0	1		
Sewing	1		0	1	R2 400	R2 400
Hunting	0		0	0		
Grand Total	200	157	223	580	R14 145 363	

Tourism was the most common source of employment, followed by a range of other sources of employment. Forestry provides less than a quarter of employment opportunities than tourism (Figure 11-5).

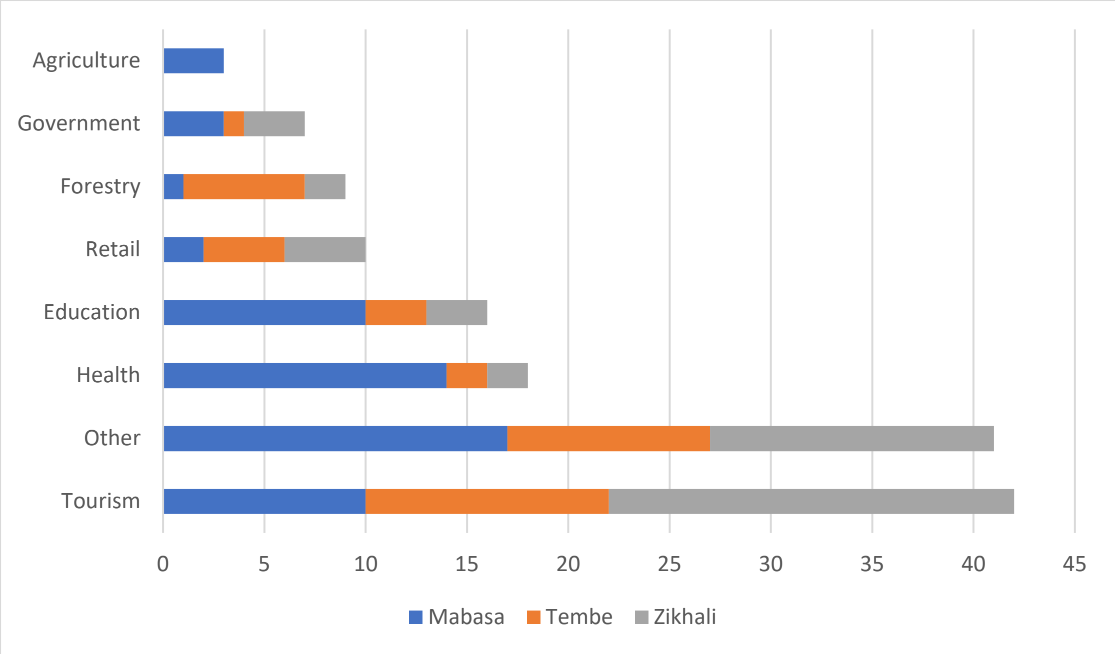


Figure 11-5 Frequency of responses per employment type for each TC

The salaries for education and health employment sectors were higher than for all other sources of employment, followed by tourism (Figure 11-6).

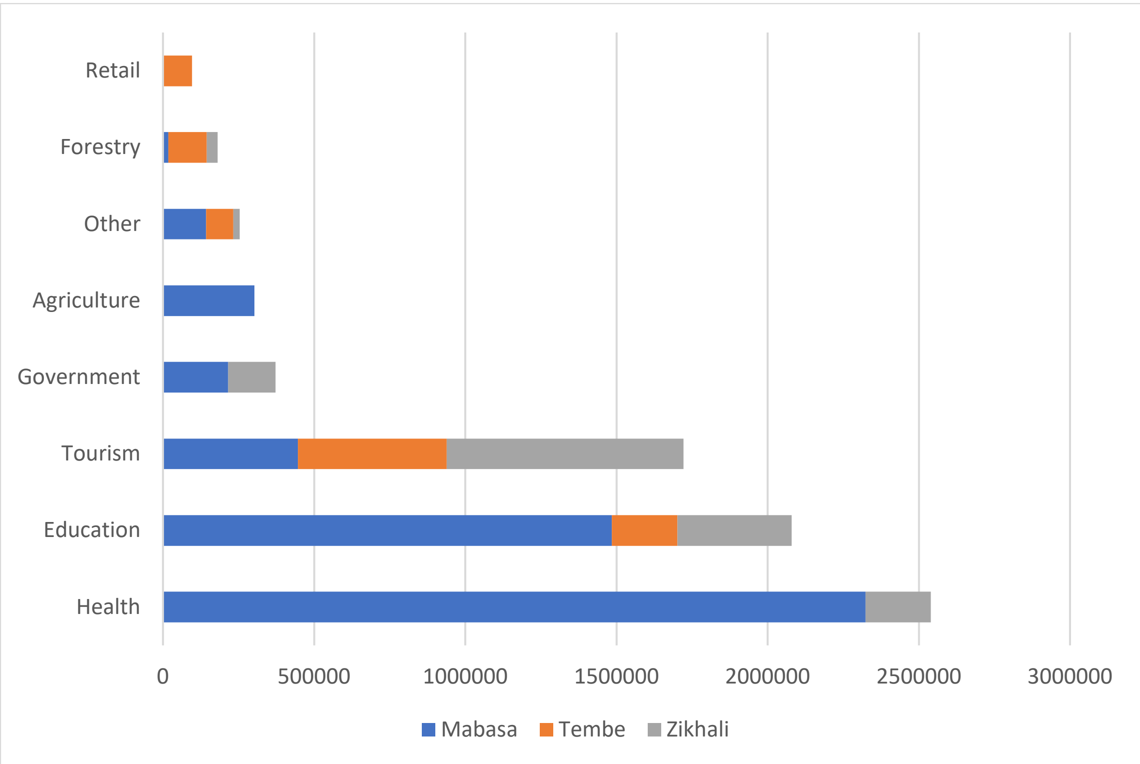


Figure 11-6 Total Income from employment per sector (annual)

Assessment of the relative contribution of all income sources categorised per sector indicated that general employment and grants are the highest contributors to household incomes. The tourism sector contributes significantly more to household income than forestry (Figure 11-7.)

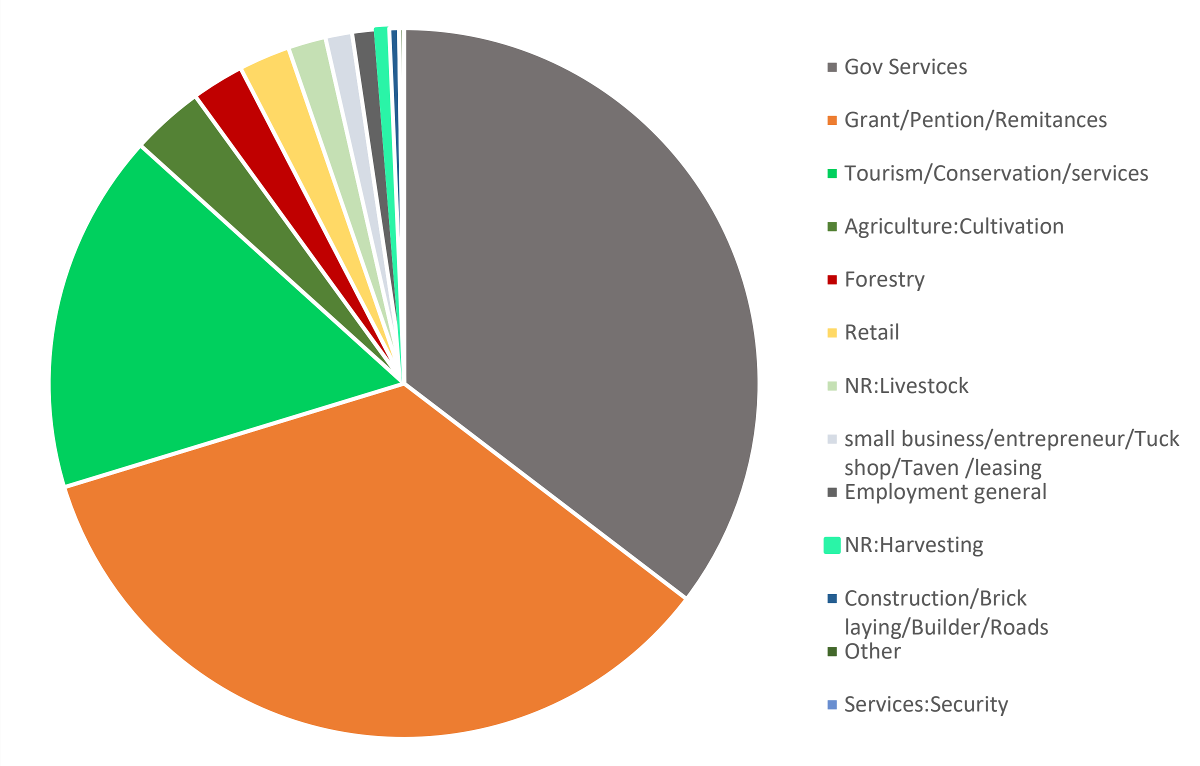


Figure 11-7 Proportional contribution of different sectors (aggregated categories) including income and employment

11.5.1.3 Future land use-climate preferences

Participants in the HH survey were asked to rank four future climate-land use scenarios in order of preference. The scenarios were explained as follows **S1:** Warmer wetter + hydro intensive (gums and macs); **S2:** *Drier warmer + hydro intensive (gums and macs);* **S3:** *Wetter warmer, + less hydro intensive (indigenous species, natural resource use, livestock, ecotourism, etc.);* **S4:** *Drier warmer + less hydro intensive (indigenous species, natural resource use, livestock, ecotourism, etc.).* Explanations were facilitated through the use of four collages, each depicting a scenario (Appendix J).

Scenario 3 (Wetter warmer, + less hydro intensive (Indigenous species, natural resource use, livestock, ecotourism, etc.)) was, by far, the most preferred scenario across all three communities. The least preferred scenario was a warmer drier future with “gum” plantations and macadamia orchards. As may be expected, the general preference was for a warmer wetter future rather than a warmer drier future. The significant aversion to the hydro-intensive land use scenario (“gum and mac”) is noteworthy and contradicts the narrative that gum plantations are valued. The less hydro-intensive land use scenario (involving tourism, natural resource use, etc.) was generally more preferred, irrespective of the climate future. Raw frequency data is in (Appendix K).

Table 11-5 Summary of future climate land use scenarios from HH surveys across the three community areas. Values are in percentages to enable comparison across community areas. "n" denotes total number of responses summed for each community area. Those ranked in the top two are denoted in dark green (most preferred) and light green (preferred) whereas the bottom two (two least preferred) are in dark brown (least preferred) and light brown (not preferred).

Climate	S1 Warmer wetter	S2 Drier warmer	S3 Wetter warmer	S4 Drier warmer
Land use	Gums and Macs		Indigenous species, natural resource use, livestock, ecotourism, etc.	
Tembe	n = 141			
Most preferred (1)	6.4	0.0	24.1	0.7
Preferred (2)	5.0	1.4	5.0	12.8
Not preferred (3)	12.8	2.8	1.4	5.7
Least preferred (4)	0.7	17.7	0.0	3.5
Mabasa	n = 212			
Most preferred	5.7	3.3	17.0	0.5
Preferred	4.2	1.4	2.8	15.6
Not preferred	15.1	6.1	0.9	2.8
Least preferred	0.5	13.7	4.7	5.7
Mbila/Zikhali	n = 221			
Most preferred	3.2	0.5	19.0	3.6
Preferred	4.5	1.8	4.1	13.6
Not preferred	14.0	5.9	1.8	2.7
Least preferred	2.7	16.3	1.8	4.5

11.5.1.4 Comments from HH survey participants

Question 67 in the HH survey was "What do you think can help improve the situation concerning income and water security for a) your household and b) the region?".

Unabridged responses are provided in Appendix L. These responses were categorised into various classes and the frequency per category counted (Table 11-6). Consistent with the challenges identified by the TCs and the results from HH surveys, addressing water security was the most common response, followed by improvement of employment opportunities that would benefit households. Several responses linked the provision of water to the ability to improve cultivation and consequent income and food security. There were calls for improved markets and access to sell produce including crafts crops and meat as well as increased tourism opportunities to create employment and reduce gum plantations.

Table 11-6 Frequency of responses for different categories of responses to question 67 a (what would improve household water and income security)

Responses to question 67 a (what would improve household water and income security)	**Category frequencies**
Improved water security (boreholes taps pipelines, harvesting tanks, etc.)	51
Create job opportunities for households (through various means)	20
Business and livelihood alternatives	10
Increase grant, sponsorship of herbicides, donations, farming subsidies	9
Improve market access for commodities, poultry, meat, crops, and craft	6
Get a borehole and use to cultivate	4
Chicken farming meat and eggs	4
Proper fencing to manage livestock and wetland cultivation areas	3
Improve education/awareness/provide bursaries for tertiary education	2
Infrastructure improvements to spur economic growth (electricity, roads, factories)	2
A place to manufacture maize meal and samp from harvested maize	1
They should reduce gumtrees	1

When asked what would be needed for the region, responses were similar to those from the household perspective but job creation was the most frequently cited as opposed to water security which was prioritised at the household level (Table 11-7).

Table 11-7 Frequency of responses for different categories of responses to question 67 b (what would improve the regional water and income security)

Responses to question 67 b (what would improve water and income security in the area)	Category Frequencies
Create Job opportunities for households (through various means, water wise industry)	39
Improved water security (boreholes taps pipelines, harvesting tanks, etc.)	24
Infrastructure improvements to spur economic growth (electricity, roads, factories)	16
Improve tourism industry for employment and improved craft sales	8
Improve market access for commodities, poultry, meat, crops, and craft	7
Develop skills workshops for youth,	5
Get boreholes for HH's to improve cultivation	4
Reduce eucalyptus plantation	4
Capital investment in agriculture	1
New toilets	1
RDP house,	1
Factories processing indigenous tree or fruits may help improve job opportunities such as Marula	1
They need good governance in the area	1
Big fishing station in the area (Mabibi)	1

The final question in the survey asked participants for any additional comments. A word cloud from comments is provided in Figure 11-8. The unabridged list of comments (Appendix M) **is worth reading,** as it provides significant insights into lived realities. Four main themes accounted 68.3% of all responses. The highest percentage of comments (24.4%) indicated that without water, people cannot cultivate and included concerns over starvation and inability to make a living from selling crops and crafts. Another 20.7% commented about how water scarcity negatively impacts on the quality and quantity of natural resource, especially reeds used for crafts, as well as traditional medicines and indigenous plants. This is significant given the number of households that rely on reed-based crafting and demonstrated the negative impact the declining water table is having on these natural resources. Testimonies over how difficult the lack of water makes life in many aspects, including health, costs of buying water, lack of food, and inability to build with bricks accounted for 16% of responses. Several respondents (7.3%) raised concern over gum plantations and how much water they use.

Sample comments from respondents to the HH survey:

"We spend our productive time fetching water which we share with livestock with potential to get sick. With water scarcity we don't get much from cultivation and food is now expensive".

"I can't survive without water provided by wetlands".

"Water scarcity impacts on income because the quantity and quality of reeds goes down".

"Without water we would starve and with water I can cultivate vegetables to sell".

"I used to have a gum lot not far from my borehole and it affected water levels so I had to cut it down".

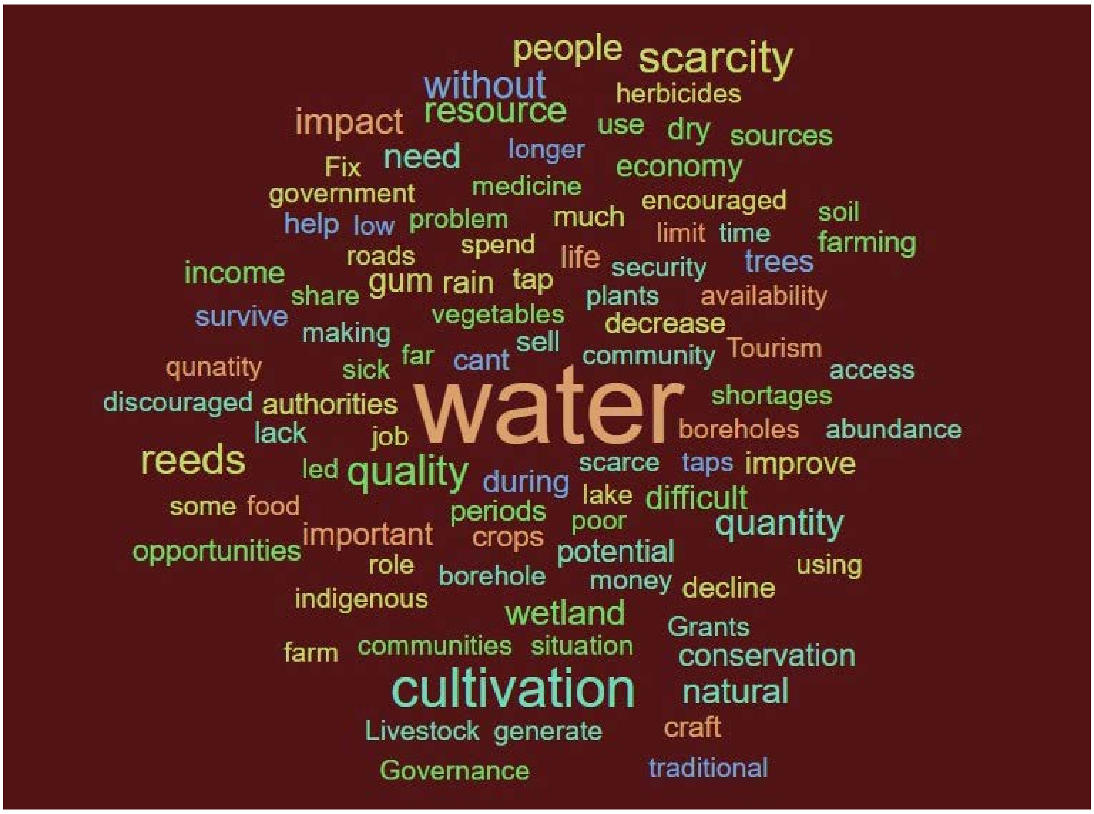


Figure 11-8 Word cloud created from the "any additional comments" question

11.5.2 Climate Change Awareness

When asked the question “Are you aware of climate change (CC) and its impact on the area?”, 49,3% (n= 217) responded “yes”. In two follow up questions on whether or not they think climate change affects rainfall and temperature, the responses were 51.2% and 36.4% respectively, with a greater number of respondents indicating impact on rainfall than “awareness” to climate change (n= 217).

When asked what “How does CC impact your household?” 98 of all participants 217 responded (45%) (Table 11-8). Of these, 83% related to impacts on crops (primarily) as well as livestock and natural resources (reeds); 3% cited crop damages related to heavy rains and wetlands becoming flooded; and the rest related to drought impacts and water shortages. Direct and indirect impacts on human health and safety were evident in 5% of responses (Table 11-8).

Table 11-8 Responses to how does climate impact your household, as frequencies of responses in aggregated categories

Climate impact	Mabasa	Mbila/Zikhali	Tembe	Grand Total
Crop: loss of yield	20	12		**32**
Crop: loss of yield/crop yield and water harvested/scarcity/borehole/supply	7	7	10	**24**
Crop loss/failure			8	**8**
Crop: It has changed the way they cultivate/unable to cultivate due to lack of water/not able to cultivate like in the past/The stream behind their house dried up which affected their cultivation site	1	3	1	**5**
Livestock crop: livestock and loss of yield	2	1		**3**
Flooded: The wetland close to her HH dried up and then got flooded/wetland plots have flooded due to 2022 April heavy rains		2	1	**3**
Crop loss and water decline in lake			2	**2**
Livestock has been migrated/livestock loss	1		1	**2**
Illness and crop failure			2	**2**
Crop yield and reed harvest			1	**1**
Water availability/supply/shortage	2	4	1	**7**
Illness from heatwaves			1	**1**
Illness sharing water with animals			1	**1**
Impact fruits and vegetables	1			**1**
Increase expenses	1			**1**
It has caused a long drought			1	**1**
It has increased the growth of alien plants		1		**1**
None		1		**1**
Thunderstorms have affected the family		1		**1**
Trees are dying		1		**1**
Grand Total	**35**	**33**	**30**	**98**

11.5.3 Food Sources

Respondents were also asked what their main sources of food were. 100% of households source most of their food from shops (Table 11-9). Cultivation, wild plants, and informal markets are the main secondary sources of food. Cultivation and wild plants were the dominant third food sources and while other sources included fishing and hunting. Overall, 147 (68.6%) households source at least some of their food from cultivation and 28.5% of households make use of wild plants, hunting and fishing to supplement the other sources of food (Table 11-9). Assessment of food sources in relation to perceived climate impacts demonstrates that, while cultivation (and natural resources) provide import sources of supplementary food for many households, they are evidently impacted by climatic conditions.

Table 11-9 Main sources of food that households reply on

	Source 1	Source 2	Source 3	Source 4	Total per source
Shops	217				**217**
Cultivates		113	36		**149**
Informal market		41	1		**42**
Wild plants		10	42	1	**53**
Fishing			4	2	**6**
Hunting			3		**3**
Gift			2	2	**4**
Grand Total	**217**	**164**	**88**	**5**	**474**

11.5.4 Household Water Use

The results on household water use patterns are presented in Table 11-10. A large proportion of households within the study area encounter challenges with water supply, with implications for both household health and the economy. The disaggregated results by traditional community area (Mabasa, Mbila/Zikhali and Tembe) demonstrate distinctions between the areas (Table 11-10). Piped water is available in all three and is the primary source of water in Mabasa, whereas boreholes are the most common source of water in the Mbila/Zikhali and Tembe community areas. Boreholes, however, necessitate investments that are unaffordable for a great number of households. Households that have boreholes also provide access to neighbours' facing limited water supplies. Average household use is 98.9 litres of water per day, based on a monthly average of 2 968.33 litres per household. Based on the average number of people in a household, each individual consumes 14.1 litres of water per day. This is less than South Africa's 25 litres of potable water per person and the World Health Organisation's 20 to 40 litres per day per person, illustrating water insecurity.

Based on the average water use per household per month (2 968 litres/month/HH), based on a conservative assumption that one eucalyptus tree uses 10 litres of water per day and in 1 ha there are 1 600 trees, this equates to (10*30*1600) 480 000 litres/month/Ha. This is 200% more water demand than households and there are more hectares of eucalyptus trees than there are households.

Table 11-10 Sources of household water supply provided as percentages of each source per community area expressed as a percentage

Water sources and status	Mabasa (n=82)	Zikhali (n=78)	Tembe (n=63)
HH water secure*	65.9%	69.2%	50%
Tap (piped water)	51.2	16.7	30.2
Borehole	20.7	29.5	33.3
Rainfall	11	9	1.6
River/streams	6.1	5.1	0
Neighbour (borehole)	6.1	20.5	3.2
Community borehole	2.4	0	0
Buy water	1.2	6.4	0
Community tank	1.2	0	0
Well	0	1.2	3.2
Springs	0	1.2	4.8
Lake	0	12.8	22.2
HH average water use	3 034 litres/month	2 894 litres/month	2 977 litres/month
Total average litres of water per month	**2 968 litres/month**		

* Percentage of Households that perceived themselves as water secure

11.5.5 Results from the System Dynamics Model (ULMCatchMod)

11.5.5.1 Household overview

This sections briefly addressed some of the findings related to the household economic dynamics from the system dynamics simulation from 2024 to 2050. The impact of climate change and land use on the economic dynamics at household level can be explored with the household economic sub-model. Currently this is not explicitly linked to the sector-based model other than totalling overall outcomes for the various variables. Most dynamics are simply linked to the population growth rate. Examples of descriptive statistics within the model and net outcomes by 2050 are provided in Appendix O. Only pertinent information and results are provided below.

