# Determining Climate Change Aspects on the Ecosystem Resilience of Headwater Wetlands in two Catchments in Eswatini (Swaziland) and in South Africa Respectively

Report to the
**Water Research Commission**

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The publication of this report emanates from a project titled *Determining climate change aspects on the ecosystem resilience of headwater wetlands in two catchments in Eswatini (Swaziland) and in South Africa* (WRC Project No. K5/2831).



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# EXECUTIVE SUMMARY

## 1. INTRODUCTION

Climate change and variability is strategically important for southern Africa's water-related needs. Intact ecosystems can buffer against environmental shocks (e.g. floods, heatwaves, droughts, storms and veld fires). Preparing for climate change, an ecosystem-based approach can pay huge dividends to society and the economy as a whole. Wetland systems are resilient (i.e. following the concept of ecosystem resilience) because they have adapted to cope with variability. Ecological processes in wetlands are largely controlled by the quantity and hydro-period of flows. Major climate change-driven changes in water flows are, however, likely to lead to changes in wetland structure and functioning and therefore likely to affect the goods and services they provide to people and communities (i.e. the concept of socio-economic resilience). When wetlands are impacted by both climate change and land use, the ecosystem and society suffer. Understanding climate change impacts is important to determine the threat it could cause to wetlands.

This Water Research Commission (WRC) project (WRC Project No. K5/2831) commenced in April 2018 and was scheduled to be completed by the end of March 2022. The overall aim of the research study was to understand the ecosystem resilience of headwater wetlands in two catchments: one situated in the Kgaswane Mountain Reserve, North West Province, South Africa, and the other in the Malolotja Nature Reserve, near Mbabane, Kingdom of Eswatini (formerly the Kingdom of Swaziland). Both areas form part of Strategic Water Source Areas within the national priority focus areas of South Africa and Eswatini and are therefore important focal areas for measuring climate change effects on Transboundary Water Management.

The specific aims of the project were as follows:

1) To discuss future rainfall predictions related to climate change for the two different countries, and to make recommendations for sustainable development solutions based on the different wetland scenarios of the headwater catchments.
2) To develop the first wetland probability map for Eswatini, and to determine the extent and distribution of Eswatini's wetlands (National scale).
3) To explain wetland geomorphic processes (geomorphology, hydrology, vegetation) at work in the Malolotja Nature Reserve, Eswatini (Catchment scale).
4) To map the different hydro-geomorphic wetland types in the Kgaswane Mountain Reserve, South Africa (Catchment scale).
5) To determine the relationships between the distribution of wetland types, the underlying geology and the related processes including hydrology, geomorphology and vegetation in Kgaswane Mountain Reserve, South Africa and to illustrate these using conceptual hydrological/geomorphic response diagrams (Catchment scale).
6) To hold a cross-cultural workshop for the role-players and interested and affected parties of the wetland systems of the two countries.

The project successfully addressed all these aims. Results from the study are summarized under the headings that relate to the chapters in the report.

## 2. WETLAND RESILIENCE IN FUTURE CLIMATE SCENARIOS

**Aim 1: The projected effects of climate change for wetland systems in South Africa and in the Kingdom of Eswatini: Future rainfall predictions and recommendations**
Completion of the 50 km resolution simulations (CCAM) was integrated in stretched grid mode over southern Africa, at a resolution of about 8 km pixels (Chapter 2). Results include average temperature, very hot days, rainfall and extreme rainfall events.

Given that the prognosis for climate change scenarios for southern Africa (in the generalized format) is a move towards higher intensity and lower frequency events, but with approximately the same net precipitation, this poses several possible outcomes:

- Under conditions of an overall good catchment management system and well-functioning sustainable land management (SLM), the emphasis will be on the amount of water available, with potential shortages in times of 'drought' and possible wetland expansion in times of excess water, water abundance, or even flooding during the 'wet' phases. There are resultant implications for both land use/occupation and for water management.
- In contrast, where SLM is either absent or poorly practised, wetlands are likely to be under stress already. Such stressors will be exacerbated by the climate change and/or climate variability that is to be expected. Here, catchment management is likely to result in overgrazing during the dry periods, enhancing the likelihood of severe sediment production and transport during the high intensity/high runoff phases. This is likely to result in severe erosion within the catchment itself, but importantly is also likely to result in a decrease in water quality in the wetland, as well as potential 'choking' of the wetland through the ingress of excess sediment which becomes trapped in the wetland vegetation.
- The potential effects for peat wetlands are more serious, in that they may be subject to a 'drying out' of the peat during the dry phases, resulting in the liberation of more greenhouse gases (GHGs), thereby further accelerating climate change and variability. The implications of the wet phases are not as clear and the study did not focus on the GHGs associated with wetlands in any detail.

Knowing the potential impact of climate change on ecosystem processes, their functions and structure (i.e. type of wetland, how it functions and the effect associated with catchment land use) might be one of the most cost-effective ways of helping southern Africa to adjust to the effects of climate change.

Based on the findings of the study, the following recommendations are made:

- The community must achieve sustainable utilization of the wetlands jointly as local institutions for local benefits as recommended by community-based natural resource management (CBNRM).
- Conduct a comparative study on the factors affecting wetland sustainability in order to make an informed choice of wetland use, then strengthen the positives and fix the loopholes in the sustainable use of wetlands.

## 3. PREDICTION OF WETLAND OCCURRENCE IN ESWATINI (NATIONAL SCALE)

**Aim 2: A wetland probability map for the Kingdom of Eswatini (National scale)**
The results of the probability mapping which are presented in Chapter 3 have contributed to providing baseline data on the distribution of wetlands across Eswatini. Statistically-derived wetland probability mapping may have yielded more accurate results than the chosen method

for this study, but the attribute/input data required for such techniques are frequently not available in developing countries such as Eswatini. This mapping exercise has also shown that large-scale attribute data can be used to partially distinguish wetlands from other types of watercourses through identifying areas with a higher probability of wetland occurrence, using relatively simple techniques. Further research is required to determine whether soil and morphometric data at a finer scale and resolution than that used in this study, as well as other types of attribute data, would have yielded more accurate results. The limitations of the wetland probability mapping and the production of the improved hydrogeomorphic-classified probability maps need to be acknowledged.

## 4. INVESTIGATING THE MALOLOTIA PEATLAND IN ESWATINI (CATCHMENT SCALE)

**Aim 3: A review of the geomorphic processes that determine the character of the main peat wetland in the Malolotja Nature Reserve, Kingdom of Eswatini (Catchment scale)**
The findings of this section of the study dealing with the Malolotja peatland are described in Chapter 4. Results have indicated a spatial and a temporal differentiation of the water table in the main peatland complex of the Malolotja wetland. The northern and central areas maintained water levels that were close to or within the root zone (i.e. within -0.3 m) even during the dry winter season. Conversely, water in the peripheral region was infrequently found in the root zone, with water levels decreasing progressively during the seasonally dry 2019 winter period. Peatlands that occur under “favourable conditions” are likely to have a water table perpetually close to the ground surface. Due to the absence of many anthropogenic pressures at the Malolotja Reserve (and hence the peatland), water loss mainly occurs via evaporation or diffuse overland or near-surface flow, from the central region of the peatland towards the peripheral regions. Water level measurements displayed a delayed response to rainfall.

## 5. EXTENT, DISTRIBUTION AND DESCRIPTION OF WETLANDS IN KGASWANE MOUNTAIN RESERVE

**Aims 4 & 5: The Kgaswane Mountain Reserve wetland map and conceptual hydrological/ geomorphology response diagrams of the Kgaswane Waterval peatland (Catchment scale)**
Results indicate that wetlands occupy 370.42 ha of Kgaswane Nature Reserve. Seep wetlands occupy the largest surface area of 244 ha, with 22 natural seeps and one incidental seep being identified. Fourteen channelled valley bottoms were identified with a total surface area of 86 ha, whilst six unchannelled valley bottoms were identified with a total surface area of 40 ha. The largest wetland that occurs in the reserve is the Waterkloof Spruit peatland, an unchannelled valley bottom, with a surface area of 28.4 ha, which forms part of the 40 ha comprising unchannelled valley-bottom wetlands. The size of the artificial depression is 0.42 ha.

The conceptual model illustrates the geomorphological and hydrological drivers of the system with the vegetation as a response to the respective drivers. It shows the surface and subsurface flow paths that sustain the Waterval peatland and the role that the peatland plays in the wider hydrology of the catchment (i.e. acting like a plug). Furthermore, it shows evidence of groundwater discharge and tributaries feeding the wetland with rainfall runoff. The geologic and geomorphic controls playing a role on the peatland formation are described in Chapter 5.

## 6. CONSERVATION AND WISE USE OF WETLANDS

**Aim 6: The outcomes of the Cross-cultural Wetland Workshop**
The Cross-cultural Wetland Workshop (Information Dissemination Report, Deliverable 5) was one of the project's aims, namely to facilitate discussion between role-players (wetland experts, government officials and students) from different countries on wetland types and their functioning. The Cross-cultural Wetland Workshop was held at *Miss Chrissies Country House* at Chrissiesmeer, Mpumalanga on 4-6 October 2019 and was attended by 17 participants representing the following countries: South Africa, Kingdom of Eswatini, The Netherlands and Australia. A mini-seminar session, where the students presented their research (and received feedback), was coupled with field trips to Tevrendenpan and Blinkpan. The focus of the field visits was to expose the students and the government officials from Eswatini to hydro-geomorphic wetland types (depressions) that are different from the peat wetland types studied at Kgaswane Mountain Reserve and Malolotja Nature Reserve.

The research presented adds to our understanding of ecosystem resilience of headwater wetlands and the findings can be used to inform catchment management towards better decision making (e.g. possible impacts and the potential consequences of climate change predictions, already alluded to above). Conservation and wise use of wetlands are discussed in detail in Chapter 6.

## 7. CONCLUSIONS AND RECOMMENDATIONS

This study showed the importance of wetland mapping as well as site-specific investigations on wetlands and peatlands coupled with climate projections of future climate change to make informed decisions regarding the conservation, wise use and rehabilitation of wetlands and peatlands. The study provided research output on national scale (wetland prediction map for Eswatini) and catchment scale of two peatlands to determine the ecosystem resilience of headwater wetlands by studying the morphological controls and hydrology.

The research results support the conservation management of the Kgaswane Mountain Reserve and the Malolotja Nature Reserve, as well as the draft wetland policy document for Eswatini, because of the proposed future focus area of sustainability and wise use of wetlands. The study also created various opportunities for capacity building and for future research. Five MSc students and two Hons students completed their studies as part of this international transboundary water research project.

Overall recommendations include the following:

- Further investigations are needed to quantify the volume of peat and carbon balance within both peatlands.
- The calculated water balance and more accurate hydrological and stratigraphic description for each of these systems will help to understand their vulnerability to environmental and climate change.
- Long-term and detailed monitoring of peatland hydrology (larger sample sizes and more transects) undertaken within Eswatini could allow for a comparison of such results with similar parameters in southern Africa and elsewhere.
- Determine whether soil and morphometric data at a finer scale and resolution, and other types of attribute data, would yield more accurate results in mapping probable areas where wetlands could occur.

- The community will only achieve sustainable utilization of the wetlands through a joint effort (e.g. community-based natural resource management).
- Conduct a comparative study on the factors affecting wetland sustainability in order to make an informed choice of wetland use, then strengthen the positives and fix the loopholes in the sustainable use of wetlands.

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- It is significant to note that two students on the project were awarded their MSc degrees *cum laude* and both have gone on to doctoral studies on wetland-related topics.

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- Special thanks to the Reference Group members:

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| | |
|---|---|
| ACCESS1-0 | Australian Community Climate and Earth System Simulator |
| a.m.s.l. | Above mean sea level |
| AR4 | Assessment Report Four |
| AR5 | Assessment Report Five |
| ARC-ISCW | Agricultural Research Council − Institute for Soil, Climate and Water |
| CABLE | CSIRO Atmosphere Biosphere Land Exchange model |
| CBNRM | Community-based natural resource management |
| CCAM | Conformal-Cubic Atmospheric Model |
| CCSM4 | Community Climate System Model |
| CHPC | Centre for High Performance Computing |
| CNRM-CM5 | National Centre for Meteorological Research-Coupled Global Climate Model, version 5 |
| $CO_2$ | Carbon dioxide |
| CSIR | Council for Scientific and Industrial Research |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DEM | Digital Elevation Model |
| DESTEA | Free State Department of Economic, Small Business Development, Tourism and Environmental Affairs |
| DFFE | Department of Forestry, Fisheries and the Environment |
| DWS | Department of Water and Sanitation |
| EC | Electrical conductivity |
| EMT | Eswatini Meteorological Service |
| ENTC | Eswatini National Trust Commission |
| FS | Free State |
| GCM | Global Climate Model |
| GFDL-CM3 | Geophysical Fluid Dynamics Laboratory-Coupled Model |
| GHG(s) | Greenhouse gas(es) |
| GIS | Geographical Information System |
| GMWL(s) | Ground monitoring water level(s) |
| GPS(s) | Global positioning system(s) |
| HGM | Hydrogeomorphic (wetland types) |
| IPCC | Intergovernmental Panel on Climate Change |
| LMWL(s) | Local monitoring water level(s) |
| MP | Mpumalanga Province |
| MPI-ESM-LR | Max Planck Institute-Earth System Model |
| MTPA | Mpumalanga Tourism and Parks Agency |
| NBA | National Biodiversity Assessment |
| NLC | National Land Cover |
| NorESM1-M | Norwegian Earth System Model |
| NW | North West Province |
| NWCS | National Wetland Classification System |
| NWI | National Wetland Indaba |
| NWM | National Wetland Map |
| PCA | Principal Component Analysis |
| PDP | Professional Development Programme |
| PES | Present ecological state |
| SAIIAE | South African Inventory of Inland Aquatic Ecosystems |

| | |
|---|---|
| SANBI | South African National Biodiversity Institute |
| SLM | Sustainable land management |
| SMOW | Standard mean ocean water |
| SNTC | Swaziland National Trust Commission |
| SPOT | *Satellite Pour l'Observation de la Terre* |
| SRTM | Shuttle Radar Topography Mission |
| SST(s) | Sea surface temperature(s) |
| SWSA | Strategic water source area |
| TTT | Tropical-temperate trough |
| UFS | University of the Free State |
| UNESWA | University of Eswatini (formerly University of Swaziland (UNISWA)) |
| UP | University of Pretoria |
| VHG | Vertical hydraulic gradient |
| WETREST | Wetland Research and Training |
| WRC | Water Research Commission |

# GLOSSARY

**Artesian springs:** springs which come from pressure in confined aquifers forcing the water to the surface.

**Bog:** a peatland that is influenced solely by water falling directly onto it, e.g. precipitation (Ewart-Smith *et al*., 2006; Grundling, 2007).

**Champagne soil form:** contains organic carbon of 10% at 0-200 mm and is saturated for extended periods with water (Soil Classification Working Group, 1991).

**Climate change:** "Climate change is a change in the usual weather found in a place. This could be a change in how much rain a place usually gets in a year. Or it could be a change in a place's usual temperature for a month or season" (May, 2017).

**Discharge:** refers to groundwater that moves upwards across the water table and discharges directly to the surface or unsaturated zone.

**Ecosystem resilience:** 1) capacity of an ecosystem to persist in its present state and to absorb change and disturbance (e.g. floods, drought, fire and pest outbreaks); 2) the rate at which an ecosystem returns to its prior equilibrium or original state, recovering from change; 3) the ecosystem's ability to adapt and benefit as a result of change (Yi and Jackson, 2021; Tooth, 2018).

**Ecosystem services:** term used to assess the goods and services that individual wetlands provide (Kotze *et al*., 2007).

**Effective recharge:** the total recharge minus losses that occur after infiltration to the groundwater.

**Fens:** peat-forming systems influenced by water derived from outside their immediate limits. Wetlands that commonly receive groundwater discharge (Winter, 1999).

**Floodplains:** these can be defined as valley-bottom areas with a well-defined meandering river system characterized by alluvial transport and deposition of sediment (Ewart-Smith *et al*., 2006).

**Geohydrology:** Vegter (2001) defines geohydrology (also hydrogeology) as the field dealing with subsurface water (i.e. water in both the saturated and unsaturated zones).

**Groundwater:** water in the saturated zone that flows into boreholes/wells or debouches as springs (Vegter, 2001).

**High organic soil:** an organic carbon-containing soil not exceeding 10% organic carbon content. Criteria used in this report: high organic soil if only 2% to 9.49% carbon.

**Hydrogeomorphic:** relates to a classification system; one based on the shape of the land (landform setting) and the patterns of surface and subsurface water flow (Ewart-Smith *et al*., 2006).

**Inland aquatic ecosystem:** an ecosystem that is permanently or periodically inundated by flowing or standing water, or which has soils that are permanently or periodically saturated within 0.5 m of the soil surface (Ollis *et al*., 2013) and which occurs inland and is not estuarine or marine in nature.

**Mire:** a term used to indicate living peatlands that actively accumulate peat (IPS/IMCG, 2010).

**Peat:** defined as a sedimentary (in situ) accumulated material that comprises at least 30% (dry mass) of dead organic matter (IPS/IMCG, 2010). A dark brown or black organic soil layer, composed of partly decomposed plant matter and formed under permanently saturated conditions (Ewart-Smith *et al*., 2006).

**Peatlands:** wetlands that have accumulated a minimum layer of 30 cm of peat (National Wetlands Working Group, 1997; Joosten & Clarke, 2002). Peatlands can be divided into fens, bogs and several swamp types (including swamp forest) based on the origin of water supply.

**Permanent wetland:** a wetland or the inner zone of a wetland that is permanently saturated (DWAF, 2005).

**Permanently inundated:** wetlands where surface water (open water) is present throughout the year (Ewart-Smith *et al*., 2006).

**Piezometers:** used to calculate hydrological gradients and then water flow within the ground (Rosenberry *et al*., 2008).

**Present ecological status (PES):** depicts the ecological condition of rivers, wetlands and estuaries, as represented by the PES score and associated Ecological Category (Kleynhans, 2000). The PES is taken into account when making management decisions relating to the sustainable use and protection (Macfarlane *et al*., 2007; Ollis & Malan, 2014).

**Recharge:** the volume of infiltrated water that crosses the water table and becomes part of the groundwater flow system (Anderson & Woessner, 1992).

**Resilience:** the ability of a system to (a) withstand disturbance, (b) recover from disturbance, or (c) adapt and evolve in response to disturbance to a more desirable (e.g. stable) state (Tooth, 2018).

**Runoff:** surface runoff occurs when water is unable to infiltrate (for whatever reason) and when the ground surface is sloping. Surface runoff rate depends on surface slope and roughness, soil moisture content at the surface, as well as on the rates at which additional water is supplied by rainfall and extracted by infiltration or evaporation.

**Saturated:** as relating to wetland sediments, waterlogged, usually resulting in hydric soils that support vegetation adapted to aquatic conditions (Ewart-Smith *et al*., 2006).

**Seasonal zone of wetness:** the zone of a wetland that lies between the temporary and permanent zones and is characterized by saturation for 3-10 months of the year, within 50 cm of the surface (DWAF, 2005).

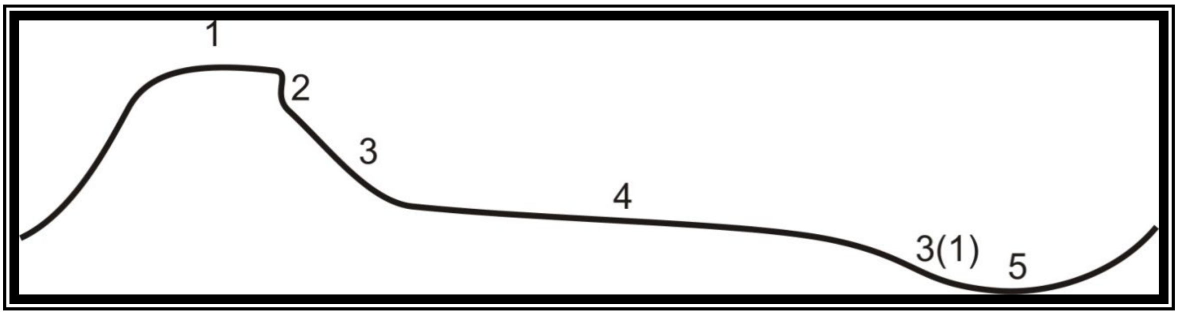
**Seep:** concave or convex area that is permanently or periodically saturated, usually on (or at the base of) a slope, where the groundwater through-flow meets the surface (Ewart-Smith *et al*., 2006).

**Spring:** an outflow of groundwater at the surface (Ewart-Smith *et al*., 2006).

**Temporarily inundated:** a wetland where surface water (open water) is present for less than three months of the year (DWAF, 2005).

**Temporary zone of wetness:** wetland area characterized by saturation within 50 cm of the soil surface for less than three months of the year, e.g. the outer zone of a wetland (DWAF, 2005).

**Terrain units:** morphological elements (units) of a landscape, broadly defined by both form and function. Terrain Unit 1 represents a crest, 2 a scarp, 3 a midslope, 3(1) a secondary midslope, 4 a footslope and 5 a valley bottom (Van den Berg *et al*., 2009).



*Terrain units (Van den Berg et al., 2009).*

**Wells:** used to measure water levels within the ground or wetland **(**Rosenberry *et al*., 2008).

**Wetlands:** defined as 'land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil' (RSA, 1998).

**Wetland delineation**: the determination and marking of the boundary of a wetland…marking the outer edge of the temporary zone of wetness (adapted from DWAF, 2008).

# 1. INTRODUCTION

## 1.1 BACKGROUND

Wetlands are key elements of the landscape and globally recognized as one of the support systems of humankind (Mitsch & Gosselink, 2007). These valuable functions are the result of the unique natural characteristics of wetlands. Despite the value and importance of the services that wetlands provide for many people, they are found to be amongst the most threatened ecosystems globally (Finlayson, 2007) and in South Africa (SANBI, 2013). Worldwide, wetlands are being subjected to increasing human impacts due to population expansion and the growing need for natural resources, which diminish their state of health or ecological condition (Brinson & Malvarez, 2002). This is especially the case in sub-Saharan Africa where there is a high dependence on natural resources, specifically wetlands that support the livelihoods of many poor people (Bikangaga *et al*., 2007). Given that approximately 13% of the land surface is made up of wetlands in the Southern African Development Community (SADC) countries, as well as the majority of wetlands being found in areas inhabited by about 60% of the population, high urbanization rates and a correspondingly high demand for urban infrastructure has placed a great demand on available land (Madebwe & Madebwe, 2005). This has resulted in competition between land uses, with wetlands often not receiving the protection that they require (Madebwe & Madebwe, 2005). In southern Africa the relationships between wetland types, hydrology (particularly hydrodynamics and hydroperiod), underlying geology and geomorphology; the connectivity between land, water, atmosphere and people; and the contribution to global change are poorly understood. Hence the need to investigate these relationships. Such investigation is all the more important in the context that wetlands have as ‘sponge areas’ and their role in runoff regulation and flood attenuation.

## 1.2 PROBLEM STATEMENT/RATIONAL

The main impact of climate change on hydrology will be on the water cycle, hence also on water bodies (Ramsar, 2007). Considering the shared water resources between the countries in southern Africa, South Africa has a vested interest in the water resources of its neighbours. Land use change and rainfall variability in a catchment have an impact on the wetlands, and these should be assessed to be able to quantify the risks and to develop strategies against environmental disasters such as droughts and floods. Therefore, a need exists to compare and understand the resilience and responses of aquatic ecosystems to environmental change in respective mountain headwater catchments. Such an investigation was undertaken in the Kgaswane Mountain Reserve, Rustenburg, South Africa, and the Malolotja Nature Reserve, near Mbabane, Kingdom of Eswatini (previously known as the Kingdom of Swaziland). In preparing for climate change resilience, an ecosystem-based approach can pay huge dividends to society and the economy as a whole (SANBI, 2013).

South Africa and the Eswatini became signatories to the Ramsar Convention in 1975 and 2013 respectively, resulting in certain obligations that the countries need to fulfil. The Ramsar Convention is an international treaty on the wise management and conservation of wetland ecosystems (Mitsch & Gosselink, 2015). One of the obligations of the convention is to compile a national wetland inventory to help prevent further wetland loss, as well as to help conserve existing wetlands. Kgaswane Mountain Reserve is recognized as an official Ramsar site (site no. 2385) of the Ramsar Convention, one of 26 such sites in South Africa (Ramsar, 2019). Therefore, the understanding of wetland processes in the reserve is crucial. Eswatini has at present three Ramsar sites, of which Hawane Dam and Nature Reserve Ramsar site (site no

2121) is located closest to Malolotja (15 km) but in a different catchment. The Malolotja Wetland, located within the Malolotja Nature Reserve, is at present not a listed Ramsar site.

## 1.3 AIMS OF THE PROJECT

The Terms of Reference for WRC project no. K5/2831 are as follows:

1) To discuss future rainfall predictions related to climate change for the two different countries, and to make recommendations for sustainable development solutions based on the different wetland scenarios of the headwater catchments.
2) To develop the first wetland probability map for Eswatini, and to determine the extent and distribution of Eswatini's wetlands (National scale).
3) To explain wetland geomorphic processes (geomorphology, hydrology, vegetation) at work in the Malolotja Nature Reserve, Eswatini (Catchment scale).
4) To map the different hydrogeomorphic wetland types in the Kgaswane Mountain Reserve, South Africa (Catchment scale).
5) To determine the relationships between the distribution of wetland types, the underlying geology and the related processes including hydrology, geomorphology and vegetation in Kgaswane Mountain Reserve, South Africa and to illustrate these using conceptual hydrological/geomorphic response diagrams (Catchment scale).
6) To hold a cross-cultural workshop for the role-players and interested and affected parties of the wetland systems of the two countries.

## 1.4 RESEARCH APPROACH, LIMITATIONS AND DELIVERABLES

The research approach focussed on three scales: national (Kingdom of Eswatini), regional and catchment scale. Field evaluation measures using groundwater monitoring and soil surveys along transects were restricted within the context of the limited budget. Furthermore, the use of the Soil and Water Assessment Tool called the SWAT model (Arnold *et al*., 1998) could not be applied due to limited information. A conceptual model was developed to support the limited field-based hydrological data. It was decided to focus on a mountain headwater catchment in the Malolotja Nature Reserve, located near Mbabane, so that in terms of topographic location the site could be compared to the Kgaswane site in South Africa. To use the entire Umbuluzi River as a transect cutting across Eswatini from west to east was considered, but proved not to be feasible. The project considered making recommendations on the WET-Health assessment system (Macfarlane *et al*., 2007), (especially the geomorphology component), but could not test the WET-Health assessment system currently being upgraded. The project Reference Group accepted these deviations from the original proposal at the inaugural meeting on 21 June 2018.

The main objectives of the project were achieved by submitting work on sections as individual deliverables shown in Appendix 1.

## 1.5 STUDY AREAS

The research focussed initially on the national scale in Eswatini, and subsequently on the catchment scale of two catchments situated in the Kgaswane Mountain Reserve (North West Province, South Africa) and the Malolotja Nature Reserve (located near Mbabane, Eswatini) (Figure 1.1). Reasons for selecting the catchments of Kgaswane Mountain Reserve and Malolotja Nature Reserve are that the peatlands are located on a similar line of latitude (near 26° S) and altitude (1300-1500 m a.m.s.l.) (Figure 1.1), as well as that the Malolotja Peatland is the only known peatland in the Kingdom of Eswatini. Kgaswane and Malolotja Peatlands both have isoerodents in the range of 250-300 units (Figure 1.2). Both these systems are also located in the headwaters, therefore no other water sources influence them which makes them ideal to study.

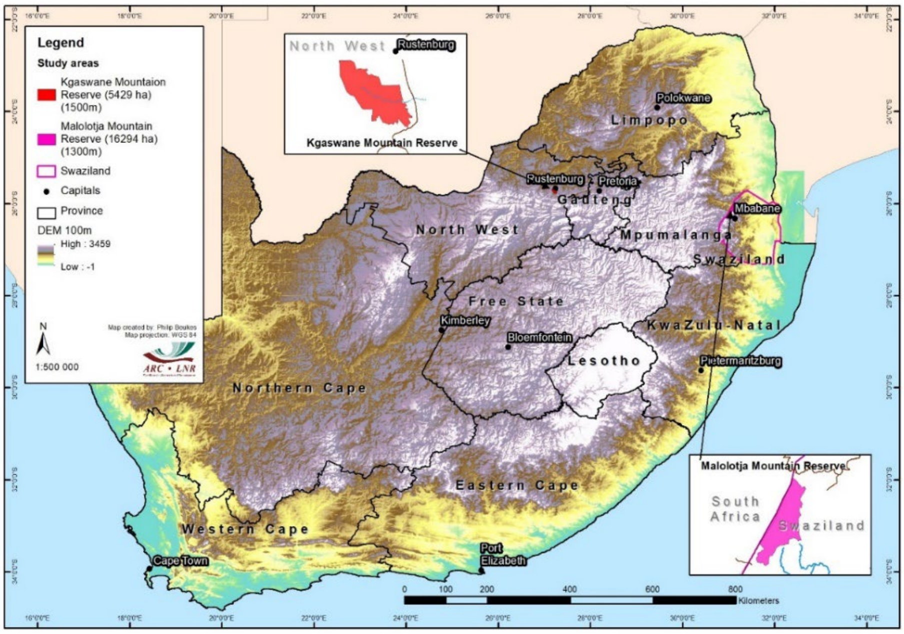



**Figure 1.1** Location of the two research catchments that served as study areas, situated in Kgaswane Mountain Reserve, South Africa and in Malolotja Nature Reserve, Eswatini.

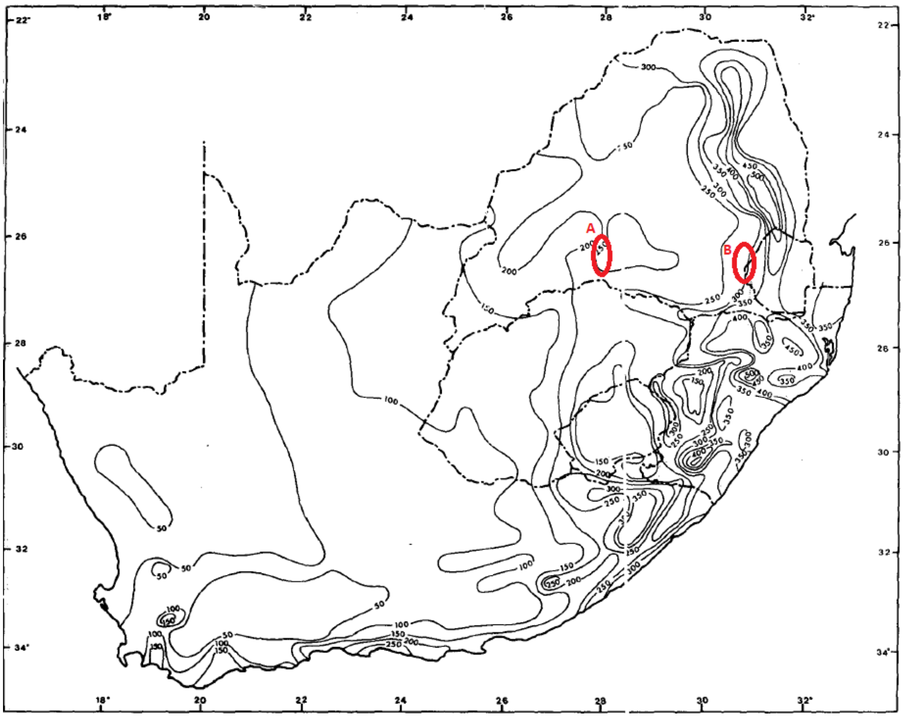



**Figure 1.2** A map of the isoerodents for southern Africa in units of $EI_{30}$ (after Smithen and Schulze, 1982). Note that Kgaswane (A) and Malolotja (B) both have isoerodents in the range of 250 to 300 units.

# 2. WETLAND RESILIENCE IN FUTURE CLIMATE SCENARIOS

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## 2.1 INTRODUCTION

The research focussed on catchment-scale processes within two catchments situated in the Kgaswane Mountain Reserve (North West Province, South Africa) and the Malolotja Nature Reserve (located near Mbabane, Eswatini). The aim of this chapter is to discuss future rainfall predictions related to climate change for the two different countries and make recommendations for sustainable development solutions based on the different wetland scenarios of headwater catchments.

## 2.2 WEATHER SYSTEMS

Kgaswane Mountain Reserve and Malolotja Nature Reserve are both located in the summer rainfall region of southern Africa. However, the former has a much drier climate than the latter, with the mean annual rainfall being approximately 600 mm and 950 mm respectively. For both locations, the rainfall season commences in September as moist air starts to be advected in over the eastern parts of the African sub-continent by ridging high pressure systems. Over the Malolotja Nature Reserve area, the ridging high pressure systems can cause overcast and cool conditions with rain as the clouds build up against the Eswatini Highveld-escarpment, whereas further to the west precipitation will rather be of a convective nature as the overcast conditions caused by ridging high pressure systems are normally confined to the east of the escarpment. It is, however, important to note that the Malolotja Nature Reserve does not experience the full effect of orographic precipitation due to the Lebombo mountain range on the far eastern border of Eswatini. On a typical summer day, thunderstorms develop east of the surface trough of low pressure. The position of this trough can vary, but is usually situated over the central interior, with a meridional alignment.

In the case of relatively weak synoptic flow apart from the surface trough, thunderstorms tend to develop over areas of elevated topography, so the Malolotja Nature Reserve is situated in a region with a higher frequency of thunderstorm activity compared to the Kgaswane Mountain Reserve. Another rain producing weather system of the summer months is the tropical-temperate trough (TTT). This is a synoptic-scale weather system characterized by a north-west to south-east aligned cloud band that moves from west to east over the country. TTTs influence both the Kgaswane Mountain Reserve and the Malolotja Nature Reserve. However, their position seems to have an association with the El Niño Southern Oscillation and will therefore not necessarily influence Kgaswane Mountain Reserve and Malolotja Nature Reserve the same way during any give rainfall season. From mid- to late summer, the atmospheric circulation over southern Africa is of a tropical nature (Rautenbach & Smith, 2001). During this time, it sometimes happens that tropical lows move in over South Africa. This can happen from north of the country, known as continental tropical lows, to influence Kgaswane Mountain Reserve, or from the Indian Ocean, to influence the Malolotja Nature Reserve (e.g. Malherbe *et al*., 2012; Malherbe *et al*., 2013). Very rarely, tropical cyclones can cause severe flooding over the north-eastern parts of southern Africa, including Eswatini, as has happened in the year 2000 (Dyson & Van Heerden, 2001) and again during 2021.

## 2.3 WETLAND SYSTEMS AND VULNERABILITY

Wetlands are most vulnerable when changes in catchment land use and infrastructure development (e.g. building of dams) influence the water availability to the wetlands. For example, over-abstraction of groundwater through the use of boreholes or alien invasive species in and around the wetland can cause peatlands to dry out and burn. Wetlands can be in a stable state but with different scenarios of land use in the catchments, dry conditions and higher sediment load (higher runoff) it can have negative impact on wetlands, leaving them vulnerable to erosion and desiccation (Gardner *et al*., 2015). The wise use (i.e. sustainable use) and rehabilitation of wetlands builds wetland resilience and should form part of the future to combat climate change.

The peatlands at Kgaswane Mountain Reserve and Malolotja Nature Reserve are categorized as a central highland peatland which performs vital functions, providing clean water to communities downstream. Peatlands are known to perform functions that manage the groundwater and surface water balance by storing precipitation and floodwater, releasing it at a steady state over time. The peatlands are therefore important for storing water.

These peatland systems, located in the headwaters, do not receive water from other areas. The groundwater generated within their catchments is local (i.e. regional groundwater with no other influence). Seepage areas feeding the main peatland are all groundwater fed. The cumulative difference between the evapotranspiration and precipitation is that the precipitation is the smaller of the two, resulting in a water deficit. The peatland systems are long linear features, limiting the evapotranspiration compared to larger wetland areas. However, wetland plants are dormant during the winter months (i.e. inactivity and reduced metabolic rate) but they grow in the summer months with surplus water. It is therefore important to calculate water balance for each of these systems to understand their vulnerability to environmental and climate change.

The geology and geomorphology of the systems are known and described as a fractured aquifer with potential flow paths below the surface (i.e. organic soil and peat layers). The geomorphology and hydrology of these systems are described in Chapter 3 and Chapter 5.

## 2.4 DETAILED PROJECTIONS OF FUTURE CLIMATE CHANGE OVER SOUTHERN AFRICA

### 2.4.1 Background

The Intergovernmental Panel on Climate Change (IPCC) has in three consecutive assessment reports [Assessment Report Four (AR4; Christensen *et al*., 2007), Assessment Report Five (AR5; Niang *et al*., 2014) and the Special Report on Global Warming of 1.5°C (SR1.5; Hoegh-Guldberg *et al*., 2018)], concluded that the southern African region is likely to become generally drier under low mitigation climate change futures. Moreover, the region is projected to become drastically warmer under low mitigation (Engelbrecht *et al*., 2015; Hoegh-Guldberg *et al*., 2018). In this present report, we make use of a recently obtained ensemble of high resolution projections of future climate change over southern Africa to demonstrate these concepts and to emphasize the need for the formulation and implementation of climate change adaptation strategies in South and southern Africa. Before the results of the future climate change projections are presented here, the status of the observed warming over the two study sites can be summarized as follows:

| | |
|---|---|
| *Temperature increase:* | Compared to the pre-industrial period, the average near-surface temperature has increased by some 1.2°C and 1°C at the Kgaswane Mountain Reserve and the Malolotja Nature Reserve respectively, over the 1961-2010 period. |
| *Rainfall:* | At the Kgaswane Mountain Reserve area, no statistical significant change has been detected in rainfall totals, although an increase in the occurrence of rainfall intensity has been observed. At the Malolotja Nature Reserve, no statistically significant changes in rainfall attributes have been observed so far, although this may be a function of data availability rather than the actual trend. |
| *Evapotranspiration:* | With the increase in near-surface temperatures, evapotranspiration would be expected to increase accordingly, thus potentially decreasing water availability in the wetland systems. |

### 2.4.2 Experimental design of the regional climate model simulations

An ensemble of very high resolution climate model simulations of present-day climate and projections of future climate change over southern Africa has been performed in 2017 and 2018 at the Council for Scientific and Industrial Research (CSIR) in South Africa. The regional climate model used is the Conformal-Cubic Atmospheric Model (CCAM), a variable resolution Global Climate Model (GCM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor, 2005; McGregor & Dix, 2001, 2008). CCAM runs coupled to a dynamic land-surface model, the CSIRO Atmosphere Biosphere Land Exchange (CABLE) model. Six GCM simulations of the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the IPCC [obtained for the emission scenario described by the Representative Concentration Pathway 8.5 (RCP8.5)] were first downscaled to a 50 km resolution globally. The simulations span the period 1960-2100. RCP8.5 is a low mitigation scenario. The downscaled GCMs include the Australian Community Climate and Earth System Simulator (ACCESS1-0); the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3); the National Centre for Meteorological Research Coupled Global Climate Model, version 5 (CNRM-CM5); the Max Planck Institute Coupled Earth System Model (MPI-ESM-LR); the Norwegian Earth System Model (NorESM1-M) and the Community Climate System Model (CCSM4).

In these simulations, CCAM was forced with the bias-corrected daily sea-surface temperatures (SSTs) and sea-ice concentrations of each host model, and with carbon dioxide ($CO_2$), sulphate and ozone forcing consistent with the RCP8.5 scenarios. The model's ability to realistically simulate present-day southern African climate has been extensively demonstrated (e.g. Engelbrecht *et al*., 2009; Engelbrecht *et al*., 2011; Engelbrecht *et al*., 2013; Malherbe *et al*., 2013; Winsemius *et al*., 2014; Engelbrecht *et al*., 2015). Most current coupled GCMs do not employ flux corrections between atmosphere and ocean, which contributes to the existence of biases in their simulations of present-day SSTs (potentially of more than 2ºC along the West African coast). An important feature of the downscalings performed here is that the model was forced with the bias-corrected SSTs and sea-ice fields of the GCMs. The bias is computed by subtracting the Reynolds (1988) SST climatology (for 1961-2000) for each month from the corresponding CGCM climatology. The bias-correction is applied consistently throughout the simulation. Through this procedure, the climatology of the SSTs applied as lower boundary forcing is the same as that of the Reynolds SSTs. However, the intra-annual variability and climate-change signal of the CGCM SSTs are preserved (Katzfey *et al.*, 2009).

A multiple-nudging strategy was followed to obtain the 8 km resolution downscalings. After completion of the 50 km resolution simulations described above, CCAM was integrated in stretched-grid mode over southern Africa, at a resolution of about 8 km (0.08° degrees in latitude and longitude). The high resolution part of the model domain was about 2000 x 2000 $km^2$ in size and centred at 28° E, 25° S. The higher resolution simulations were nudged within the quasi-uniform global simulations, through the application of a digital filter using a 600 km length scale. The filter was applied at 6-hourly intervals and from 900 hPa upwards. The simulations were performed on supercomputers of the Centre for High Performance Computing (CHPC) of the Meraka Institute at the CSIR in South Africa. The 8 km resolution simulations were subsequently bias-corrected to observed data from the Climatic Research Unit (CRU), following the methodology of Engelbrecht *et al.* (2015).

### 2.4.3 Results of future climate change projections for the two catchments

Results are shown for four different climate metrics, listed in Table 2.1. The projected changes are expressed for the period 2070-2099 relative to the 1961-1990 period.

**Table 2.1** Definition of relevant climate variables and their units

| Variable | Description and/or units |
|---|---|
| Average temperature | °C |
| Very hot days | A day when the maximum temperature exceeds 35°C. Units are number of events per grid point per year. |
| Rainfall | mm |
| Extreme rainfall | More than 20 mm of rain falling within 24 hours over an area of 64 $km^2$. Units are number of events per grid point per year. |

The model-projected changes in mean annual average temperature (°C) over southern Africa for the period 2070-2099 (far-future) relative to the period 1961-1990 (present-day; baseline) are shown in Figure 2.1. The following is evident from the figure, in conjunction with the AR5 assessment of Niang *et al.* (2014), Engelbrecht *et al.* (2015) and the SR1.5 assessment of Hoegh-Guldberg *et al.* (2018):

- Rapid rises in the annual-average near-surface temperatures are projected to occur over the interior of southern Africa during the late 21st century. Temperatures over this region are projected to rise at about twice the global rate of temperature increase (Engelbrecht *et al.*, 2015).
- For the period 2070-2099 relative to the period 1961-1990 under low mitigation, temperature increases of more than 4°C are projected to occur over large portions of the southern African interior relative to the baseline period, with increases reaching values as high as 6°C over the western interior and northwards into Botswana (Figure 2.1). Smaller temperature increases, in the order of 3°C, are projected for the coastal areas (Figure 2.1).
- Such drastic temperature increases would have significant impacts on numerous sectors, including agriculture, water and energy. It may firstly be noted that increasing temperatures would contribute to enhanced evaporation of soil moisture (Engelbrecht *et al.*, 2015) and also from surface water resources. The consequence for many wetlands would be a severe

decrease in size, if not their total disappearance. Associated increases in temperature extremes (see below) are likely to impact directly on human health, crop yield, livestock, the household demand for energy and increase the fire risk.

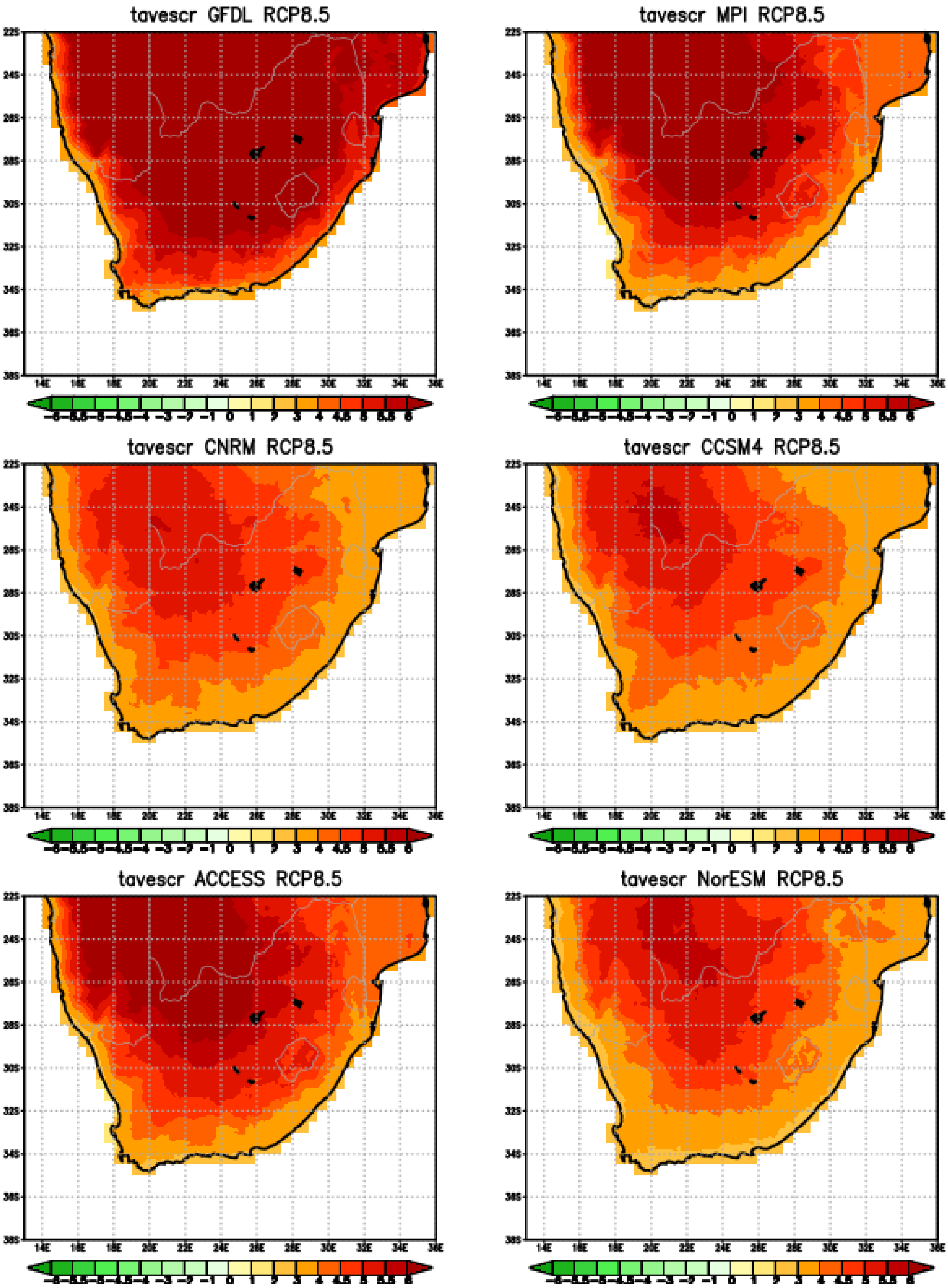


**Figure 2.1** CCAM projected change in annual average temperature (°C) over southern Africa for the time-slab 2070-2099 relative to 1961-1990. The projections are shown for an ensemble of downscalings of six CMIP5 GCM projections under RCP8.5.

#### *2.4.3.1 Incidence of very hot days*

The model-projected changes in the annual average number of very hot days (days when the maximum temperature exceeds 35°C, units are number of days per model grid point) for the period 2070-2099 (far-future), relative to the period 1961-1990 (present-day baseline), are shown in Figure 2.2. The following is evident from the figure, in conjunction with the AR5 assessment of Niang *et al*. (2014), Engelbrecht *et al*. (2015), Garland *et al*. (2015) and the SR1.5 assessment of Hoegh-Guldberg *et al*. (2018):

- In association with drastically rising maximum temperatures (Figure 2.2), the frequency of occurrence of very hot days is also projected to increase drastically under the projected climate change scenarios.
- For the period 2070-2099 relative to 1961-1990, under low mitigation, very hot days are projected to increase by about 60 days or more per year for large parts of the western interior of South Africa, Botswana and in the Limpopo River basin (Figure 2.2). Relatively smaller increases in the occurrence of very hot days are projected over the eastern interior, including Eswatini, and along coastal areas (Figure 2.2).
- Increases in the occurrence of very hot days occur in association with projected increases in the frequency of occurrence of heatwave days and high fire danger days (Engelbrecht *et al*., 2015). These changes may impact on human and animal health through increased heat stress (Garland *et al*., 2015), are likely to impact negatively on crop yield (Landman *et al*., 2017) and are conducive to the occurrence of veld and forest fires (Engelbrecht *et al*., 2015).

#### *2.4.3.2 Projected changes in rainfall for southern Africa*

The model-projected changes in annual average rainfall (mm) over southern Africa for the period 2070-2099 relative to the period 1961-1990 (present-day baseline) are shown in Figure 2.3. The following is evident from the figure, in conjunction with the AR5 assessment of Niang *et al*. (2014), Christensen *et al*. (2007), Engelbrecht *et al*. (2009), Engelbrecht *et al*. (2015) and the SR1.5 assessment of Hoegh-Guldberg *et al*. (2018):

- A general decrease in rainfall over southern Africa is likely to occur under low mitigation climate change futures (e.g. Christensen *et al*., 2007; Engelbrecht *et al*., 2009; Niang *et al*., 2014; Engelbrecht *et al*., 2015).
- For the period 2070-2099 relative to the period 1961-1990, under low mitigation, general reductions in rainfall are projected for the southern African region (Figure 2.3). Uncertainty exists in terms of the rainfall futures of Lesotho and the eastern escarpment region of South Africa, where some climate models are indicative of rainfall increases rather than decreases (Figure 2.3; Niang *et al*., 2014). Some climate models extend this region of rainfall increases into the eastern Free State. There are also some climate models that project rainfall increases over southern Mozambique, plausibly because of an increase in the number of land-falling tropical lows and cyclones. This would then affect Eswatini. It is, of course, important to remember that such rainfall is likely to be related to high intensity events and would thus be highly erosive. Wetlands would be of critical importance under these conditions to mitigate runoff and replenish natural sponge areas, provided the wetland systems are still sufficiently functional to achieve this.

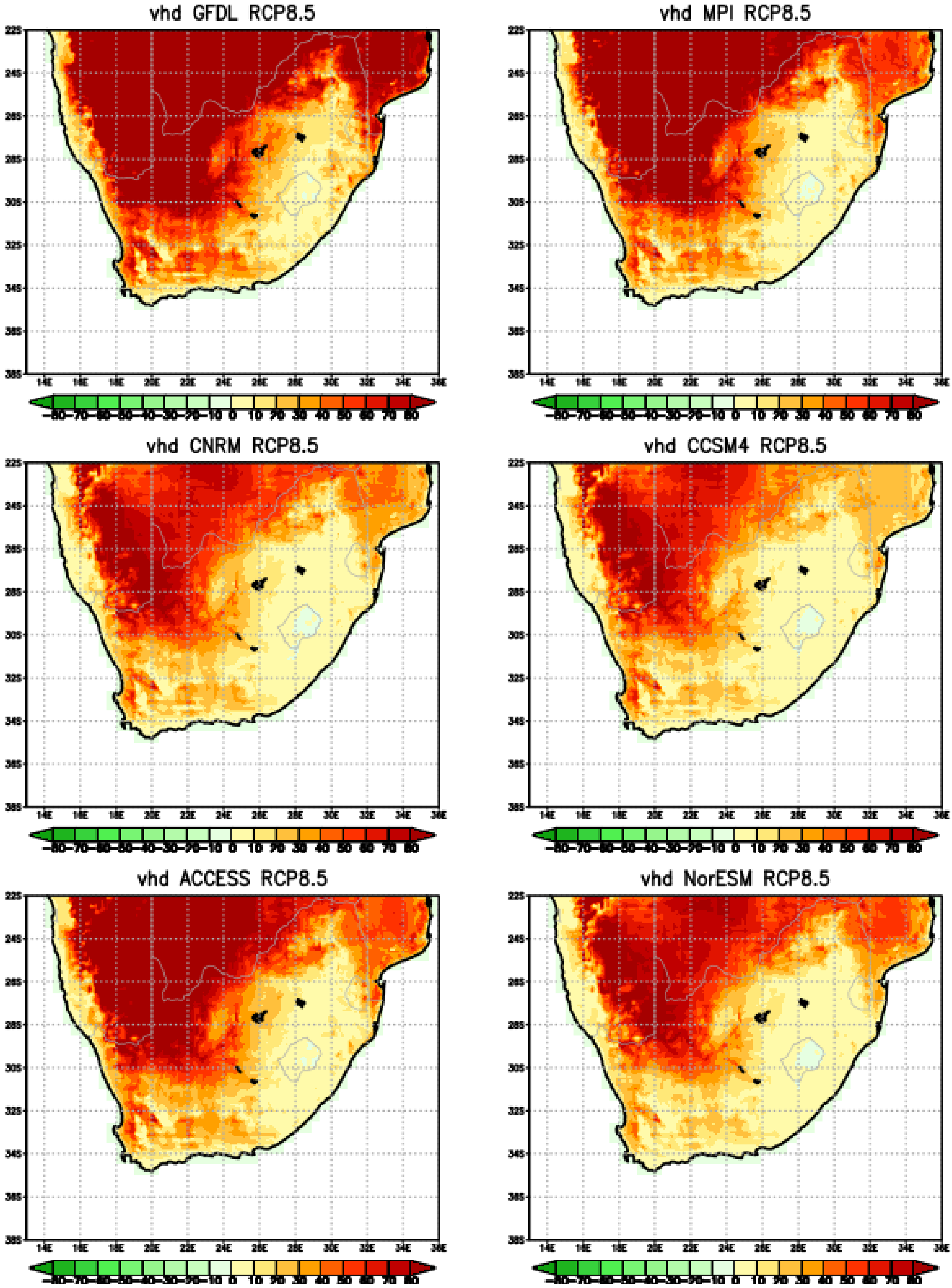


**Figure 2.2** CCAM projected change in the annual average number of very hot days (units are number of days per grid point per year) over southern Africa for the time-slab 2070-2099 relative to 1961-1990. The projections are shown for an ensemble of downscalings of six CMIP5 GCM projections under RCP8.5.