Population dynamics are captured in the ULMCatchMOD model as the population size is set to influence the number of households simulated as households are the units used in the model, not population. By applying the most recent population growth data from the uMhlabuyalingana Local Municipality from Statistics South Africa (0.115% per month) the model estimated a total population of 44 825 as of December 2023 within the area of interest defined in CHAPTER 4:. Based on the survey data from this project, the average household size in the study area is 6.88. The model used a rounded number of 7 as the mean household size. The total number of households in the study area as of 2023 was thus calculated as 6 515 (44 825/7). At the individual community area level, 16 372 (2 339) people (households) reside in Mabasa, 21 755 (3 108) in Mbila/Zikhali, and 6 698 (957) in Tembe tribal areas. Based on a historical net population growth rate of 0.115% per month, the study area will have approximately 64 975 inhabitants in 2050, or 9 282 households. The net population growth can be adjusted within the model according to revised data as it becomes available.

11.5.5.1.1 Valuation of household land use-based economic activities'

Income is the primary indicator used to assess the value economic activities of various livelihood options in the study area. Appendix N details the factors that influence economic value under various land uses. The economic value in the model is cumulative. Values include the value of goods produced by households that are consumed by the household. For example, if a household harvests five tons of maize in 2024, sells three tons, and consumes the remainder, the economic value of maize cultivation is the value of five tons if they were all sold, i.e. imputed income.

Cumulative income was projected to 2050, based on the current SQ activities, under three future climate storylines: C6Dry, C6Wet, and the ERA5Wet, representing worst- and best-case future climate storylines. The driest future total potential income from cultivation is less than that of the wettest (ERA5Wet) climate storyline, due to lower yields.

Given the impact of climate on cultivation and its importance to households, the yield of each crop maize (Figure 11-9), cassava (Figure 11-10) and groundnuts (Figure 11-11) for the study area was assessed under the driest (C6Dry), slightly wetter, relative to C6Dry (C6Wet) and wettest (ERA5Wet) future climatic storylines.

Maize yield for the respective future climate storylines in tonnes by 2050 were 1 322.75 (C6Dry), 1 332.26 (C6Wet) and 4 341.21 (ERA5Wet) (Figure 11-9). The wettest future has a big impact on yield (higher) but fluctuates significantly; there was no clear difference between the C6Dry and C6Wet futures.

Cassava yield for the respective future climate storylines in tonnes by 2050 was 238.72 (C6Dry), 210 (C6Wet), and 565.22 (ERA5Wet) (Figure 11-10). The wettest climate future had the most positive effect on yield, with small differences between the C6Dry and C6Wet futures. The productivity of cassava was the least sensitive to the drier (C6Dry and C6Wet) climate futures, in comparison to the other crops, hence it was decided to include a cassava only simulation in the ULMCatchMod.

Groundnut yield for the respective future climate storylines in tonnes by 2050 were: 7 044.77 (C6Dry), 5 491.3 and (C6Wet) 8 500.71 (ERA5Wet) (Figure 11-11). Yields were best for the wettest future followed by the driest future, but with large fluctuations in the wetter future characterised by period extreme events.

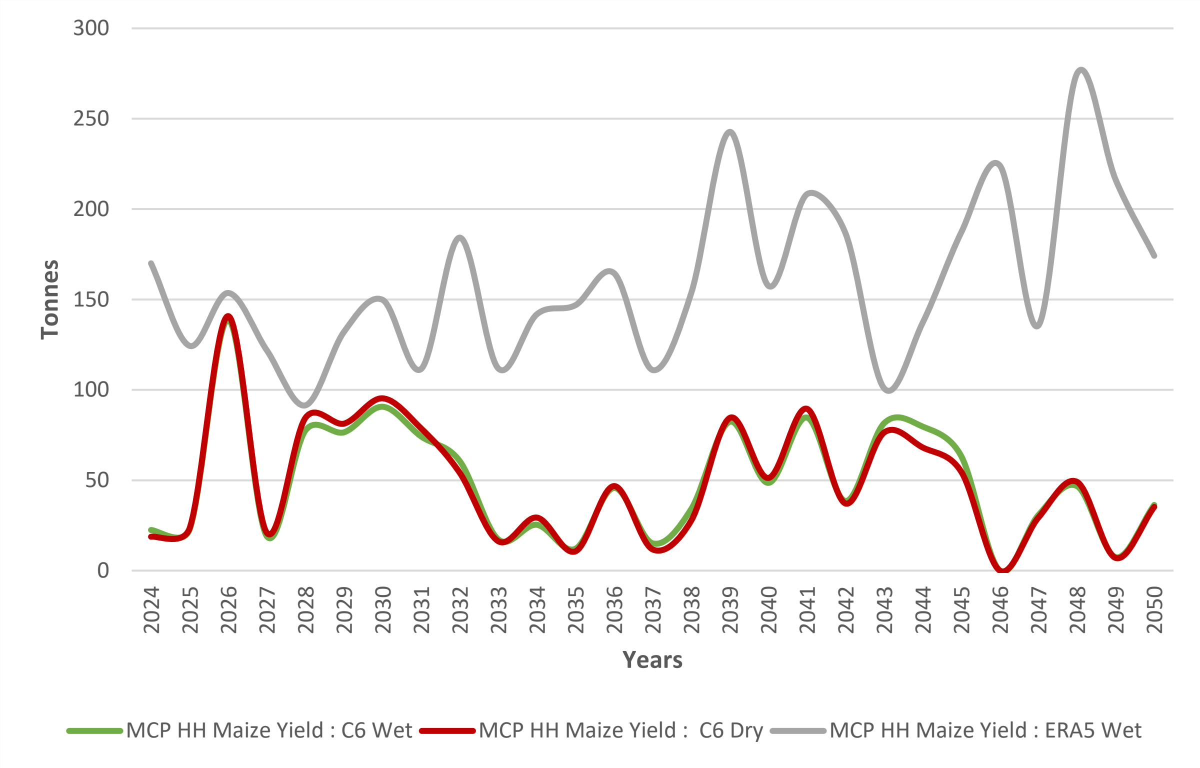


Figure 11-9 Total household maize yield using current production data based on HH surveys with LULC remaining constant but under three future climate storylines; a warmer drier climate (C6Dry: red line), warmer slightly wetter (C6Wet: green line) and warmer, much wetter climate (ERA5Wet: grey line)

By 2050, maize, groundnuts and cassava had all achieved better yields in the wettest (ERA5Wet) climate storyline, but the extent to which this future is beneficial to each crop varied. It was most beneficial for maize, followed by cassava and then groundnuts. The variability in yield was generally higher in the warmer wettest future (ERA5Wet). These results highlight two things: while the data in the model is currently coarse, it can be used to explore nuances in different choices of agricultural/agroforestry crops to assess long-term impacts on yield, which can then be translated to financial implications. Secondly, it demonstrates that, out of the crops currently being farmed, based on the current input data, groundnuts and cassava are likely to be the most climate-resilient in a drier future. Assessment of these impacts is made possible through the DF within the mode.

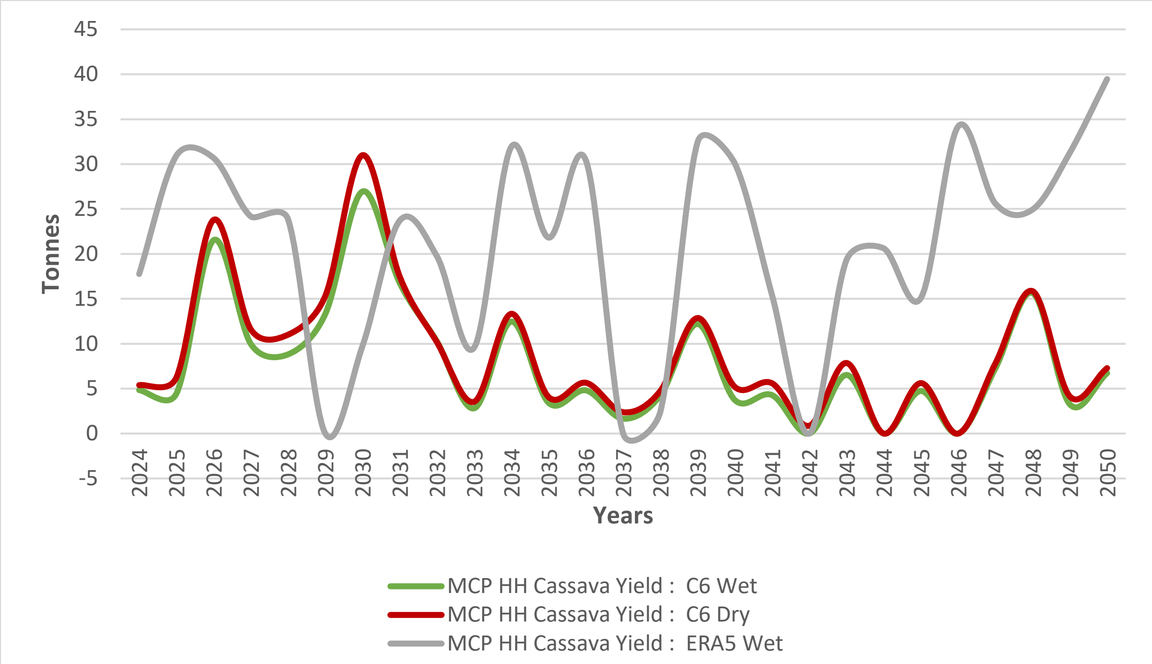


Figure 11-10 Total household cassava yield using current production data based on HH surveys with LULC remaining constant but under three future climate storylines; a warmer drier climate (C6Dry: red line), warmer slightly wetter (C6Wet: green line) and warmer, much wetter climate (ERA5Wet: grey line)

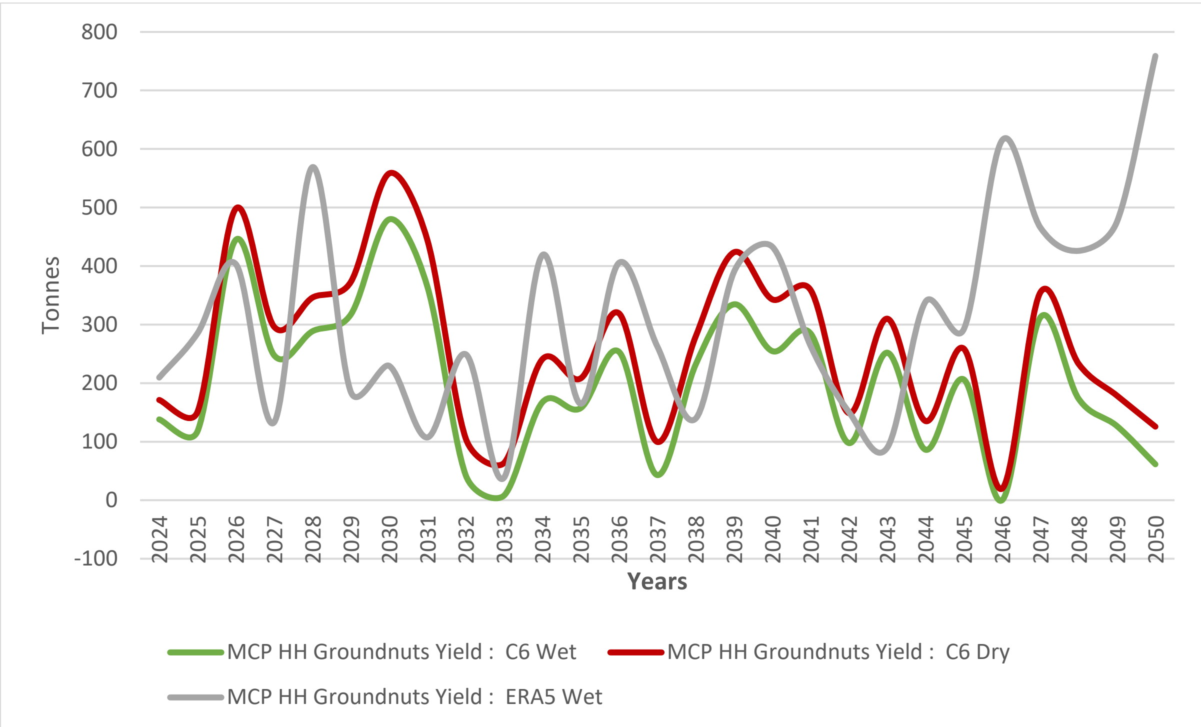


Figure 11-11 Total household groundnuts yield using current production data based on HH surveys with LULC remaining constant but under three future climate storylines; a warmer drier climate (C6Dry: red line), warmer slightly wetter (C6Wet: green line) and warmer, much wetter climate (ERA5Wet: grey line)

Grasslands are used for communal grazing and, even though the area has a high livestock population, current income from sales is low. The grasslands also have Lala Palm (*Hyphaene coriacea),* which are used to produce traditional drinks and crafts. Households also harvest medicinal plants to sell. The HH survey did not adequality capture the value related to the use of natural forests gained from, for example, crafts and traditional medicine, hence, income for natural forest land cover absent from the assessment. Reeds, a common craft material that grow in wetlands and around the lake, have a high economic value, for example, R98 49 million in the Mbila/Zikhali traditional community area.

Table 11-11 Rough estimates of cumulative economic income for households based on current economic activities. The only values that are influenced in the ULMCatchMod by the different climate future storylines, (C6Dry, C6Wet, and ERA5Wet) are for cultivation, as determined through the use of the DF. Note: values are very course approximates based on household data collected and should only be viewed in relative terms

Household land use based economic activities	Cumulative economic value in million Rands (2024-2050) per activity		
	Mabasa	Mbila/Zikhali	Tembe
Cultivation			
Dryland cultivation: C6Dry/C6Wet/ERA5Wet	50 46/39 98/66.84	27 78/21.84/35.51	11 26/8 85/14.29
Wetland cultivation*	R28 14	R70 5	R67 60
Grasslands			
Cattle	R37 55	R22 14	R40 49
Goats	R7 01	0	R3 53
Lala (Hyphaene coriacea)	R7 7	R9 07	R11 4
Thicket and forest	Not assessed	Not assessed	Not assessed
Medicinal plants	R31 97	R25 96	0
Aquatic systems			
Reeds	R5 94	R98 49	R24 27

ULMCatchMOD estimated the cumulative value (summed across community areas) of household economic activities under the three future climate storylines (Figure 11-12). Only values for cultivation were set up to be affected by the climate futures. Based on ULMCatchMOD estimates, cultivation provides the highest income compared to other economic activities (Figure 11-12). Outcomes are best under the wettest climate future. The fact that the C6Dry climate future does slightly better than the C6Wet future may be related to temperature impacts within the C6Wet scenario. This needs to be explored in more detail. Reeds harvesting and crafting provide the second most beneficial incomes (Figure 11-12), consistent with TC workshop predications and HH survey data. The results provide an indication of the contribution of the informal economy to households. More importantly, they highlight the significance of natural resource (ecosystem) integrity and water security, as these support the top two income sources.

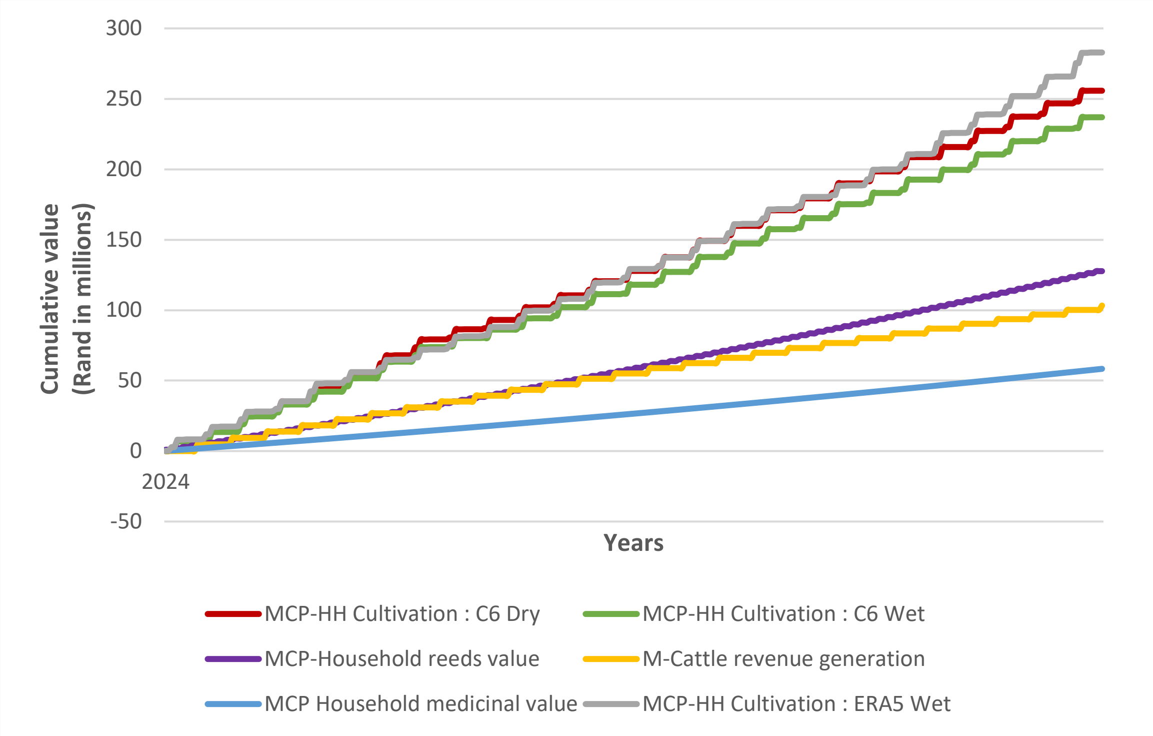


Figure 11-12 Cumulative value of household economic activities under the dry climate storyline future using the SQ land use

In summary, household economies differ across the three community areas. Households are engaged in a variety of resource and land use-based activities, primarily agriculture, livestock, and natural resource harvesting. Household data indicated that, collectively, natural resources provide the highest economic value whereas the ULMCatchMOD indicated cultivation as a key income source. This discrepancy indicates that more robust data parametrisation of the model maybe required. The relative performance of different crops under different future climate scenarios will be dependant of the crop type and use of the DF within the ULMCatchMOD is a useful tool explore these dynamics.

Cultivation provides an important supplementary food source for households (Table 11-9). Agriculture and natural resources are reliant on a high-water table, hence declining trends in groundwater impact on food production, reed availability, and income (based on responses in section 0). Climate has a direct impact on agricultural yield and, thus, economic outcomes under different future climates within the ULMCatchMOD. Responses from HH surveys (Table 11-8) provide evidence that climate and associated water shortages already impact negatively on crop yield.

11.5.5.2 Formal sector scenario dynamics

Currently, the study area has two formal economic sectors: forestry and tourism. The intention was to model several alternative scenarios as defined by the community. To establish a benchmark against which outcomes could be compared, priority was given to the SQ scenario, with no change in land use, under the three future climate storylines. Subsequent scenario selections were prioritised based on results from the hydrological modelling and plausibility in relation to hydrological impacts. This section presents the findings on the outcomes of alternative LULC scenarios under different climate future storylines to determine relative outcomes in relation to economic and employment benefits – key challenges identified at the TC workshops. Economic results are provided as net present value (NPV), determined by the ULMCatchMOD. NPV is a financial concept used to evaluate the profitability of an investment. It calculates the present value of all expected future cash flows generated by the investment, discounted at a specific rate of return (discount rate). The basic idea behind NPV is that a sum of money today is worth more than the same sum in the future due to the opportunity to invest and earn a return. Put another way its money's potential to earn a return over time. The NPV was calculated using a social discount rate of 15% which is subjectively determined. A discount rate represents the time value of money; an indication of the rate at which the value of money depreciates over time. The more impoverished and vulnerable an individual is, the faster the time value of money depreciates. A discount rate of 15% was selected, rather than the nationally acceptable rates of between 6%-8%, based on the current context in the study area, namely its elevated poverty rate and the potential impact to boost economic through the promotion of prompt investment. Applying a 6% or 10% discount rate would not alter the overall outcomes, but it would result in considerably higher values. Refer to Appendix P for variables used in the formal sector model.

11.5.5.2.1 Status Quo Scenario (SQ)

The SQ scenario results assess the outcomes of the current 2020 LULC, held constant until 2050, under each of the three climate storylines. This provides an idea of the “baseline” outcomes of not doing anything.

11.5.5.2.1.1 Employment

The SQ has two formal economic sectors: forestry and tourism. The measure of employment rate per sector for these two differs in that the number of people employed in forestry is calculated on a per hectare basis. On average, the forestry industry employs 0.075 people per hectare (see Appendix P). Tourism uses different units, such as people per bed (1.06). Current input files for tourism are based on scant data and do not include activities related to tourism (restaurants, diving, retail, etc.) have not been included the model but should be considered in future iterations. Figure 11-13 shows employment estimates, with an estimated total of 3 438 people employed in the two formal sectors. In the ULMCatchMOD, the SQ, forestry employs more people than tourism, based on the available input data. Because employment rates used different units, this finding should be interpreted with caution and are in contrast to the HH survey results, which show much higher employment in tourism than forestry. Input data can be adjusted easily based on additional data and expert input. In the ULMCatchMOD, employment rate is not influenced by climate; only sector-based changes such as occupancy rate.

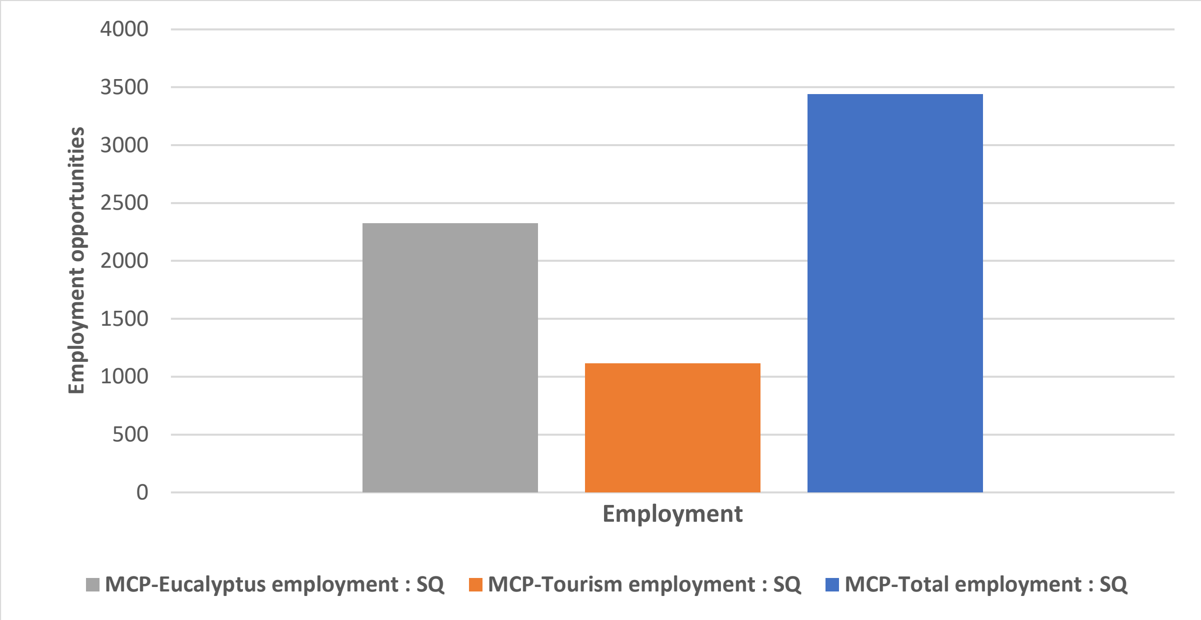


Figure 11-13 Status Quo sector employment trends

11.5.5.2.1.2 Economic value

The model estimates that the NPV value is higher in the wetter scenario compared to the drier scenario for the total area as well as for eucalyptus (Figure 11-14). It is important to note that the eucalyptus sub-routine routine did not contain a DF but rather a differentiated growth rate. In drier conditions the model is set up such that eucalyptus trees take more time to reach maturity and, hence, have a lower frequency of harvest compared to the wet future. The occupancy rate for tourism was held constant under both futures. The results estimated for tourism (accommodation) appear to generate fewer benefits compared to eucalyptus. This is inconsistent with HH survey results and does not include spend on activities. Using the average occupancy rate of 36% the amount spent by tourists in the area was calculated. Based on an assumed average daily spend per tourist of R466 a day in the area, the model estimated that over the 27-year period this is equivalent to R1 76 billion. This contribution is currently NOT included in the NPV calculations and would change the outcome. Further development is needed to link these components within the model.

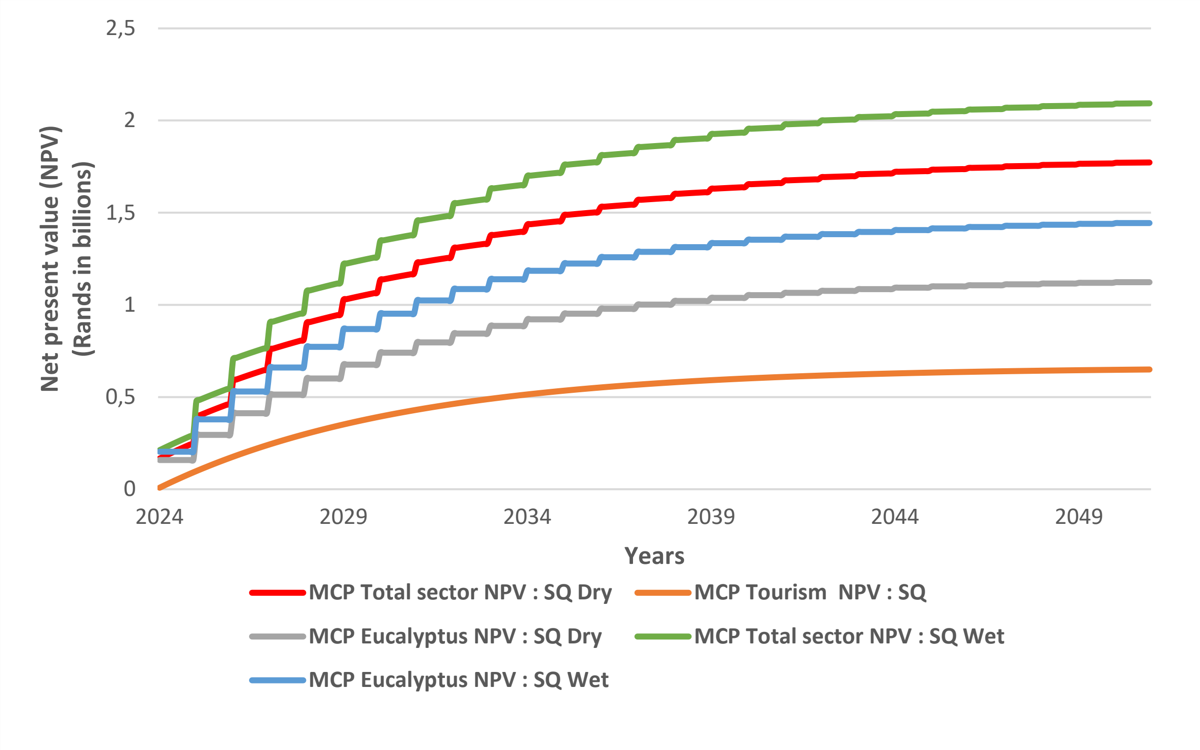


Figure 11-14 Status Quo scenario for C6Wet and C6Dry future storylines, with activities held constant at 2020 LULC (SQ), social discount rate at 15%

To test the impact of an improved tourism industry, sans daily spend, the SQ was re-run with a 60% occupancy under the dry and wet eucalyptus yield runs. This resulted in a significantly positive impact on the local economy (Figure 11-15) with a higher NPV for the eucalyptus, especially for the future with slower growth rates typical of extended dry periods.

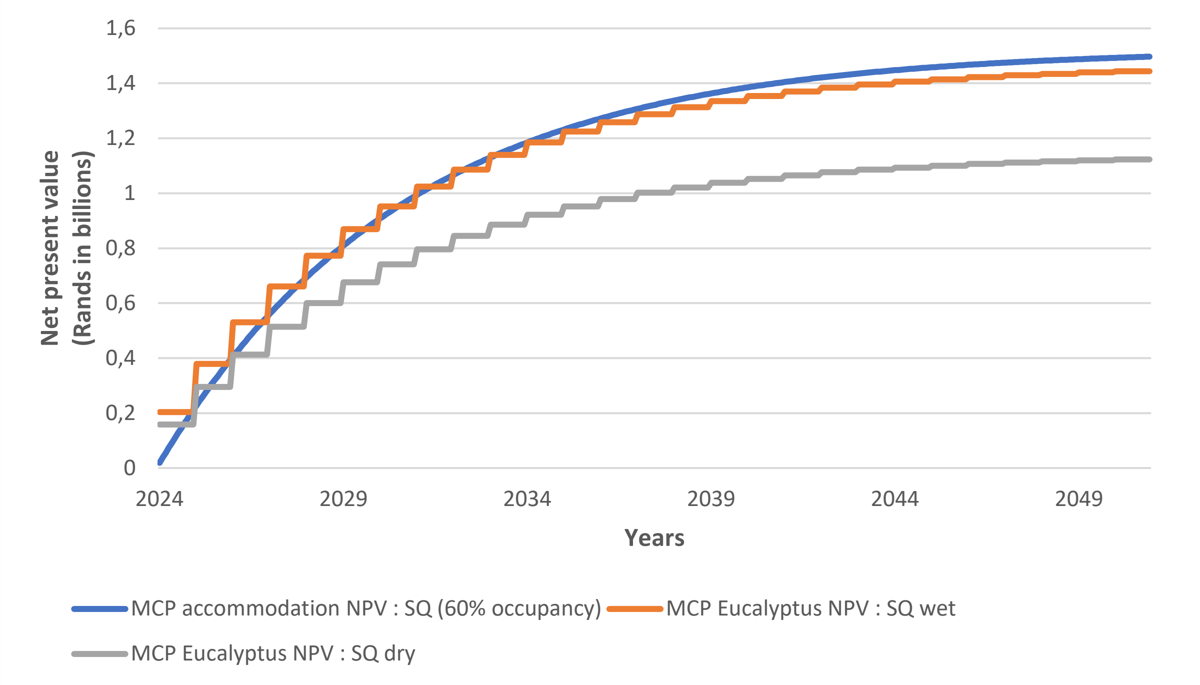


Figure 11-15 Tourism and forestry NPV at a social discount rate of 15% using SQ LULC conditions under the C6Dry and C6Wet future climate storylines

11.5.5.2.2 Half eucalyptus area converted to crop scenarios

Commercial crop production was proposed as an alternative to eucalyptus at the TC workshops. The economic value of a crop mix (maize = 20%, groundnuts = 45%, cassava = 30%, and vegetables = 5%), converting 50% of the eucalyptus to crops (within the changed area, see CHAPTER 4:), was thus investigated. Scenarios were assessed for rainfed (Dryland Crop) and Irrigated Crop LULC scenarios. An assessment of individual crop performance (not shown) demonstrated that the NPV per hectare of cassava is more beneficial than the crop mix, hence this was included in the ULMCatchMOD. The Dryland Crop scenario also provided the hydrology team with a better understanding of how the region's water resources would respond if half of the eucalyptus trees were removed.

11.5.5.2.2.1 Employment

The employment figures were consistent across future climate storylines (see Appendix P for input values per sector). It was estimated that employment opportunities from all sectors combined under the crop scenarios was 18.5% higher than the SQ (Figure 11-16). The job losses from the 50% decrease in forestry were more than compensated for by jobs created in the crop land use and land-cover (LULC) scenario. Tourism occupancy was held constant. Results show that commercial-scale crop farming resulted in an overall increase in employment opportunities (just over 4 000) compared to the SQ. (Figure 11-13) (just under 3 500), employing an estimated one and a half times more per unit area compared to eucalyptus forestry.

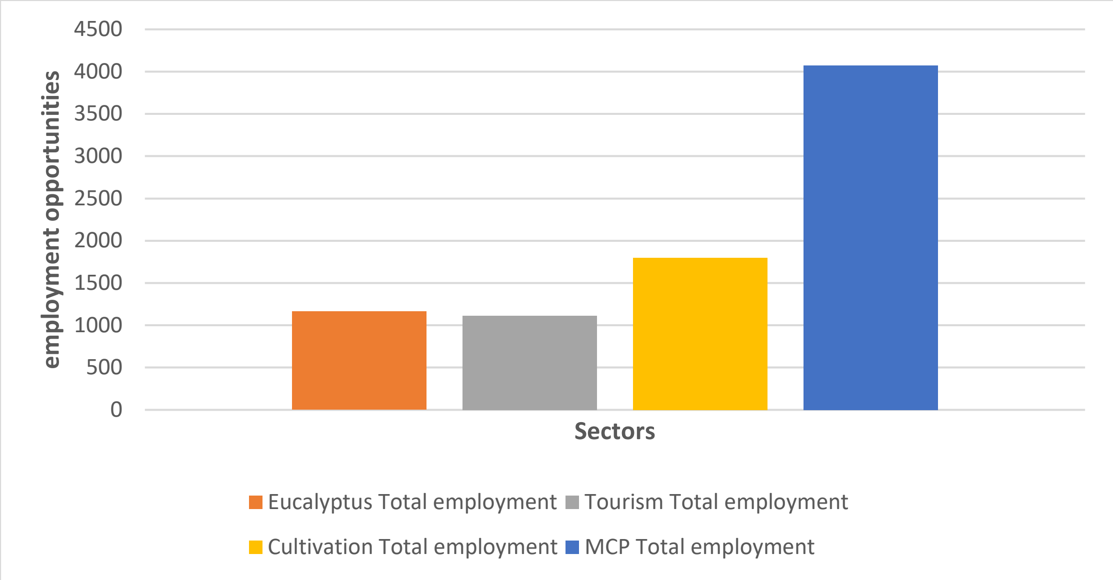


Figure 11-16 Rainfed Dryland Crop scenario total employment figures and figures per sector

11.5.5.2.2.2 Economic value

The NPV estimates for the C6Dry climate future storyline, based on ULMCatchMOD, show that Irrigated Crop and Dryland Crop (mixed crop) LULC scenarios are not viable economic alternatives to the SQ under this climate future (Figure 11-17). The lack of performance under the irrigated scenario is a result of insufficient groundwater to meet plant irrigation demand (see CHAPTER 10:). Water availability for irrigation became a key link between the hydrological and the systems models as irrigation could be "constrained" by available groundwater, thus affecting yield. The impact of this is captured within the ULMCatchMOD through the DF. The dryland cassava option, however, outperforms the SQ, indicating that it is not only more resilient than a mixed crop scenario but also that it is a better investment than the SQ (commercial plantation forestry). However, it is important to reminder that the costs of conversion are not captured in the model. The outcomes of the NPV results for these LULC scenarios under the C6Wet scenario area consistent with those of the C6Dry scenario.

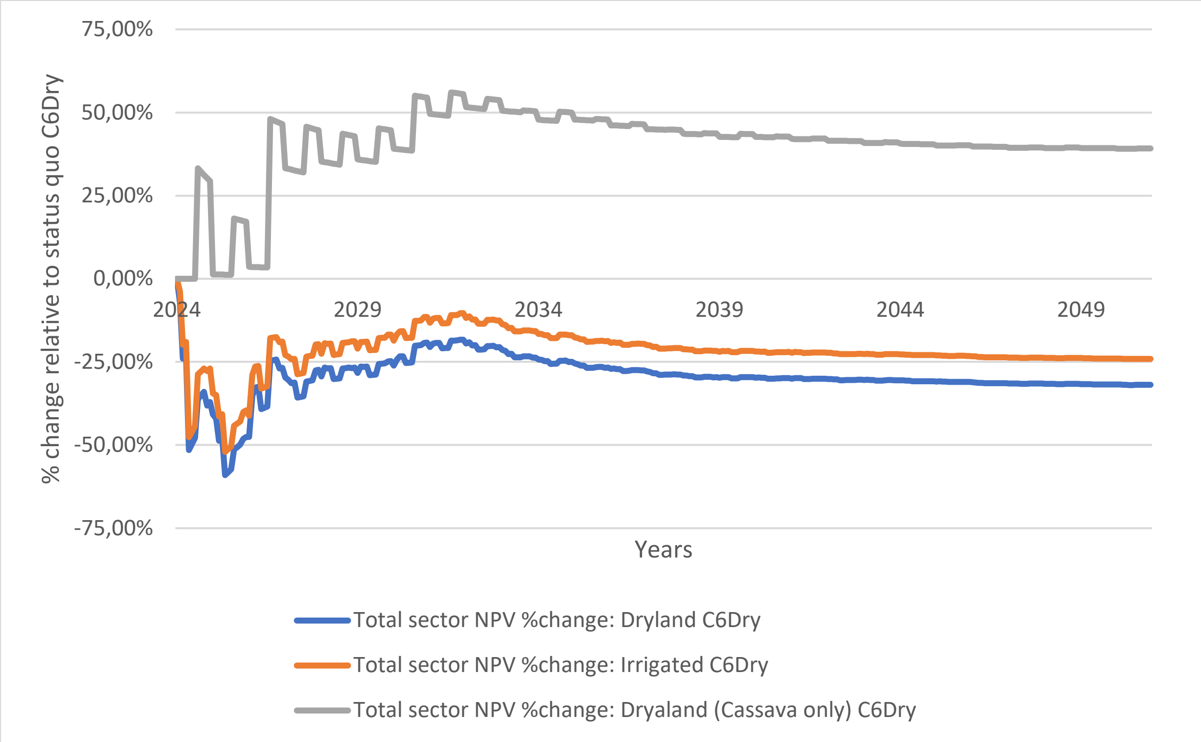


Figure 11-17 Percentage difference of NPV of different crop LULC scenarios under the C6Dry future climate storyline relative to the SQ under the same future climate

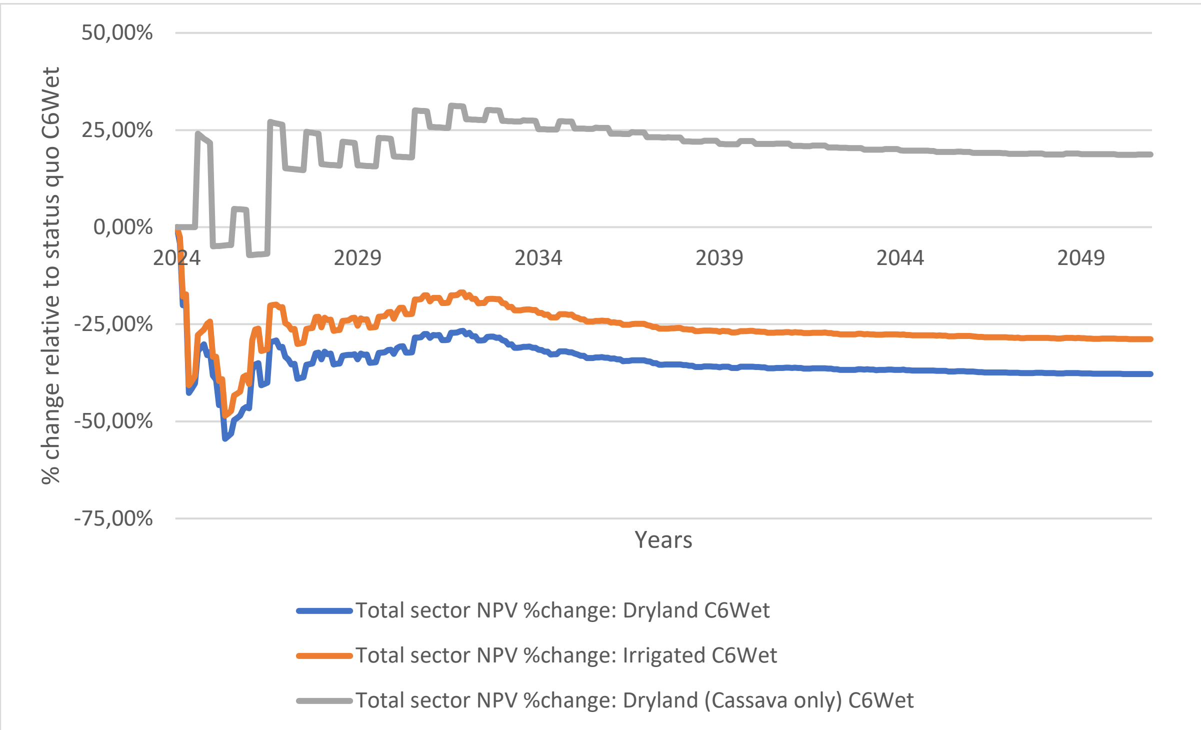


Figure 11-18 Percentage difference of NPV of different crop LULC scenarios under the C6Wet future climate storyline relative to the SQ under the same future climate

Under the much wetter (ERA5Wet) future climate storyline, all crops LULC scenarios provided a better NPV then the SQ (Figure 11-19) and rainfed cassava provided the best NPV of all crop scenarios.

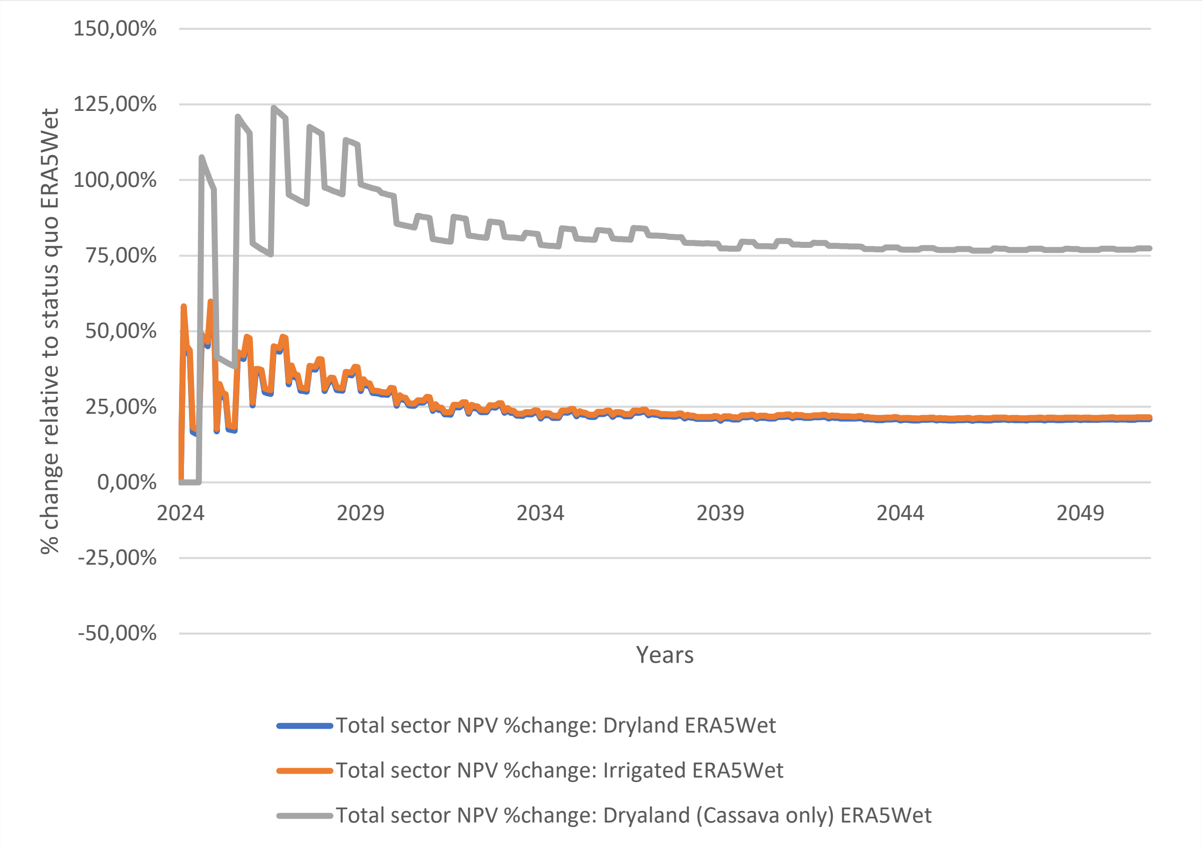


Figure 11-19 Percentage difference of NPV of different crop LULC scenarios under the ERA5Wet future climate storyline relative to the SQ under the same future climate

11.5.5.2.3 Half eucalyptus area to macadamia or Marula

The results on the performance of the Dryland and Irrigated Macadamia LULC scenarios as well as Dryland and Irrigated Marula LULC scenarios, relative to the SQ, under the three future climate storylines (C6Dry, C6Wet and ERA5Wet) are presented below.

There is currently some interest macadamia nut farming as an alternative to eucalyptus and this was proposed several times as a scenario at the TC workshops. One novel suggestion from the TC workshops was to convert eucalyptus plantations to Marula, an indigenous tree utilised for many purposes (Shackleton et al., 2002, Sinthumule and Mzamani, 2019). Marula has potential commercial value (ABS 2020) and is likely to be a resilient species under climate change (Jinga et al., 2022). Most Marula products currently emanate from wild harvested populations (Shackleton et al., 2003), which can post a risk to sustainability (Murye and Pelser, 2018). Production guidelines have previously been developed (DAFF 2010). There is a growing emphasis on the commercialisation of indigenous resources, such as Marula, which are known for their resilience to extreme climates. However, commercial scale operations are not common – despite high demand for oil, hence, scant data is available for orchard type production.