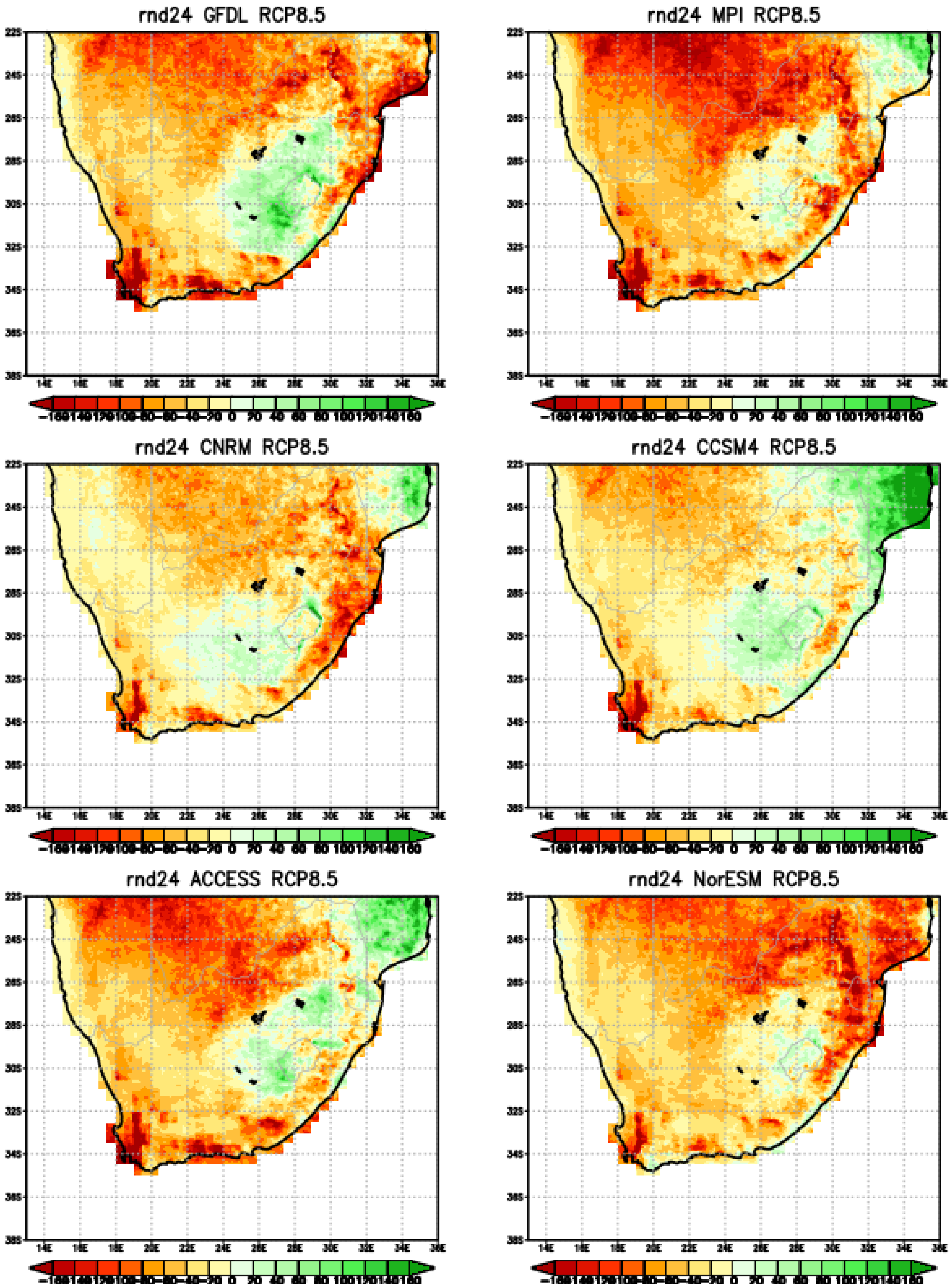


**Figure 2.3** CCAM projected change in annual average rainfall (mm) over southern Africa for the time-slab 2070-2099 relative to 1961-1990. The projections are shown for an ensemble of downscalings of six CMIP5 GCM projections under RCP8.5.

### *2.4.3.3 Occurrence of extreme rainfall events*

The model-projected changes in extreme rainfall events over southern Africa for the period 2070-2099 relative to the period 1961-1990 are shown in Figure 2.4 (frequencies units are number of events per model grid box per year). Here an extreme rainfall event is defined as 20 mm of rain occurring within 24 hours over an area of 64 $km^2$. The following observations are evident from Figure 2.4, in conjunction with the AR5 assessment of Niang *et al*. (2014), Engelbrecht *et al*. (2009), Engelbrecht *et al*. (2013) and the SR1.5 assessment of Hoegh-Guldberg *et al*. (2018):

- Extreme rainfall events are projected to decrease in frequency over the winter and all-year rainfall regions of South Africa and also over the northern parts of southern Africa during the far-future period of 2070-2099, relative to the present-day period (Figure 2.4). However, despite the general reductions projected in terms of rainfall totals (Figure 2.3), extreme rainfall events are projected to *increase* in general over eastern southern Africa (including Eswatini), with these increases extending into the western interior of South Africa (Figure 2.4). The largest increases in extreme rainfall events are projected over Lesotho and the eastern escarpment regions of southern Africa (Figure 2.4).
- Extreme rainfall events over the eastern parts of southern Africa are mostly caused by intense thunderstorms, which are often also associated with lightning, hail, damaging winds and flash floods. Therefore, adaptation policies will need to take into account the possibility that extreme rainfall events may well increase in their frequency of occurrence, despite the likelihood of decreases in net annual rainfall totals.

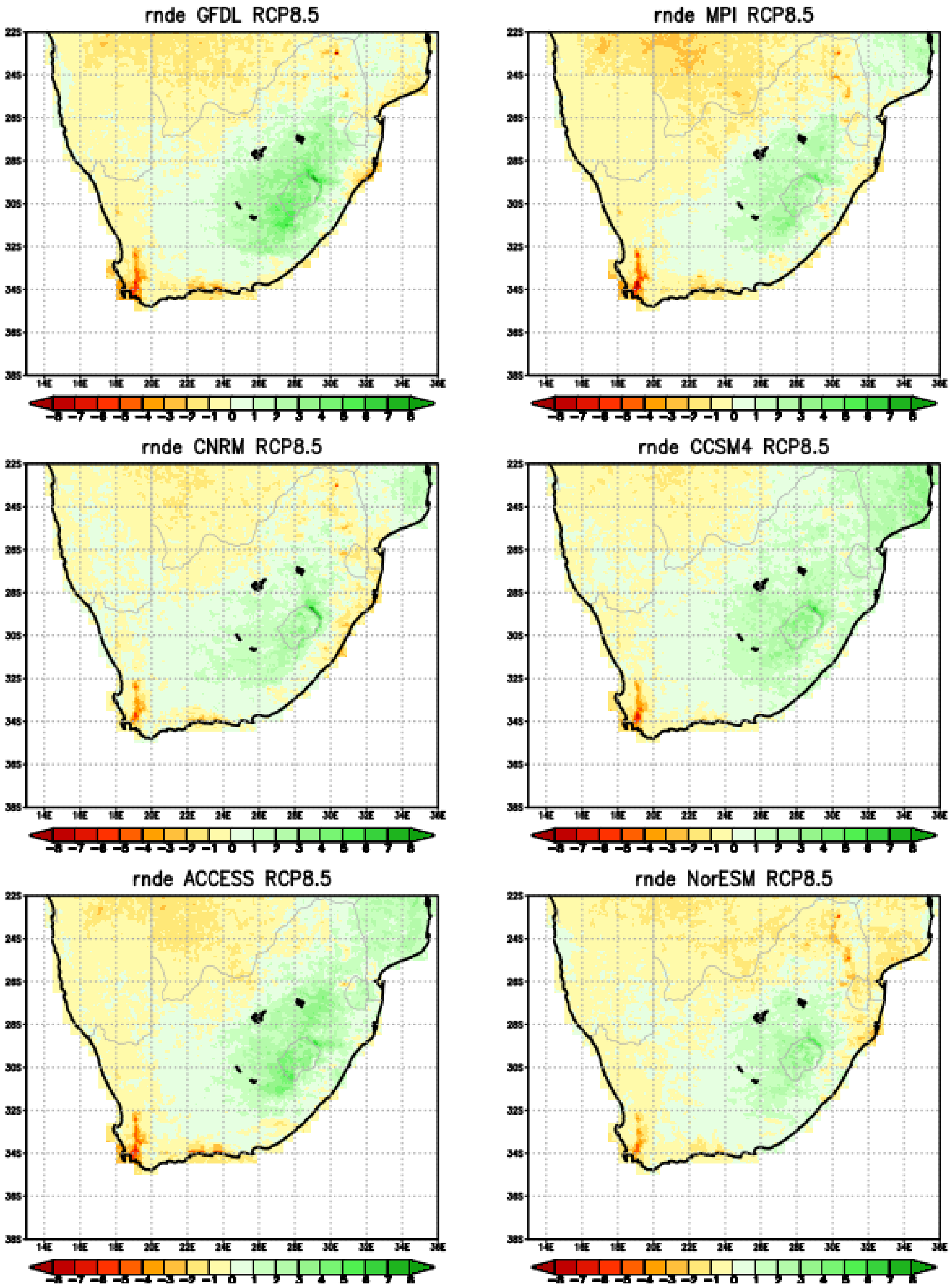


**Figure 2.4** CCAM projected change in the annual number of extreme rainfall events (units are number of days per grid point per year) over southern Africa for the time-slab 2070-2099 relative to 1961-1990. The projections are shown for an ensemble of downscalings of six CMIP5 GCM projections under RCP8.5.

## 2.5 LONG-TERM RAINFALL DATA TRENDS

Weather station data (weather station nos. 30627 and 30105) was acquired from the ARC-ISCW (2018) for the Kgaswane catchment (North West Province, South Africa) and is shown in Figure 2.5A. Six weather stations are scattered across the entire Umbaluzi River catchment, Eswatini, with good representation (Figure 2.5B) (Climate Information Platform, 2018; Eswatini Meteorological Service, 2018). They are: Mbabane, Matsapha, Mpisi, Siteki, Mananga and Mhlume.

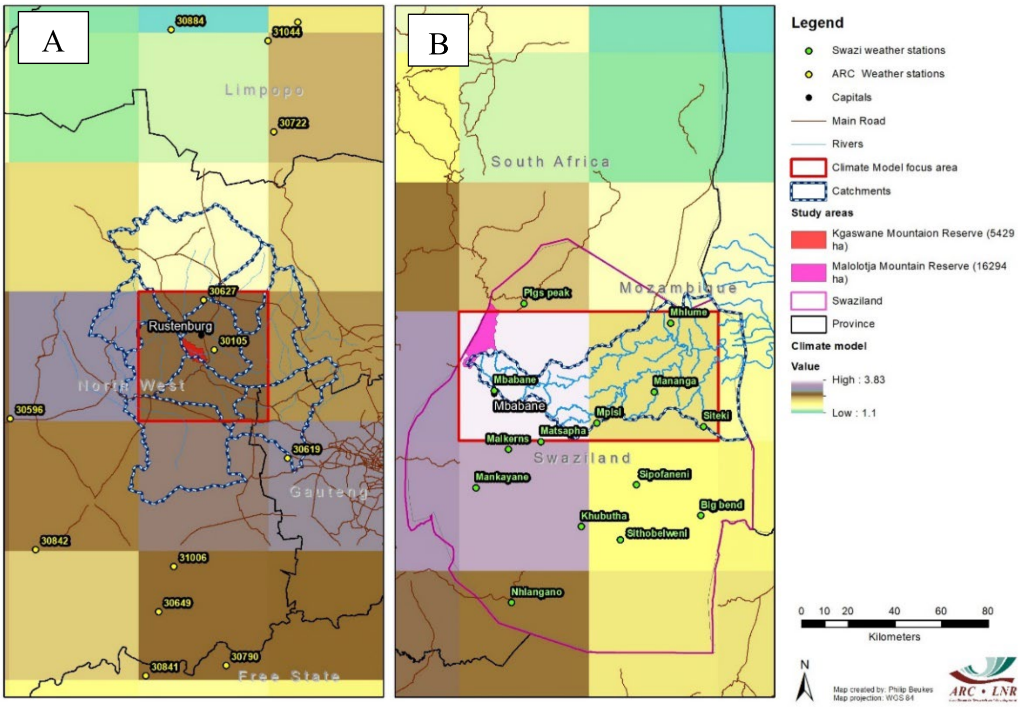


**Figure 2.5** Climate model grid cells (red boundary) that indicate the area of interest for Kgaswane Mountain Reserve, South Africa (A), and the Malolotja Nature Reserve and Umbaluzi River Catchment, Eswatini (B).

## 2.6 DISCUSSION OF THE FINDINGS AND STATEMENT OF CONCLUSIONS

This report is based on an ensemble of high resolution projections of future climate change over Africa and southern Africa in particular, obtained by using the regional climate model CCAM to downscale the output of a number of CMIP5 (AR5) GCMs. The report is also informed by the IPCC Assessment Reports of recent years, namely AR4 (Christensen *et al*., 2007), AR5 (Niang *et al*., 2014) and SR1.5 (Hoegh-Guldberg *et al*., 2018). This body of evidence suggests that the southern African region is likely to become drier and drastically warmer during the 21$^{st}$ century under low global net mitigation. Extreme rainfall events are projected to occur more frequently over the eastern parts of southern Africa, with this pattern extending into the western interior of South Africa, implying that Eswatini may be more severely impacted than South Africa. A generally drier and warmer regional climate system limits the options for adaptation, and requires the timeous and careful formulation of adaptation strategies across the sectors of agriculture, water and energy.

Alluvial fans in the main system at the Kgaswane Mountain Reserve act like a “plug” that influences the groundwater levels in the main system and immediate surrounding areas. The “plug” is under pressure (e.g. the peat found in the lower part subsided), which means there is now less water and carbon storage capacity. In addition, the flow changes from dispersed flow to saturated overland flow, which also affects the peatland condition and functioning. The animals tend to congregate in the subsided area for grazing and pose a threat in terms of trampling and causing erosion if not properly managed. Rehabilitation structures in the Kgaswane Mountain Reserve contributed to sediment saturation, and over the long term, consistent water release downstream, putting resilience back in the system. The seeps, on the other hand, are more vulnerable to overgrazing, trampling and structure change (limit their water-holding capacity) and need special attention to conserve them for their biodiversity contribution.

The peatland at the Malolotja Nature Reserve has a similar setting to that at the Kgaswane Mountain Reserve but it seems that this system has a larger dependability on water received from stream flows. The surrounding landscape shows scars of previous mining activities coupled with dewatering, causing the peat to subside and channels to erode. However, its vulnerability under climate change predictions is unclear at this stage but it seems to be more vulnerable than the peatland at the Kgaswane Mountain Reserve. Prolonged dry periods can cause the peat to dry out in the valley bottom next to the gully. Of concern is the increase in frequency of intense storms with high runoff and higher flow volumes, which will also limit the water storage capacity of the peatland system.

# 3. PREDICTION OF WETLAND OCCURRENCE IN ESWATINI (NATIONAL SCALE)

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## 3.1 INTRODUCTION

In southern Africa, the degradation of wetlands is often a result of authorities and landowners not having the resources and information needed to mitigate against anthropogenic impacts in vulnerable wetlands (Mwendera, 2003; Masarirambi *et al*., 2010; Marambanyika & Beckedahl, 2017). This is especially the case for land use changes such as agriculture and urban expansion which result in wetlands being drained (Madebwe & Madebwe, 2005; Jackson *et al*., 2016). In order to combat wetland degradation, many governments have established specific laws and policies that aim to protect and govern their use. An overarching accord that steers many of these policies relating to wetlands is the Ramsar Convention. The Kingdom of Eswatini completed the accession to the Ramsar Convention on 15 June 2013 and currently has three wetland sites designated as Wetlands of International Importance (Ramsar sites). Despite the country having numerous natural wetland systems (Hughes & Hughes, 1992), their Ramsar sites are all lacustrine systems (dams) with a combined surface area of 1183 hectares and include:

1. Van Eck Dam, Ramsar site number 2123.19 ha.
2. Hawane Dam and Nature Reserve, Ramsar site number 2121.23 ha.
3. Sand River Dam, Ramsar site number 2122.76 ha.

Eswatini's wetlands have historically been heavily over-utilized and under-managed (Mwendera, 2002; Masarirambi *et al*., 2010). There is also a dearth of knowledge relating to the wetlands of Eswatini, with scattered pieces of literature in various international reports and reviews, as well as smaller contributions from academic institutions and local government organizations.

Apart from Eswatini's obligations to the Ramsar Convention, having the necessary foundations in place, such as the location of wetlands across the country, to manage their wetlands will also benefit many inhabitants across the country. Given the generally low income levels of Eswatini, many people depend directly on wetlands for their livelihood. Wetlands serve as an important water supply for many people and provide grazing resources that can be used for dry season cropping (Mwendera, 2002). Many women in Eswatini use wetlands as an economic resource and earn a living off using plants found in wetlands to make various crafts which include sleeping mats, bags, baskets, handcrafts as well as medication (Dlamini, 1981; Mwendera, 2003; Zwane *et al*., 2011). Important cultural ceremonies, including the maiden reed dance, also make use of wetland vegetation, most commonly *Phragmites australis* (Mwendera, 2003).

It is important to note that a white paper on the national wetland policy has been in its final draft stage for some time, and finally became available in December 2020 (ENTC, 2020a). Even though only a few wetland studies have been conducted in Eswatini, the country's consensus has remained clear in that there is an urgent need to compile an accurate scientific baseline of information, to develop a wetlands policy and regulation, and to protect wetlands so as to preserve all their critical ecosystem services (Ramsar Convention, 2015; ENTC, 2018).

Along with many other recommendations, the Ramsar Convention's handbooks emphasize that national inventories are an essential basis for the formulation of national wetland policy, the identification of sites as Wetlands of International Importance, quantification of the global wetland resource, documentation of sites suitable for restoration, as well as risk and vulnerability assessments (Ramsar Convention Secretariat, 2010a,b,c). In addition to determining the extent and distribution of wetlands, a classification system that distinguishes between different types of wetlands is fundamental to the compilation of a national inventory (Ewart-Smith *et al*., 2006). Sieben *et al*. (2018) explain that one of the most important aims of allocating wetlands to a certain type or class is to provide information about the ecosystem services that the wetland provides. Varying forms of evaluation, management and conservation are then also needed for subdivision into different wetland types (Dini & Cowan, 2001).

There have been incomplete attempts to map the country's wetlands (Masarirambi *et al*., 2010; Franke *et al*., 2013) and as a result, the country does not have a complete wetland map nor inventory (for a full description of previous wetland mapping in Eswatini readers are referred to Le Roux, 2020). Eswatini also does not have or use a uniform classification system, apart from the three Ramsar sites that are classified according to the Ramsar classification system, which is intended to be used for sites of international importance and not as a national classification system (Kabii, 1998). This therefore calls for Eswatini to develop their own wetland classification system, or to adopt one that is suited to the wetlands found in that country. Given that Eswatini is mostly bordered by South Africa, there is a high likelihood that the wetland mapping techniques developed in South Africa would be applicable to Eswatini.

With most peatland studies being conducted in the northern hemisphere and tropical regions of the world, processes that give rise to peatlands in other parts of the world are poorly understood (Joosten & Clarke, 2002; Grundling & Grobler, 2005). Extensive studies are therefore required so as to ensure the effective management of peatlands in other hydrological environments in southern Africa (Grundling *et al*., 2015). This is due to hydrology likely being the single most important factor determining the nature of wetland and peatland ecology, its development, functions and processes (Rydin & Jeglum, 2013).

This chapter focusses on wetlands in Eswatini and includes two sections after discussing the general environmental and physiographic setting of the region. The first section focusses on identifying wetlands across Eswatini together with their likely occurrence, whilst the second is the first study of its kind in the Kingdom and aims to understand the hydrology of a peatland located in the Malolotja Nature Reserve.

### 3.1.1 The environmental setting of Eswatini

The Kingdom of Eswatini hosts a wide range of physiographic landscapes (Remmelzwaal, 1993; Dlamini, 2017). The country is bordered by South Africa in the north, west and south, and by Mozambique in the east (Figure 3.1), and covers 17 364 km$^2$. Elevation ranges from over 1 800 m a.m.s.l. in the western plateaux to under 100 m a.m.s.l. in the east. It is separated from the Mozambique coastal plains by the Lebombo Mountain range that rises to 600 m a.m.s.l. (Remmelzwaal, 1993).

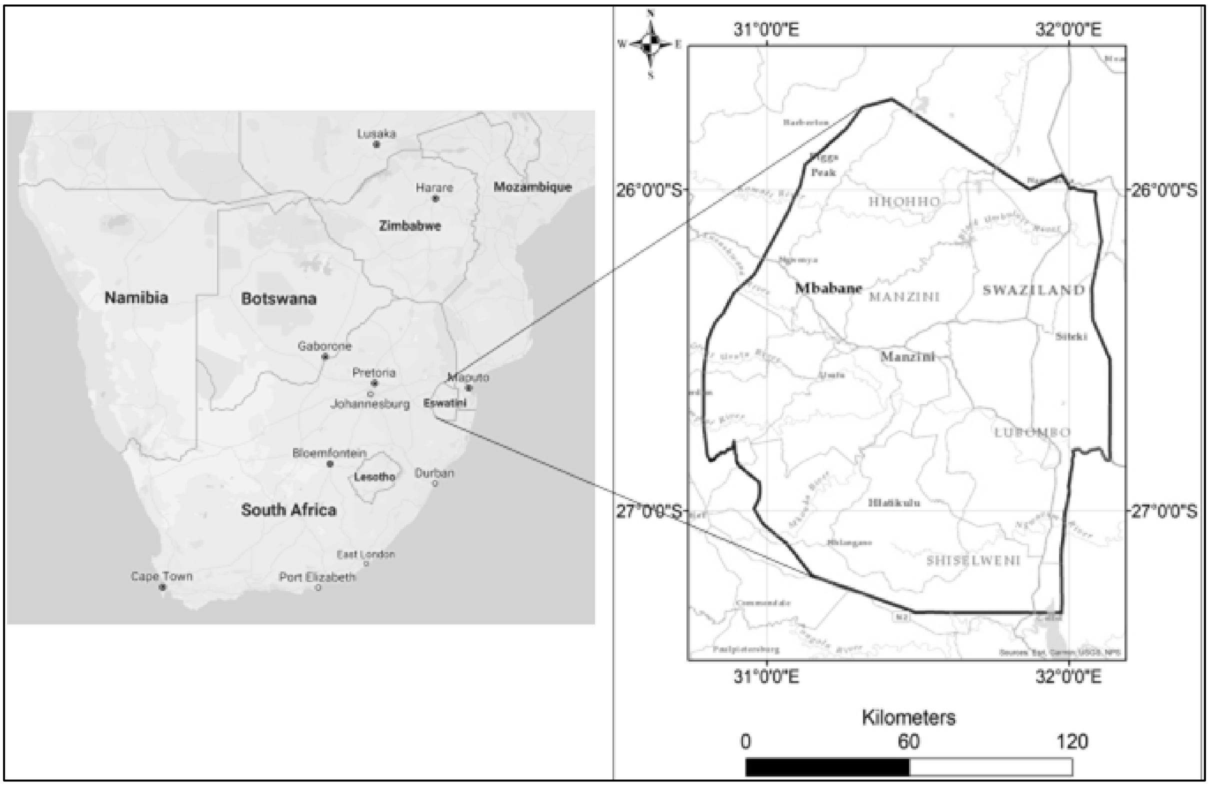


**Figure 3.1** Location map for Eswatini within southern Africa.

Eswatini has a sub-tropical climate, with warm wet summers and cool dry winters (Government of Eswatini, 2015). Most of the rains (75%) fall in the summer months (October-March) and about 25% fall in the winter months (April-September), with convectional and tropical storms bringing rainfall during summer and frontal showers during winter (Matondo *et al*., 2004). The western escarpment is characterized by wet summers and dry winters with an average annual rainfall of 1 500 mm and mean temperatures between 16ºC and 22 ºC. Central Eswatini and the Lebombo regions of Eswatini receive 800-1200 mm of rain annually with mean annual temperatures of 20ºC and 22ºC respectively. The low-lying eastern plains receive on average 450 mm of rain annually, with temperatures exceeding 30ºC in the summer (Matondo *et al*., 2005).