The 50% area change to macadamia has potential to create 9 972 employment opportunities which is significantly higher the than the number of people employed compared to the same size of land for eucalyptus.

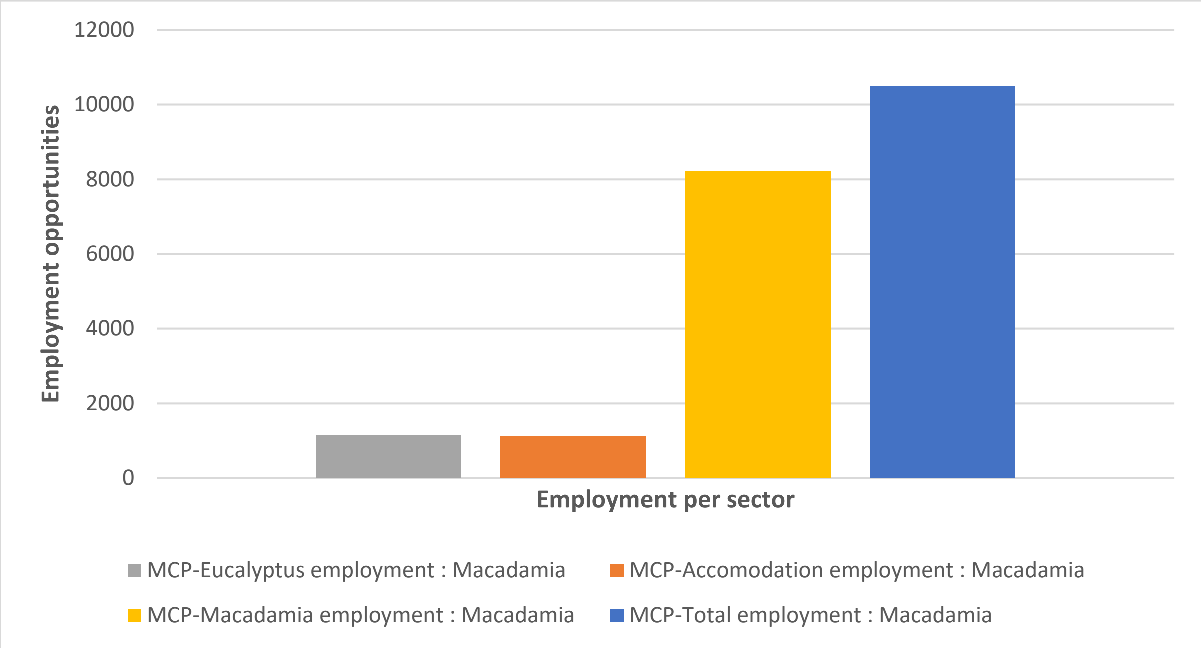


Figure 11-20 Rainfed Macadamia LULC scenario total and per sector employment figures

11.5.5.2.3.1 Economic value

The model estimated that converting 50% of eucalyptus plantation area to Dryland Macadamia would result in a higher NPV relative to the SQ (by about 25%) under a warmer drier future (C6Dry) (Figure 11-20), despite a lag in time to production. Irrigated Macadamia gave a slightly better NPV then the Dryland Macadamia, but not significantly. Dryland Marula also provides a better NPV compared to the SQ LULC under this climate future storyline and is equivalent to the NPVs from Dryland and Irrigated Macadamia (Figure 11-21). A reminder that even with the irrigated scenarios, there was a deficit relative to crop demand based on available groundwater for irrigation. Macadamia is known to require irrigation under most circumstances in South Africa

Under the C6Wet future climate storyline, the NPVs for both Irrigated and Dryland Macadamia and Dryland Marula, followed a similar pattern to that of the C6Dry scenario LULCs with all providing a better NPV relative to the SQ LULC (Figure 11-22). Under both the C6Dry and C6Wet, the increases in NPV coupled with the employment rate would result in a net positive outcome relative to the SQ, based on the input data used.

In running the very wet future climate storyline (ERA5Wet) when plant water demand is worked out, it was found that rainfall would meet all plant demands hence no irrigation scenarios were run for this climate future for Marula and Macadamia LULC scenarios. The NPV for Macadamia was over 200% better than the SQ under the very wet future climate storyline (ERA5Wet). The Marula NPV was only slightly better than the SQ, however it is likely that the potential value of commercial scale production, with the processing of high value components (oil) on site has been underestimated. Marula oil sells for approximately R350 for 100 ml currently.

The water production function can be used to understand the effect of water deficits on herbaceous and woody species (Steduto et al., 2012). Due to its simplicity and minimal data requirements, this was applied to macadamia and Marula. To utilise this approach, the yield response factor (K_y) is required. It must be noted that assumptions were made on the values of K_y for macadamia (1.1) and Marula (0.7) in considering their sensitivity to water deficits (Steduto et al., 2012). It should be emphasised that, due to the project's scope and timeframe, it was not possible to fully comprehend the intricacies of agronomic processes. As a result, the model-generated estimates for macadamia and Marula should be considered as coarse, and should be interpreted with caution.

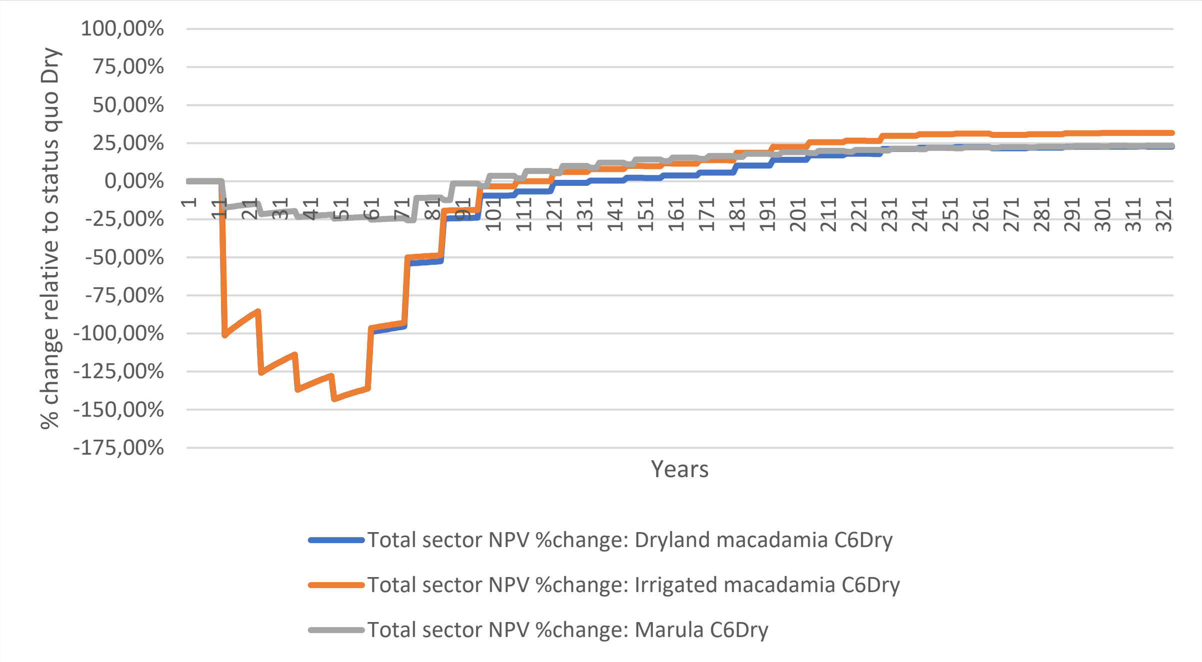


Figure 11-21 Percentage difference of NPV of Dryland and Irrigated Macadamia LULC scenarios and Dryland Marula LULC scenario under the C6Dry future climate storyline relative to the SQ under the same future climate

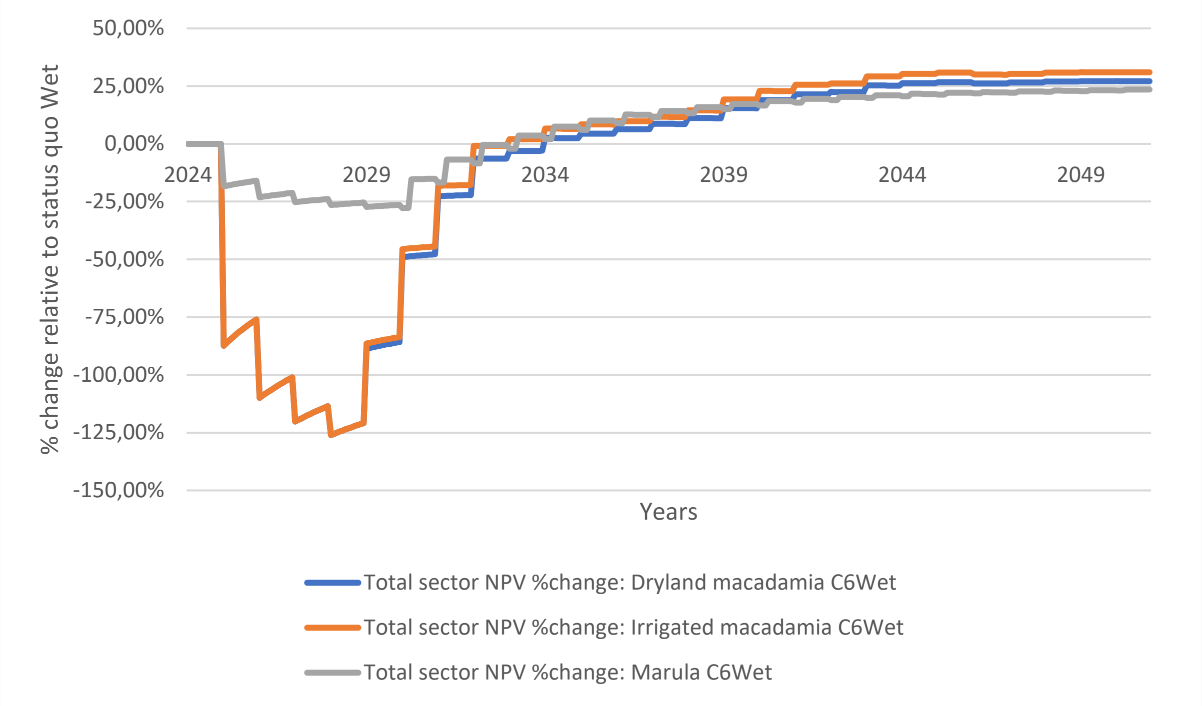


Figure 11-22 Percentage difference of NPV of Dryland and Irrigated Macadamia LULC scenarios and Dryland Marula LULC scenario under the C6Wet future climate storyline relative to the SQ under the same future climate

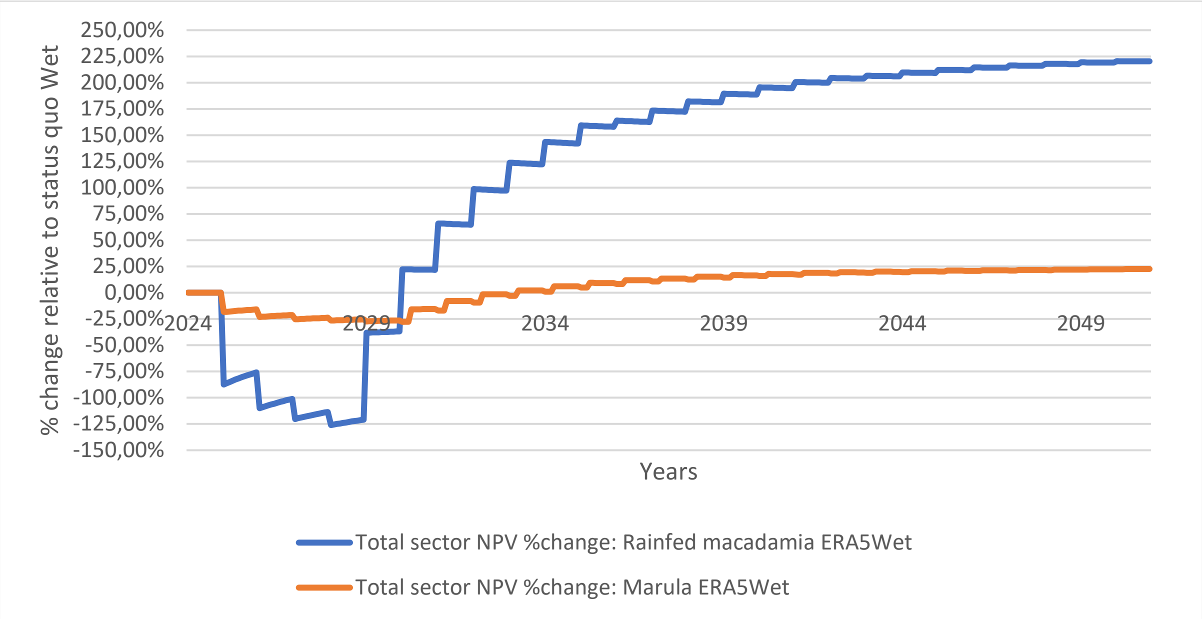


Figure 11-23 Percentage difference of NPV of Dryland and Irrigated Macadamia LULC scenarios and Dryland Marula LULC scenario under the C6Wet future climate storyline relative to the SQ under the same future climate

11.5.5.2.4 Half grasslands size to bush encroachment

Historically, grassland extent was far greater than it is now. Bush encroachment was highlighted at the TC workshops as a concern, a sentiment echoed in several subsequent engagements. Community members contend that the increase in indigenous woody species (bush encroachment) may also have an impact on the water resources and impact on the area available for cattle grazing. The loss of grasslands affects livestock productivity, because of reduced grazing capacity. Cattle farming was modelled at the household level, using the region's grazing capacity. increasing the area of bush encroachment decreases grassland are, and resulted in a negative impact on cattle farming relative to the SQ (Figure 11-24) due to the reduced grazing capacity.

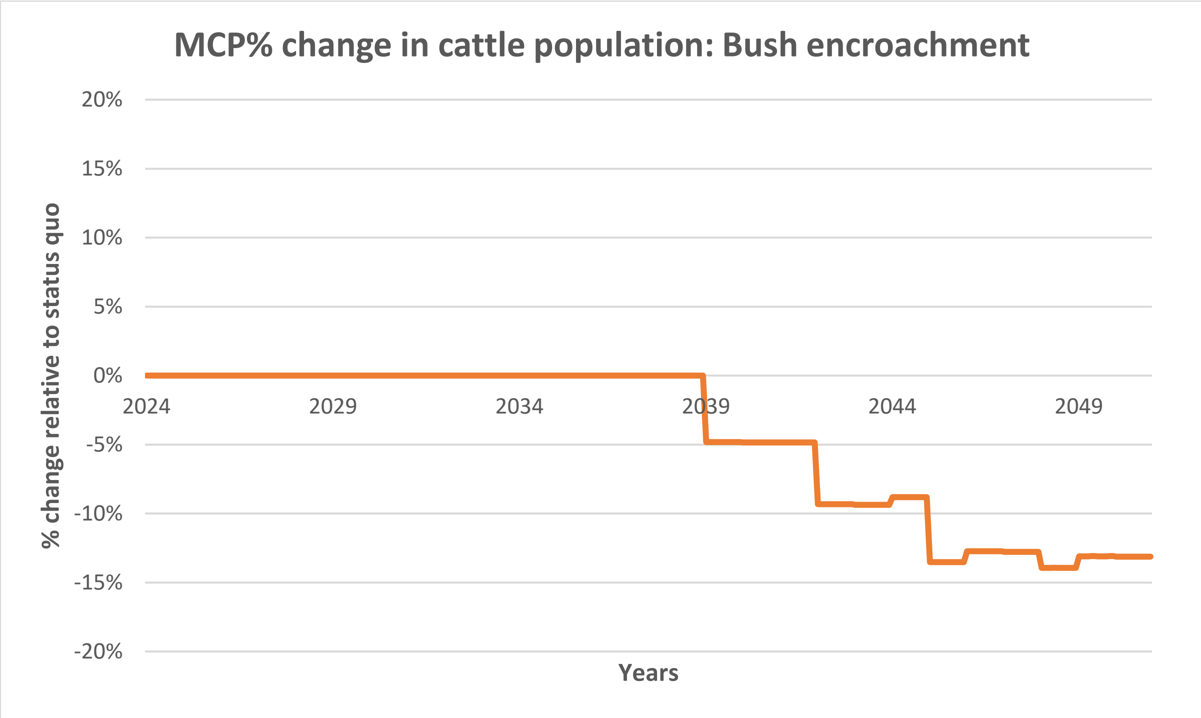


Figure 11-24 Comparing economic value of cattle between SQ and loosing 50% of grasslands to bush encroachment

11.5.5.2.5 Summary of the Sector Economy Sub Model Results

In summary, choices made now have varied impacts on future outcomes. A subsample of results was presented to illustrate how ULMCatchMOD can be utilised to explore different choices. The primary focus was on the model configuration. Scrutiny and improvements are required for input data which may affect the outcomes, before the results can be used to inform decisions with confidence. In its current form, the model demonstrates the potential relative impacts based on available data of different scenarios. So far, cassava appears to be the safest option in an uncertain future, both economically and in terms of employment benefits. Macadamia in a much wetter future may provide higher benefits.

11.6 DISCUSSION

Mounting evidence for current and project impacts of climate change on lives and livelihoods (Lee et al., 2023, Pörtner et al., 2023) emphasis the need for actionable research outcomes that can inform bottom up adaptation strategies (Shepherd et al., 2018, Rodrigues and Shepherd, 2022). Vulnerable communities, associated with low income, low adaptive capacity and declining ecosystem integrity are likely to be most affected in the absence of radical intervention. Quaternary catchment W70A, within the ULM in Northern KwaZulu-Natal, epitomise this situation (Patrick, 2021).

The overall objective of the study was, thus, to develop an integrated model to evaluate the combined impact of climate and LULC change on water resources with ensuing feedback on sectoral and household outcomes, the economy of the region, and employment. Household surveys were undertaken to provide a baseline understanding of the current situation and to inform the development of a systems model (ULMCatchMOD). ULMCatchMOD was then used to develop subroutines for the household and sector level dynamics.

Participatory approaches, involving three traditional councils within the Lake Sibaya groundwater catchment area, identified four top challenges. Water security emerged unanimously as the primary concern. The MCP hydrological system is sensitive owing to its dependence on rainfall for groundwater recharge, combined with LULC impacts on the groundwater resource. Water for household use is a constitutional right, while water required for production is subject to regulation. Lack of employment, low economic status, and the degradation of natural resources people rely on were also identified as priorities by the TC.

The main challenges and economic activities emergent from HH survey data were consistent with those identified in the TC workshops for the first two issues – water shortage and unemployment. Households expressed a greater degree of concern for the lack of infrastructure and crime, with natural resources being less of an issue (Table 11-1). However, in comments received in the HH surveys, alluded to significant concern about the impact of the declining water table on cultivation (204.4%) and natural resources (20.4%), and 7% expressed concern over gum plantations (Appendix M).

HH survey data revealed that a significant number (38.5%) of households are water insecure. Tembe households showed the highest probability of experiencing water insecurity among the traditional communities. There is variation in the primary water sources among the traditional communities: in Mabasa and Tembe, most households depend on piped water, while in Mbila/Zikhali, boreholes are the most used primary water source. However, not all households can afford to invest in boreholes. Households responses indicated that water security should be improved through improved infrastructure (bores, taps, pipelines, rainwater harvesting tanks, etc.) (Table 11-6 and Table 11-7). Only one respondent suggested a reduction in the gumtrees to improve water security at the household level (Table 11-6) whereas only four identified this as an intervention for the region as a whole (Table 11-7). The results of this study are consistent with findings from Patrick (2021), who also highlights the increased risk for conflict related to increasing water insecurity in the region.

The study found that household obtain income from diverse sources, and this varies somewhat between the community areas. Despite the diverse livelihoods, the socio-economic status is low, with an average household income of R5 090 per month, consistent with findings from other studies (Cunningham, 1990, Mountain, 1990, Gaugris and Van Rooyen, 2010, Hazell, 2010). Employment by the government (ranging from R102 000 to R141 000 on average per year) are the highest form of income generation. Grants, pensions, and remittances are approximately R20 000 on average per year, which is about the same as income from forestry, but half that from tourism (R41 000) (Table 11-4). In total, 70% of the total household income is derived from Government employment, grants, pensions, and remittances. Tourism contributes 16% of total income, with commercial plantation forestry 2% in total (Figure 11-7). Dryland crop cultivation is the primary source of household income from household economic activities, followed by wetland cultivation and livestock farming (Table 11-11).

The dependence on subsistence farming and income from natural resources, combined with low economic status, highlights the vulnerability and low adaptive capacity of households in the region

(Lottering et al., 2021), which emphases the need for urgent intervention in the face of climate change (Pörtner et al., 2023). The lived reality of this is evident in the number of respondents who noted the negative impact that the declining water resource has on reeds used for crafts, a key income source. In verbal responses from HH survey very few comments (five in total) connected their concern with the water shortage to eucalyptus. Preferences solicited from the TCs and households revealed an aversion to forestry and a preference for tourism, commercialisation of indigenous resources and cultivation.

All households rely on shops for food (Table 11-9) but 68.6% of households supplement their food through cultivation. Wild fruits, hunting, and fishing provide supplementary food for 28.5% of households. Of concern, therefore, is that in questions related to climate change awareness, of those who responded that they are impacted by climate change (45%), 83.7% cited negative impacts on crop yield loss or failure, livestock, and natural resources primarily due to water shortage and dry conditions.

Suggestions for alterative land uses from the TC workshops were distilled into several scenarios, the net outcomes of which were explored using a systems model approach, which incorporated links to climate hydrological outcomes. A wetter future will likely result in higher income generation than a dry future for SQ conditions (Figure 11-14). Under a C6Dry and C6Wet climate futures, Dryland Crop provided more employment but will generate less income then the SQ. This trend is reversed for the wetter future (ERA5Wet), where income generation is higher than SQ with the same employment rate. Cassava demonstrated high potential is a climate smart crop, thus risk, based on the input data used. The Crop Irrigation LULC scenario under the C6Dry and C6Wet future storylines was so limited by water availability that the NPV was below that of the SQ (Figure 11-17 and Figure 11-18). If tourism were optimised it would improve income generation and employment across all scenarios (Figure 11-15). Simulations for the Dryland Macadamia LULC (Figure 11-21 and Figure 11-22) indicted a relative increase compared to the baseline in sector-wide income if the eucalyptus is replaced by macadamia under all climate futures.

A subsample of results from the system model demonstrated the model's capabilities in assessing major land use choices on income and employment under dry and wetter climate scenarios. The model was able to show how climate can directly influence economic outcomes (NPV), particularly for crops, forestry, and agroforestry systems. Furthermore, it revealed that some crops are more resilient than others. Most importantly, the net impact of a choice made today can be assessed into the future in relation to the current SQ to determine whether it would be more beneficial or not (% change from SQ). For example, model results showed that commercial scale cassava farming would greatly improve the employment and economic status of the region compared to the SQ (forestry). Non-land-based activities were also tested using the model, such as an increase in tourism occupancy, which also significantly improved employment and regional income.

The system model developed can be utilised to explore outcomes of different land use and economic activities. However, while the model structure is in place, outcomes are dependent on accurate parameterisation. More data is required in this regard and refinements can still be made within the model structure to enhance its power in exploring system feedbacks more dynamically.

11.7 CONCLUSION

The study's goal was to develop a tool to explore the net impacts of various climate and land use scenarios for the Lake Sibaya catchment area within the ULM. The region is a one of the poorest in South Africa, with a low employment rate.

Four key challenges experienced in this area by the communities are water security, lack of employment, low economic status, and declining natural resource (ecosystem)/ integrity (degradation). Data gathered has as contributed information on the baseline economic conditions in the region as well as people's preferences for the future. The information is, thus, deeply contextual. Household data has contributed valuable quantitative and qualitative information to test narratives and perceptions, which challenges the notion that forestry is a valued and beneficial land use, and provides evidence for its negative impact on other livelihoods, e.g. reeds and associated crafts, through its impact on the water table.

A systems model, ULMCatchMOD, was developed to demonstrate the relative performance of different LULC scenarios under various climate future storylines. The model illustrates not only the negative impact that different climate futures may have on various land use options but also the benefits of others, including those that show more resilience, such as cassava. The household data and ULMCatchMOD outcomes confirm the need for the development of proactive coping mechanisms to mitigate climate impacts. This involves diversifying livelihoods towards water-wise, climate-smart alternatives. An observation of concern is the low level of climate change awareness, especially considering that knowledge about climate change is a crucial enabler to promote action to enhance adaptive capacity.

CHAPTER 12: SUMMARY MATRIX

By S Janse van Rensburg, LN Gule, MH Maseko S Maseko, and J Blignaut

In this chapter a simple framework to tie hydrological, natural resource integrity, and socio-economic results is presented, further contributing to Aim 1 "*The development of a system-wide resource economics model with appropriately scaled and integrated climatological, land cover and hydrological components of the region as a decision support tool to explore net effects of plausible future trajectories for quaternary catchment W70A with Lake Sibaya's groundwater catchment as the primary response variable*" and Aim 5 of the project "*Estimate the net economy-wide impacts and consequences of several plausible trajectories of climate and compatible land use-land cover change for the quaternary catchment W70A region*".

12.1 INTRODUCTION

There is a well-recognised gap between climate change science and usable reliable climate information relevant for local scale decision support (Rodrigues and Shepherd, 2022). Furthermore, uncertainties in climate projections present challenges to informing adaptation strategies. Storyline approaches can be used as caricatures to describe a discrete range of potential climate futures (Shepherd et al., 2018). They are a useful tool in data poor environments for the exploration of potential impacts at local scales and can be strengthened by the incorporation of context-relevant information (Young et al., 2021).

In this project the aim was to try and explore the net impact of land use decisions made now on the future well-being of the region under plausible climate future storylines with the three communities within the study area. The study's contention was that "well-being" needs to be assessed in relation to issues defined by the people living in the area.

12.2 SYNTHESIS OF STEPS TO DETERMINE NET OUTCOMES

Engagements with TCs, along with quantitative and qualitative data collected from HH surveys, revealed common challenges that faced households within the region. The most pressing of these challenges were distilled into four key measures: water security, employment, economic status, and natural resource integrity. Subsequently, these measures were used to assess the outcomes of various LULC decisions made today by 2050 under different future climate storylines.

A range of spatially-diverse future economic activity preferences was provided through group work by the TCs. Notably, no groups suggested a scenario with increased commercial plantation forestry. To assess the relative hydrological impacts of these, the suggestions were simplified into a set of "single land use change" scenarios, that encompass both common and novel suggestions while addressing a specific concern. Additionally, a baseline (SQ) was included against which other scenarios could be tested. A central question addressed by this project was whether the perceived benefits of the current dominant land use-based sector (commercial plantation forestry) outweigh its known negative impacts on water resources and the adaptive capacity of the region and households to climate change. Consequently, a "No Forestry" scenario was included.

Household surveys provided baseline socioeconomic information. A systems model (ULMCatchMod) integrated components of the hydrological outcomes as well as climatological data to explore the economic and employment outcomes at the household level and, primarily, for sector-based alternatives to commercial plantation forestry. The later included both land-based changes (as used in the hydrological modes, as well as non-land-based choices, for example changes in tourism occupancy.

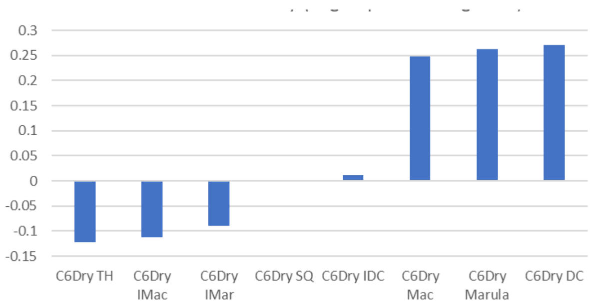
The ULMCatchMod was able to integrate climate impacts on productivity, using the DF approach, to test the relative impacts of climate on the production yield of different land use choices.

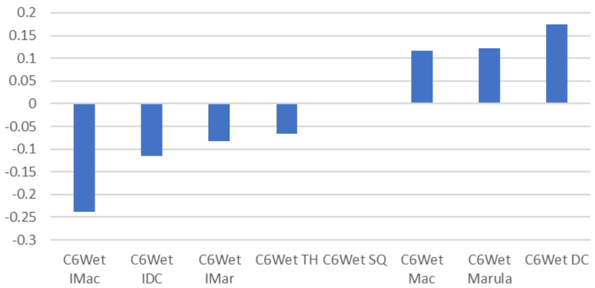
12.3 SIMPLE SUMMARY MATRIX

Previous chapters have provided a subset of results that needed to be integrated into a simplified framework to provide an overview of the net relative outcomes to facilitate engagement. Given uncertainties related to various data inputs, the recommendation is that outcomes should be assessed in relative terms. The approach used is to assess each LULC choice in relation to the four challenges distilled from the TC workshops in relation to their respective SQ within each climate storyline. The outcomes for each are provided in a simple comparative matrix. One needs to select a choice within a climate future matrix, not between matrices.

Very simply, if the scenario results help to alleviate the challenge, (a positive outcome), in relation to the SQ, it gets a +1. If there is no change it is a 0 and if there is a negative impact it gets a -1. This scale should be expanded, as data integrity is improved, to incorporate richer information with regard to the relative magnitude of the outcomes over a wider range, but the scale (weighting) needs to be consistent for each. The way each "challenge" was assessed is described below:

- Economic and employment challenge evaluations were made from the outcomes of the ULMCatchMOD using NPV and employment numbers relative to their respective SQs. Where figures are better than the SQ, they get a +1 and, where worse, a -1.
- For natural resource integrity, an assessment of lake level trends in relation to the drought level set by the reserve determination is used. The rule applied is that if water levels have a continued declining trend, it gets a -1, but if there is recovery trend towards and above the drought threshold for most of the simulation periods it gets a +1.
- For the water security challenge, the average lake level from September 2049 to August 2050 was used to assess relative outcomes of different LULC scenarios in relation to the SQ for each climate storyline Figure 12-1). If the outcome of the challenge for the LULC scenario was >10 cm less than the SQ) it gets a -1, if the same, it is 0, and if it is above the SQ by >10 cm, it gets a +1.





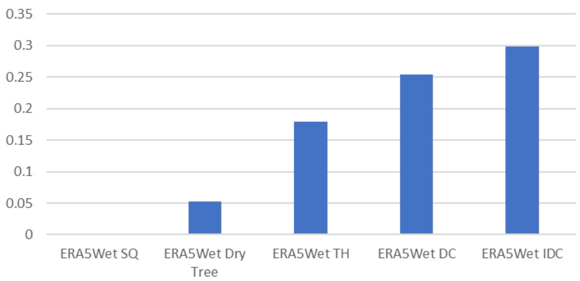


Figure 12-1 Difference in water level outcomes between the LULC scenarios in relation to the SQ average lake level from September 2049 to August 2050 for the C6Dry (top left) C6Wet (top right) and ERA5Wet (left)

Results for the C6Dry, C6Wet and ERA5 Wet future climate storylines are shown in Table 12-1, Table 12-2, and Table 12-3 respectively. As an example, under the warmer drier future climate storyline (C6Dry, Table 12-1), the Bush Encroachment LULC scenario, with no reduction in forestry, has the worst outcome (-3), whereas Dryland Crop, using only cassava as a crop, provides the best (+3), improving the outcomes in relation to all challenges other than natural resource integrity as the water table stays well below the ecological reserve under this climate storyline. The bush encroachment with no change in forestry seems to be the worst option under all future climate storylines, corroborating concerns raised by community members.

Table 12-1 Summary matrix of impacts of different LULC scenarios under the warmer drier (C6Dry) climate future storyline relation to 4 key challenges. Green indicates a positive impact relative to the SQ, orange indicates a negative impact relative to the SQ, clear is no change. Red text indicates that in reality, there is no allocable water for that scenario based on the water level in relation to the RQOs

Very dry few extreme rainfall events (C6Dry) Climate future storyline	Water	Employment	Economic status	Natural resource/ Ecosystem integrity	Net outcome
Bush Encroachment	Worse (-1)	No change (0)	Worse (-1)	Worse (-1)	-3
Dryland Crop	Better (+1)	Better (+1)	Worse (-1)	Worse (-1)	0
Irrigated Crop	Worse (-1)	Better (+1)	Worse (-1)	Worse (-1)	-1
Dryland Cassava	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Dryland Macadamia	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Dryland Marula	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Irrigated Macadamia	Worse (-1)	Better (+1)	Better (+1)	Worse (-1)	0
Irrigated Marula	Worse (-1)	Better (+1)		Worse (-1)	
Status quo +60% Tourism	No Change	Better (+1)	Better (+1)	Worse (-1)	1

Table 12-2 Summary matrix of impacts of different LULC scenarios under the warmer slightly wetter (C6Wet) climate future storyline relation to 4 key challenges. Green indicates a positive impact relative to the SQ, orange indicates a negative impact relative to the SQ, clear is no change. Red text indicates that in reality, there is no allocable water for that scenario based on the water level in relation to the RQOs

Warmer, slightly wetter few extreme rainfall events (C6Wet) climate future storyline	Water	Employment	Economic status	Natural resource/ Ecosystem integrity	Net outcome
Bush Encroachment	Worse (-1)	No change (0)	Worse (-1)	Worse (-1)	-3
Dryland Crop	Better (+1)	Better (+1)	Worse (-1)	Worse (-1)	0
Irrigated Crop	Better (+1)	Better (+1)	Worse (-1)	Worse (-1)	0
Dryland Cassava	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Dryland Macadamia	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Dryland Marula	Better (+1)	Better (+1)	Better (+1)	Worse (-1)	2
Irrigated Macadamia	Worse (-1)	Better (+1)	Better (+1)	Worse (-1)	0
Irrigated Marula	Worse (-1)	Better (+1)	Better (+1)	Worse (-1)	0
Status quo +60% Tourism	SQ	Better (+1)	Better (+1)	Worse (-1)	2

Table 12-3 Summary matrix of impacts impact of different LULC scenarios under the warmer much wetter (ERA5Wet) climate future storyline relation to 4 key challenges. Green indicates a positive impact relative to the SQ, orange indicates a negative impact relative to the SQ, clear is no change

Warmer, very wet, with extreme rainfall events (ERA5Wet) Climate future storyline	Water	Employment	Economic status	Natural resource/ Ecosystem integrity	Net outcome
Bush Encroachment	Better (+1)	No change (0)	Worse (-1)	Better (+1)	1
Dryland Crop	Better (+1)	Better (+1)	Better (+1)	Better (+1)	4
Irrigated Crop	Better (+1)	Better (+1)	Better (+1)	Better (+1)	4
Dryland Cassava	Better (+1)	Better (+1)	Better (+1)	Better (+1)	4
Dryland Macadamia	Better (+1)	Better (+1)	Better (+1)	Better (+1)	4
Dryland Marula	Better (+1)	Better (+1)	Better (+1)	Better (+1)	4
Irrigated Macadamia (Not required)	Better (+1)	Better (+1)	Better (+1)	Better (+1)	4
Irrigated Marula (Not required)	Better (+1)	Better (+1)	Better (+1)	Better (+1)	4
Status quo +60% Tourism	SQ	Better (+1)	Better (+1)	Better (+1)	3

These matrices provide simple summary "storyboard" for assessing the relative outcomes of different choices in relation to key challenges. For example, it is easy to see that in the C6 climate futures, with few extreme rainfall events, the worse option is the SQ (commercial plantation forestry) coupled with increased bush encroachment.

The ERA5Wet scenario clearly provides optimal results This climate future storyline is not based on climate projections as such, but rather provides a storyline that explores regular extreme rainfall event influences on the system. Climate projection assessments suggest model agreement (CMIP6 and

CORDEX ensembles) for a drying trend for Southern Africa, however, there is still uncertainty and weak model agreement (conflicting signals) for KZN with respect to rainfall (Engelbrecht et al., 2024). This emphasises the need for improved parametrisation as well as more effort to improve the understanding of processes that influence this region. The implication is that the likelihood of such a wet climate future is low but uncertain, but it demonstrates the importance of extreme events and provides insights as to how the system behaves under different LULC scenarios relative to other climate storylines. An important reminder is that the derivation of all the future climate storylines was somewhat influenced by the use of the ERA5 data. This study demonstrated that this data source under-predicts rainfall, the net results of which is potentially a 30% underestimation in recharge.

The Dryland Cassava LULC scenario demonstrates the most resilient response under all climate future storylines but would be insufficient in the CMIP6 futures to compensate for the climate impact in the water resource. Dryland Macadamia and Marula appear to both do well and be on par, but the NPV for macadamia is much higher than that of the Marula. This demonstrates the need for a wider scale to differentiate significant differences in NPV. Regarding all irrigation LULC scenarios, the system currently faces a significant water deficit, well below the requirements of the ecological reserve. This implies that there is no more water available to allocate for human demand related to population growth, let alone to meet the needs of those currently without water. Even if capital investment was available for large-scale irrigated commercial agriculture, there is no water available to allocate for agriculture or SFRAs. With no room for the expansion of irrigation, it is virtually impossible for emerging farmers to enter the sector, as has been previously argued under similar historic conditions at a national level (Blignaut et al., 2009). This narrative needs to accompany explanations of the irrigation outcomes.

Simulations indicated that improving tourism occupancy would yield significant employment and economic benefits. This finding aligns with Oldham et al.'s (2000) work in other regions within the country, demonstrating that ecotourism generates more revenue per hectare than forestry.

The LULC scenarios modelled were, by necessity, simple for hydrological analysis. Net outcomes are neither precise nor are we predicting anything. They are stories and narratives in numbers, relative to a baseline. This framework provides a simple storyboard approach to summarising the net outcomes of alternative choices made now into the future. The intention is to demonstrate proof of concept. The next step is to refine in the scales used to improve nuanced differentiation once model parametrisation is improved.

CHAPTER 13: OUTCOMES FROM CO-GENERATIVE APPROACHES AND ENGAGEMENT

By LN Gule, S Mfeka, MH Maseko, S Maseko, and S Janse van Rensburg

This chapter addresses, in part, Aim 6: *Use co-generative approaches to ensure context relevant and plausible development alternatives that reflect the aspirations of local communities within the MCP and in doing so advance multiway knowledge transfer and decision support.*

13.1 INTRODUCTION

There is often a significant gap between Global Change research and the provision of appropriate information to support adaptation strategies for societal impact (Rodrigues and Shepherd, 2022, Oliver et al., 2023). Participatory approaches help to connect with the actual needs of the end users (Eriksen et al., 2021, Pörtner et al., 2023) and finding ways to address these together.

While not "experts" in engaged research and participatory approaches, the project team was committed to learning and rooting the work within the local context through invitations to participate and learn together to the communities within the study area. This chapter reflects on the different engagements that took place with various stakeholders and community members. It provides a record if the emergent understanding and experiential transformations for participants and the project team as well as some detail of the insights gained through the engagements with various stakeholders. The project aimed to bring about a transformative experience for the project team. Evidence of this success lies in the insistence by team members to actively reach beyond the obligations of the project and to help escalate issues identified in order to incite action and facilitate appropriate interventions; "We have to be the voice of the community". Examples of contrasting narratives that were observed are also provided to highlight the diversity, and hence complexity, of the dynamics within the study area.

Through engagements, opportunities became evident through interactions which the project acted on, including a knowledge exchange facilitated by the project team which was immensely beneficial and a way to give back the community members. Within this chapter, key outcomes and highlights are summarised. Additional details are provided in Appendix R.

13.2 FIRST CONTACT: ENGAGEMENT FROM THE START

13.2.1 Securing Permissions

At the very beginning of the project secured appointments with each community area to attend their one of their monthly TC meetings. During these meetings one is allotted a short time to engage. We briefly explained the project ideas and requested permissions to proceed. Permission was granted by all three TCs.

13.2.2 First Round of Tradition Council Workshops to Inform Project Direction

The background aims and "quantitative" outcomes of these workshops are described in CHAPTER 4: The workshops were very valuable for the project team it connected with the realities on the ground. A full account of the experiences is provided in Appendix R. In summary, the workshops started with dialogues to assess the community's understanding of climate change and its implications. Despite low climate change literacy among council members, discussions helped reveal diverse perspectives and beliefs, such as the attribution of water scarcity to spiritual influences. A subsequent presentation, combining English slides with isiZulu explanations, covered climate change, the greenhouse effect, and the unique hydrological system of the study area. Linking climate change to the hydrological system, economic challenges, and potential benefits resonated with the community once participants understood the important link between rainfall and the groundwater resource. Discussions also provided the opportunity to share perspectives on the uniqueness of the system.

The key message to explain the project addressed the issue that climate change would impact rainfall patterns, but "we do not know how", and this will influence water security. Land use also affects the groundwater resource and land use choices could exacerbate or mitigate these effects. In acknowledgement of the economic challenges of the area, it was explained how the project was a response to people seeking alternatives to eucalyptus plantations and the aim of the study was to connect climate, land use, water resources, and economics to explore the net impact of decisions made today on future the wellbeing in the area.

Group activities revealed common as well as nuanced challenges and aspirations. The reactions of participants underscored the need for a solutions-focused approach, with tangible steps forward. Transdisciplinary networks will be required to help achieve this. It was admittedly very difficult to have conversations about climate change and its potential risks, when these communities have had little to do with its cause and have so many challenges to face as it is. This raised the question of climate justice, emphasising the importance of Government and NGO attention for effective adaptation strategies at the community level. The necessity for practical solutions and support is a vital message echoed at subsequent engagements.

We also learnt and evolved our approach through these workshops. For example, initially the workshop planned to involved group work with frequent group rotations and debriefs after each activity. However, the disruption caused by moving participants became apparent and prompted a shift to fixed groups that remained seated together during activities, ending with a plenary debrief that brought all participants together.

With regards to the use of maps, challenges arose with large printed colour maps that depicted various land uses in "arbitrary" colours, as council members struggled to comprehend them. The team had to adapt through the incorporation of satellite overlay on their phones for better orientation. The combination of satellite maps and color-coded land use maps improved understanding. In future engagements greater use of satellite image maps was made, with "classification maps" for own reference when needed. This prompted the development of a game that was used for later workshops, which used historic and current aerial images that participants had to "match" (by finding a partner with the same image taken at a different time). A brief explanation of known places was first given so participants could orientate themselves with the image.

An issue that emerged in the first two TC workshops, was that some felt uneasy making changes to areas on the maps outside of their areas of leadership. This concern was addressed in the final workshop by the omission of maps and instead have members select and rank their top two preferences for future land use changes from a table, rather than spatially which avoided mapping-related issues.

Most importantly these engagements enriched the research process and illuminated several issues and opportunities would otherwise not have identified.

From a team member in relation to their experience in the TC workshops:

"*When you listen to the conversations, you can hear that people are willing to let go of the plantation because they can see the damage they are doing to the area in terms of water, and they are willing to do it gradually while they try other options to use the land for income. The Council says that the people are attached to the plantations because they have seen first-hand how they can make them an income,* *and if they see another option that works as well as the eucalyptus plantations but does major damage, they will let go of them. Another point raised was that a lot more people depend on crop farming, whether dry or wet, to make money or feed their families. They also mentioned that Lala palm wine and cattle farming had gotten many students through school, and they would sell the cattle in the area or sometimes a bit far to put their kids through school.*"

13.3 KNOWLEDGE EXCHANGE: MATATIELE, ERS AND THE MEAT NATURALLY PROGRAM

Given the interest in the commercialisation of cattle, the project the team decided to arrange a knowledge exchange in partnership with WILDTRUST. The intention was to provide a platform where MCP community members could learn about rangeland management, animal husbandry, and a live mobile auction from other communities with first and experience. It was organised and sponsored by NRF-SAEON with support from WILDTRUST and hosted by Environmental Rural Solutions (ERS) in Matatiele. ERS is a small NGO in the Eastern Cape that works to improve ecosystem health and human wellbeing.

The participants for the knowledge exchange included three community members from each traditional community area within the study area (Tembe, Mbila/Zikhali, and Mabasa). NRF-SAEON requested each TC to provide three community members from each traditional community area, one of which was to be under the age of 35 years. The selection process by TC was different, but they all made sure that the people selected were passionate about cattle farming, the wellbeing of their communities, and the development of ULM and this was evident in the way the participated in the knowledge exchange and gave feedback to the TCs upon their return.

The Mbila/Zikhali TC held a meeting to gather individuals interested in cattle farming, specifically inviting both older and young enthusiasts. After meeting, participants were selected through a vote, including the chairperson of the Umhlabuyalingana Farmers' Association, a retired lady, and a young gentleman community area

In the Tembe TC, the Council selected three mature gentlemen, all commercial cattle farmers, including one from the Tembe Royal family. They explained that, after consideration, no youth interested in cattle were found in the area, hence no youth were selected.

Mabasa TC collectively selected the Nduna nKulu, a commercial farmer, and a young cattle enthusiast to participate. Most participants from the Tembe community area had no prior interaction with NRF-SAEON, lacking knowledge of NRF-SAEON's activities. This posed challenges during the initial dinner, as participants had expectations of funding. The NRF-SAEON team clarified their research-focused role, fostering understanding through dialog and on-site discussions. Eventually, participants recognised and appreciated the value of the intervention.

13.3.1 Activities

The knowledge exchange took place over three days, the 14th, 15th and 16th of November 2023. The first day the ULM community team visited was the Black Diamond community where they learned from the community about rangeland management. ERS has conservation agreements with five different traditional authorities, through which the conservation agreement the communities agree to rest some grazing areas for six months while ERS monitors those grazing areas during the rest period. The ERS then provides incentives for communities that follow through with the agreement. Incentives include deworming, vaccinations, provision of live mobile auctions through Meat Naturally, a reduced 6% commission fee from the auction sales instead of 8% and different capacity building training, e.g. animal husbandry, and fire management.