There are six physiographic zones across the country (Figure 3.2): Highveld, Upper Middleveld, Lower Middleveld, Western Lowveld, Eastern Lowveld and the Lebombo (Remmelzwaal, 1993). The geology of each physiographic region as well as other attributes are listed in Table 3.1, along with descriptions of the topography and their dominant landforms. Not surprisingly, the physiographic zones broadly mirror the underlying geology.

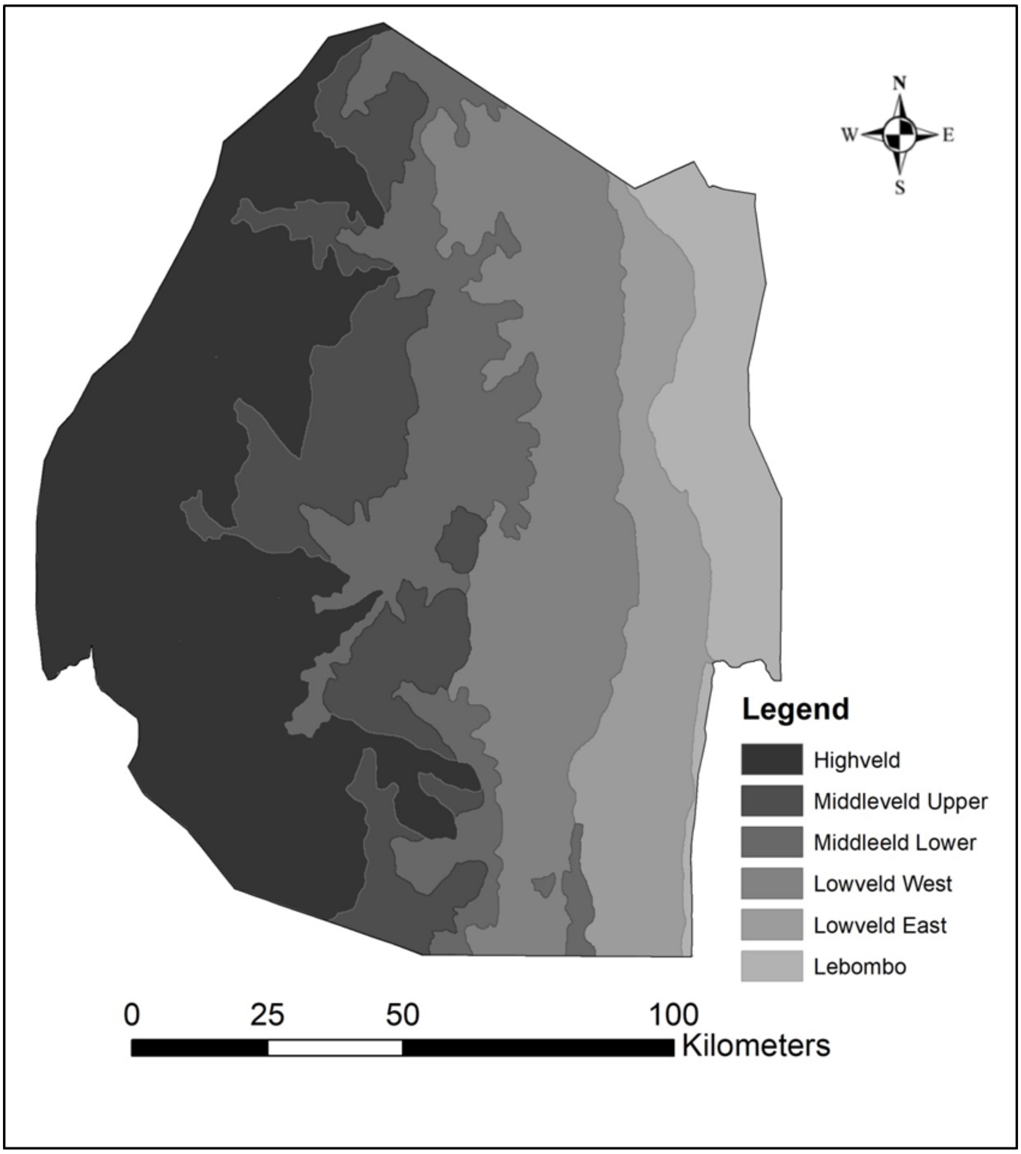


**Figure 3.2** Physiographic regions of Eswatini (adapted from Remmelzwaal, 1993).

**Table 3.1** Attributes of the physiographic zones of Eswatini (modified from Remmelzwaal, 1993)

| **Physio-graphic zone** | **Surface area** | **Altitude: Average** (m) **(min-max)** | **Landforms** | **Topography** | **Geology** |
|---|---|---|---|---|---|
| Highveld | 5680 $km^2$ (33%) | 900-1400 (600-1850) | Medium Hills with associated high hills and plateaux | Steeply dissected escarpment, transitions to undulating plateaux | Gneiss, Quartzite, lava |
| Upper Middleveld | 2420 $km^2$ (14%) | 600-800 (400-1000) | Medium Hills with associated low hills and basins | Hilly plateau remnants and undulating basins | Granodiorite, Granite, Gneiss, Shale |
| Lower Middleveld | 2420 $km^2$ (14%) | 400-600 (250-800) | Plains associated with low hills | Rolling piedmont, undulating basins and isolated hills | Gneiss, Granite, Granodiorite |
| Western Lowveld | 3410 $km^2$ (20%) | 250-400 (200-500) | Plain | Undulating part rolling | Sandstone, claystone with dolerite intrusions |
| Eastern Lowveld | 1960 $km^2$ (11%) | 200-300 (200-500) | Plain | Gently undulating part rolling | Basalt |
| Lebombo Range | 1480 $km^2$ (8%) | 250-600 (100-750) | Plateau dissected | Undulating cuesta, part hilly and steeply dissected. | Rhyolite, Ignimbrite |

Eswatini's geology (Figure 3.3) is dominated by Precambrian rocks of mostly Archean Age in the west, and sedimentary and volcanic rocks of Karoo age in the east (Wilson, 1982; Schlüter, 2008). The geology consists of the ancient Ngwane Gneisses, the Barberton Supergroup of the Paleoarchean era, the Pongola Supergroup of the Mesoarchean era, rocks of the Neoarchean age and the Karoo Supergroup of the Phanerozoic era (Wilson, 1982).

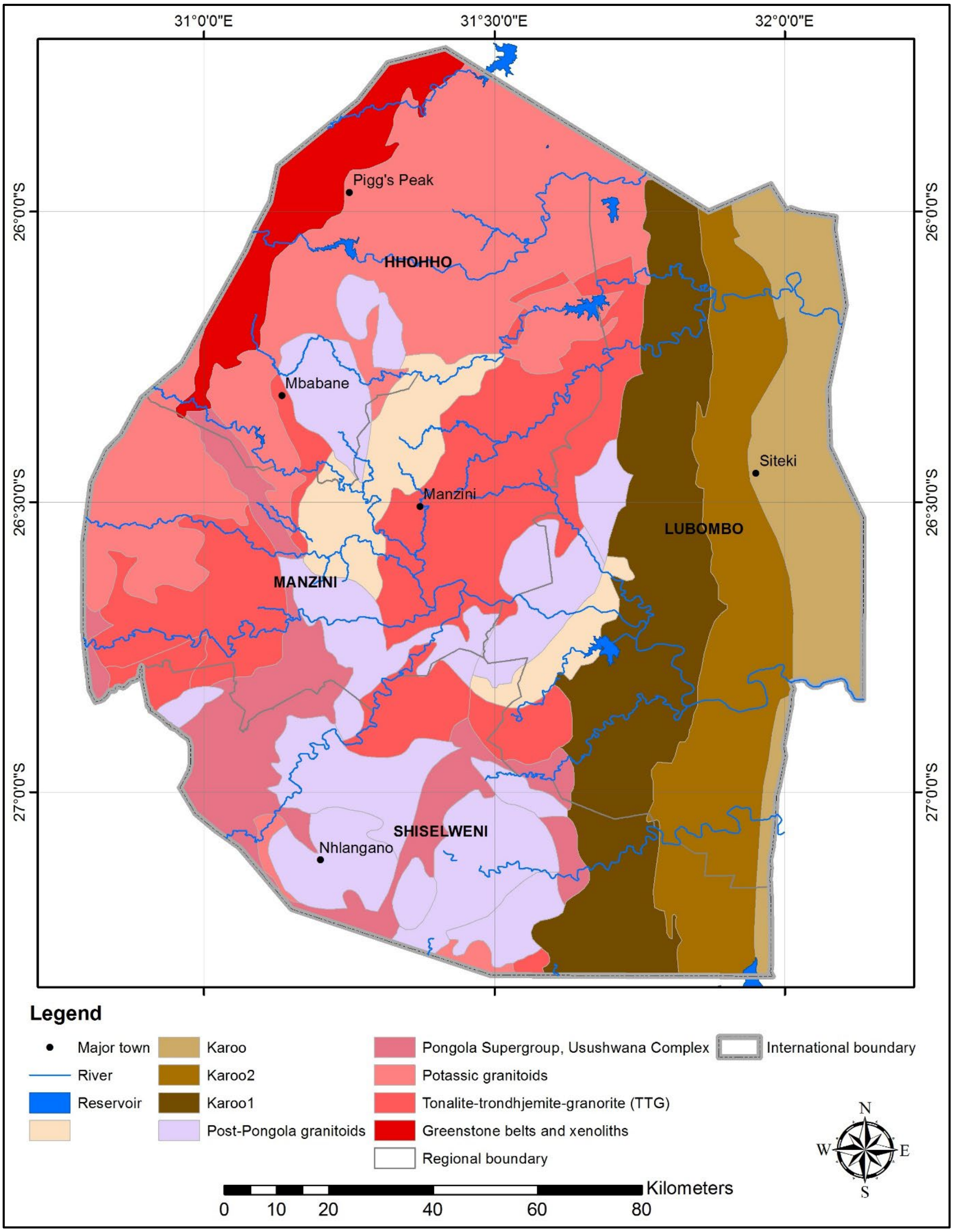


**Figure 3.3** The geology, major districts, towns and streams of Eswatini. Note the position of the Greenstone belt, which includes the oldest rocks in Africa (adapted from Schlüter, 2008).

### 3.1.2 Wetland distribution across Eswatini in relation to the geology

Hughes and Hughes (1992) originally stated that there are no major wetlands in Eswatini. Results of the wetland probability maps would appear to support this statement. However, there are numerous relatively large (>5 ha) wetland systems across the different physiographic zones of Eswatini that were identified from the wetland probability maps produced in this study and could therefore be attributed to the definition of 'major wetlands'. Notwithstanding such an argument, it should be evident that the need for wetland conservation in Eswatini is dire.

In the Highveld, north-east of Bulembu, numerous drainage lines originate on the rocks of the Onverwacht Group and flow in a north-westerly direction to make contact with the weathered slates and quartzites of the Fig Tree group (part of the Greenstone belt, Figure 3.3). These most likely act as an impeding barrier to water flow, thereby creating a relatively large, predominantly seep-based wetland. A large channelled valley-bottom system occurs along the Mkomazane River, a tributary of the Komati River, on the contact zone between the Mswati and Mpuluzi Granites within a valley surrounded by steep hills south of Piggs Peak. Various medium sized (4 ha) wetland systems occur in the valleys and breaks-in-slope along the headwaters of the Mbuluzi River in the west of the Highveld. To the east of Ngwenya are numerous long and thin valley-bottom wetlands in the shallow valleys of the Onverwacht and Usushwana complex that are fed by extensive seep wetlands, including the main Malolotja wetland to be discussed in greater detail later. Amongst the many tributaries of the Usuthu River, the Ngwenibisana, Mlambo and Ngwempisi rivers contain numerous wetland systems when they flow over outcrops of the Ngwane Gneiss where the channels of the rivers slow down and spread out towards the west of Mbabane. In the south-west of Eswatini, a large, channelled valley-bottom wetland occurs in a shallow valley that lies near the contact zone between Mozaan sediments and the Insuzi lavas, located near Sicunusa.

The only large wetland systems in the upper Middleveld occur along the White and Black Mbuluzi rivers to the west of Luve and the Little Usuthu and Umtilane rivers which are tributaries of the Usuthu River, located to the west of Manzini. These occur in valleys that form the edge of the escarpment where the gradient of the various hills decreases and where the geology changes from the granites of the Highveld (Mswati and Mpuluzi) to the Usuthu Granodiorites of the Middleveld. Three large wetland systems were also identified in the south of the Upper Middleveld near Mhlosheni, within the valleys of the Kwetta Granites.

Towards the north of the lower Middleveld, north-east of Ngoni near the South African border, is a long channelled valley-bottom wetland that exists along the Milabmi River that flows into the Drieskoppies Dam in South Africa. To the east of this is a large wetland system dominated by headwater, unchannelled valley-bottom and seep wetlands on the Mpuluzi Granites. These wetlands originate in Eswatini and also flow into the above mentioned dam. Near Herefords, the Ngwane gneiss hosts numerous large wetlands in the centre of the lower Middleveld, which occur at the piedmont of the escarpment. In the south of the Lower Middleveld near Hluit, the granites contain basements where water collects into a valley-bottom wetland system. Dolerite sills have intruded into the Kwetta and Hlatikulu granites, causing an impeding effect on water flow that also resulted in various small (<1 ha) wetland systems.

Many wetland systems occur where the slopes of Middleveld meet the plains of the Lowveld. This can be explained by the many rivers losing their carrying capacity, depositing their sediments and spreading out their flow. Large wetlands also occur within the Western Lowveld, along the contact zones of the Swazian, Ngwane and Mswati granites with the Karoo sediments that comprise shale and sandstone. The larger of these systems are located along the Komati River in the north of Eswatini, as well as north of Mliba near the Mnjoli Dam. Similar to the Lower Middleveld, dolerite sills in southern Eswatini have intruded into Karoo sediments, causing a damming effect on water, which has resulted in two large wetland systems along the Sitilo River and an unnamed stream, which are both tributaries of the Pongola River.

In the north of the Eastern Lowveld where fine-grained sandstone of the Clarens formation dissects Karoo sediments, a large wetland system has developed. The Lebombo Rhyolites act as large impeding barrier to many rivers that flow from western Eswatini, where many wetlands have formed in the clays that have weathered from the Sabie River basalts in the Eastern Lowveld which have limited infiltration capacity (Murdoch, 1970). The largest of these wetland systems are located north of Big Bend, around Nsoko and north of Lavumisa. The wetland probability map identified a fewer wetlands in the Lebombo Mountains when compared to the rest of Eswatini. This can possibly be attributed to the more resistant Rhyolites that do not provide as much colluvial material that aids in supporting hillslope seepage, which is a major contributor to wetlands in southern Africa. Of the few wetlands that were identified, most were headwater seeps as well as scattered valley-bottom wetlands in the valleys of the respective mountains, particularly east of Siteki.

The above observations have identified three main reasons for the presence of large wetlands across Eswatini, which are similar to reasons for wetlands developing in South Africa (Tooth & McCarthy, 2007; Ellery *et al*., 2008). The first is changes in topography, for example where the mountains of the Highveld meet the hills of the Middleveld, and the hills of the Middleveld meet the plains of the Lowveld. The second is contact zones between different types of geologies, for example the Mswati Granites and Karoo sediments and the Insuzi lavas and Mozaan sediments. The third factor is impeding geological features, which include dolerite sills and the more resistant rhyolites of the Lebombo mountain range that retard water movement and result in a damming effect, which creates a wetland. Figure 3.4 indicates examples of large wetland systems (>5 ha) that occur due to changes in elevation, whilst Figure 3.5 indicates examples of large wetland systems that occur on the contact zones between different geologies.

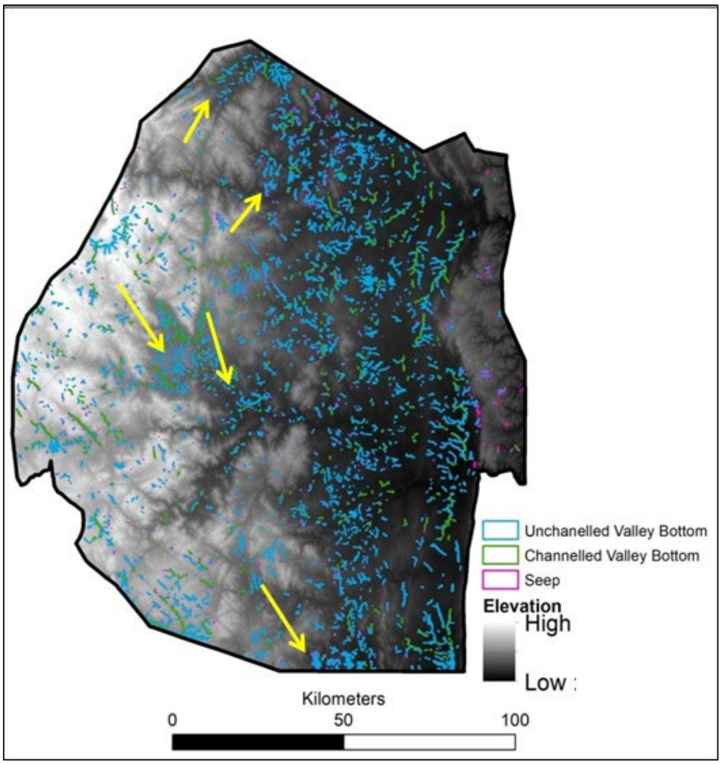


**Figure 3.4** Large wetland systems (>5 ha) that occur due to a change in elevation, indicated by yellow arrows.

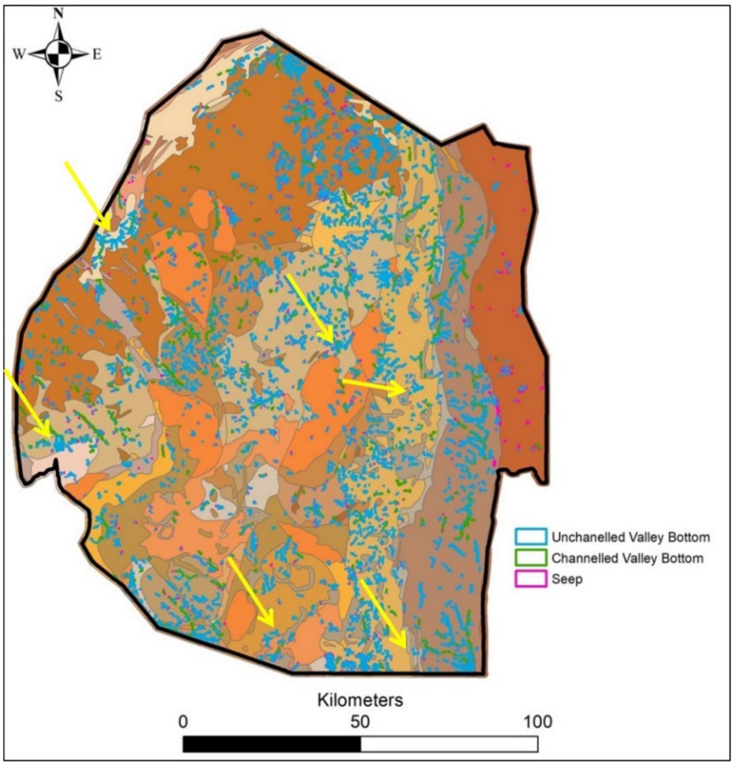


**Figure 3.5** Large wetland systems that occur on the contact zones between different geologies, indicated by yellow arrows.

## 3.2 OBJECTIVES OF THE MAPPING EXERCISE FOR ESWATINI

Eswatini shares the majority of its border with South Africa as a political construct, rather than an ecological divide (Figure 3.1). As already stated, there is thus a high likelihood that the wetland mapping techniques developed in South Africa will also be applicable in Eswatini. Further, most of the strategic water sources are shared by the two countries (Le Maitre *et al*., 2018). South Africa recently updated their national South African Inventory of Inland Aquatic Ecosystems (SAIIAE) and their National Wetland Map version 5 (NWM5) as one of the layers in the SAIIAE (Van Deventer *et al*., 2018a, 2020), as users of the previous South African wetland map (Nel *et al*., 2011) noted many problems with its accuracy (Grundling *et al*., 2013; Grundling, 2014; Mbona *et al*., 2015; Rebelo *et al*. 2017; Collins, 2018; Van Deventer *et al*., 2018b). Van Deventer *et al*. (2018a, 2020) integrated data from a variety of sources that was predominantly heads-up digitized. The previous version of the NWM4, used in the National Biodiversity Assessment of 2011 (Nel *et al*., 2011), showed a large number of commission errors resulting from the remote sensing classification of SPOT (*Satellite Pour l'Observation de la Terre*) and Landsat images in the National Land Cover of 2000 (Van den Berg *et al*., 2009), while the hydrogeomorphic (HGM) units were modelled from landforms derived from a 50-m Digital Elevation Model (DEM) (Van Deventer *et al*., 2018a,b). These commission errors were reduced in NWM5 through using only heads-up digitizing methods and classifying the HGM units manually. Coupled with the challenges of remotely sensed wetland data outlined above, the time and monetary constraints of this present study to manually digitize the wetlands of Eswatini, as well as the absence of any previously digitized wetlands, suggested that alternative methods to map the wetlands of Eswatini were required.

There has been a recent increase in mapping wetland probability approaches, both internationally (Pantaleoni *et al*., 2009; Nyarko *et al*., 2015; Nyandwi *et al*., 2016; Stein *et al*., 2016) and locally in South Africa (Hiestermann & Rivers-Moore, 2015; Melly *et al*., 2017; Collins, 2018). However, the approaches that yield relatively high accuracies are based on complex statistical models such as Logistic Regression and Bayesian Network Models that require input variables that are either not available for countries such as Eswatini, or not available at a fine enough scale. These forms of prediction models also require an existing inventory of wetlands types (Melly *et al*., 2017), which again is not available for Eswatini. A wetland probability mapping approach that differs to the conventional statistical approach is that of Collins (2018), developed in South Africa as an alternative method to remotely sensed wetland mapping. Rather, the technique is similar to onscreen digitizing, but instead of identifying each individual wetland, the modelled approach simultaneously maps wetlands identified within a respective mapping region using an 'overall best fit' approach.

The probability mapping technique of Collins (2018) is based on a DEM, with the assumption that water will accumulate in the lowest positions of the landscape which are then likely to be the areas of highest likelihood (probability) for wetland occurrence (Collins, 2018). The method therefore focusses on the landscape position criterion for identifying and delineating wetlands in South Africa (DWAF, 2005). Collins (2018) explains that although wetlands are most likely to develop within these low-lying areas, watercourses other than wetlands may also be present and subsequently mapped in error. This is due to the fact that these low-lying areas may also not always contain wetlands, as wetland development not only requires the presence of low-lying areas, but also numerous other factors, including mean annual precipitation, slope and soil depth (Ellery *et al*., 2008; Collins 2018). The watercourses include rivers, wetlands, lakes, dams, springs and natural areas in which water will flow regularly or intermittently. Another disadvantage of the wetland probability mapping technique is that it does not map depressional wetlands or seep wetlands not connected to a valley bottom, as it focusses on wetlands within and adjacent to valley bottom positions. However, riverine wetlands are the most common wetland type in Eswatini (IUCN, 1997), which is the type of wetland that the wetland probability mapping technique is best suited to map (Collins, 2018). Further, the data required to produce such probability map only includes remotely sensed imagery (either aerial photographs or satellite imagery) and a DEM which are both available for Eswatini. Collins (2018) also explained how the wetland probability map can be improved through the use of ancillary attribute data.

In the context of the above, this project therefore set out to produce a wetland probability map for Eswatini.

In order to provide baseline data on the distribution of wetlands across Eswatini, the following objectives were set out:

1. To apply the method of Collins (2018) to Eswatini.
2. To improve the method of Collins (2018) to distinguish wetlands from other types of watercourses.
3. To classify areas with the highest probability of wetland occurrence into hydro-geomorphic units.

## 3.3 METHODS OF OBTAINING THE WETLAND PROBABILITY MAP FOR ESWATINI

There are many definitions for the term 'wetland' across the world and for many years this has caused much confusion as to what technically qualifies as a wetland (Scott & Jones, 1995; Mitsch & Gosselink, 2015). Given that Eswatini uses the broad Ramsar definition for wetlands, which includes water that can be static or flowing (Ramsar Convention Secretariat, 2010a), watercourses such as rivers and drainage lines would be included under this definition, implying that the method of Collins (2018) should be well suited to identify such wetland types. The technique of Collins (2018) was initially applied to Eswatini, followed by an attempt to improve the map through distinguishing wetlands from other types of watercourses and classifying the areas with the highest probability of wetland occurrence into hydro-geomorphic units.

The wetland probability mapping technique requires remotely sensed imagery (either aerial photographs or satellite imagery) and a DEM. This study used the 2008 SPOT images (SANSA, 2013), acquired from ARC-ISCW, with 10 m resolution, along with the Shuttle Radar Topography Mission (SRTM) DEM (NASA, 2000). The 2008 SPOT images were ortho-rectified using the 30 m x 30 m Shuttle Radar Topography Mission (SRTM) DEM (NASA, 2000) and using the original UTM (Universal Transverse Mercator; Datum World Geodetic System 84) projection. Thereafter, it was re-projected to the Africa Albers Geographic (Datum World Geodetic System 84) projection. The DEM was pre-processed using the "Breach depression" tool of Whitebox GIS (Lindsay, 2014) to be consistent with the methods of Collins (2018).

The mapping technique begins by subdividing the study area into mapping regions based on factors pertaining to wetland development and include rainfall, relief and generalized geology. Thereafter, parameters for flow accumulation and a percentile filter analysis are determined for each mapping region. This is based on a trial-and-error approach using the subjective identification of aerial imagery that displays distinct changes in vegetation, perceived through expert opinion to be associated with a change in moisture conditions consequential to the presence of a wetland at a 1:50 000 scale. Flow accumulation is used to map cells that surface water flows through in low-lying areas whilst the 'percentile filter' tool of Whitebox GIS (Lindsay, 2014) is used to perform a percentile analysis, on the DEM to map the broader valley-bottom systems. An example of flow accumulation and percentile filter analysis is illustrated in Figure 3.6. Where it was found that thresholds did not adequately map probable wetland areas, the initial mapping regions (n = 22) were further subdivided to give 160 regions. Further information on the method of the wetland probability map is available in Collins (2018).

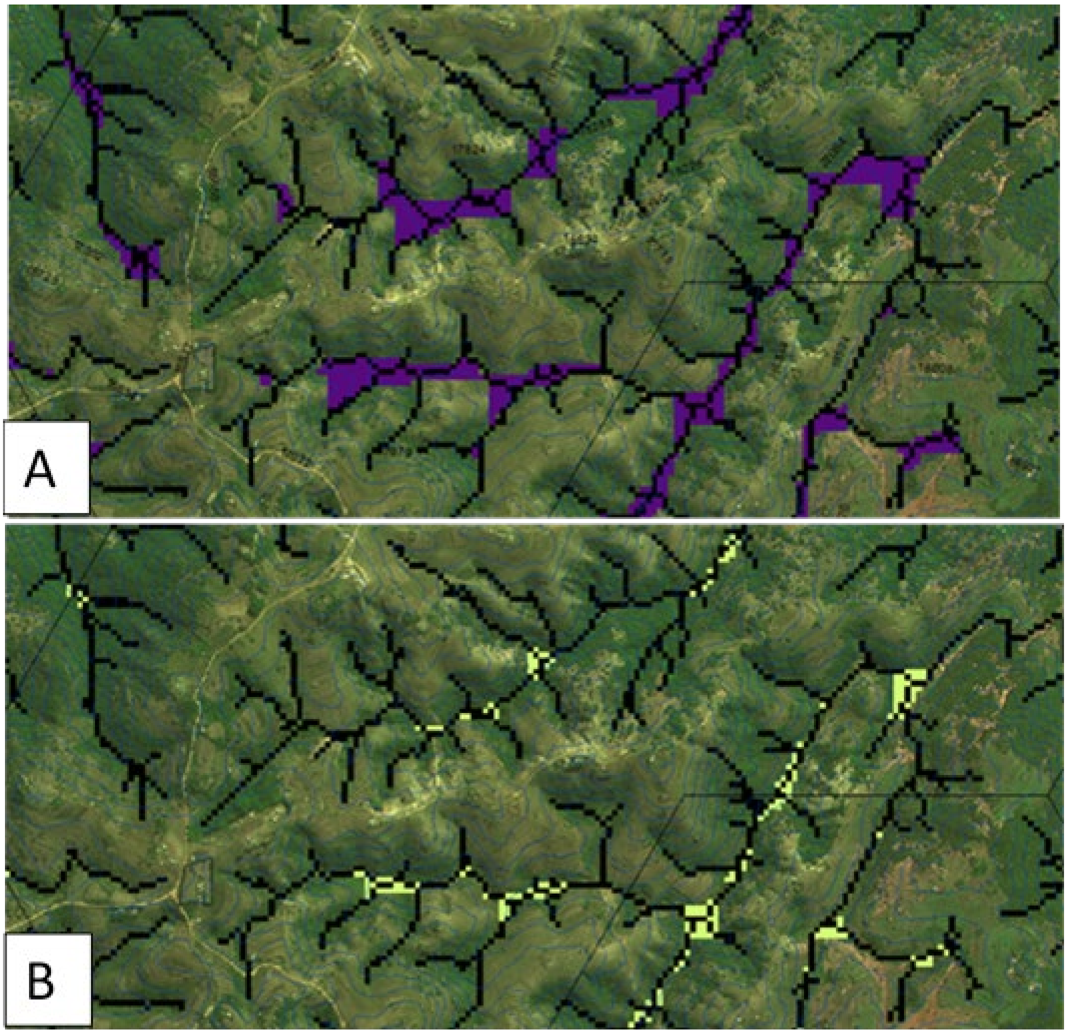


**Figure 3.6** Examples of percentile filter maps (yellow and purple) on top of flow accumulation maps (black) used to detect probable areas of wetland occurrence. Figure 3.6A used a larger moving window (15x15) compared to Figure 3.6B (9x9).

To determine the accuracy of the initial wetland probability map, both field-based and desktop-based accuracy assessments were undertaken. These sought to determine the accuracy of the initial probability map with regard to how it maps wetlands under the Ramsar definition (Ramsar Convention Secretariat, 2010a), as well as its accuracy when applying the more specific definition used in South Africa. The field accuracy assessment traversed 510 km through Eswatini. Each watercourse, identified and described based on DWAF (2005) totalling 369 observation points, was marked using a Garmin 62 GPS and classified as: i) a wetland, ii) other type of watercourse, or iii) not a watercourse. Wetlands were further classified into the hydro-geomorphic units of Ollis *et al.* (2013), whereas other types of watercourses were classified into steep first and second order drainage lines, riparian zones DWAF (2005), and rivers (Table 3.2). The second desktop-based accuracy assessment then used the ArcGIS random points tool (ESRI, 2018) to establish 2000 random points distributed across Eswatini. The number of points chosen was found to be the smallest number of points, within the confines of the study, to adequately cover the surface area of the country. They were distributed according to stratified random sampling, where the number of random points assigned to a physiographic region was based on the area of each respective region. The points were then converted to *kml* format and imported into Google Earth Pro (Google Earth Pro Inc., 2018).

**Table 3.2** Types of watercourses used to classify points identified in the accuracy assessments

| Type of watercourse | Description |
|---|---|
| Wetland | Hydrogeomorphic unit |
| Other type of watercourse | Steep first/second order drainage line<br>Riparian zone<br>River |
| Not a watercourse | N/A |

Each point was subsequently classified in the same manner as the field-based accuracy assessment (Table 3.2). This was considered an acceptable method, following Melly *et al*. (2017) in the Eastern Cape and Van Deventer *et al*. (2018c) who used heads-up digitizing of aerial photography to create South Africa's NWM5. Riparian zones were differentiated from steep first/second order drainage lines using the elevation profile tool of Google Earth Pro (Google Earth Pro Inc., 2018). Points that were too disturbed to classify as one of the three classes were classed as "disturbed" and excluded from the analysis. Disturbed points were often found to be as a result of land transformation due to forestry and sugarcane plantations, or dams and urbanization. In total, 265 points were classed as 'disturbed', which resulted in 1735 points remaining that were used to calculate the accuracy of the initial wetland probability map. This accuracy assessment, however, only tested for errors of ***commission*** since wetlands occupy such a small percentage of surface area (Lehner & Döll, 2004) that it is not practical to distribute random points outside of the wetland probability map. The wetlands that would have been identified as ***omission*** errors would have resulted in an additional sample of similar size to the field-based accuracy assessment, and were deemed to add little value to the overall assessment of the accuracy of the map.

## 3.4 IMPROVING THE INITIAL WETLAND PROBABILITY MAP FOR ESWATINI

Attribute data used to improve the accuracy of the wetland probability map included morphometrics derived from the SRTM DEM (NASA, 2000) as well as the Soil Map of Eswatini (Murdoch, 1970). This map contained 32 soil sets, mapped at a scale of 1:250 000. The soil sets of Murdoch (1970) were grouped into classes according to their hydrological functioning and degree of saturation, using the hydrological soil types of Van Tol *et al.* (2013), and the wetness regimes of soil forms listed in the South African wetland delineation guidelines (DWAF, 2005). The two soil classifications were merged into one system, shown in Table 3.3 . Morphometrics, derived from the SRTM DEM (NASA, 2000), included slope, ground curvature, plane curvature, profile curvature and elevation. Statistical analysis (not shown here) determined that the majority of these attributes differed significantly across the physiographic regions of Eswatini, which warranted them to be assessed separately for each region.

**Table 3.3** Combined soil classes of Van Tol *et al.* (2013) and DWAF (2005)

| **Hydropedology classes** (Van Tol *et al.*, 2013) | **SA wetness regimes** (DWAF, 2005) |
|---|---|
| Recharge | Seasonal** |
| | Terrestrial |
| Interflow AB | Permanent |
| | Seasonal |
| | Terrestrial |
| Interflow rock | Seasonal |
| | Terrestrial |
| Responsive* | Permanent |
| | Seasonal |

* Responsive shallow and Responsive saturated were grouped into one class. The reason being that the Responsive Shallow class is geographically very small and occurs in isolated patches in the landscape and would therefore not have been included in a national soil map at 1:250 000 scale (Van de Waals: Personal communication, 2019).

**Soils referred to as "seasonal refer to the soil forms classed as seasonally or temporarily saturated in the South African wetland delineation guidelines (DWAF, 2005).

The 2000 random points (reduced to 1735) used in the desktop accuracy assessment were used to differentiate wetlands from other types of watercourses. The soil class (Table 3.4) as well as the slope value for each point were subsequently extracted and attributed to each reference point. The percentage occurrence of the different types of watercourses (identified from the 1735 points mentioned above) for each soil class per physiographic region, was then calculated. If a type of watercourse occurred on a given soil class more than 75% of the time per physiographic region, that respective soil class was categorized as either i) "probably a wetland", ii) "probably other watercourse (excluding wetlands)", or iii) "probably not a watercourse" soil. Soil classes that did not have over 75% of a type of watercourse occurring on them were categorized as a "either wetland or other watercourse" soil. The latter category was deemed acceptable, given that it is not uncommon for a watercourse to show both wetland and riparian zone characteristics (DWAF, 2005). The cut-off value of 75% was based on the intended accuracy of the refined wetland probability map. The initial wetland probability map was then divided into these categories based on the soils that the areas of probable wetland occurrence were found on.

Since wetlands and other types of watercourses (e.g. riparian zones and rivers) can occur in similar landscape positions, slope values could not be used to differentiate wetlands from all other types of watercourses. Instead, the information was used to improve the map by differentiating steep first and second order drainage lines (which were often mapped by the initial wetland probability map) from wetlands where the slope gradient would make it unlikely for a wetland to occur. Cumulative frequencies were determined for wetlands and first and second order drainage lines along slope intervals (in degrees) for every physiographic region. Due to wetlands mostly having a lower slope value than steep first and second order drainage lines, a cut-off slope value was identified where the most wetlands would be included, and as many as possible first and second order drainage lines would occur above that slope value. This was done through plotting the cumulative frequencies of wetland slope values against the inverse cumulative frequency slope values of steep first and second order drainage lines for each respective physiographic region. The cut-off slope value was identified as the intersection between the two frequency lines. Table 3.4 shows the cut-off values for each region and the percentages of wetlands and first/second order drainage lines included in the respective values. The Western and Eastern Lowveld did not contain sufficient first order drainage lines to calculate a slope value that could be used to distinguish them from wetlands. Slope raster layers were reclassed into the respective cut-off values for each region and converted to vectors.

Sections of the initial wetland probability map that were included in the "probably a wetland" soil category that fell above the respective cut-off slope value (per physiographic region) were then moved into the "either wetland or other watercourse" class.

**Table 3.4** Slope cut-off values used to partially differentiate wetlands from steep first/second order drainage lines

| Region | Cut-off slope value (degrees) | Wetland | | First/second order drainage line | |
|---|---|---|---|---|---|
| | | % less than cut-off value | % greater than cut-off value | % less than cut-off value | % greater than cut-off value |
| Highveld | <=7 | 82 | 18 | 34 | 66 |
| Upper Middleveld | <=7 | 85 | 15 | 47 | 53 |
| Lower Middleveld | <=5 | 81 | 19 | 41 | 59 |
| Lebombo | <=2 | 50 | 50 | 61 | 39 |

The field verification points were used to test the accuracy of the improved wetland probability map. Two approaches to a standard accuracy assessment, based on the methods of Story & Congalton (1986), as well as an intuitive accuracy test were used to determine the accuracy of the refined wetland probability map. In other words, the initial wetland probability map was categorized into the previously mentioned three categories of "probably a wetland", "either wetland or other watercourse" and "probably other watercourse" to create the initial wetland map data, which was then filtered as indicated above to produce the improved wetland probability map. The full details of the different accuracy assessments are provided in Le Roux (2020).

### 3.4.1 Hydro-geomorphic classification of wetlands in Eswatini

Watercourses with the highest probability of being a wetland (i.e. the "probably a wetland" map layer) were classified into the hydro-geomorphic units of Ollis *et al.* (2013) which is the most widely used classification system in South Africa. Wetlands were classified to Level 4A, which is the focal point of the classification system and is the same level used by the South African Wetland Inventory (Van Deventer *et al.*, 2018c). The wetland probability map has the ability to identify floodplains, channelled valley bottoms, unchannelled valley bottoms and, to a limited extent, seeps (Collins, 2018). The first three HGM units all occur in the valley-bottom landscape position, whilst seep wetlands do not. Slope values, extracted from the 1735 random points, were used to differentiate these valley-bottom wetlands from seeps, using the same methodology that differentiated wetlands from steep first/second order drainage lines (i.e. determining a cut-off slope value from cumulative frequencies) as seeps generally have steeper slopes than valley-bottom wetlands (Ollis *et al.*, 2013; Grundling, 2014). Slope values were determined separately for each physiographic zone. Due to the small number of seeps identified with the random sample points in the Lowveld, as well as the gentle slopes in the region, the Western and Eastern Lowveld physiographic zones were combined (Table 3.5).

To distinguish valley-bottom wetlands from each other, the *rivers layer* of Eswatini National Trust Commission ENTC (2017) was used to differentiate channelled from unchannelled valley bottoms, based on the methods of Grundling *et al.* (2014). The "probably a wetland" layer was intersected with the rivers layer (ENTC, 2017) to extract channelled valley-bottom wetlands. Buffers of 100 m were used to account for misalignment of the rivers layer with imagery that was noticeable below a scale of 1:60 000.

**Table 3.5** Slope cut-off values used to distinguish valley-bottom wetlands from seeps

| **Region** | **Cut-off slope value** (degrees) | **Valley bottom** | | **Seep** | |
|---|---|---|---|---|---|
| | | **% less than cut-off** | **% greater than cut-off** | **% less than cut-off** | **% greater than cut-off** |
| Highveld | <=4 | 65 | 35 | 35 | 65 |
| Upper Middleveld | <=4 | 72 | 28 | 61 | 39 |
| Lower Middleveld | <=3 | 63 | 37 | 44 | 56 |
| Lowveld | <=2 | 65 | 35 | 55 | 45 |
| Lebombo | <=2 | 67 | 33 | 40 | 60 |

Wetlands falling outside of the buffer were classed as unchannelled valley bottoms. Although the *rivers layer* is relatively extensive, it was observed from satellite imagery (ArcMap basemaps (ESRI, 2018)) that minor rivers and streams occur in Eswatini that are not included in this layer. Therefore, wetlands classified as unchannelled valley bottoms may sometimes contain a channel, but due to the relatively small size of these streams, they can be described as being driven mainly through lateral inputs. In order to identify floodplain HGM units in Eswatini, the major rivers in Eswatini were scanned in Google Earth Pro (Google Earth Pro Inc., 2018) at a scale of 1: 50 000, to identify the features that are characteristic of a floodplain HGM unit as defined by Ollis *et al*. (2013). This includes geomorphological features associated with river-derived depositional processes and includes point bars, scroll bars, oxbow lakes and levees. None of these features were, however, identified when scanning Google Earth Pro (Google Earth Pro Inc., 2018), and therefore no floodplain wetlands were included in the classified wetland probability map.

### 3.4.2 Results for the initial wetland probability map for Eswatini

The initial wetland probably map created for Eswatini mapped 92 979 800 ha of land, which is 5.4% of the country (Figure 3.7), with examples displayed in Figure 3.8. Not surprisingly, the results of both the field (Table 3.6) and desktop (Table 3.7) accuracy assessment indicate that the probability map is heavily reliant on the definition of a wetland. When using the Ramsar definition, the field-based accuracy assessment found that the accuracy is 82%, with commission and omission errors being 12% and 6% respectively. However, when using the South African definition of a wetland, the map received an accuracy of only 47%, with omission errors of 3% and commission errors of 50%. Wetlands falling under the Ramsar definition (but not the South African definition) made up 39% of the watercourses mapped by the probability map, whilst wetlands falling under the South African definition constituted 48%. The desktop-based accuracy assessment found that when using the Ramsar definition (as is the case in Eswatini), 93% of the points were successfully classified as a wetland. When using the South African definition of a wetland, only 31% of the points were classified as a wetland.

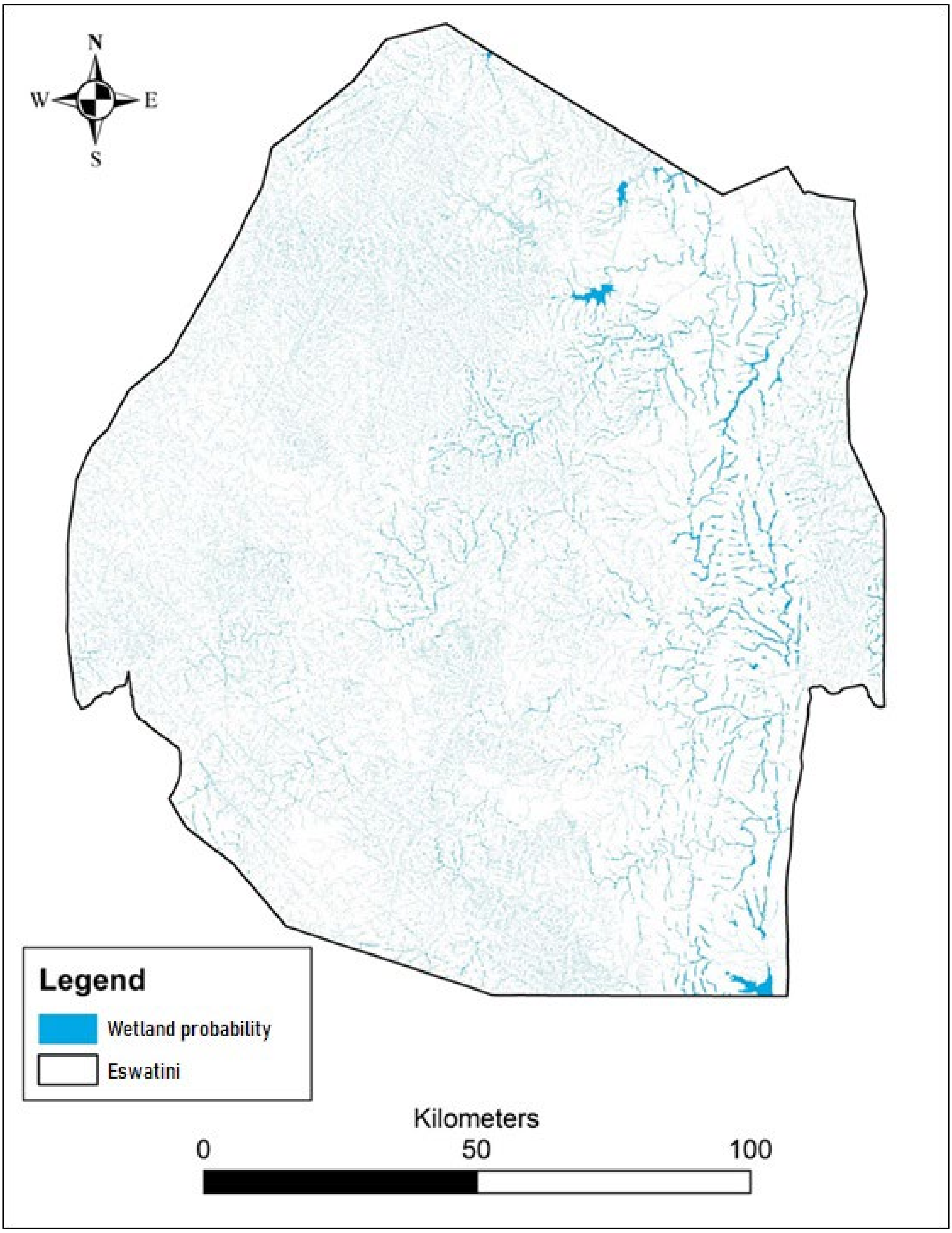


**Figure 3.7** The initial prediction map, showing probable wetland locations in Eswatini.

**Table 3.6** Results of the field-based accuracy assessment using both the Ramsar and South African definitions of a wetland

| **Based on the Ramsar definition of a wetland** (Ramsar Convention Secretariat, 2010a) | **Number of points** | **Percentage** (%) |
|---|---|---|
| Wetland mapped and identified in the field | 303 | 82 |
| Wetland mapped but not identified in the field (commission) | 44 | 12 |
| Wetland identified in the field but not mapped (omission) | 22 | 6 |
| **Total** | **369** | **100** |
| **Based on the South African definition of a wetland** (RSA, 1998) | **Number of points** | **Percentage** (%) |
| Wetland mapped and identified in the field | 173 | 47 |
| Wetland mapped but not identified in the field (commission) | 185 | 50 |
| Wetland identified in the field but not mapped (omission) | 11 | 3 |
| **Total** | **369** | **100** |

**Table 3.7** Results of the desktop-based accuracy assessment based on the Ramsar and South African definitions of a wetland

| **Physiographic zone** | **Wetlands defined under the Ramsar definition** (%) | **Wetlands defined under the South African definition** (%) | **Other type of watercourses excluding wetlands defined under the South African definition** (%) | **Not any type of watercourse** (%) **(commission)** | **Total count of points** |
|---|---|---|---|---|---|
| Highveld | 96 | 50 | 46 | 4 | 563 |
| Upper Middleveld | 93 | 49 | 44 | 7 | 178 |
| Lower Middleveld | 89 | 21 | 69 | 10 | 156 |
| Western Lowveld | 86 | 21 | 65 | 14 | 325 |
| Eastern Lowveld | 93 | 19 | 73 | 7 | 248 |
| Lebombo | 98 | 6 | 92 | 2 | 265 |
| **Total** | **93** | **31** | **62** | **7** | **1735** |

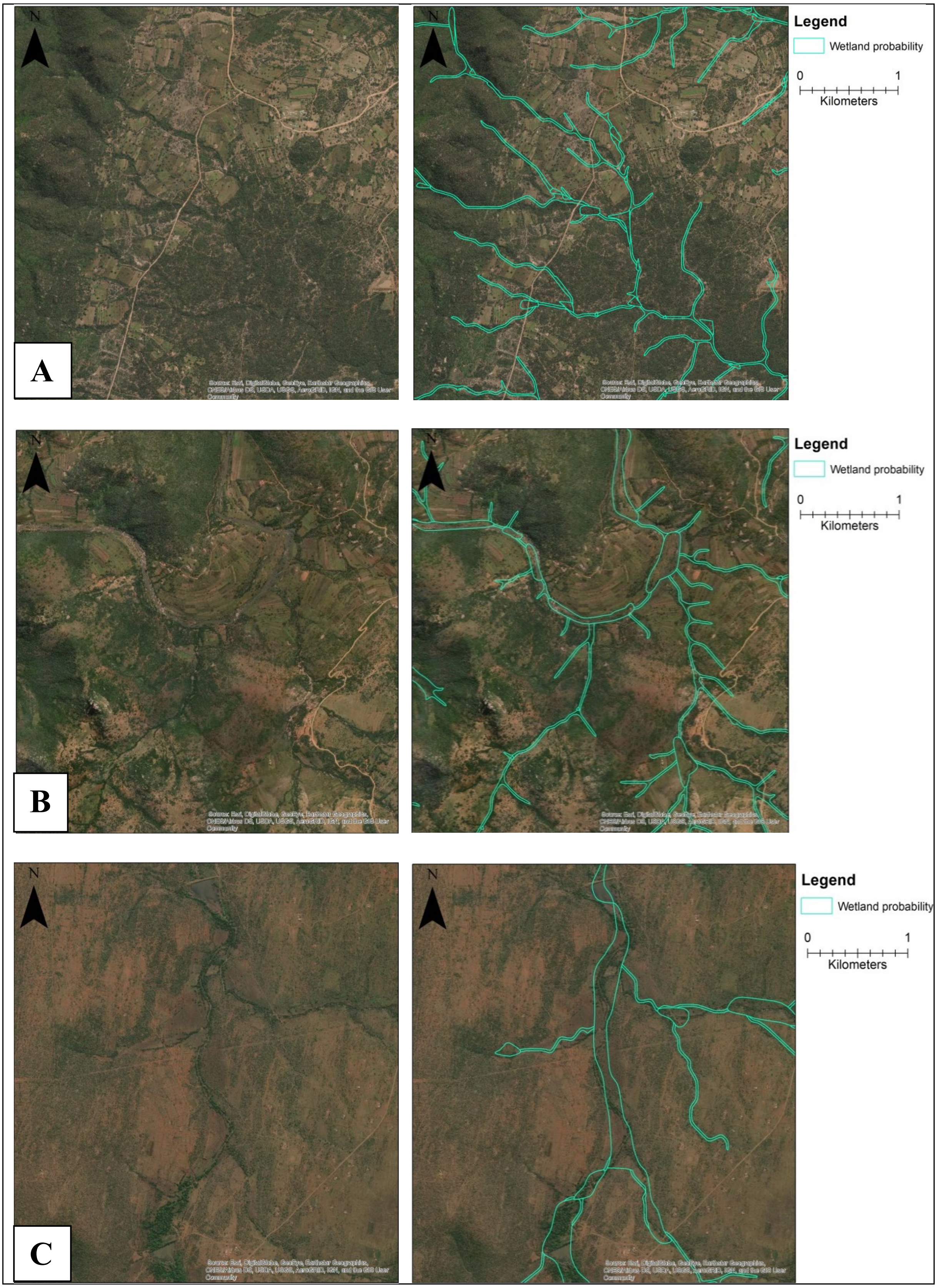


**Figure 3.8** Examples of the wetland probability map in different landscape settings. A - Mountains of the Middleveld extends into the plains of the Western Lowveld; B - a river in the Mountainous Highveld; C - the Eastern Lowveld plains.

An example of the improved wetland probability map is displayed in Figure 3.9, with its accuracy explained in Table 3.8. The total surface area of each layer is as follows:

- Probably a wetland = 149 $km^2$ (16% of the initial wetland probability layer and 0.9% surface area of Eswatini).
- Either wetland or other watercourse = 650 $km^2$ (70% of the initial wetland probability layer and 3.7% surface area of Eswatini).
- Probably other watercourse = 131 $km^2$ (14% of the initial wetland probability layer and 0.8% surface area of Eswatini).