Yonela Sipeka from ERS demonstrated how the grass is monitored inside the grazing camps and outside for comparison using a Disk Pasture Measure (DPM) and tape measure to observe the grass biodiversity and productivity as well as grass increasers and decreasers. The camps are monitored when the camp is closed and for six months after that. Following this, he spoke about the WWF-ERS invasive plant clearing projects implemented throughout the catchment and showed the MCP delegates how to clear invasive vegetation without the use of poison. The use of poison to control aliens is not an option when cattle also graze in the same grassland. He explained that they cut the tree down and peel back the bark which causes the tree to die. Nomzamo, who works as an eco-champ at ERS, displayed the reusable diapers that they have introduced to the communities to tackle the issue of litter. One of the participants from MCP asked how they deal with other issues of litter that are not diapers and they said they dig big holes and bury it. The last activity for the day was the observation of spring protection and areas that have been cleared of wattle to enhance water availability for humans and cattle in the area. The Black Diamond community shared that previously they would get four if not five buckets of water while after the wattle was cleared they were able to get more than 40 buckets of water with enough left over for cattle.

Figure 13-1 (Left) Yonela from ERS displaying how they use a DPM to monitor pastures (Right) the MCP community with the Black diamond community

On the second day the team observed a mass deworming of goat and sheep in Mafube community. They also met and learned from the farmers in the area about animal husbandry. The team visited and observed fenced grazing camps and they learned from two Indunas about how they manage the rangelands and how they work with communities to keep grazing camps closed. The MCP team shared how the traditional authority works in ULM and found it to be the same as EC. Lastly, they visited a wetland and learned about their importance for society and for grazing lands and why they should be protected at all cost. The NRF-SAEON team explained the differences between ULM and Matatiele wetlands. Siphiwe Mfeka from NRF-SAEON explained the importance of peatlands and how much damage the burning of Vasi pan has caused. He linked peatlands to climate change and explained how important they are as carbon sequesters. He explained that even swamp forests are important for biodiversity and should be protected rather than cut down for cultivation. The ULM participants were able to make the connection, and indicated that all the wetlands in ULM were gone, they also explained that, in ULM, the landscape was 60% wetlands and that now there are only a few wetlands. They said that their cattle did not even have water to drink in the grazing areas. They also did not know about the fires at Vasi pan and thought this to be another piece of important information that should be passed through to the larger community by NRF-SAEON.

Figure 13-2 Tokolo deworming sheep and goat in Mafube

Figure 13-3 (Left) MCP team with ERS staff after knowledge exchange with sheep and goat farmers (Right) Siphiwe Mfeka explaining the importance of wetlands

On the third and final day the team observed a mobile auction in the Mafube community facilitated by Meat Naturally. They also met and learned from the farmers in the area how to take care of cattle; how often they sell cattle; and whether they find the auctions beneficial. The last activity on the last day was giving feedback to the founder of ERS on everything learned and how they would have done certain things differently in terms of the challenges faced. After having observed the auction, the participants expressed their like for the idea of the auction and wanted the same thing for ULM. When chatting to the people from Meat Naturally they learned that they needed to have a variety of breeds and not just the Nguni breed to be able to sell their livestock for good money should the auction come to MCP. This is due to the Nguni cattle lacking weight. However, Mr Tembe thought some of the prices were fair, especially for some Brahman heifers which made the importance of breeds clearer for him.

Figure 13-4 (left) Mr Nsele from MCP observing the cattle auction (right) MCP participants with NRF-SAEON and ERS team

13.3.2 Interactions and Reflections During the Knowledge Exchange

- Some participants in Matatiele were initially unaware of the purpose of their visit, as the TCs that selected them did not provide clear explanations. Out of the nine participants, only two had prior knowledge of NRF-SAEON through TC workshops. This lack of understanding created frustration, especially among those from Tembe and Mbila/Zikhali, who expected funding for projects from NRF-SAEON. The team clarified NRF-SAEON's role in research and explained that they could connect the TCs with NGOs for project implementation. Despite initial challenges, the team emphasised the value of the knowledge exchange, encouraged participants to take notes for improvement, and apologised for any confusion. Ultimately, participants regained enthusiasm for the exchange. They wanted NRF-SAEON to tell them exactly what they should do about bush encroachment in the area, which is one of the main issues for cattle farmers

- Setting the scene for the knowledge exchange was done by Sissie Matela, the co-founder of ERS, and Zuko Fekisi, who works as a rangeland coordinator at ERS offices in Matatiele town. Sissie explained that ERS was founded 21 years ago to improve the livelihoods of people in the area and to restore the ecosystem in the Drakensberg Mountains which South Africa shares with Lesotho. To solve the issue of over grazing in the area, ERS spoke with the communities to find out how the older generation managed grazing lands. What they found was that in the past they had proper land use planning – there were allocated areas for grazing and allocated areas for farming and settlements, etc. Grazing land was rested regularly. This land use planning stopped post-1994, because children were going to school and thus there was no one left to herd the cattle who were left to grazing everywhere. Through dialogue with ERS, communities agreed to go back to the proper management of the grazing lands through the creation of combined herds grazing in allocated areas. They also used mobile kraals to recover degraded land. The large herds would be moved to a degraded area and kept there for a certain period, to allow the cattle hooves to loosen the soil and directly deposit nutrients into the soil. Cow urine and dung is high in nitrogen which helps soil fertility and water retention. At the start of the intervention, the community's reasons for keeping cattle were varied but all related to cultural purposes. However, when communities started taking care of their rangelands and cattle had grass throughout the year they became fat, which created a commercial opportunity. The community needed markets to sell the cattle so ERS, in partnership with Meat Naturally, started organising mobile cattle auctions. They used these auctions as an incentive for rangeland management. Other interventions by ERS in the area include wattle clearing to improve water availability and spring protection to make sure the water humans drink is safe. These protected springs have an overflow that flows to a man-made pond that is used by cattle. Sissie stated that, in trying to solve problems, others arose and the problems that required solutions were endless. She further iterated that ERS encourages communities to solve their own issues.

- On the evening of the 14th, the team had a reflection discussion on what they learned, what they would use back in ULM, and what they did not find useful. The Tembe participants started with their reflections. Mr Tembe was inspired by the knowledge exchange. He was impressed by how the communities came together to cut wattle, which solved their water issues, and that they now knew what to do in ULM in order to improve water supply. He shared that, from the activities of the 14th, what really stood out for him was the importance of land use planning. The leadership in ULM did not plan their land use wisely and it resulted in them not being able to use their land well. He also shared that they. as a group, think the ULM problem should be looked at without borders, all the TCs need to have a common understanding and try to work together. He shared that the land belongs to the people and they should be able to use it to make a living and that the land should not only benefit the few people in charge.

- The Mabasa representative, Chief Nduna, Mr Nxumalo, shared that he loved to observe how the community worked well together and with ward councillors. He noted that even though the problems of Matatiele were different from theirs in ULM, they were similar in some ways. He made the connection between eucalyptus and wattle and stated that they need to fight the issue of eucalyptus plantations in the ULM because they are the ‘wattle’ of MCP only they are planted by people and not invasive as Wattle in Matatiele. Chief Nduna mentioned they that have to work together without borders to fight the issue of eucalyptus plantations, and to do this they needed to talk to people who had cattle and get them to stand up for their land. He mentioned that NRF-SAEON needed to go to communities to explain the science and the whole problem so they get to know about it to be able to make decisions.

- The Mbila/Zikhali participant, Mr Ntuli, shared that he loved the work done by ERS, because they had a working relationship with the community and echoed that they as a group have discussed and wished to have a similar working relationship with NRF-SAEON, and wished for NRF-SAEON to “hold their hands” through the process of change supported by research. Mr Ntuli, chairperson of Umhlabuyalingana livestock association, said that he wished for the nine participants who attended the knowledge exchange to form a body/committee so they could approach the three chieftaincies together as one entity. He said that the IDP had money that the communities have no access to and enquired if it is possible to repurpose that money for other things, e.g. money allocated for community halls could be redirected to alien clearance as they do not need too many community halls in the area and the money should be rather used for more important and urgent issues that affect livelihoods directly. He also mentioned that the induna and the kings needed to have a better land use plan and there needed to be distinct separate areas of plantations, grazing lands, burial lands, settlements, cultivation, etc. They needed to stop allocating people to areas that were previously wet, such as floodplains and wetlands, because, should the rains come back, there would be a disaster.

- Mr Mdletsh, from Mbila/Zikhali, shared that he liked that there was no litter, even in the town and that was impressive. He loved the idea of reusable diapers because it had a possibility to save money, and could possibly solve the litter issue which had become a big problem in the Mabasa area where people from Mbazwana drove to Mabasa to dispose of litter there. He had a different opinion as far as the eucalyptus plantation was concerned, as he knew that the eucalyptus plantations were bad for the area, but, he explained that he also knew that they make a huge contribution towards the economy of the area. He believed that they should not get rid of them completely, but rather be planted in moderation, in specific areas away from water sources. The NRF-SAEON team explained that the system is connected. However, he indicated that, even though he understood, he still thought that eucalyptus benefits outweigh the cost to the ecosystem. He did mention that he received his money from cattle as well as eucalyptus plantations and that was why he believed in their contribution to the economy. He also does a lot of cultivation (watermelon). He suggested that should request allocated grazing area where they could burn yearly to avoid bush encroachment as they had been doing years before.

- Since it was echoed that NRF-SAEON needed to reach the communities with information, the team asked what they could do to make sure that the information reached the larger communities. Nduna Nkulu Nxumalo from Mabasa mentioned that, as the TC, they are provided with so much information from different organisations constantly that the information overwhelms and does not reach. They have to be selective about which of the information gets passed to communities and often do not remember details or all of the information they received.

13.3.3 Feedback to Sissie

On the afternoon of the 16th, following the auction, participants and the NRF-SAEON team had lunch at ERS offices with Sissie and provided feedback. Mr Tembe expressed admiration for ERS's work and suggested the municipality meet ERS halfway by providing pipes and pumps to bring water closer to villages, citing the upcoming election year as an opportune time for requests. Mr Nsele praised ERS's efforts but criticised cattle auction prices, urging ERS to review them to prevent seller discouragement. Mr Mdletshe appreciated ERS's work but lamented the abandonment of previously farmed land, suggesting continued cultivation to benefit the local economy. Mr Tembe expressed interest in the establishment of a similar NGO in ULM, seeking advice on donors and success prospects. Participants also expressed interest in a visit from Sissie and her team to MCP to learn from their area. They expressed gratitude for the hospitality and learning opportunity provided by Sissie and the ERS team.

Figure 13-5 MCP team with Sissie her ERS team as well NRF-SAEON team at the ERS offices

13.3.4 Feedback Provided by Participants at TC workshops

The knowledge exchange participants were invited to the feedback workshops in January 2024 to give feedback to the communities on what they learnt. Their presentations showed that the knowledge gained and their perception of research could be a solution to many of their issues.

During the Mabasa workshop, Mr Mdletshe shared that he saw a clean place with no litter in Matatiele; he liked the idea of reusable nappies because disposable nappies are a pandemic in the area and have caused a lot of cattle deaths. He pleaded with the TC to bring the youth closer because that is what he saw in Matatiele, that the TCs worked closely with the youth and, in ULM, they keep the youth out of TC meetings. He said the decisions made now about their land would affect the youth more than it would affect the older generation and the youth needed to be a part of the decision-making process. He also said the council needed to stand up against TMM, which benefits a few people while the land degradation affected everyone. There was a comment by one Induna that the litter issue in Mabasa had become a huge problem because people came from Mbazwana to dispose of their litter in Mabasa and that cattle eat it and die. He was glad people went to Matatiele to learn about waste management and that there needed to be much done about the waste issue in the area.

The Mbila/Zikhali participants selected Mrs Nsele and Mr Ntuli to give feedback. They gave a comprehensive overview of the entire trip and emphasised that the TC needed to work with NRF-SAEON to solve the issue of disappearing pastures (grasslands).

In Tembe, Mr Nkwanyana and Mr Nsele gave the feedback to a group of cattle farmers and some TC members. As part of their feedback they shared that farmers should invest money towards medicine, de-wormers, and dipping or spraying because their cattle would die while they waited for help. The response from the cattle farmers to the feedback was welcoming and they requested that NRF-SAEON try to get them mobile auctions that accommodated Nguni cattle at good prices because they did not want to change to other breeds that require more effort to be taken care of.

A common thread expressed by the knowledge exchange participants during their feedback was that the TCs needed to work hand-in hand with NRF-SAEON.


Figure 13-6 (left) Mr Mdletshe giving feedback from the knowledge exchange(right) Mrs Nsele giving feedback from the knowledge exchange


Figure 13-7 (left) Mr Ntuli giving feedback from the knowledge exchange (right) Mr Nsele giving feedback from the knowledge exchange

Figure 13-8 Mr Nkwanyanae giving feedback from the knowledge exchange

13.3.5 Project Team Reflections on the Experience

The project team members who attended the knowledge exchange learned much from meeting with the cattle farmers from both ULM and Matatiele. The team enjoyed seeing the communities in Matatiele work together to improve their livelihoods, by holding their own land without Government assistance. Their grazing management and alien invasive trees control were impressive. It showed how far good governance can take communities.

During conversations with the ULM participants, concerns about the loss of grazing to bush encroachment and lack of water were regularly raised. The MCP farmers stated that they all took their cattle to Lake Sibaya to get water. This created over grazing because all cattle in the area basically lived at the lake.

It was inspirational for the team to watch the attitude of the MCP participants go from wanting external help to the facilitation of change to wanting to do something themselves to make a change and having an interest in the establishment of an NGO of the same nature as ERS in ULM. There was a question that the ULM delegates asked during the first night's dinner about whether the information that they would acquire with regard to the knowledge exchange trip would change their lives or benefit them in any way. The team believed that the knowledge exchange would have a positive impact on their lives if they used what was learnt, and would like to hear from them again about their situation after three or four years.

The team believed that there was a lot of work to be done to provide climate change awareness in the communities. NRF-SAEON needed to bring them closer to Government agencies such as the Department of Agriculture to help them with more information on animal husbandry, even though it was not NRF-SAEON's mandate.

13.4 PROJECT PROGRESS FEEDBACK WORKSHOPS WITH TCs

The intention of this project was to work with communities through each major phase of the project to ensure that their inputs would be considered in the final product. To this end, feedback workshops were arranged to deliberate on semi-final outcomes and incorporate perspectives into the final report.

13.4.1 Program and Activities: The Need for Flexibility

The workshops took place at Mabasa on 20th November 2023, Mbila/Zikhali on the 21st, and Tembe on the 23rd. The Mabasa workshop faced delays due to a CoGTA headcount on the same day, which led to a late start. Despite challenges with load shedding and adjustments to the program, the team used laptops to facilitate presentations in small groups.

The Mabasa workshop served as a learning curve for the team as it allowed them to address and clarify presentation challenges for subsequent workshops in the week. Despite the late start, attendance in Mabasa was good, with amaphoyisa representing absent indunas. AVCO presented a potential project, and representatives from CSIR discussed swamp forest research in the area.

The Mbila/Zikhali workshop was well-attended by iziNduna, with apologies from the king but the chief Nduna present. Challenges included a projector malfunction, which was resolved when on was borrowed from the nearby educator centre. The workshop proceeded smoothly. The group was just the right size to facilitate interactive activities which helped to promote dialog.

The Tembe workshop had a smaller number of Indunas as well as a significant turnout of cattle farmers. Some Indunas, who could not attend sent messengers to listen for them. The workshop included feedback on swamp forest research by Heidi and Nkosingizwile. Challenges included addressing an audience largely unfamiliar with the initial workshop content. Despite difficulties, it allowed for the re-explanation of NRF-SAEON's research, climate change, and funding-related queries. Load shedding and another projector malfunction posed challenges, but the team adapted, and conducted the last presentation on flipchart paper.

Figure 13-9 (left)workshop attendees in Mabasa TC (right) workshop attendees in Mbila/Zikhali workshop

Figure 13-10 (left)workshop attendees in Mbila/Zikhali workshop (right) workshop attendees in Mbila/Zikhali workshop

Figure 13-11 (left)workshop attendees in Tembe TC (right) workshop attendees in Tembe TC

13.4.2 Feedback and Questions Raised from the Project Feedback Workshops

The participants from Mabasa and Mbila/Zikhali appreciated NRF-SAEON's research and its importance, particularly placing a value on the concept of long-term research to understand system changes. They were interested in learning about changes and their causes. In contrast, the Tembe workshop had more one-way interaction, with a focus on issues affecting cattle and potential resolutions, driven mainly by cattle farmers' attendance. Some participants viewed NRF-SAEON as highly interconnected with Government entities and had limited understanding of its role. Interestingly, attendees within each TC sometimes answered questions posed, which indicated support, and an understanding of NRF-SAEON's objectives. The first two TCs seemed to be growing accustomed to NRF-SAEON's presence, while most Tembe attendees were unaware of NRF-SAEON until that day. The workshops highlighted the need for agricultural alternatives, training, and tools, with a focus on cattle grazing and health concerns across all TC areas. Despite varied levels of familiarity, all TCs understood NRF-SAEON's work and expressed an openness to future workshops. NRF-SAEON was encouraged to connect communities with NGOs, agricultural training entities, and university professors for the implementation of changes. The Tembe workshop emphasised the community's desire for economically feasible alternatives without direct Government imposition of issues on them without consultation. A common thread was that people wanted tangible solutions to combat the issue of the eucalyptus plantations because, while it has been preached many times, people have not stopped plantations expanding.

One of the community members emphasised the value of having an unbiased party (SAEON) share information objectively to the larger community. All three TCs requested a copy of the full report from this project as well as a written summary in IsiZulu. One suggestion for an early warning system related to water security was to get communities to track changes in the rainfall and groundwater levels in their boreholes. They also would like have interactions with the NRF-SAEON and EFTEON team twice a year and as needed. Below are questions and requests from the workshops.

- They want to know why the Government brought gums trees to the area years ago and benefited from them but now that the communities were supposed to benefit from using gums to earn an income they are suddenly causing environmental problems.
- They want to know why the gums trees in St Lucia are not causing issues but only the ones in MCP are causing a problem with the water table. Here we explained that they are causing a problem in those areas, however that system has five rivers importing water into it so not as sensitive. We also explained that a proportion of forestry had been removed within the iSimangaliso wetland park.)
- They wanted to know why NRF-SAEON chose the area for the research. (Here we explained the uniqueness of the area; the fact that it was in a climate transition zone; awareness of the water security threat; wanting to help understand what was causing this; and the fact that it was been neglected from a research and monitoring perspective).
- They wanted to know what the solution to the bush encroachment was as it was a big problem for them, especially the cattle farmers because they had run out of grazing land.
- They want to know how bush encroachment affected the water availability and why it has only recently become such a big problem.
- They wanted to know the causes of the below average rainfall. The project team explained the possible linked to climate change in this regard.
- How can they get protected from thunderstorms and lighting?
- They want to know if NRF-SAEON could add a section on the economics model to calculate income from cattle farming and then present the results in areas where they do large scale cattle farming, and provide feedback to them.

- Concerns over bush encroachment and invasive plants, as tend to overtake grazing land, and may use more water than grasslands. They need assistance in combating these threats. A request was made for alien plant control training.
- SAEON should make plans to reach larger communities with information and include community members in future feedback sessions.
- Likewise, there was a suggestion to have targeted interventions with eucalyptus, cattle farming, and farmer associations.
- They wanted water day theme day event in 2024 with communities.
- They needed a market for Nguni cattle and not just Brahman because they want to continue breeding pure Nguni.
- They needed lessons on how to identify pure bred Nguni.
- Cattle in the area were dying and they needed research on why this was happening.
- They needed help with deworming, dipping, and spraying of cattle.
- They needed training on how to perform artificial insemination; how to manage feedlots; select breeds that can survive the climate in ULM; and general animal husbandry.
- They needed tractors and other assistance in the area to enhance farming.
- They needed connections to businesses and partners that want to invest in the alternative businesses suggested.
- They needed more experiments on the crops that could be alternatives to eucalyptus plantations in MCP to see if they could produce good yields because of the unique hydrology, climate and geomorphology, suggestions of plots allocated.
- Concerns were raised regarding the lack of indigenous knowledge transfer between the elders and the youth and how to bring the youth closer to these issues.
- They requested that NRF-SAEON should "go to the Government" with these issues, solutions, and reports (i.e. make the results known within appropriate government departments as well as the challenges the people are facing).

Some suggestions provided by the project team to address some concerns included:

- Clear, shared goals;
- Bottom-up developed land use plans;
- Good governance structures;
- Water committees with the power to veto water impact development activities;
- Knowledge sharing platforms within and across their communities, e.g. local radio, on opportunities and creating awareness;
- Early warning systems;
- Groundwater Measurements,
- Access to seasonal forecasts (ARC/SAWS),

- Key resources (natural assets) monitoring;
- Community-driven science and monitoring (citizen science);
- Diversification of income streams both land-base as well as growing service-based income streams;
- Ensure market access beforehand and focus on high value goods with on-site processing;
- Long-term planning with short term flexibility;
- Exploration of nature-based solutions climate funding;
- Ecosystems-based adaptation (healthy ecosystems are safer because they buffer against extreme events);
- Wetlands protection/wise use;
- Avoid building in flood plains/restoration
- Climate smart agriculture
- Circular economy
- Tourism is a potential draw card if well managed and developed together at a regional level

Through this process the project team also identified the need to make clear the value chain between research and action-based implementation; no single group can address all these needs.

13.4.3 Project Team Reflections on the Workshops

The participants from Mabasa and Mbila/Zikhali appreciated NRF-SAEON's research and its importance, and particularly valued the concept of long-term research to understand system changes. They were interested in learning about changes and their causes. In contrast, the Tembe workshop had more of a one-way interaction, with a focus on issues that affected cattle and potential resolutions, driven mainly by cattle farmers' attendance. Some participants viewed NRF-SAEON as highly interconnected with Government entities and had a limited understanding of its role. Interestingly, attendees within each TC sometimes answered questions posed, which indicated support for and understanding of NRF-SAEON's objectives. The first two TCs seemed to be growing accustomed to NRF-SAEON's presence, while most Tembe attendees were unaware of NRF-SAEON until that day.

The workshops highlighted the need for agricultural alternatives, training, and tools, with a focus on cattle grazing and health concerns across all TC areas. Despite varied levels of familiarity, all TCs ultimately understood NRF-SAEON's work The Tembe workshop emphasised the community's desire for economically feasible alternatives without direct government imposition.

13.5 MOVING FORWARD RECOMMENDATIONS FOR FINAL WORKSHOP (POST PROJECT)

Following the feedback workshop and the expressed desire for assistance, NRF-SAEON plans to hold a think tank with NGOs, Government departments and interested stakeholders, in order to determine what can be offered realistically if TCs want to take things forwards, and to map possibly actionable interventions.

After providing brief final results from the project at this post-project workshop, the focus would primarily be on interventions possible and connections with appropriate stakeholders within different government business and NGO organisations. Together with these role players, the aim is to conceptualise a value change of “partners needed” to take research results on aspirational activities to the next step and beyond to providing communities with a network of touchpoints they may engage with to move forward.

The TCs have asked for the full project reports.