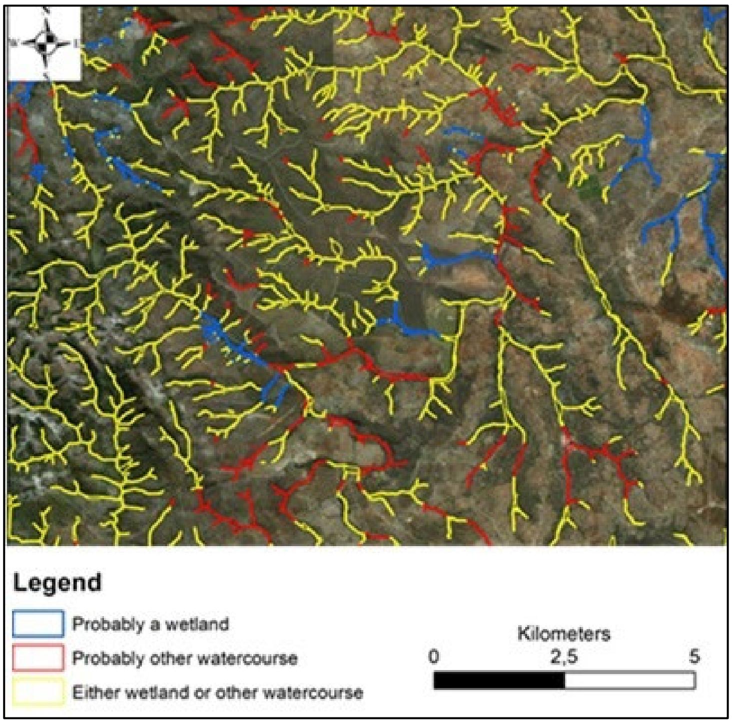


**Figure 3.9** An enample of the improved wetland probability map.

**Table 3.8** Overview of the accuracy of the improved wetland probability map for Eswatini

| Main layer/ category | Surface area (%) of initial wetland probability map | % of wetlands in Eswatini that occur in this layer | % of other watercourses (excluding wetlands) in Eswatini that occur in this layer | Probability of watercourses mapped by this layer being a wetland | Probability of watercourses mapped by this layer being another type of watercourse (excluding wetlands) |
|---|---|---|---|---|---|
| Probably a wetland | 15 | 52 | 3 | 77 | 23 |
| Either wetland or other watercourse | 75 | 45 | 71 | 26 | 74 |
| Probably other watercourse | 10 | 3 | 20 | 7 | 93 |

Although the '*probably a wetland*' map layer only makes up 16% of the surface area of the initial wetland probability map, it includes 52% of the identified wetlands and only 3% of the identified other watercourses from the 1735 random points. Of the watercourses mapped by the '*probably a wetland*' layer, 77% are wetlands and 23% are other watercourses. The *either wetland* or *other watercourse* map layer makes up 70% of the surface area of the initial probability map's extent, and includes 45% of the wetlands and 71% of the other watercourses. Of the watercourses mapped by the *either wetland* or *other watercourse* map layer, 26% were wetlands and 74% were other watercourses. The *probably other watercourse* map layer makes up 14% of the surface area of the initial wetland probability map and includes 20% of the other watercourses and 3% of the wetlands. Of the watercourses mapped by the *probably other watercourse* map layer, 93% were other watercourses and 7% were wetlands.

### 3.4.3 Enhanced or reclassified wetland probability map for Eswatini

An example of the re-classified wetland probability map is illustrated in Figure 3.10 with the summarized results of the accuracy assessment displayed in Table 3.9. Although the number of sample points used for the accuracy assessment of the re-classified wetland map was relatively small (n = 51), the results have shown that the methods used to classify wetlands into HGM units were partially able to distinguish valley-bottom wetlands from seep wetlands, as well as channelled valley bottoms from unchannelled valley bottoms. The producer's accuracy of the re-classified map, which tests the percentage of field points that were accurately predicted by the map, had an average accuracy of 86%, with seeps being the highest at 100% and channelled valley bottoms the lowest at 73%. Unchannelled valley bottoms resulted in an 86% accuracy. The results of the user's accuracy, which tests whether the map correctly predicts the type of HGM unit, were slightly less accurate with an average of 73%. Seeps were again the highest at 88%, unchannelled valley bottoms the lowest at 57% and channelled valley bottoms at 73%.

**Table 3.9** Results for the accuracy of the improved wetland probability map of Eswatini

| | **Producer's accuracy (%)** | **User's accuracy (%)** |
|---|---|---|
| Channelled valley bottom | 73 | 73 |
| Unchannelled valley bottom | 86 | 57 |
| Seep | 100 | 88 |

### 3.4.4 Discussion of the initial and improved wetland probability maps for Eswatini

When using the Ramsar definition of a wetland, the initial wetland probability map received predictive accuracies ranging from 82-93%, implying that this approach has the ability to identify most wetlands falling under such definition in a country with physiographic landscapes such as Eswatini. The commission errors (of not mapping any type of watercourse) for both the field- and desktop-based accuracy assessments were relatively similar (6% and 7%). However, the percentage of wetlands that would fall under the Ramsar definition, but not the South African definition, differed substantially between the two accuracy assessments (39% and 62%). This may be attributed to the biased sampling of the field-based accuracy assessment, which was restricted to road access and therefore mostly excluded steep slopes, where many first and second order drainage lines were mapped. Therefore, the initial wetland probability map does not suffice as a wetland map for countries such as South Africa, who use a more specific definition for the term 'wetland' (RSA, 1998), as the map received accuracies of 47% and 31% when using the South African definition of a wetland. A comprehensive wetland map was, however, not the intended purpose of the wetland probability map created by Collins (2018). The intended purpose was to map extensive areas with limited data and cost (Collins, 2018). For this, it is well suited, especially for countries that are signatories of the Ramsar Convention but do not have the means to produce a highly detailed wetland map, as is the case in Eswatini. Considering that Eswatini uses the Ramsar definition of a wetland and that riverine wetlands are the most common wetland type in that country (IUCN, 1997), the initial wetland probability map is suited to be used as a baseline source of information with regard to the approximate distribution of wetlands across the country. The methods used to improve the wetland probability map were not able to definitively distinguish wetlands from other types of watercourses but were able to identify watercourses with a higher probability of being a 'true wetland', as opposed to other types of watercourses.

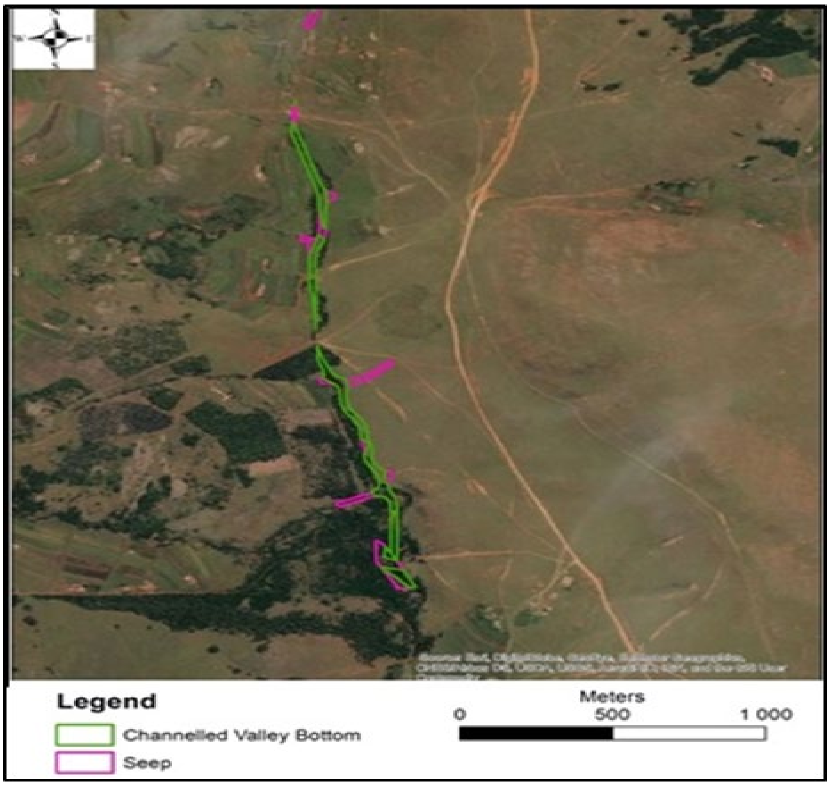


**Figure 3.10** An example of the improved wetland probability map for Eswatini.

Neither wetlands nor other types of watercourses were solely attributed to a particular soil class. This could be partially due to the generalized 1:125 000 scale of the soil map (Murdoch, 1970), as it is unlikely that soils classed as responsive and permanently saturated would be attributed to steep first/second order drainage lines. It was also identified that wetlands and first/second order drainage lines can occur on the same slope gradients; however, the method of intersecting cumulative frequencies was able to include a relatively large percentage of wetlands below certain slope values in respective physiographic zones. In the Highveld, Upper and Lower Middleveld, 82%, 85% and 81% of the respective sample wetlands occurred below these slope values. These cut-off slope values, however, also resulted in respectively 34%, 47% and 41% of the first/second order drainage lines in the above physiographic units being included below the respective cut-off values. Results of using this method in the Lebombo region were less favourable as only 50% of the sample wetlands and 61% of the first/second order drainage lines were located below the cut-off slope values. The relatively small slope differences between the slopes of wetlands and first/second order drainage lines in the Lowveld did not allow this method to partially differentiate between the two. Cut-off slope values also ranged from 2-7 degrees across the different physiographic regions, highlighting that wetlands form on different slope positions across Eswatini. This phenomenon could be due to other variables such as geomorphology (driven in turn largely by geology and climate) that vary amongst physiographic zones (Remmelzwaal, 1993). In general, the slope of wetlands was found to be concentrated around lower values for slope gradient and first/second order drainage lines were relatively spread out.

Similar difficulties were observed when attempting to distinguish valley-bottom wetlands from seep wetlands. The cut-off slope values ranged from 4-2 degrees and were only able to partially distinguish these types of wetlands from each other. This could be due to the scale of the 30 m SRTM DEM (NASA, 2000), but it is not uncommon for seep wetlands to also occur on relatively flat areas (Ollis *et al.*, 2013). For example, in the Highveld, a cut-off slope value was identified that included 65% of valley-bottom wetlands below the value but also 35% of seeps. The methods used to partially distinguish first/second order drainage lines from wetlands and valley-bottom from seep wetlands are therefore coarse, but do provide some indication of the processes that are fundamental to the sustained existence of different wetland ecosystems (Brinson, 1993). Given the limited number of sample points used to verify the accuracy of the classified map, further research is needed to test the accuracy of this map. Additional research should also attempt to use a DEM that has a finer scale resolution than the 30 m SRTM DEM, as this may have contributed to the large amount of overlapping slope values.

## 3.5 CONCLUSION OF THE WETLAND PROBABILITY MAP FOR ESWATINI

The results of the probability mapping, which applied the technique of Collins (2018) and improved on that initial map using attribute data, have contributed to providing baseline data on the distribution of wetlands across Eswatini. Statistically-derived wetland probability mapping (Hiestermann & Rivers-Moore, 2015; Melly *et al.*, 2017) may have yielded more accurate results but the attribute/input data required for such techniques are frequently not available in developing countries such as Eswatini. This mapping exercise has also shown that large-scale attribute data can be used to partially distinguish wetlands from other types of watercourses through identifying areas with a higher probability of wetland occurrence, using relatively simple techniques. Further research is required to determine whether soil and morphometric data at a finer scale and resolution than that used in this study, as well as other types of attribute data, would have yielded more accurate results.

The limitations of the wetland probability mapping and the production of the improved HGM-classified probability maps of wetlands need to be acknowledged. The maps do not identify depressional wetlands that have previously been identified in the Lowveld (Hughes & Hughes, 1992) and Lebombo physiographic regions of Eswatini (Watson, 1986), and seeps not connected to the valley bottom. In addition, they are not at present able to definitively distinguish between wetlands and other types of watercourses, nor valley-bottom wetlands from seeps. However, it is argued that the advantages of the maps outweigh their limitations. The maps are still able to locate most areas with a high probability of wetland occurrence and can serve as preliminary guides to locate wetlands across Eswatini.

# 4. INVESTIGATING THE MALOLOTJA PEATLAND IN ESWATINI (CATCHMENT SCALE)

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## 4.1 INTRODUCTION

The Malolotja Nature Reserve (26°08’S; 31°05’E), under the management of the ENTC, is located in the north-western part of Eswatini (Figure 4.1) and extends over an area of 18 000 ha (ENTC, 2018). The elevation within the reserve ranges between 640 m at the Nkomati River Valley to 1829 m at the peak of the Ngwenya Mountain. The main reasons for which the area was proclaimed include protection of habitats, protection of geological (the oldest rocks on the African continent) and landscape features, coupled with ecotourism (ENTC, 2018). The environmental setting of the Malolotja Peatland was investigated and described in a more detailed catchment-scale approach.

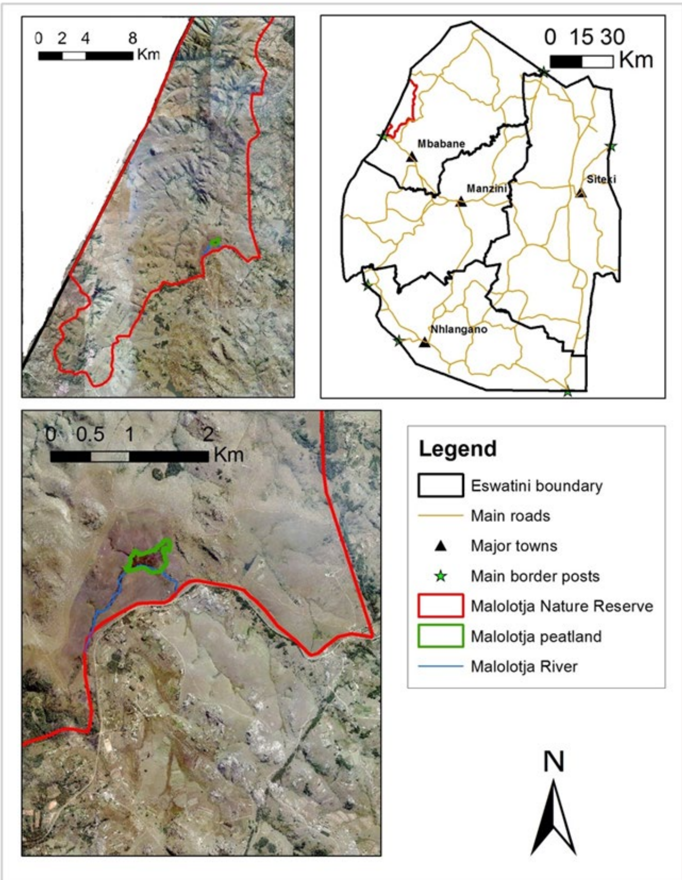


**Figure 4.1** Map showing the location of the dominant peatland within Malolotja Nature Reserve.

The area receives an average of 1150 mm of rainfall per year as thunderstorms or as relief rainfall (Boycott, 1989; ENTC, 2020b). Most of the rainfall is received during summer and falls between December and March. The June-July winter period is often the driest and the coldest, although occasional cold wet snaps may be experienced at other times. Even though temperatures differ within the reserve, data collected from the weather station located at the main entrance (which stands at an elevation of 1500 m a.m.s.l.) demonstrates a variance in daily mean temperatures from 18°C in summer to about 11°C in winter, although temperatures can drop to 5°C in the June-July winter period. The relative humidity is often very high (85%) in summer and decreases during winter to about 65% (Roques, 2002).

A network of mountain streams flow down steep-sided valleys into four major perennial rivers. These include the Malolotja River (after which the Reserve was named), the Mgwayiza, Mhlangamphepha and the Nkomati rivers. While the whole catchment area for the Malolotja, Mgwayiza and Mhlangamphepha rivers is contained within the reserve (ENTC, 2020a), the Nkomati River runs through the reserve from South Africa in the west to the east. Before the reserve was identified as protection-worthy, dams, weirs as well as barrages were constructed on the rivers. Even so, no boreholes or any artificial watering points currently exist within the reserve. While some pollution has been noted, particularly on the Malolotja River, the ENTC (2020a) states that the overall water quality is generally considered as suitable for consumption.

Malolotja Nature Reserve is located on the great southern African escarpment which comprises the ecotope between the Highveld and Middleveld. Rocks that are located within the reserve are amongst the oldest in the world, and the oldest on the African continent (ENTC, 2020a). In an area covering approximately 13 500 ha are the Swaziland/Eswatini Supergroup, which are amongst the oldest metamorphic rocks (meta-sediments) in the world (Forrester, 2005). A geological overview of Eswatini developed by Schlüter (2008) shows that the Malolotja Nature Reserve is dominated by the Swaziland Supergroup (i.e. the Onverwacht, Fig Tree and Moodies groups). A soil and land capability map developed in 1968 by Murdoch for Eswatini categorizes most of the soils as "rock outcrops and stony ground including raw mineral soil" (Murdoch, 1970). He also identified patches of highly organic soils especially in the south of the reserve.

The main Malolotja wetland and associated peatland occurs at an elevation ranging from 1410-1435 m in a grassland valley with fairly steep slopes and covers about 20 ha. The average peat depth varies between 1.5 and 5 m. About 19 ha of the peatland can be classified as a channelled valley-bottom mire with groundwater input from various springs in seep zones, whilst the adjacent 1 ha is an unchannelled valley-bottom system (Grundling, 2018).

### 4.1.1 Focus of the peatland study in the Malolotja Reserve

The aim of this component of the study was to analyse the hydrology and water quality of the dominant peatland complex located in the Malolotja Nature Reserve. In order to achieve this aim, the following objectives were identified for this part of the study:

1. To assess the temporal and spatial variability of water within the peatland, and so to determine the seasonal patterns of the water table within the peatland.
2. To assess the nature and extent of any vertical water flow within the peatland.
3. To trace the physico-chemical characteristics of the water in the main peat complex (physical – pH and temperature; and chemical – electric conductivity, ammonium, nitrate, nitrite, phosphate and hardness).
4. To characterize the Malolotja peatland on the strength of the field data collected.

Before concentrating on the nature of the research that was undertaken, it is necessary to digress and deal briefly with some foundational background concerning peatlands and their hydrological character. Hydrology is one the main factors determining the form of a peatland, its function and development (Weiss *et al.*, 2006; Mitsch & Gosselink, 2000; Mitsch &

Gosselink, 2007). Therefore, variations in water flow paths and water fluxes brought about by environmental change may influence the manner in which soluble and particulate carbon is redistributed within, or lost from, peatlands. In that sense, predictions of the consequences of environmental change on peatlands require a thorough understanding of the spatial and temporal variability of hydrological processes that occur within a peat wetland (Holden, 2006).

Information on the water levels and flows of water also offer an insight on where the water that maintains a peatland originates from, the direction it is moving towards as well as understanding the causes of changes, if any, in a peatland's water supply (Rydin & Jeglum, 2013). The height above the water table, which is the distance between the ground surface and the water table, is one of the important influences on vegetation structure, occurrence and growth (Hall *et al*., 2001). The water table tends to be close to the ground surface in "pristine" peatlands for the better part of the year (Rydin & Jeglum, 2013). Monitoring of wetland hydrology can also be conducted to determine if groundwater is a major contributor to the hydrology of the system.

Naturally, water contains various dissolved substances and suspended particles that are derived from the geology/rock, soil, air and organisms which influences the flora and fauna that can occur on a peatland and subsequently, the character of the organic material found on a peatland (Rydin & Jeglum, 2013). The water quality in peatlands is generally dependent upon the way that the water moves and its interaction with the peat layer (Freeze & Cherry, 1979; Daniels *et al*., 2010; Labadz *et al*., 2011). Additionally, the availability of plant nutrients such as carbon dioxide, phosphorus, potassium and nitrogen have been known to encourage high production rates (Parish *et al*., 2008).

Factors that may influence these movements and interactions include the underlying geology, the number and sources of water and the chemical characteristics of the atmosphere, as well as the vegetation and the peat itself (Labadz *et al*., 2011). Reactions with the soil and the bedrock occur as precipitation moves through the ground, altering the chemistry of the water. Consequently, Hall *et al*. (2001) note that water in the ground often has higher levels of cations and nitrogen, and a higher conductivity and pH in comparison to precipitation. The water quality of a wetlands, in general, is best described by the chemical composition of both the water at the wetland surface and below the surface (Mohamed & Zahir, 2013).

Monitoring the temporal and spatial variability of the water chemistry can reveal how the sources of water change in space and time (e.g. Urban *et al*., 1989; Constantz, 1998; Hayashi & Rosenberry, 2002; Lowry *et al*., 2007; Boreham, 2018). It may also suggest what the effects of external factors are on water chemistry (Johnson, 2004). This is often based on the differences in the water chemistry of precipitation and surface water samples. Water samples that have a groundwater influence have differing water chemistry from precipitation while water samples with limited groundwater influence have relatively similar water chemistry when compared to precipitation (Hoy, 2012).

## 4.2 METHODS USED TO INVESTIGATE THE DOMINANT PEATLAND AT MALOLOTJA

To gain insight into the hydrological processes that occur within the Malolotja peatland, a network of 10 wells and 18 piezometers was installed. The wells and piezometers were constructed of 5 cm diameter PVC piping and inserted into the peat using a hand auger to pre-drill and then manual pressure. The wells and piezometers located at specific monitoring points were prefixed with a letter from A to K referring to that point. Therefore, if a well (W) is located at point A, it was labelled "A-W" whereas a piezometer (P) would be labelled "A-P1" if it was piezometer 1 (Figure 4.2). The location and elevation of all the monitoring points was determined through a survey using a theodolite with monitoring points typically located 5-145 m apart (dependent on gradient and clear line-of-sight). The depth of the wells was determined by the occurrence of an impermeable layer with all 10 wells being approximately 2 m deep. The depth of the piezometers was dependent on the depth of peat and on whether or not inundation was observed at that specific monitoring point. More piezometers were installed on sites that had deep peat. Wells were slotted and covered in permeable filter throughout their entire length. Piezometers were slotted and covered with permeable material at the bottom 20 cm so as to provide a good indication of water flow and water pressure in the peat wetland. The vertical hydraulic gradient (VHG), which describes the difference in hydraulic head along a vertical flow path, was used to understand the direction of vertical water flow (Barackman & Brusseau, 2004). The VHG was calculated with the equation provided by Lee and Cherry (1978): ($\Delta h$ piezometer – $\Delta h$ well) / depth to piezometer screen. A positive VHG would be indicative of upwelling of water or discharge of water from an aquifer. Conversely, a negative VHG indicates down-welling (or aquifer recharge). Where no difference in hydraulic head was observed, the contribution of groundwater was deemed negligible. The locations and depths of the wells and piezometers are shown in Table 4.1.


**Figure 4.2** Map showing the locality of the network of wells and piezometers at points A to K (base map from Google Earth Pro Inc., 2020).

**Table 4.1** Locations and details of the wells and piezometers installed in the Malolotja peatland at points A to K

| Monitoring point | Latitude | Longitude | Elevation (m) | Description | Depth of well / piezometer (m) |
|---|---|---|---|---|---|
| A | S 26.13716° | E 031.11515° | 1 435 | Well | 1.75 |
| | | | | P1 | 1.26 |
| B | S 26.13727° | E 031.11484° | 1 428 | Well | 1.73 |
| | | | | P1 | 1.06 |
| | | | | P2 | 1.78 |
| | | | | P3 | 2.67 |
| C | S 26.13737° | E 031.11461° | 1 427 | Well | 1.75 |
| | | | | P1 | 1.26 |
| D | S 26.13746° | E 031.11450° | 1 425 | Well | 1.25 |
| E | S 26.13753° | E 031.11438° | 1 423 | Well | 1.7 |
| | | | | P1 | 1.24 |
| | | | | P2 | 1.96 |
| F | S 26.13809° | E 031.11402° | 1 419 | Well | 1.68 |
| | | | | P1 | 1.94 |
| | | | | P2 | 3.55 |
| | | | | P3 | 4.05 |
| G | S 26.13895° | E 031.11294° | 1 413 | Well | 1.75 |
| | | | | P1 | 0.79 |
| | | | | P2 | 1.72 |
| H | S 26.13988° | E 031.11272° | 1 413 | Well | 1.72 |
| | | | | P1 | 1.24 |
| | | | | P2 | 1.79 |
| I | S 26.13991° | E 031.11272° | 1 412 | Stream P1 | 1.68 |
| J | S 26.14007° | E 031.11264° | 1 414 | Well | 1.52 |
| | | | | P1 | 1.3 |
| K | S 26.14021° | E 031.11257° | 1 414 | Well | 1.61 |
| | | | | P1 | 0.64 |
| | | | | P2 | 1.61 |
| Rain gauge | S 26.13727° | E 031.11489° | 1 430 | Rain gauge | - |

At each of the cluster sites shown in Figure 4.2, the variables of temperature and water level in the wells and piezometers were monitored on a weekly basis from 14 April 2019 to 31 May 2020. Precipitation was monitored concomitant with these. In addition, water chemistry variables were monitored twice in winter (dry period) and again in summer (the wet period). A water pump allowed for a sample of water to be extracted from the pipes for the wells and piezometers, following which the electrical conductivity (EC) and the temperature were measured with an EC meter and a thermometer, respectively. EC was measured in $\mu S\ cm^{-1}$ (micro-Siemens per centimetre) at all the wells and piezometers as well as the Malolotja stream using a Hanna Instruments (HI-8733) portable multi-range conductivity meter, whilst water temperature was recorded using a Brannan digital test thermometer.

As indicated, water quality tests were conducted on four separate occasions: twice in the winter of 2019 for all wells, piezometers and the stream; and twice in the summer of 2020 for all wells, piezometers, the stream and the rain gauge. Tests were performed using the Merck MQuant® compact field laboratory kit for water testing. Samples were tested on site in the field to eliminate sample deterioration during transport. The parameters ammonium, nitrite, nitrate,

phosphate, residual hardness and pH were determined colorimetrically while carbonate hardness and total hardness involved titrimetric tests.
Rainfall data was collected from the on-site (standard) rainfall totalizer rain gauge (Figure 4.2), located at an altitude of 1430 m a.m.s.l. Rainfall data was also supplied by the Malolotja Nature Reserve through the weather station situated at the entrance of the reserve. This data was used on occasions where heavy rainfall was received or when equipment failure occurred such as the rain gauge tipping over due to animal interference.

## 4.3 STATISTICAL ANALYSIS OF THE DATA OBTAINED FROM FIELD INSTRUMENTATION

Descriptive or summary statistics (total number of observations, mean, standard deviation, minimum and maximum values) for each parameter were calculated in order to summarize the data in an organized manner and to uncover the basic characteristics of the hydrological variables. The statistical analyses that were undertaken as well as the software used are presented in Table 4.2.

**Table 4.2** Overview of statistical analyses undertaken on the data obtained at Malolotja

| Statistical analysis | Variables analysed | Software used |
|---|---|---|
| (i) Descriptive statistics – total number of observations, mean, standard deviation, minimum and maximum values | Water level, electrical conductivity, water temperature, pH, ammonium, nitrate, nitrite, phosphate and hardness | Microsoft Excel version 16.41 |
| (ii) Linear regression | Water level and rainfall, electrical conductivity and rainfall, water temperature and rainfall, water temperature and air temperature | Microsoft Excel version 16.41 |
| (iii) Shapiro-Wilk's and Levene's tests | Water level, electrical conductivity, water temperature | Statistical Package for Social Sciences (SPSS) version 20 |
| (iv) Kruskal-Wallis test | Water level, electrical conductivity, water temperature | SPSS version 20 |
| (v) Principal component analysis or factor analysis | Water level, electrical conductivity, water temperature, air temperature and rainfall | SPSS version 20 |
| (vi) Pearson's R correlation | pH, ammonium, nitrate, nitrite, phosphate, carbonate hardness and total hardness | SPSS version 20 |

The percentage of the time that the water table was within 0.3 m of the ground surface, i.e. the root zone of plants, was determined for each well. Water levels were referenced to zero as the ground level, therefore negative values indicate that water levels were below the ground surface and positive values show inundation (water above ground). Linear regression was used to assess whether variances in certain dependent hydrological variables (water level, electrical conductivity and water temperature) could be explained by selected independent variables (rainfall and air temperature). Regression was therefore used to assess the relationships between weekly rainfall and water level, weekly rainfall and electrical conductivity, weekly rainfall and water temperature, as well as air temperature and water temperature for individual wells, piezometers and stream. Additionally, regression was used to investigate delayed response times of the dependent variables (water level, electrical conductivity and water temperature) to weekly rainfall for periods of 1 to 4 weeks by "lagging" the dependent variables. The data were also assessed for normality and homogeneity of variance through the use of the Shapiro-Wilk's and Levene's tests, respectively.

The data was non-normal, therefore the non-parametric Kruskal-Wallis test was conducted to test for differences in water level, electrical conductivity and water temperature between the wells and piezometers. This also enabled pairwise comparisons of mean ranks to be assessed so as to identify which wells and piezometers behaved similarly. Multivariate analysis of continuous data was undertaken using principal component analysis (PCA) in order to classify the variables according to correlation and help uncover any relationships that may not have been apparent in the raw data. Finally, the strength of the relationships between the water quality parameters – pH, ammonium, nitrate, nitrite, phosphate and hardness – was estimated by using Pearson's R correlation.

## 4.4 RESULTS OBTAINED FROM THE FIELD DATA DERIVED FROM THE WELLS AND PIEZOMETERS

The elevation profile of the monitoring points located within the peatland complex are displayed in Figure 4.3. The mean water table during the monitoring period was -0.4 m with water levels ranging from -1.41 m to 0.06 m; the former was recorded from well K-W on 20 October 2019 and the latter from well F-W on 14 April 2019. The descriptive statistics of well water levels are presented in Table 4.3. Well F-W had the highest mean water level (mean = -0.034 m; n = 58), while the lowest mean water level was recorded from well K (mean = -0.990 m; n = 58). Well E-W exhibited the most stable water level in comparison with the other wells.

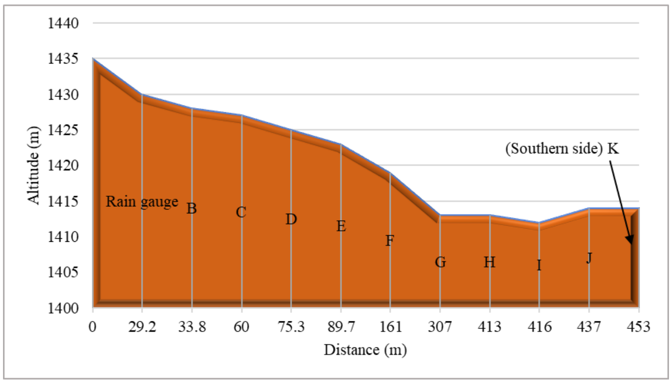


**Figure 4.3** Elevation profile of the peatland complex showing the location of the monitoring points.

**Table 4.3** Descriptive statistics of well water levels from 14 April 2019 to 31 May 2020

| Well | Number of observations | Mean water level (m) | Standard deviation | Minimum value (m) | Maximum value (m) | % water table >0.3 m |
|---|---|---|---|---|---|---|
| A-W | 58 | -0.590 | 0.043 | -0.73 | -0.49 | 0 |
| B-W | 58 | -0.067 | 0.067 | -0.33 | 0.01 | 98 |
| C-W | 58 | -0.044 | 0.062 | -0.22 | 0.05 | 100 |
| D-W | 58 | -0.834 | 0.080 | -1.07 | -0.7 | 0 |
| E-W | 58 | -0.084 | 0.010 | -0.34 | 0.02 | 98 |
| F-W | 58 | -0.034 | 0.066 | -0.26 | 0.06 | 100 |
| G-W | 58 | -0.084 | 0.064 | -0.32 | 0 | 97 |
| H-W | 58 | -0.625 | 0.138 | -0.97 | -0.44 | 0 |
| J-W | 58 | -0.618 | 0.207 | -1.07 | -0.28 | 2 |
| K-W | 58 | -0.990 | 0.223 | -1.41 | -0.53 | 0 |

The Kruskal-Wallis analysis, used to test if any significant differences in water levels existed between the individual wells, identified that there was a statistically significant difference in mean water levels between the 10 wells ($H = 480$; $df = 9$; $p = 0.000$). Generally, significant differences (at the 95% level) in water level were observed between the peripheral and central wells.

Well water level was also used to assess the hydrologic behaviour within the root zone of plants, (i.e. 0.3 m depth). The percentage that the water level was found within this zone was calculated for each well. All variations in water levels that occurred at wells B-W, C-W, E-W, F-W and G-W were close to or within the root zone (-0.3 m) regardless of the amount of rainfall received. In other words, these wells did not appear to be particularly sensitive to rainfall. There was noticeably more vegetation around these wells. Water levels in wells C-W and F-W remained in the root zone throughout the monitoring period. On the other hand, the water table was in the root zone for 0-2% of the time for wells A-W, D-W, H-W, J-W and K-W.

Figure 4.4 shows that the peripheral wells, especially those located on the southern side of the peatland, had lower mean water levels when compared to the north-eastern wells. Figure 4.5A and Figure 4.5B split the wells into two clusters: (A) wells B-W, C-W, E-W, F-W and G-W, in which the water table was frequently found within the root zone (97-100% of the monitoring period); and (B) wells A-W, D-W, H-W, J-W and K-W, in which the water table was infrequently found in the root zone (0-2%). Figure 4.4 and Figure 4.5 indicate that peripheral areas were drier than the central region of the peatland. It was surprising that the driest wells were the ones closest to the stream (H-W, J-W and K-W) because stream water was expected to be a major source of water either through surface or subsurface flow (i.e. base flow).

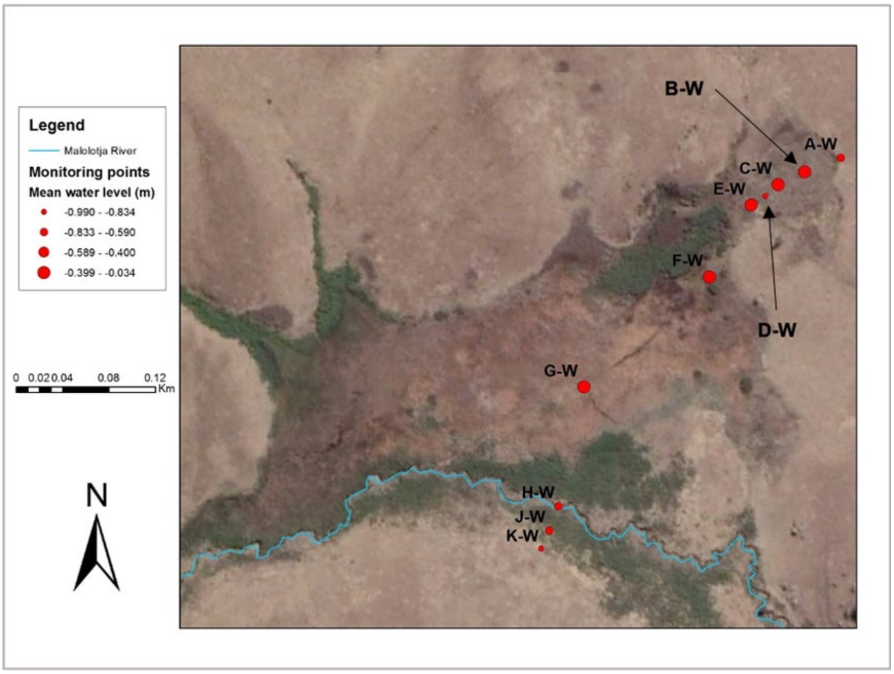


**Figure 4.4** Map showing the variation of water levels in the wells from 14 April 2019 to 31 May 2020.

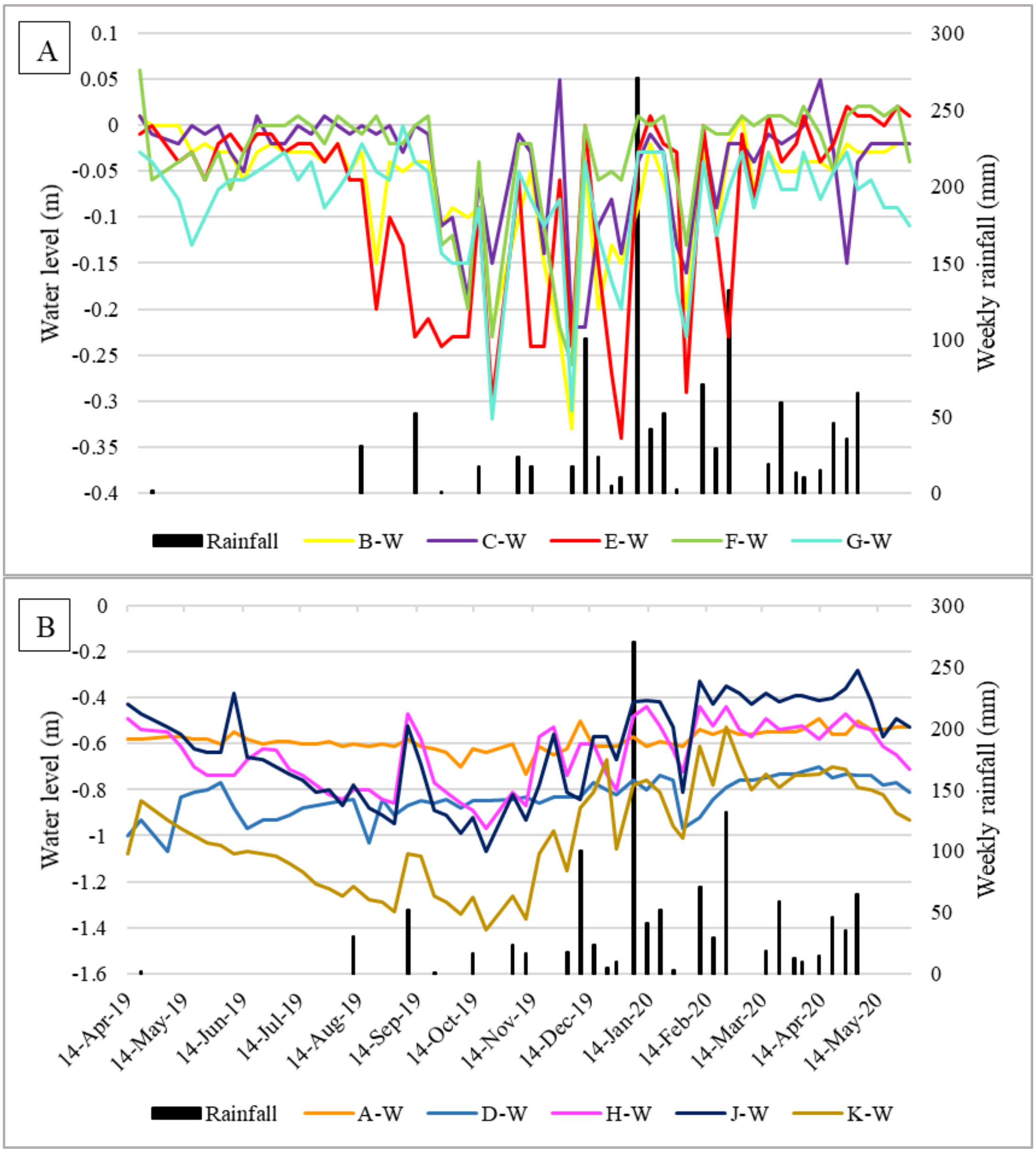


**Figure 4.5** Temporal variation of well water levels and rainfall from 14 April 2019 to 31 May 2020. Letters A to K represent the monitoring point and W indicates that this is well data only. (A) shows wells with a water table close to or within the root zone throughout the monitoring period and (B) shows wells with a water table infrequently found in the root zone.

The wells in Figure 4.5A and Figure 4.5B show a decline of water levels during periods of no rainfall. Figure 4.5A shows that water levels in wells B-W and E-W fell below 0.3 m on one occasion, while this occurred twice in well G-W. There was a drawdown in wells H-W, J-W and K-W in response to a dry period from April 2019 until August 2019 (Figure 4.5B). Water levels appeared to rise temporarily when rainfall was received and then dropped in the absence of rainfall. This suggests that a relationship exists between rainfall and water level at these aforementioned wells.

The relationship between rainfall and water level was investigated using a simple linear regression, with tests conducted at a 95% confidence rating. The five wells shown in Figure

4.5B (A-W, D-W, H-W, J-W and K-W) showed a significant regression of depth to water level on weekly rainfall, as shown in Table 4.4. Notably, these were the same wells in which the water table was infrequently found in the root zone. The significant p-values were, however, coupled with low $r^2$ values which infers that while precipitation has an influence on the water level, it could not account for all variations in the data. Water levels at wells B-W, C-W, E-W, F-W and G-W, on the other hand, did not show a significant regression of depth to water level on weekly rainfall. This therefore suggests that there are other sources of water that influence the peatland such as groundwater, surface or base flow from the stream and seepage from the adjacent slope.

The poor relationship between rainfall and depth-to-water level prompted an investigation into whether or not a delayed response in well water levels (or lag time) existed. Lag time was tested through a simple regression analysis at a 95% confidence rating. Analysis suggests that a lag time of some one to two weeks might exist for the southernmost wells that are closest to the stream (H-W, J-W and K-W). The simple, direct regression model could only explain 10% of the variation in well J-W after a week-long lag, which was higher than when no lags were considered. There were no significant relationships between well water levels and rainfall when lag times of between one and four weeks are taken into account for the remaining wells. The low $r^2$ values, however, fuel the assumption that the system is sustained by other sources of water, which explains why it is not as responsive to rainfall. It is also possible that the water at the peatland has a longer than expected lag or a delayed response of more than four weeks.

**Table 4.4** Linear regression between well water levels and rainfall ($r^2$ is the coefficient of determination and $p < 0.05$ indicates that the correlation is significant (shaded))

| Well | $r^2$ | p-value |
|---|---|---|
| A-W | 0.07 | 0.04 |
| B-W | 0.07 | 0.06 |
| C-W | 0 | 0.71 |
| D-W | 0.06 | 0.05 |
| E-W | 0 | 0.58 |
| F-W | 0.03 | 0.13 |
| G-W | 0.04 | 0.11 |
| H-W | 0.17 | 0.001 |
| J-W | 0.09 | 0.02 |
| K-W | 0.15 | 0.002 |

Shifting the focus away from the wells and onto the piezometers, Table 4.5 shows that piezometer water levels ranged from -1.39 m to 0.04 m, with the former recorded from K-P2 on 20 October 2019 and the latter from B-P3 on 15 July 2019. The mean water level for the entire monitoring period was -0.34 m. The negative value indicates that the water was below the ground surface. Piezometer K-P2 had the lowest mean water level (mean = -1.01 m, n=58), and corresponds to the well water level data because well K-W had the lowest mean water level. The highest mean water level, on the other hand, was recorded from piezometer B-P3 (mean = -0.03 m; n = 58).

**Table 4.5** Descriptive statistics of piezometer water levels from 14 April 2019 to 31 May 2020

| Piezometer | Number of observations | Mean water level (m) | Standard deviation | Minimum value (m) | Maximum value (m) |
|---|---|---|---|---|---|
| A-P1 | 58 | -0.77 | 0.07 | -1.01 | -0.61 |
| B-P1 | 58 | -0.11 | -0.6 | -0.30 | -0.03 |
| B-P2 | 58 | -0.14 | 0.06 | -0.39 | -0.06 |
| B-P3 | 58 | -0.03 | 0.06 | -0.31 | 0.04 |
| C-P1 | 58 | -0.41 | 0.14 | -0.84 | -0.20 |
| E-P1 | 58 | -0.25 | 0.11 | -0.63 | 0.12 |
| E-P2 | 58 | -0.37 | 0.17 | -1.06 | -0.19 |
| F-P1 | 58 | -0.15 | 0.06 | -0.38 | -0.08 |
| F-P2 | 58 | -0.26 | 0.05 | -0.35 | -0.13 |
| F-P3 | 58 | -0.23 | 0.07 | -0.42 | -0.03 |
| G-P1 | 58 | -0.09 | 0.06 | -0.31 | -0.02 |
| G-P2 | 58 | -0.26 | 0.11 | -0.78 | -0.11 |
| H-P1 | 58 | -0.69 | 0.14 | -0.97 | -0.33 |
| H-P2 | 58 | -0.69 | 0.14 | -0.97 | -0.3 |
| I-P1 | 58 | 0.26 | 0.14 | -0.01 | 0.67 |
| J-P1 | 58 | -0.61 | 0.2 | -1.02 | -0.31 |
| K-P1 | 1 | - | - | - | - |
| K-P2 | 58 | -1.01 | 0.2 | -1.39 | -0.64 |

Water levels at piezometer I-P1 (located in the stream) ranged from -0.01 m to 0.67 m. Water in this piezometer remained above the ground surface throughout the study period, save for three monitoring days. Piezometer K-P1 was dry on all but one day (3 May 2020). This occurred following eight weeks of rainfall totalling 261 mm. This not only suggests that a correlation between water levels and rainfall exists for the peripheral areas of the peatland, but also implies that there must be a delayed response in water levels following rainfall events. A Kruskal-Wallis analysis was conducted to test for significant differences in water levels across the piezometers. The analysis revealed that water levels differed significantly between the piezometers in a similar manner to that observed from the well water levels ($H = 870$; $df = 16$; $p = 0.0001$).

Variations in piezometer water levels occurred regardless of the amount of rainfall received (Figure 4.6). Piezometers at monitoring points B, E, F and G maintained water levels close to the ground surface throughout the monitoring period. The persistence of the water levels within the root zone even during the dry winter period suggested that groundwater contributed to the hydrology of the central region. This had already been observed from the well water levels. Water levels at monitoring points C, E, F and G rose during the dry period from April to August 2019. This may be a further indication of groundwater input in the central area of the system. Water levels in piezometers at monitoring points H, I, J and K, on the other hand, decreased progressively from April 2019, peaking in September following the second rainfall event, suggesting a relationship with rainfall. This strongly suggests that the central region of the peatland is mainly influenced by groundwater, while the periphery is influenced by rainfall to some degree.

The peripheral piezometers had the deepest water levels (Figure 4.6). These dry piezometers included the ones located south of the stream. Piezometer A-P1 had one of the lowest water levels observed from the system. Due to its high elevation it is likely that rainfall flows quickly, both in the lateral and vertical directions towards points B. This would also explain why point B was one of the most severely flooded throughout the monitoring period. A linear regression analysis was undertaken to test whether a significant relationship existed between rainfall and piezometer water levels. The results (Table 4.6) identified that 10 out of 17 piezometers did not show a significant regression of water level to rainfall at the 95% level. Those that did show a significant regression were located in the central and southern areas of the peatland. Piezometer I-P1 (located in the stream) had the most significant relationship ($p = 0.0002$), even though only 21% variation in the data could be explained by the regression model. It is important to highlight that stream flow could not be measured during this study period, but the data shows that a relationship between the stream flow and water levels in this piezometer needs to be investigated further. The two piezometers at the nest closest to the stream (H-P1 and H-P2) also had high significant p-values ($p = 0.002$) but the model could only explain a 15% variation in the data.

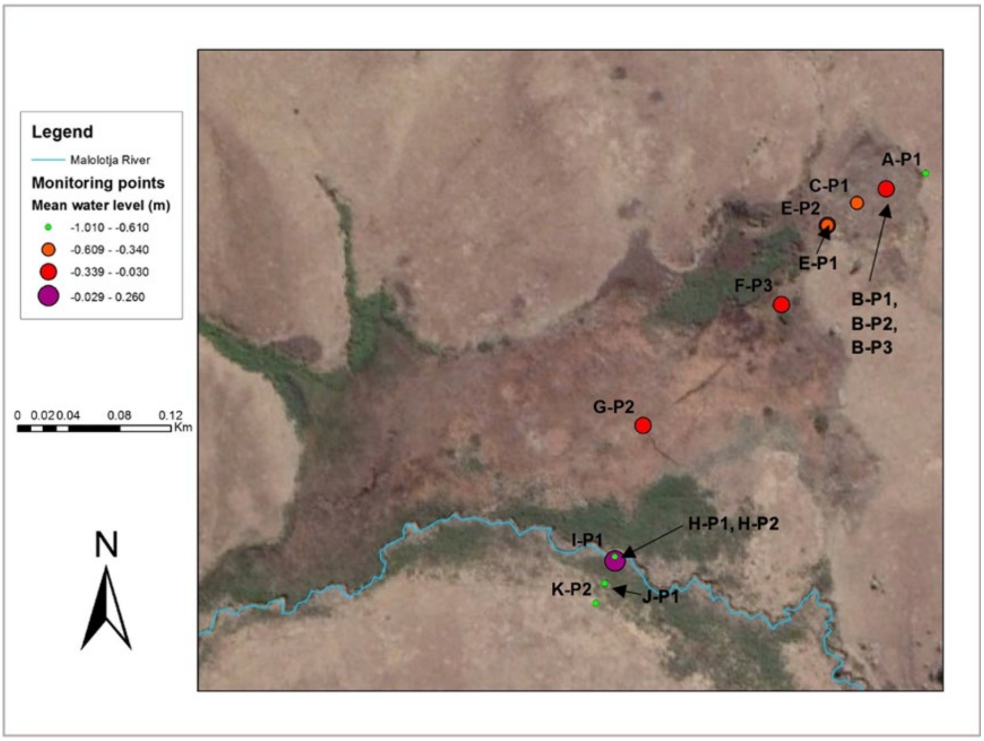


**Figure 4.6** Map showing the variation of water levels in the piezometers from 14 April 2019 to 31 May 2020.

**Table 4.6** Linear regression between piezometer water levels and rainfall ($r^2$ is the coefficient of determination and $p < 0.05$ indicates that the correlation is significant (shaded))

| Piezometer | $r^2$ | p-value |
|---|---|---|
| A-P1 | 0.02 | 0.24 |
| B-P1 | 0.01 | 0.53 |
| B-P2 | 0.01 | 0.42 |
| B-P3 | 0 | 0.66 |
| C-P1 | 0 | 0.95 |
| E-P1 | 0 | 0.78 |
| E-P2 | 0.05 | 0.10 |
| F-P1 | 0.03 | 0.17 |
| F-P2 | 0.04 | 0.11 |
| F-P3 | 0.06 | 0.05 |
| G-P1 | 0.06 | 0.05 |
| G-P2 | 0.09 | 0.02 |
| H-P1 | 0.15 | 0.002 |
| H-P2 | 0.15 | 0.002 |
| I-P1 | 0.21 | 0.0002 |
| J-P1 | 0.06 | 0.05 |
| K-P2 | 0.06 | 0.06 |

### 4.4.1 Nature of the hydrological flows within the Malolotja Peatland

The mean EC for all wells was relatively low (53.1 µS $cm^{-1}$). Descriptive statistics in Table 4.7 indicate that the EC ranged from 11 µS $cm^{-1}$ (well K-W) to 145.5 µS $cm^{-1}$ (well D-W). The lowest mean EC was recorded from well J-W (mean = 25.6 µS $cm^{-1}$; n = 55) while the highest mean EC was recorded from well D-W (mean = 92.56 µS $cm^{-1}$; n = 54). Well D-W had a larger range in electrical conductivity, as evidenced by the highest standard deviation of 20.3.

**Table 4.7** Descriptive statistics of electrical conductivity from 14 April 2019 to 24 May 2020

| Well | Number of observations | Mean EC (µS $cm^{-1}$) | Standard deviation | Minimum value (µS $cm^{-1}$) | Maximum value (µS $cm^{-1}$) |
|---|---|---|---|---|---|
| A-W | 54 | 61.11 | 16.24 | 33 | 106 |
| B-W | 54 | 56.91 | 9.63 | 35.5 | 80 |
| C-W | 54 | 69.61 | 7.25 | 51 | 85.5 |
| D-W | 54 | 92.56 | 20.3 | 62.1 | 145.5 |
| E-W | 54 | 50.17 | 9.64 | 34.4 | 74 |
| F-W | 55 | 58.01 | 19.74 | 32 | 106.1 |
| G-W | 55 | 43.17 | 10.07 | 28.4 | 66.3 |
| H-W | 55 | 41.71 | 7.61 | 32 | 67.8 |
| J-W | 55 | 25.60 | 6.94 | 15.7 | 55.1 |
| K-W | 52 | 32.11 | 14.53 | 11 | 68.7 |

A Kruskal-Wallis analysis showed that EC differed significantly by well (H = 369; df = 9; p = 0.000). Results of multiple comparisons of mean ranks for EC showed that the stream electrical conductivity was statistically different from all but two of the wells: J-W and K-W. Because those two wells are located close to the stream, the similarity in EC may suggest that there is some exchange of water between the stream and the adjacent peatland. It was also noted that wells E-W, F-W and G-W had similar conductivities. Due to the elevation profile of these three wells, it can be assumed that water flows from well E-W to wells F-W and G-W. Figure 4.7 shows a spatial difference in EC, with the north-eastern wells exhibiting higher ECs while the central and southern wells had lower mean ECs. Considering the fact that the north-eastern wells did not show a significant regression of water to weekly rainfall, it can be assumed that groundwater is a major influence on the north-eastern region of the peatland.