13.6 CONTRASTING NARRATIVES

During the workshops, conversations and HH surveys, a few key contrasting narratives emerged that were important to note as they highlight the fact that there are diverse aspirations and perspectives in the ULM area. Each of these narratives are briefly outlined below:

Eucalyptus plantation and employment

Most community members do not believe that forestry plantation is essential or has improved the area's economy. They think that only a few people benefit from the plantations, with those being the people that have planted trees on massive areas. The jobs that the plantations have provided for the community pay close to nothing for back-breaking physical work, and which is seasonal. People make R80 to R100 a day working in forestry depending on what kind of job they are doing. In contrast, other people believe that plantations provide jobs and are a perfect source of income because they do not require much effort. They also insist that the plantations create jobs because the poverty rates are so high; the R80 to three people makes a difference.

The Wetland farming narrative

There are contrasting narratives in relation to wetland farming as these narratives are location specific. The communities around Othungwini (Sodwana Bay area) have experienced frequent extreme flooding of their wetland gardens. If there have been heavy rains they will not be able to harvest anything for that season because everything rots under the water, regardless of the depth of the channels. However, the communities around Mseleni do not experience that; they have not lost any produce due to extreme weather events or it has not happened that often to them. People in more inland areas can no longer use local wetlands and they have all dried up.

The yes to tourism and no to tourism narrative

The tourism topic is a sensitive one, especially with the older generation. The younger generation likes the idea of tourism as, to them, it means employment and consistent income, while the older generation is against it because it means conservation of areas they use to collect reeds and wetland farming, which is how they make a living. Most of the older generation interviewed during the project are old enough to remember the feeling of being moved from their homes for conservation and are totally against an increase in ecotourism.

The climate change narrative

When speaking about climate change with the different members of the community, there are different narratives. Some believe that there is no change to the climate, that the climate has always been like this; sometimes it rained sometimes it did not that the rains always came back and the heat is still the same. Others believe that the climate has changed drastically in recent years and they are worried about it.

Love for cultivation

The narrative around cultivation is another age or generation-specific one. The older generation believes in farming to a point where they walk long distances to get to their wetland farms. The younger generation does not like cultivation as they think it is hard physical labour and they are not interested in it. This drives the contrasting narrative that cultivation is increasing as well as decreasing.

13.7 CONCLUSION

The adoption of a participatory approach enriched the research process, as it illuminated several issues and opportunities that would otherwise not have been identified. It helped to root the work and perceptions in the context of the area. The richness of experience and observation of challenges first hand by embedding the activities within the area, “humanised” the project team, and motivated them to see how they could translate research findings into action. The aspiration expressed for feeding back information from the project was a humbling experience and one that is far from over, as now the team has been invited to work hand in hand with communities. This emphasis the value and importance of long-term relationships between communities are research groups and the appreciation gained by listening and feeding back information.

In terms of the achievement of traction towards the exploration of alternatives, this project served to enhance mutual understanding and spur interest in trying alternatives, but that will only be possible with multi-institutional support.

CHAPTER 14: SYNTHESIS DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

By: S Janse van Rensburg, ML Toucher, S Maseko, S. Mfeka, MH Maseko, LN Gule, J Blignaut, S Kebede, T Nsibande, M Pienaar, P Gordijn, RC Blamey, CJC Reason, N Mkhize, and B Kelbe

In this chapter, the outcomes from the science, integration, and engagement processes undertaken within this project are consolidated. Advances in knowledge creation are presented. The immersive learning platform created by this novel undertaking provided an opportunity to explore possibilities and assess what is realistically achievable, from which challenges and recommendations for enhancing future work of this nature are provided.

14.1 ADDRESSING SOCIETAL NEEDS (WHY)

Ingonyama Trust Board land is an important development context within South Africa, and represents large sections of untransformed land. However, transformation rates are increasing rapidly, which affects ecosystem services, lowering adaptive capacity. These changes, often driven by external players, lead to conflict over scarce resources and can precipitate tensions within communities as well as threaten conservation objectives.

To achieve sustainable development, as prescribed by South Africa's National Development Plan (NDP), the challenge is to strike a balance between equitable economic development, environmental sustainability, and resilience to anticipated climate change impacts. To date, this has been an elusive outcome in the ULM within the MCP. One avenue for addressing adaptive capacity is to empower vulnerable households and communities.

South Africa's legislation mandates securing enough water for both human needs and the ecological requirements of natural systems. Surpluses in water supply can be allocated to regulated production activities. It is crucial to balance water demand and supply to optimise equitable outcomes in human welfare, ecosystem integrity, and economic prosperity. The reserve determination for Lake Sibaya specifies that the drought water level threshold should not exceed five consecutive years with the lake level below 16.5 m AMSL (DWS, 2015). However, lake levels have remained below this threshold for over 14 years. This demonstrates that water security in the ULM region has declined to the extent that there is technically no allocable water for human use. Water insecurity in the broader region is escalating, leading to increased potential for conflict (Patrick, 2021). Demand for water from various users has essentially surpassed the available yield potential (Johnson, 2021). As a result, the adaptive capacity has declined, at a time when every effort should be made to strengthen adaptation strategies in the face of climate change.

Immediate and rapid adaptation is imperative to reduce climate change impacts (Pörtner et al., 2023). While climate change science and adaptation strategies receive considerable attention globally and nationally, the lived realities of climate impacts and the implementation of adaptation actions are often experienced at individual and household levels. Top-down interventions that disregard local context frequently exacerbate already vulnerable situations (Eriksen et al., 2021, Rahman et al., 2023). Furthermore, while there is progress within South Africa, significant barriers to the effective implementation of climate adaptation strategies within Government structures exist, particularly at the district and local municipal levels (Sibiya et al., 2023).

Given the impact of land use on water security within ULM, considering land use options should be an important component in adaptation strategies. Participatory and engagement methodologies that incorporate local roleplays are increasingly being advocated to catalyse contextually appropriate and acceptable adaptation strategies at local levels (Oliver et al., 2023, Pörtner et al., 2023). The manner in which this is done should aim to empower and promote local agency but are not without their own risks and complexities (Oliver et al., 2023). For scientists, the challenge is to suspend scientific thinking enough to listen as well as learn to value multiple forms of knowledge, including local experience and indigenous knowledge systems. The reward is a co-learning process which enriches emergent science outcomes that are more likely to translate into societal impact.

This project aspired to develop a means to empower vulnerable local communities to make informed land use choices for the optimisation of beneficial outcomes in the context of climate change adaptation. This was addressed in several ways: the scientific research to advance knowledge on the climatological, hydrological, and economic dynamics within the ULM; engagement and multiway knowledge sharing with people living in the area towards improving awareness of climate change risks and promoting personal agency in addressing these; and attempting to developed an integrated decision support tool that promotes an understanding of the potential implications (risks/opportunities) of land use choices made today on future outcomes under different climate futures.

The primary aim of this project, (Aim 1), was to integrate appropriately scaled climate, hydrological, and economic components and use this to explore the net effects of plausible future LULC scenarios under different future climate storylines within quaternary catchment W70A, focusing on the Lake Sibaya groundwater catchment. This was informed by climate analyses (Aim 2) as well as determining the relative impacts of LULC and climate on the hydrological response of the Lake Sibaya groundwater catchment from the past to present period (Aim 3 and Aim 4). Co-generative engagement processes (Aim 6) were used to inform potential future land use scenarios and several future climate storylines were developed (Aim 4). Household surveys and systems dynamics economic modelling were used to estimate the socio-economic consequences of these alternative land use scenarios under future storylines (Aim 5). This systems dynamic model (ULMCatchMod) integrated climate, economic, and hydrological information towards achieving Aim 1. As the hydrological modelling outcomes could not be fully coupled within ULMCatchMod, a simple summary framework was developed to provide comparative storyboards for contrasting the consequences of different land use choices under the different climate futures. These consequences are assessed against four context relevant challenges, as defined by TCs.

14.2 INTEGRATION: CHALLENGES AND KNOWLEDGE ADVANCEMENTS

While general principles can guide global and national adaptation strategies, specific information on anticipated local future climate conditions is required to empower communities to take decisions that reduce their vulnerability to climate change. Effective resource management needs to integrate assessments of climate, land use and water dynamics (Howells et al., 2013). In the context of a changing climate, which is already resulting in economic losses (Pörtner et al., 2023), it is also essential to consider the relative socioeconomic and environmental costs and benefits associated with various choices holistically, and how these choices will contribute to adaptive capacity under climate change (Foley et al., 2005, Bailey et al., 2016, Pörtner et al., 2023).

This project aimed to integrate hydrological, climatological, and economic aspects to assess the potential impacts of land use and climate change on the future well-being of a region. This attempt provided a platform to explore possibilities, describe achievable outcomes, and identify areas for further effort to enhance similar undertakings aimed at integrating across disciplines.

The first, albeit expected, challenge encountered in integration across the disciplines was the misalignment of the spatial and temporal scales between the climate, surface water, groundwater, and economic models. The climate models used have large spatial resolutions ranging from the 100 km x 100 km scale of the Global Climate models to the ~30 km x 30 km ERA5 grid scale and covers large areas from national to global scale, whereas they have a mix of coarse (monthly) to fine temporal scale sub-daily data. The ACRU model is ideally used at a catchment scale not exceeding 50 km^2 and a temporal scale of daily. The MODFLOW model is a grid-based model of varied size which operates at the relevant spatial scale to capture the groundwater processes influencing a focal groundwater catchment area, and operates at a monthly time-step. The economic model is more concerned with the political boundaries than the natural system boundaries and operates at a monthly timescale, however crop DF calculations used within the ULMCatchMod should, ideally, account for daily and seasonal impacts. With model outputs required as inputs to other models, novel approaches were considered to align the spatial and temporal scales to enable the data flows. Using a grid scale across the hydrological model domain was agreed upon, and the temporal scale was set at daily with aggregation to monthly. The climate and groundwater models are suited to grid scale, whereas configuring the ACRU model as a grid was a novel approach. Although challenges were encountered by the configuration of the ACRU model as a grid, it facilitated the translation of the input climate information from the climate models from a coarser grid to an output of recharge from ACRU on a finer scale grid that matched that of the grid scale required for the groundwater model (MODFLOW).

There is a lack of good quality, continuous historical climate data for the ULM. The lack of observed climate data meant that the hydrological modelling had to make use of the ERA5 climate product which is a combination of observations, satellite data, and modelling to produce a gridded-consistent climate product. As the ERA5 product makes use of observed climate data in the assimilation process, it, too, is influenced by the lack of climate data available for the area. Using the ERA5 product as input to a hydrological model cascades and amplifies uncertainties and errors in the rainfall through the modelled hydrological cycle as rainfall is the primary driver of the hydrological cycle. A comparison of limited observations and ERA5 data, in this study for the ULM area, revealed an average 11% underestimation of ERA5 data which translated to a 30% underestimation in recharge.

The challenges related to the climate data were even greater when it came to the development of data sets for the future climate storylines for use in the hydrological models. Due to the complexity in the rainfall mechanisms, rainfall is the climate variable with the greatest uncertainty in the climate models, given that it is a parameterised output. Results from the CMIP6 global analyses were used to develop plausible future climate storylines. While general trends in the global-scale CMIP6 projections were useful, assessing these at the local scale demonstrated the need for bias corrections. In this project, correction factors were calculated from CMIP6 projections and applied to historic ERA5 data from 1991 to 2020. This approach revealed a pattern of increased drying trends which led to continued declines in the groundwater system. As an alternative, a wetter ERA5 data period was selected and 10% added, providing a relatively wetter “best-case scenario”. It is acknowledged that the approach used in this project to develop future datasets was not ideal. A key recommendation is that more detailed work is required to improve methods for model selection and downscaling as well as bias corrections to accurately capture the patterns projected by the GCMs, such as those used by Adeyeri et al. (2024), that focus on assessing and improving uncertainties on indices relevant to resolving the water balance. Downscaling challenges highlight that GCMs, while fit for purpose for large-scale climate change indicators at the global scale, still do not provide sufficiently reliable “actionable information” for local scale decision support. This is consistent with findings from other studies (Rodrigues and Shepherd, 2022).

The decision to use a wetter ERA5 data period with more extreme events and to add 10% was informed by the isotope study and an assessment of the historical trends in the Lake Sibaya water levels in relation to extreme events. The isotopic analysis in this study demonstrated that heavy rainfall events of greater than 30 mm are important for recharging the groundwater aquifer and associate wetlands including Lake Sibaya. Observation data on past Lake Sibaya water levels, relative to rainfall trends, show that consecutive years with one or more extreme rainfall events annually played a crucial role in the replenishment of the connected groundwater-lake system, corroborating the isotope results in this study. A notable example culminated in the evacuation of the Rhodes Research Station at Lake Sibaya in 1977 (Bruton, 1979b).

In the early 1970s, in response to a drought, Lake Sibaya water levels had dropped to 16.61 m AMSL. In subsequent years there were several storm events; two in February 1972; one each in September 1972 and February 1975; and an extreme event in January 1976 (>300 mm) linked to very Intense Tropical Cyclone Danae (total Jan 1976 rainfall of 464.8 mm). In 1977, one January event (>20 mm, total monthly rainfall of 312.5 mm) was followed by two extreme rainfall events in February (5-7th >100 mm, 15-17th >51 mm) with a total February rainfall of 205 mm at Mbazwana station. Throughout this period, Lake Sibaya water levels continued to rise and the research station was consequently flooded and evacuated on 01 March 1977. Additional events took place in March, April and December of 1977 (Botes, 2014). The year 1977 holds the record for the highest number of storm events (five) in one year and corresponded to the highest lake level readings ever recorded from 1966 to the present day (20.25 m AMSL, 11 March 1977). Understanding the responses of the groundwater system and lake levels to large rainfall events assisted in the configuration of the hydrological models and in interpreting the output from the models. However, it also placed a heavy emphasis on the need for accurate rainfall input into the model, and for the rainfall to be well represented spatially over the catchment to reduce uncertainties in the hydrological modelling.

The key hydrological modelling output required for this project was the change in Lake Sibaya's water level and surrounding groundwater levels. The isotope study filled knowledge gaps which included understanding whether recharge takes place from focused sources along preferential paths or if it is a diffused recharge throughout the landscape. Results confirmed a hydraulically well-connected aquifer system and that the major water inflow zones were from the northern, western, and south western parts of the lake, i.e. relatively diffuse recharge. There is an additional contribution, previously unrecorded, from the north eastern part of the lake. As the isotope study and hydrological modelling were undertaken simultaneously, timing did not facilitate the isotope results being used to inform the groundwater model. However, by building on prior approaches and making improvements to an established groundwater model (Kelbe, 2019, 2020), reduced uncertainty in the simulated water levels for Lake Sibaya was achieved through the improved spatial representation of rainfall as well as incorporating actual vegetation change over time, all be it for only four time slices from 1990. Loosely coupling the ACRU and MODFLOW model at a matched spatial grid was a major conceptual advancement that also led to a large amount of learning and aided in the identification of errors in both models. Despite the improvements made, there is still significant work to be done related to the modelling to further reduce uncertainties and improve convergence in water balance results from modelling and isotope studies.

A comparison of Lake Sibaya's water balances from the isotope results and the original as well as updated groundwater models are presented in Table 14-1. Simulation data from the models for the year 2016 was chosen for comparison, as it aligned with the publication year used for much of the isotope water balance data. The E/I (evaporation/total inflow) ratio, signifying the system's water flow rate, serves as a key metric. The previous model (E/I = 0.6) and isotope data (E/I = 0.7) both indicate substantial evaporation, suggesting a slower flow rate. Conversely, the updated model shows a lower E/I ratio of 0.4, implying less pronounced evaporation and a faster water flow rate through the system.

Table 14-1 Comparison modelled and isotope water balance results from various studies

	Lake Evaporation 10^6 m^3/yr (Weitz, 2016)	E/I (Isotope based)	Total inflow (including groundwater, rainfall on the lake and runoff) 10^6 m^3/yr	Groundwater Outflow 10^6 m^3/yr	Groundwater Inflow 10^6 m^3/yr	Precipitation on the lake 10^6 m^3/yr (Weitz, 2016)
Isotope	109	0.7	156	47	77	74
Previous model (2016 only)	10.7	0.6	18.3	5.29	2.52	6.27
Updated model (2016 only)	50	0.4	113	61.6	33.4	57

The previous model and isotope data presented in Table 14-1 indicate a significant influence of lake evaporation compared to other water balance parameters (refer to Figure 9-22 and Figure 9-23). However, the updated models' water balance indicated that surface water inflow and groundwater outflow (Figure 9-22 and Figure 9-23) have greater influence compared to evaporation on the system. These findings indicate a misalignment of results and emphasises the importance of improved evaporation measurements over the lake as well as the need to integrate available isotope information to inform improvements in existing models or in constructing a new groundwater model for Lake Sibaya.

It must be noted that the hydrological system is complex, characterised by temporal and spatial water and energy fluxes and displays non-linear behaviour (Adeyeri et al., 2024). A hydrological model is an imperfect mathematical description of this complex system. It is a way of trying to explain and organise the complex system to allow for understanding and providing insights to facilitate decision making. Any hydrological model results must be seen in this context as they are not a true representation of reality. However, the patterns, trends, and relative changes in the results can help in understanding processes and influences in the system and in making decisions. The lake levels simulated in this project need to be viewed in this light. The value of the results presented lies in the patterns and relative changes, not in the actual lake level values.

The initial intention was to use the ULMCatchMOD to assess feedbacks between land use choices, employment, economic prosperity, and water response. Climatological data could be integrated easily into the model. Integrating hydrological outcomes proved more challenging but were achieved to some degree through available water for irrigation. However, we could not utilise the full potential of feedbacks within the systems model as the hydrological and ULMCatchMOD could not be fully coupled. However, the basic structure of the ULMCatchMOD model provides a solid foundation on which to build. Developing feedbacks within the model should be further explored.

14.3 RECOMMENDATIONS

For the hydrological modelling component of the study, the lack of accurate, local-scale, high-resolution rainfall data for both the historical period and moving to the future scenarios, was a major limitation. The uncertainties introduced by this cascaded from the surface-water ACRU model, through the groundwater MODFLOW model and into the economics system dynamics modelling. At each step the uncertainties were further amplified. Advancements are being made to improve the density of rainfall stations within the area including the expanded rain gauge and weather stations array implemented by

NRF-SAEON within the groundwater catchment, as recommended by Pitman and Hutchison (1975). Unfortunately, the short record length of these new stations did not allow from them to be used in the hydrological modelling. However, potential avenues of being able to exploit the advantages of this denser rainfall network are being investigated, such as using the available short record from the denser network of gauges to groundtruth various sources of climate data, such as the ERA5 data; CHIRPS or IMERG rainfall data; and other sources of remotely sensed or modelled climate data.

Evaporative demand will increase in a warmer future (Condon et al., 2020). Given the size of Lake Sibaya, evaporation forms a significant component of the water balance for the lake, and, under changes in climate, this component will become more important (Condon et al., 2020, Adeyeri et al., 2024). However, there has been a lack of research focused on open water evaporation (Savage et al., 2017). The only study to date in South Africa focused on open-water evaporation was undertaken by Savage et al. (2017) who demonstrated that, over open water bodies, night time evaporation accounted for 44% of the daily total evaporation, whereas over-land night time ET is considered to be 0. Further Savage et al. (2017) showed the importance of the collection of above-water weather data to estimate the evaporation accurately. To date, no above-water climatological measurements exist for Lake Sibaya. Given the extent of the water body, the large evaporation component from the Lake, and conflicting results on its relative impact on the water balance, as well as the potential impacts of climate change in the region, collecting above-water climatological data should be given priority within Lake Sibaya.

Not only is the past and current climatological data a concern, but also the confidence in future projections to enable local-scale decisions, hence the improvement of downscaled future scenarios is a priority. Given the reliance of catchment W70A on local rainfall for recharge, the sensitivity of the hydrological system (and the hydrological models) to precipitation (amount and intensity), as well as the potential impacts of climate change on the water balance through processes such as increased evaporative demand (Condon et al., 2020, Adeyeri et al., 2024), attention to hydrometeorological parameters for this region in particular is required. Discussion summaries from the recent WCRP OPC noted the need for improved and tailored predictions that speak more directly to the requirements of the end users who need to make decisions for adaptation. Improved data from Africa will improve GCMs while regional climate modelling efforts that focus on parametrisation of earth system feedbacks and regional processes are likely to provide better bottom-up climate projections. The CMIP6 models on their own do not represent the area and need to be improved by the incorporation of local processes the importance of which has been demonstrated in recent studies (Barimalala et al., 2022).

As mentioned above, hydrological models are a simplified mathematical representation of a complex hydrological system. Although a perfect representation of the system will not be possible to achieve, there are opportunities to further reduce the uncertainties in the modelling, such as improved bias correction techniques (Adeyeri et al., 2024). Despite the challenges encountered, progress was made in enhancing the model simulations of climate and LULC change for quaternary catchment W70A and the associated ULM, as well as revealing areas where further studies should focus. This project provided proof of concept for the value of a more spatially explicit representation of metrological data as an input into the hydrological models. The ultimate aim should be to improve the reliability of these parameters for past to current simulations and reduce their uncertainty in future projections, in order to enhance confidence in model outputs. For the past to current period, this needs to incorporate a more accurately assessed LULC change time series, ideally extending back to at least 1957, combined with improved data on the water use of different LULC types. Research and modelling to assess how evapotranspiration will be influenced by future climate, and the consequences of this for recharge and the groundwater store requires attention. Results using multivariate bias correction techniques specifically designed to improve water balance closure, incorporating indices that impact on water storage, provide further evidence for the importance of these processes and their impact at local scale (Condon et al., 2020).

All models are only as good as the input data used and the process representation in the model. Both are strongly tied to field-based measurements and observations. The climatological data needs have been discussed above, but, beyond this, field-based observation of lake level, boreholes, an improved high-resolution DEM, further isotope studies, a time series of properly groundtruthed high resolution land cover maps and *in situ* ET measurements over varied land uses as well as the lake, are all key to reducing uncertainties in the modelling. Data, whether the quantity or quality, should not be a restriction to research or action. The focus should be on the usefulness of the information that stems from the science with recognition of the shortcomings.

A limitation of the configuration of the ACRU model as a distributed grid is that the shallow groundwater routine could not be used. The shallow groundwater routine allows for the deep-rooted trees to take up water from the groundwater store. In this study, given the sensitivity of recharge to rainfall the improvements in the spatial representation of rainfall in the model outweighed the shortcoming of not being able to use this routine. However, moving forward, either a change to the model code to allow the use of the shallow groundwater routine in distributed mode is needed, or possible alternative surface water models should be explored.

In terms of MODFLOW, a review of the geological and hydrogeological data available for use in the model should be undertaken given that recent geophysical survey data illustrates a different spatial distribution of geohydrological features (aquifers) and certain hydraulic properties than what was initially understood for the lake area. The spatial distribution of the hydraulic conductivity parameters as well as the storage parameters should be refined, with a focus on the use of Pilot Points in the calibration process. This was not done initially due to the time implications; however, recent streamflow conductance calibrations greatly improved the lake simulations which supports the initiative to look at other calibration approaches. There are concerns regard to the representation of interflow between the main basin and south basin in the model, as the model is currently simulating a significantly high amount of flow from the main basin to the south basin, which is being disputed, with a suggestion that more groundwater seepage on the eastern side of the main basin is taking place. Therefore, exploring methods on how to improve the confidence in these flow volumes (from the main basin to the ocean) should be given attention. Recent isotope work on the interconnectivity, the above-mentioned geophysical study, and improved methods and measurements for understanding the flow of water within the groundwater system of Lake Sibaya, can advise on how to further improve the groundwater model. Lastly, the conceptual model for the Lake Sibaya groundwater catchment needs to be revised based on knowledge gained within this project, particularly from the isotope studies.

Regarding temperature impacts, as explained in CHAPTER 5:, El Niño-Southern Oscillation (ENSO) events, which are often associated with warmer temperatures, are expected to increase into the future. The lack of a significant ENSO correlation with heat wave numbers experienced thus far from analyses in CHAPTER 5: may be attributed to the fact that, by definition, to be classified as a heat waves requires meeting the criterion over at least three consecutive days. There is already strong evidence for heating over the Southern African region, and high confidence that temperatures, extreme heat days, and heatwaves will increase (Engelbrecht et al., 2015). A robust signal from all models indicates a substantial temperature increase towards the end of the century. The entire model ensemble suggests a potential rise of 2°C or more in temperature, with some models even projecting an 8°C increase by the end of the 21st century. These warmer temperatures, coupled with decreases in early summer rainfall, could significantly impact agricultural activities at the beginning of the summer. The temperature analyses in CHAPTER 5: did not account for single-day extremes. Likewise, the methodology used to assess DFs (CHAPTER 11:) used monthly average T max values. The impacts of individual extreme heat day events are thus not accounted for in the current ULMCatchMod systems model. Effects of single day extreme heat events have been observed to have significant effects on crops (e.g. macadamia) and wildlife (e.g. bats) (Pers. Obs.). Furthermore, while there is confident in an increasing temperature trend the actual values for the projected temperature need to be benchmarked against observed data. Given the above, it is recommended that further refinements to the temperature component in all analyses, as well as the inclusion of an extreme heat day temperature component in accounting for net effects within the ULMCatchMOD.

To advance the systems dynamics modelling (ULMCatchMod), exploring hydrological and economic feedbacks, understanding the impact of flows (i.e. water in and out of the system) under different climate futures is necessary to comprehend the behaviour of the entire system, encompassing both the economy and the hydrological system, given the close interdependence between economic activities and the hydrological system (Luna-Reyes et al., 2013). While a solid foundation for the model structure was achieved, the potential to incorporate more sophisticated feedbacks should be explored, particularly between sector and household subroutines. Furthermore, how to include dynamic response changes in the area extent of different land uses can be explored, where land uses that provide improved benefits are likely to expand. There is also potential to quantify the value of natural resource assets, e.g. water; wetlands; reeds, more explicitly and assess the dynamic gains and losses of these under different scenarios within the ULMCatchMod.

Further coupling between the hydrological outcomes and ULMCatchMOD would be valuable. The main link between the hydrological model and the ULMCatchMOD was only for the irrigated scenarios, where deficits in irrigation requirements where incorporated into the DF calculations within the ULMCatchMOD which influenced yield determinations. Again, this provided a valuable proof of concept. Results can be enhanced through the use of a sophisticated crop model. The qualitative and quantitative data gathered, provided ample grounds for narrative storylines to illustrate how changes in water resources affect people's livelihoods. However, further consideration on how best to couple hydrological outcomes in the ULMCatchMOD is worthy of attention. A fine scale DEM would assist in this process as it would enable a more accurate hydrological model in which target points in wetlands can be assessed in relation to groundwater levels. This would provide a wetland status, e.g. flooded, bone dry, optimal, to feed into crop yield determinations in the wetland sub routine in ULMCatchMOD, which was an aspiration of this project that could not be realised because of the coarse scale of the elevation data.

Improving the commercialisation of livestock was an aspiration identified within the TC workshops and the ULMCatchMOD is partly set up to test this. There was an explicit request at the feedback workshops in November 2023 to refine this component of the model. The next step is linking production to distance from water (with links to groundwater availability from the hydrological model), as well as including impacts on productivity through the degree of animal husbandry applied. Traditional council engagements identified several other “commercialisation” activities which have not yet been included in the ULMCatchMOD. These can still be added to the ULMCatchMOD to explore these ideas, such as improved market access and the commercialisation of indigenous products (oil from Marula and Lala wine).

Integration across different disciplines requires a common understanding of terminology; openness from the team members and willingness to compromise or be innovative to allow linkages between models to be achieved. Furthermore, a mutual commitment to the ultimate impact of the project, not just academically, but for the communities within the area, is important. The data flow from the climate models (both ERA5 and CMIP6) through the surface and groundwater models to the economic system dynamics model was a significant outcome achieved by the project and involved much learning. Time restricted further iterations of improving the linkages and building feedbacks from the economic model to the hydrological models. The resources invested in being able to achieve the level of integration should be recognised and built on.

14.4 SYNTHESIS DISCUSSION

This study addressed a societal need for improved water and economic security in the ULM region. Households within ULM are experiencing high unemployment, poverty, ecosystem degradation, and declining water security. Wetlands, aquatic habitats, and natural resources contribute a large proportion of livelihood income for most households.

14.4.1 Past to current

Despite concerns from inception that commercial plantation forestry may not be an appropriate development option for this sensitive region, (Pitman and Hutchison, 1975, Odendal and Schoeman, 1990), the extent of these plantations has expanded to over 40 000 ha within the ULM (Ramjeawon et al., 2020). The development and expansion of commercial forestry plantations occurred historically under the influence of Government and, more recently, external profit-driven companies that appear to be externalising the risk, water deficit related costs, and impacts of the plantations to the environment and communities.

The negative impacts of commercial plantation forestry on the region in general (Vaeret et al., 2009, Bate, 2016) and on the W70A catchment and Lake Sibaya region specifically (Weitz and Demlie, 2014, Smithers et al., 2017, Bate et al., 2018, Everson et al., 2019, Graham et al., 2020, Ramjeawon et al., 2020) have previously been demonstrated. The declining water table has also been attributed to below-average rainfall (Weitz and Demlie, 2014, DWS 2015, Smithers et al., 2017, Nsubuga et al., 2019, Johnson, 2021). Utilising improved *in situ* data, novel modelling configurations that account for spatiotemporal LULC change and climate parameters, and assessing future LULC-climate storylines, this study provides further definitive evidence for the relative impacts of climate and LULC on the Lake Sibaya groundwater catchment within the UML.

Quantitative data from HH surveys conducted as part of this study underscore the high degree of dependence on wetlands for both subsistence and the sale of agricultural products. A significant number of comments gathered provided substantial qualitative evidence on how the quantity and quality of reeds is decreasing, and on the inability to cultivate in wetlands due to water shortage. A digitising exercise confirmed that 59% of wetlands assessed around the lake were dry and degraded. These findings confirm that the decline in the water table has negatively impacted food security and livelihoods associated with wetlands and aquatic ecosystems.

Simulation results from the groundwater model provide substantive evidence that the 14-year breach in the drought threshold for the lake (not more than 5 years below 16.5 m AMLS) would have been avoided at the current time had commercial plantation forestry not been imposed on the area. Lake Sibaya water levels, which reflect groundwater dynamics, have been below 16.5 since 2011. Based on qualitative and quantitative information on the impact of these current conditions, we can conclude that commercial plantation forestry has unequivocally compromised adaptive capacity by reducing natural resource-based livelihoods, which, according to HH survey data, support a far greater number of households than benefit from forestry. Continued expansion of commercial forestry plantations will further compromise livelihoods and increase tensions between various land users within communities as well as threaten conservation objectives.

The impacts of commercial plantation forestry have been exacerbated by below average rainfall and the reduced frequency of extreme rainfall events. Improved understanding of the hydrological system was gained through *in situ* measurements, isotope studies, and climate analysis which, collectively, demonstrate the importance of extreme rainfall events for recharging the groundwater table. Occasionally the region does experience significant tropical cyclone rainfall input. Of concern, therefore, is the projected decrease in the occurrence of tropical systems (cyclones, depressions, and lows) that originate from the southwest Indian Ocean and make landfall over the Southern African subcontinent (Malherbe et al., 2012), as these are responsible for widespread heavy rainfall events (Malherbe et al., 2012). However, others have predicted a southwards shift of cyclonic systems (Fitchett and Grab, 2014). There are indications that overall Southern Africa is more likely to show a drying trend with conflicting projections for KwaZulu-Natal, with some indications of drying in early summer and more extreme rainfall events in the late summer (Engelbrecht et al., 2024). Stringently bias corrected projections, focused on assessing the impact of climate change on the water balance, projected deficits in water storage (groundwater) for Southern Africa (Adeyeri et al., 2024). Furthermore, there is evidence that increased evaporative demand will negatively affect shallow groundwater resources (Condon et al., 2020). Given available evidence, regardless of uncertainty, a least regret approach emphasises the obligation to identify alternative land uses that are both economically viable and water-efficient to provide sustainable solutions amid potential climate change futures for the ULM.

14.4.2 Future scenarios

The original approach for incorporating plausible future climate projections used bias corrections based on two CMIP6 model outputs, applied to recharge data from the ACRU model. The ACRU model used ERA5 data for the period 1991 to 2020 as input data. Utilisation of this recharge data, showed the groundwater model consistently simulated a concerning decline in groundwater levels into the future for all land use scenarios. The decline was evident for both the “C6Wet” and “C6Dry” CMIP6 bias corrected data. This period experienced few extreme events and rather severe drought conditions, making both bias-corrected scenarios “worst-case” wet and dry future storylines due to the absence of extreme rainfall. A reminder also that the ERA5 data to which corrections were applied also under simulated rainfall, leading to a potential underestimation of 30% in groundwater recharge.

The two C6 and the ERA5Wet storylines represent extended periods of possible worst- and best-case future climate storylines. The “best-case” storyline (ERA5Wet) can be used to demonstrate the importance of consecutive wet years and frequent extreme precipitation events. It is improbable that an extended period of up to 60 years (as that modelled for 1990 to 2050) of below average rainfall will unfold without being punctuated by wet periods and extreme rainfall events, as has already been witnessed since 2020. The climate future storylines are within the range projected by CMIP6 ensembles which range from a -7% decrease in summer rainfall to an increase of +19%. This study, essentially tested the impact of extended periods of time that represent conditions with either a higher or lower frequency of extreme rainfall events.

Nine alternative LULC scenarios were tested for their hydrological impact within the model domain. Status Quo and all LULC simulations revealed declining trends in the lake level (used as the hydrological system response variable) under the C6Dry and C6Wet future climate storylines. This demonstrated the overriding impact of warmer, extended drier, and slightly wetter future storylines typified by few extreme rainfall events. An equivalent precipitation period to this is the historic period from 1991 to 2020. All C6Wet scenarios showed a slightly less dramatic decline than the C6Dry scenarios. Removing 50% of commercial plantation forestry and replacing it with “Dryland Crop” or “Dryland Marula” resulted in a more positive effect on lake levels relative to the SQ, especially towards the end of the simulation period, hinting at lag effects. However, these impacts were insufficient within the simulation period to result in lake level recovery to pre-2010 levels.

In stark contrast to the C6 future climate storylines, recovery was consistently observed for all future LULC scenarios, from the current declining trend, under the ERA5Wet future climate storyline. This storyline represents a wetter precipitation period than the 1971 to 2000 period, which was characterised by a higher number of extreme rainfall events then the 1991 to 2020 period.

The No Forestry scenario vividly demonstrated the extent of the impact of plantation forestry on the water table, a crucial point conveyed during community workshops. Had commercial plantation forestry never been introduced (“No Forestry” LULC scenario), current lake levels would be at least 1.5 m higher than they are today despite two decades of low rainfall leading up to 2020, and the 14-year current breach in drought reserve would not have occurred. Water levels remained above 16.6 m AMSL up to 2020. Under the C6Dry climate future storyline, the recent crisis conditions would only have been reached by the mid to late 2040s. A declining trend under the “No Forestry” scenario for both C6 future climate storylines demonstrates the dominant impact of a climate future with few extreme rainfall events. In the ERA5Wet future storyline, the system recovers rapidly to over 19 m AMSL by 2050. In contrast, under the ERA5Wet (best-case) climate future storyline, under SQ conditions (no reduction in forestry), the lake system, which had fallen below 15 m AMSL by 2020, had not recovered above 17.8 m AMSL by 2050, indicating a cumulative and potentially escalating deficit in the water resource. Maintaining the SQ land use in combination with bush encroachment is the worst option under all climate futures. Collectively, these results demonstrate that commercial plantation forestry exacerbated the impact of below-average rainfall in the region.

In this study extended periods of time that represent conditions with either a higher or lower frequency of extreme rainfall events were tested. In such cases, climate signatures would be the predominant influence on the groundwater resource. A more probable future is likely to be one with more interspersed extreme wet and dry periods, i.e. not such lengthy extended periods of one or the other. In such cases, land use choices will likely exert a more pronounced influence on the net outcome.

14.4.3 Solutions

Survey data and engagement with the TCs revealed an aversion to commercial plantation forestry as a future land use. Removing 50% of the formal plantation forestry blocks resulted in a relative improvement on the water table compared to the SQ. Cassava and Marula emerged as potential water wise climate options. From a practical “alternatives” perspective, there is significant unexplored potential to utilise indigenous species for non-timber forest products (NTFPs). Research within the study area assessing abandoned and clear-felled plantations demonstrated the ecological potential of several indigenous forest species (known to contribute to the informal economy) to provide NTFPs for commercial gain (Starke et al., 2023). These species are adapted to fire and use less water than eucalyptus plantations, thereby improving environmental conditions. Tapping into indigenous knowledge systems regarding the utilisation of indigenous species has the potential to enhance social benefits, including a sense of ownership and agency. Modalities for small scale agro-processing initiatives exist within South Africa and research has shown how they benefit from capacity building as well as developing improve business networks which lead to better access to markets and business success outcomes (Manasoe et al., 2022). The next actionable step that needs urgent attention is working with interested households to determine the economic potential of a diversified agroforestry production system, incorporating indigenous species such as Marula (*Sclerocarya birrea*) and the Pepper bark tree *(Warburgia salutaris)*.

The conservation value and tourism potential of this region have long been recognised, along with its vulnerability and limited capacity to support local populations (Bruton, 1980, Mountain, 1990), yet tourism potential remains unrealised. Tourism and the livelihood benefits stemming from the area's biodiversity assets have the potential to complement each other. These advantages could be enhanced by applying South Africa's Ecosystem-Based Adaptation (EbA) principles, which aim to increase societal resilience and reduce vulnerability to climate change impacts by promoting ecosystem integrity. Odendaal and Schoeman (1990) argue that external “experts” cannot drive the long-term sustainability of tourism initiatives, but rather should promote appropriate skills transfer and self-reliance and be rooted in the ideals and needs of the people within the area. They advocate multiphase and adequate planning approaches to address, among other things, internal constraints such as conflicts of interests. The importance of empowerment and participatory planning, management and control of tourism initiatives are recognised as important success factors in advancing tourism venture success (Van Rooyen, 2006). Furthermore, innovative strategies with respect to employment structure to deal with the seasonality of tourism in a manner that promotes consistent income to local households would be beneficial.

The need for a 'master plan' to guide sustainable economic development within the region has been mentioned numerous times (Bruton, 1980, Mountain, 1990). In general, ITB land is characterised by poorly defined property rights and is often associated with challenges to planning (Kloppers, 2003; Jones, 2006; Jury et al., 2009). Integrated spatial planning is a requirement in South Africa governed by various policies and legislative frameworks which consider traditional structures (Ndebele, 2016). However, on ITB land, there are apparent challenges to the implementation of well-planned and documented local municipal integrated development plans. This is evidenced by the lack of implementation of such plans and/or incongruous land use changes in conflict with the stated plans. Ndebele (2016) argues that part of the reason for this includes challenges in defining the roles and responsibilities of TCs in spatial planning within these frameworks as does Clarke (2018). Additional factors identified include weak or poor participation and consultation processes and lack of ownership by TCs over spatial plans (Ndebele, 2016). We argue that a bottom up land use plan, incorporating integrated sector planning (food production, high value climate smart crops, grazing plans, water, energy, and tourism planning) may be a valuable tool in overcoming some of the barriers to achieve improved outcomes. The knowledge exchange facilitated through this project has laid the foundation for promoting integrated land use planning, as evidenced by the testimonies of those from ULM who participated.

14.5 CONCLUSIONS

Anticipated impacts of climate change, including an increase in the severity and frequency of extreme events, will exacerbate poverty and vulnerability if no proactive action is taken to empower communities to adapt. While temperature increases are inevitable, the trends in precipitation at local scales are less clear. Unpredictability in rainfall patterns and higher temperatures will impact food security and incomes derived from natural resource-based livelihoods.

This project aspired to develop a means to empower vulnerable local communities to make informed choices for the optimisation of beneficial outcomes in the context of climate change adaptation. The project aims were achieved through (i) scientific research to advance knowledge on the climatological, hydrological, and economic dynamics within the ULM; (ii) engagement and multiway knowledge sharing with people living in the area to ensure context relevance, enhance awareness of climate change risks and promoting personal agency in addressing these; and (iii) integrating information to provide decision storylines that promote an understanding of the potential implications (risks/opportunities) of land use choices made today, on future outcomes under different climate futures.

The impact of nine land use choices on water security under three (in some cases four) climate future storylines was achieved. Climate, economic and hydrological parameters were integrated using a systems dynamic model to assessed the consequences of LULC choices. This was supplemented by a summary matrix that incorporated additional hydrological consequences. These consequences were assessed in relation to water security, employment, economic status, natural resource (ecosystem) integrity, and under different climate future storylines. Caricatured climate future storylines and “immediate” LULC switch scenarios were used to test if integration was possible. The integration achieved demonstrated a sound proof-of-concept which can now be refined by focus on parameterisation. While the results from individual components provide useful insights, the net effect outcomes should be used for demonstration purposes only, until various components are more adequately parameterised. The project was successful in enhancing awareness of climate change risks and the sensitivity of the water resources to LULC choices. *“The youth need to be brought closer as the decisions we take now will affect their future*” (workshop participant).

The project significantly advanced the scientific understanding of the intricate relationship between rainfall, LULC, and recharge values, refining the conceptual understanding of the system. A key finding highlights the crucial importance of extreme rainfall events in replenishing the groundwater table, emphasising the urgent need for an improved understanding of potential changes in rainfall dynamics for future decision support. Understanding the responses to storm events, particularly extreme rainfall, aids in interpreting long-term groundwater trends. While climate projections have inherent uncertainties, it is reasonably certain that consecutive years with low or no extreme events compromise water security, while the opposite holds true if there are consecutive years of high rainfall with a higher frequency of extreme rainfall events, particularly when commercial plantation forestry is removed.

Commercial plantation forestry did not provide more benefits than other forms of income and livelihoods at the household level. Tourism and government employment provided more significant benefits to the region. Furthermore, results of both the hydrological modelling and HH surveys corroborate a decline in ecosystem services and associated negative impacts on benefits from natural habitats for the current SQ dominated by large-scale eucalyptus forestry. Households that rely on natural resources and ecosystem services for food, water and informal economy have been negatively affected due to the impact of commercial plantation forestry on the groundwater table, reducing their resilience and adaptation potential. These impacts are exacerbated by below average rainfall, but would not have been felt in the absence of commercial plantation forestry.

If the goal is a net improvement for all in the region, radical change in production systems is required. Choices made now need to address the primary challenges identified by the TCs namely; water security, employment, economic status, and natural resource degradation. The ideal land use choice scenarios are ones where commercial scale production systems provide a sustainable source of employment and income while also promoting natural resource (ecosystem) integrity and optimising economic benefits gained from these under an uncertain climate future. The trade-offs between formal economically driven production systems, the associated changes/losses in ecosystems services and associated economic benefits/losses thus need to be considered holistically.

A least regret strategy should, as a priority, protect the remaining grassland areas within the region and management thereof, and may include a significant conversion of commercial plantation forestry to water-wise, climate-smart alternatives, e.g. cassava and Marula, combined with improving animal husbandry, commercial processing of high value products from these, as well as optimising benefits from tourism. Service-based industries provide further potential for enhancing net outcomes and thereby improving adaptive capacity, through decoupling dependence on subsistence livelihoods which are high risk under climate change.

The success of any scenario selected is likely to depend on: the degree to which a socially acceptable and internally driven integrated land use and development plan can be implemented; the strength of the governance structures that can promote collective cooperation and beneficiation as identified by the participants who attended the knowledge exchange; and benevolent support and capacity development to facilitate transition to alternatives. Any intervention should ensure that profits gained are retained within the system, with communities themselves as the primary shareholders in large scale commercial ventures, with equitable distribution. Modalities that concentrate power and profits for a few, or are driven by an external shareholder base, should be avoided.

Numerous challenges encountered in this study in trying to integrate across disciplines demonstrated the need and value of reiterative reflection and decision flexibility, with continual information exchange and communication being crucially important. Perceptions of what is possible and what integration means needed to be re-formulated, reshaped, and deepened through interaction, dialogue, data sharing and reflection in iterative feedback loops.

It must be stressed that this project was a first attempt to see if it was possible to develop a dynamic and interactive decision support tool to explore consequences of land use choices made now into the future. The scenario-based LULC hydrological outcomes were useful for assessing different scenarios. However, to configure and run the models requires significant time and a sophisticated level of data processing, and the accuracy of outcomes is highly dependent on the data available related to each scenario.

Progress was made towards an interactive decision support tool (ULMCatchMod). The ULMCatchMOD has flexibility that can be optimised to greater effect, provided it is parameterised with appropriate data, to explore relative outcomes. A simple summary matrix, using outcomes from the hydrological and UMLCatchMod, (both of which integrate climate implicitly) provides the proof of concept for sharing the outcomes in a simple, yet comparative, manner. In effect, rather than an interactive decision support “tool”, the outcomes of this work provided valuable storyboards which we could use to demonstrate concepts when engaging with the communities. When sharing these, it became clear that the level of sophistication we attempted within the system model was surpassed by the urgency expressed by communities for actionable steps on the ground. Engagements revealed that their interest was not in the “tool” itself, as the storylines were sufficient to focus their attention on alternatives. They were therefore more interested in tangible steps forward. This spotlights the need for transdisciplinary networks to come together, from NGOs, to agricultural institutions, to help co-develop and act on tangibles steps to work out fine-scale practical details about how to make changes community members may want to make. In this regard, the onus falls on the project team to 'pass on the ball' by trying to link those interested with appropriate implementation organisations.

The study underscores the interconnectedness of economic, environmental, and social factors in the ULM, emphasising the need for comprehensive and collaborative approaches to address current challenges and future uncertainties. There is a complex interplay between climate, land use, and economic factors, emphasising the need for holistic strategies and adaptive approaches in the face of evolving conditions. A major concern therefore is the lack of climate change awareness at the household level. This is an essential gap that needs to be addressed as a primer for any adaptation interventions. This need was echoed by all three TCs who have requested that we spread the information on climate change; its risks; and the uniqueness of their system; to the broader community.

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