Five wells (A-W, B-W, C-W, D-W and F-W) had an EC that was above the overall average of 53.1 µS $cm^{-1}$ (Figure 4.8A) while the other five wells (E-W, G-W, H-W, J-W and K-W) had an EC that was below the overall average (Figure 4.8B). This means that the north-eastern area, save for well E-W, was characterized by higher ECs. Well D-W maintained the highest during the driest and wettest conditions of the study period. It is assumed that there is a change in geological strata at that monitoring point. Figure 4.8A also shows that EC steadily declined during the 2019 winter season. The graph shows a tendency of the EC in the five aforementioned wells (A-W, B-W, C-W, D-W and F-W) to be high in winter, a season that is characterized by little to no rainfall. EC values appeared to drop in summer when rainfall was received. This might be an indication that groundwater dominated the system in winter, leading to higher conductivity.

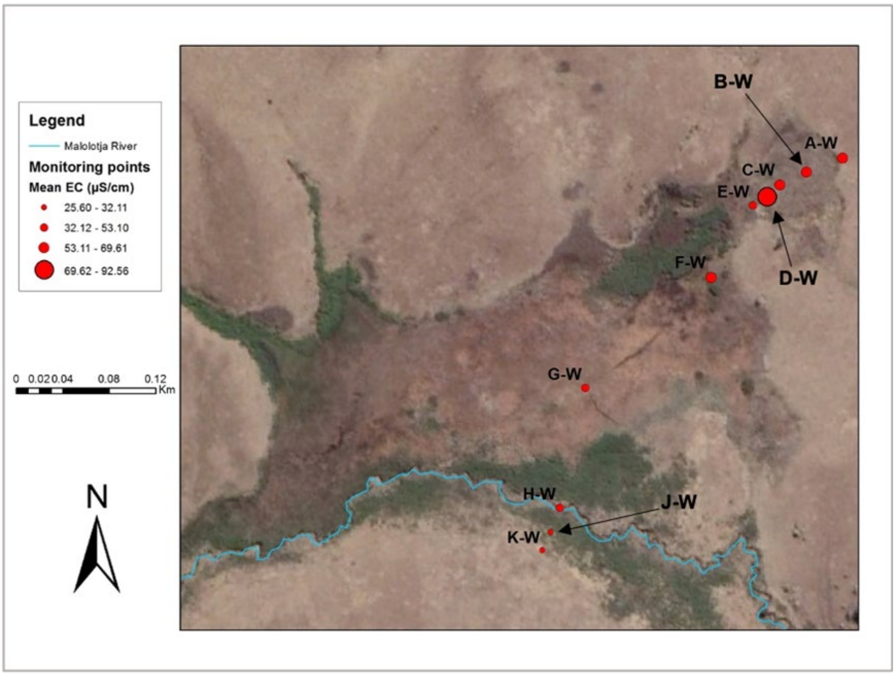


**Figure 4.7** Map showing the variation of electrical conductivity in the wells from 14 April 2019 to 24 May 2020.

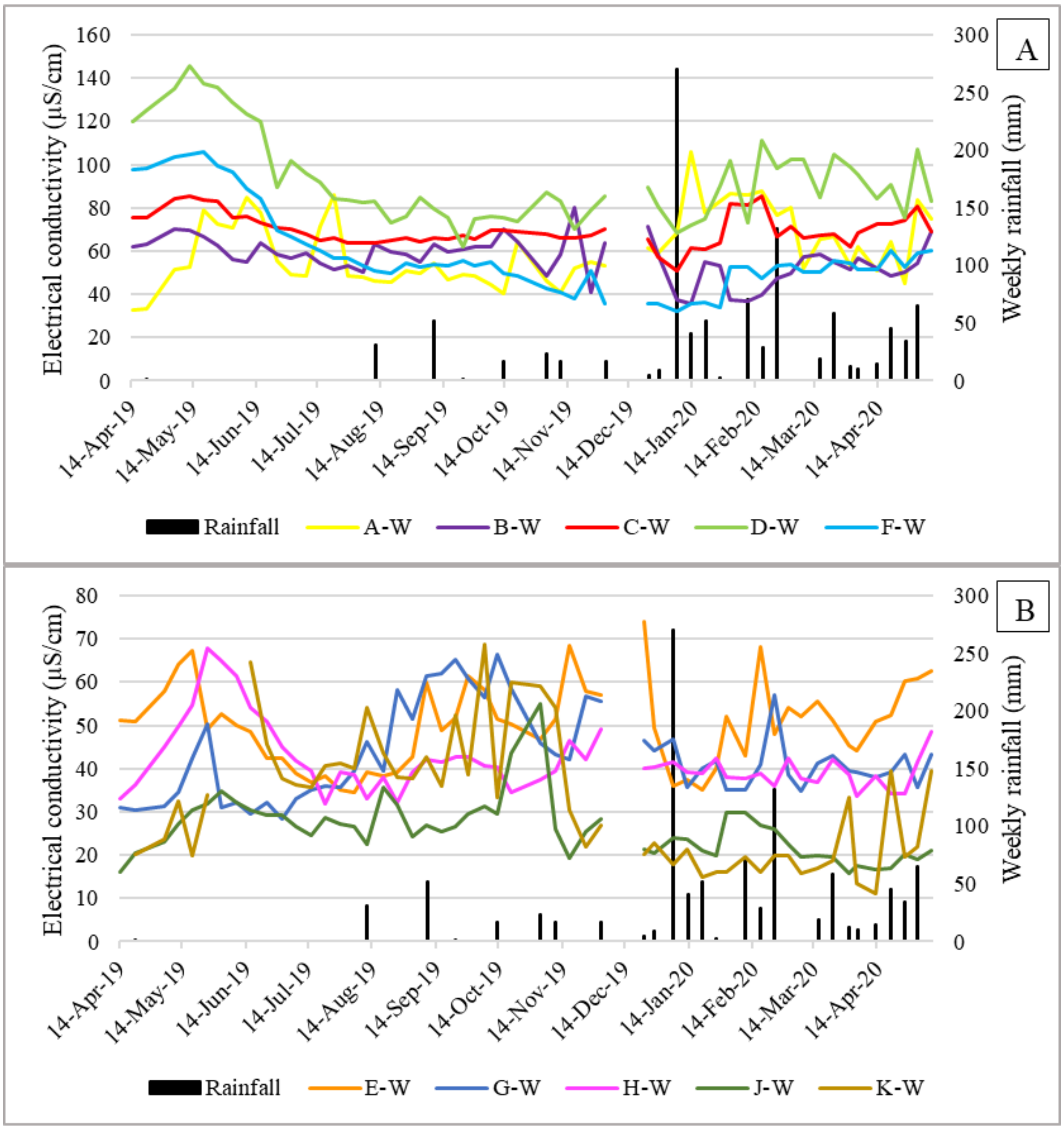


**Figure 4.8** Temporal variation of well electrical conductivity and rainfall from 14 April 2019 to 24 May 2020. Letters A to K represent the monitoring point and W indicates that this is well data only. (A) shows wells with an EC that was higher than the mean EC of the peatland and (B) shows wells with an EC that was lower than the mean.

In order to test for a relationship between rainfall and EC, a linear regression model was used. The results showed that the regression model between EC and rainfall was very weak, with four wells (B-W, C-W, F-W and K-W) exhibiting a significant regression of EC to rainfall at the 95% level (Table 4.8). Well B had the most significant p-value ($p = 0.0009$), even though only a 19% variation in the EC data could be attributed to rainfall. Due to the relatively low $r^2$ values identified in the analysis, it can be deduced that EC is not very sensitive to variations in rainfall.

**Table 4.8** Linear regression between well electrical conductivity and rainfall ($r^2$ is the coefficient of determination and $p < 0.05$ indicates that the correlation is significant (shaded))

| Well | $r^2$ | p-value |
|---|---|---|
| A-W | 0.05 | 0.1 |
| B-W | 0.19 | 0.0009 |
| C-W | 0.08 | 0.03 |
| D-W | 0.04 | 0.14 |
| E-W | 0.03 | 0.2 |
| F-W | 0.08 | 0.04 |
| G-W | 0.01 | 0.4 |
| H-W | 0.02 | 0.28 |
| J-W | 0.01 | 0.49 |
| K-W | 0.07 | 0.06 |

As before, it was also tested whether a lag time might exist between a rainfall event and a response of the EC recorded from the wells. The fact that the EC for the water might be dependent on multiple factors, such as the underlying geology, was also taken into account. Considering a lag time of one week, 23% of the variation at well A-W could be explained by the model. This was the highest $r^2$ value recorded from the analysis, including when no lag time was taken into account. The southern wells J-W and K-W exhibited lag times of between two to three weeks, even though the regression model could explain small variations in the EC. From this data it can be deduced that there is certainly some potential for a lag time to exist between EC and rainfall. This could be explored further when the data covering longer monitoring periods such as two to three years is available.

Turning attention to the piezometers, Figure 4.10 shows that the mean electrical conductivity for all piezometers was generally low (64.9 µS $cm^{-1}$). Summary statistics presented in Table 4.8 indicate that EC ranged from 19 µS $cm^{-1}$ in piezometer K-P2 to 266 µS $cm^{-1}$ in piezometer G-P2. The lowest mean EC was recorded from piezometer J-P1 (mean = 31.34 µS $cm^{-1}$; n = 55) while the highest mean EC was recorded from piezometer E-P2 (mean = 104.45 µS $cm^{-1}$; n = 54).

Figure 4.10 shows that the EC in piezometer G-P2 was very erratic and this was proven by the high standard deviation of 52.07 (Table 4.9). High conductivities were recorded in this piezometer from April 2019 and dropped in June of the same year. The available data cannot explain this occurrence. It is important to note, however, that while the EC was decreasing, a gradual increase in water levels was also observed during that same period. The same behaviour can be observed at monitoring point E, where the EC in the two piezometers was relatively high at the beginning of the monitoring period but decreased in June/July. Water levels at that monitoring point rose during the April/June period.

In general, lower ECs were recorded from the southern piezometers as shown by Figure 4.10. For this study, EC values were higher in the north-eastern region, supporting earlier observations concerning a high groundwater influence in that area. This might also be due to differences of underlying geology. There were also differences observed in EC between the shallow and deep piezometers. The shallower piezometers at points G (G-P1) and H (H-P1) had low EC values while the deeper piezometers (G-P2 and H-P2) had higher EC values. The same observation can be made at nest B, as the deepest piezometer (B-P3) maintained higher EC values by comparison with the shallower and intermediate piezometers at that nest, suggesting that the EC increases with depth here. This may be ascribed to an increase in inorganic solutes with depth. Piezometer I-P1 (in the stream) exhibited the least variation in EC as evidenced by the lowest standard deviation of only 4.42.

The results of multiple comparisons of mean ranks to assess pairwise differences in piezometer EC showed that, in a manner similar to that observed from the analysis involving wells, the stream had similar EC values to the piezometers at monitoring points J and K (Figure 4.11). In addition, the stream also had similar ECs to the shallower piezometers at monitoring points G and H. As previously stated, this might suggest that the stream contributes to the peatland hydrology of the points that are in close proximity to it.

**Table 4.9** Descriptive statistics of piezometer electrical conductivity from 14 April 2019 to 24 May 2020

| **Piezometer** | **Number of observations** | **Mean EC** (µS $cm^{-1}$) | **Standard deviation** | **Minimum value** (µS $cm^{-1}$) | **Maximum value** (µS $cm^{-1}$) |
|---|---|---|---|---|---|
| A-P1 | 54 | 67.79 | 20.63 | 38.6 | 114,3 |
| B-P1 | 54 | 74.88 | 5.61 | 55.1 | 83 |
| B-P2 | 54 | 78.51 | 7.35 | 61,4 | 97.5 |
| B-P3 | 54 | 97.12 | 9.18 | 54,2 | 119.5 |
| C-P1 | 54 | 83.55 | 10.63 | 57,2 | 114 |
| E-P1 | 54 | 102.57 | 35.98 | 51.8 | 199.5 |
| E-P2 | 54 | 104.45 | 33.12 | 70.8 | 22.8 |
| F-P1 | 55 | 55.28 | 5.72 | 33.5 | 66.9 |
| F-P2 | 55 | 53.45 | 12.42 | 30.3 | 82.5 |
| F-P3 | 55 | 51.6 | 8.16 | 28.1 | 69.9 |
| G-P1 | 55 | 33.83 | 5.73 | 20 | 54.3 |
| G-P2 | 55 | 98.07 | 52.07 | 49.3 | 266 |
| H-P1 | 55 | 36.15 | 5.77 | 25.4 | 52 |
| H-P2 | 55 | 44.92 | 8.55 | 26 | 57.3 |
| I-P1 | 55 | 56.49 | 4.42 | 45.7 | 67.1 |
| J-P1 | 55 | 31.34 | 6.67 | 19 | 43.3 |
| K-P1 | 1 | - | - | - | - |
| K-P2 | 52 | 32.84 | 11.31 | 18 | 78.2 |

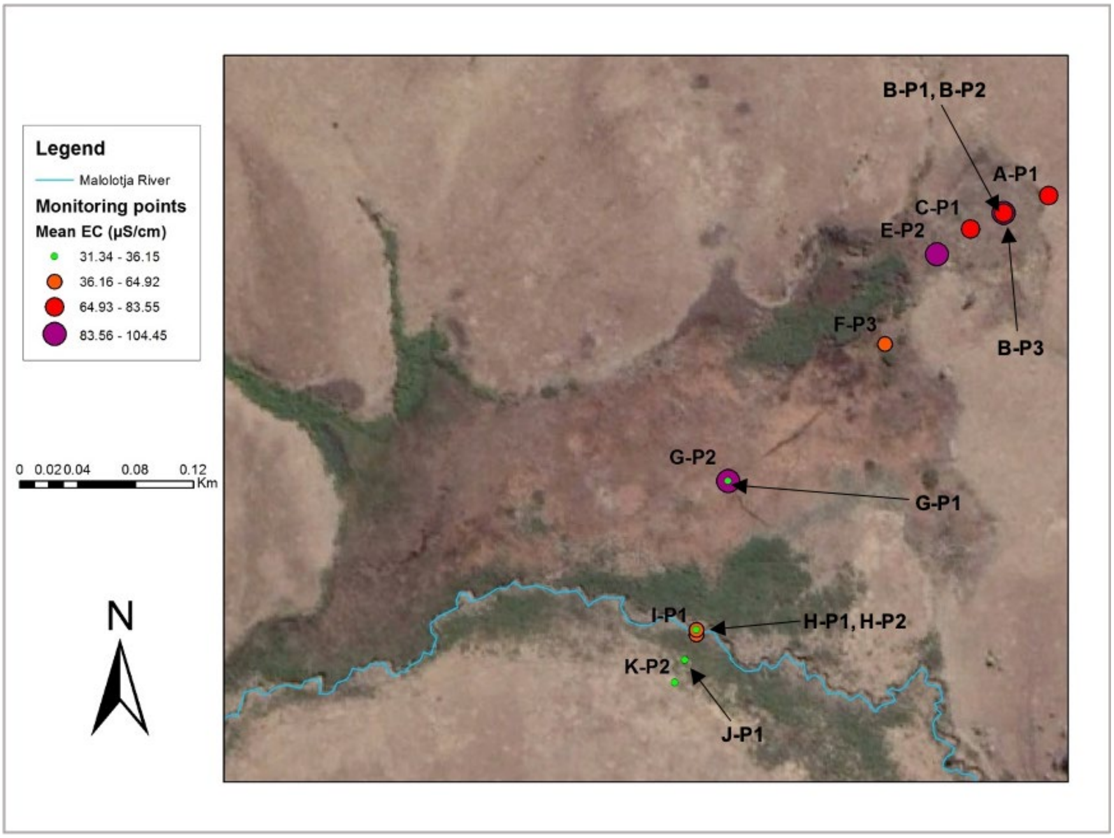


**Figure 4.9** Map showing the variation of piezometer electrical conductivity in the peatland from 14 April 2019 to 31 May 2020.


**Figure 4.10** Temporal variation of piezometer electrical conductivity and rainfall from 14 April 2019 to 24 May 2020. Letters A to K represent monitoring point and P1, P2, P3, etc. indicate that these are different piezometers.

A linear regression analysis was undertaken to test for a relationship between rainfall and electrical conductivity. The analysis in Table 4.10 reveals that only three piezometers showed a significant regression of EC to rainfall at a 95% confidence rating. The $r^2$ values were, however, extremely low, leading to the conclusion that no relationship exists between rainfall and EC in this analysis.

**Table 4.10** Linear regression between piezometer electrical conductivity and rainfall ($r^2$ is the coefficient of determination and $p < 0.05$ indicates that the correlation is significant (shaded))

| Piezometer | $r^2$ | p-value |
|---|---|---|
| A-P1 | 0.02 | 0.32 |
| B-P1 | 0.01 | 0.02 |
| B-P2 | 0.05 | 0.1 |
| B-P3 | 0 | 0.78 |
| C-P1 | 0.04 | 0.16 |
| E-P1 | 0.06 | 0.09 |
| E-P2 | 0.04 | 0.13 |
| F-P1 | 0 | 0.89 |
| F-P2 | 0.08 | 0.04 |
| F-P3 | 0.07 | 0.06 |
| G-P1 | 0.04 | 0.15 |
| G-P2 | 0.04 | 0.15 |
| H-P1 | 0 | 0.9 |
| H-P2 | 0.02 | 0.36 |
| I-P1 | 0.03 | 0.24 |
| J-P1 | 0.09 | 0.02 |
| K-P2 | 0.01 | 0.45 |

The likely existence of a delayed response between piezometer EC and weekly rainfall was again explored using a linear regression. As before, the regression model suggested the possibility of a lag time (Table 4.11). The model was stronger for most piezometers at a lag time of two weeks. The highest $r^2$ value, however, was recorded from piezometer B-P1 at a lag time of one week. There does not appear to be an important spatial difference in the delayed responses observed from analysis of the data. Additionally, both shallow and deep piezometers appear to have similar lag times.

**Table 4.11** Linear regression between piezometer electrical conductivity and rainfall for different lag times ($r^2$ is the coefficient of determination and $p < 0.05$ indicates that the correlation is significant (shaded))

| Piezometer | Lag = 1 week | | Lag = 2 weeks | | Lag = 3 weeks | | Lag = 4 weeks | |
|---|---|---|---|---|---|---|---|---|
| | $r^2$ | p-value | $r^2$ | p-value | $r^2$ | p-value | $r^2$ | p-value |
| A-P1 | 0.01 | 0.63 | 0.02 | 0.37 | 0.02 | 0.30 | 0.10 | 0.50 |
| B-P1 | 0.21 | 0.00 | 0.04 | 0.14 | 0.04 | 0.17 | 0.00 | 0.76 |
| B-P2 | 0.03 | 0.26 | 0.09 | 0.03 | 0.08 | 0.04 | 0.06 | 0.10 |
| B-P3 | 0.09 | 0.03 | 0.00 | 0.97 | 0.01 | 0.45 | 0.09 | 0.04 |
| C-P1 | 0.05 | 0.10 | 0.07 | 0.06 | 0.04 | 0.14 | 0.10 | 0.03 |
| E-P1 | 0.06 | 0.08 | 0.07 | 0.05 | 0.05 | 0.13 | 0.08 | 0.05 |
| E-P2 | 0.04 | 0.16 | 0.09 | 0.03 | 0.06 | 0.09 | 0.01 | 0.60 |
| F-P1 | 0.01 | 0.58 | 0.03 | 0.20 | 0.01 | 0.63 | 0.01 | 0.63 |
| F-P2 | 0.09 | 0.03 | 0.12 | 0.01 | 0.12 | 0.01 | 0.11 | 0.02 |
| F-P3 | 0.05 | 0.10 | 0.10 | 0.03 | 0.03 | 0.22 | 0.06 | 0.08 |
| G-P1 | 0.00 | 0.84 | 0.01 | 0.46 | 0.00 | 0.85 | 0.05 | 0.13 |
| G-P2 | 0.00 | 0.84 | 0.06 | 0.09 | 0.04 | 0.14 | 0.02 | 0.37 |
| H-P1 | 0.00 | 0.64 | 0.01 | 0.57 | 0.00 | 0.74 | 0.00 | 0.96 |
| H-P2 | 0.01 | 0.54 | 0.03 | 0.26 | 0.00 | 0.70 | 0.04 | 0.15 |
| I-P1 | 0.00 | 0.74 | 0.01 | 0.40 | 0.08 | 0.04 | 0.18 | 0.00 |
| J-P1 | 0.13 | 0.01 | 0.15 | 0.00 | 0.20 | 0.00 | 0.03 | 0.25 |
| K-P2 | 0.01 | 0.43 | 0.06 | 0.12 | 0.04 | 0.22 | 0.04 | 0.20 |

The analysis thus far has considered both the well water and the piezometers in terms of electrical conductivity. Figure 4.11 shows the temporal variation of EC in the Malolotja Stream, as well as weekly rainfall from 14 April 2019 to 17 May 2020. The obvious gaps in the data were due to equipment failure. The EC ranged from 20.8 $\mu S\ cm^{-1}$ to 34.7 $\mu S\ cm^{-1}$, with a mean value of 28.3 $\mu S\ cm^{-1}$ ($n = 54$). Many factors influence EC in rivers, including land-use and management (and thus potential pollution), land cover, geology, soil type, topography and catchment hydrology. It can be assumed that, since the entire catchment of the Malolotja River is contained within the reserve, land-use and management is one of the main factors that explains the relatively low EC values in the Malolotja Stream. In other words, the presence of the nature reserve means that most anthropogenic activities that could negatively impact the river chemistry are effectively minimized. The graph in Figure 4.11 shows that variations in EC occurred whether or not rainfall was received. Statistically, there was no significant relationship between EC and weekly rainfall ($r^2 = 0.0001$; $p = 0.936$). This indicates that intense rain events had no dilution effect on the surface water quality.

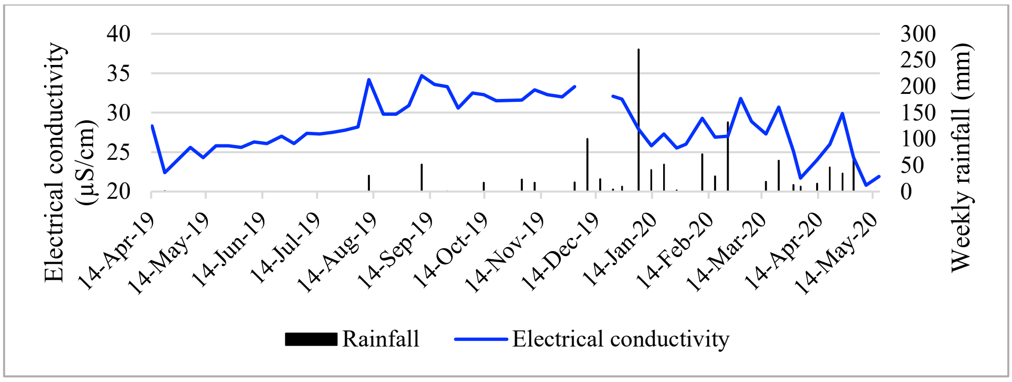


**Figure 4.11** Temporal variation of electrical conductivity of the Malolotja stream and rainfall from April 2019 to May 2020.

Reflecting on the electrical conductivity data, piezometers maintained the highest average EC throughout the monitoring period in comparison to both the wells and the stream, probably due to the increase of inorganic solutes with depth. The well EC was relatively low for all monitoring points where a well-piezometer network existed. Mots'ets'e (2016) found the opposite of this, with lower conductivities being recorded from the piezometers instead of the stream. It was argued in that study that this was likely a consequence of high organic matter in the soil, producing relatively high concentrations of carbon dioxide. Given that the Malolotja case is in a peatland (i.e. also high organic matter), there must be other factors at play to differentiate the results from these two studies.

### 4.4.2 Spatio-temporal variability of electrical conductivity in wells and piezometers and the Malolotja stream

Water temperature ranged from 12°C in winter to 22°C in summer which is indicative of a seasonal variation in temperature. All mean temperature values were in the range 16-17°C, with very slight differences in standard deviation (Table 4.12).

**Table 4.12** Descriptive statistics for well water temperature from 14 April 2019 to 31 May 2020

| Well | Number of observations | Mean temperature (°C) | Standard deviation | Minimum value (°C) | Maximum value (°C) |
|---|---|---|---|---|---|
| A-W | 51 | 17.65 | 1.68 | 13 | 22 |
| B-W | 51 | 17.06 | 2.19 | 12 | 22 |
| C-W | 51 | 16.63 | 2.28 | 13 | 22 |
| D-W | 51 | 16.86 | 2.27 | 12 | 22 |
| E-W | 51 | 17.12 | 2.35 | 12 | 22 |
| F-W | 51 | 16.61 | 2.35 | 12 | 22 |
| G-W | 52 | 16.58 | 2.46 | 12 | 22 |
| H-W | 51 | 16.51 | 1.95 | 12 | 22 |
| J-W | 52 | 17.15 | 2.15 | 13 | 20 |
| K-W | 52 | 17.81 | 2.04 | 14 | 22 |

Figure 4.12 shows the temporal variation of water temperature from all wells (locations as indicated in Figure 4.7), air temperature and rainfall as recorded from 14 April 2019 to 31 May 2020. Air temperature data was obtained from a weather station situated at the entrance of Malolotja Nature Reserve. The data plotted in Figure 4.12 suggests that there are minimal

differences in water temperature across the wells. The validity of this was tested with a Kruskal-Wallis analysis which showed that water temperatures did not differ significantly from well to well ($H = 19$; $df = 9$; $p = 0.122$). The wells were split into two clusters, one consisting of wells with a water temperature above the mean of 17°C and the other consisting of wells with water temperatures below the mean. As expected, a drop in the water temperature was observed from the all the wells during the winter period of June/July 2019. Data show a momentary rise in water temperatures following the rainfall events in August and September. It appears, however, that there was again a delay in the response of water levels of about a week following these rainfall events. In general, the lower temperatures were recorded at the central monitoring points, which were mostly inundated and/or surrounded by vegetation. It can therefore be assumed that the lower temperatures could have been a consequence of the shadowing effect of the vegetation. Maxwell (2016) reported similar findings in that the dryer wells had an average water temperature of 17.3°C while inundated wells had an average water temperature of 16.5°C.

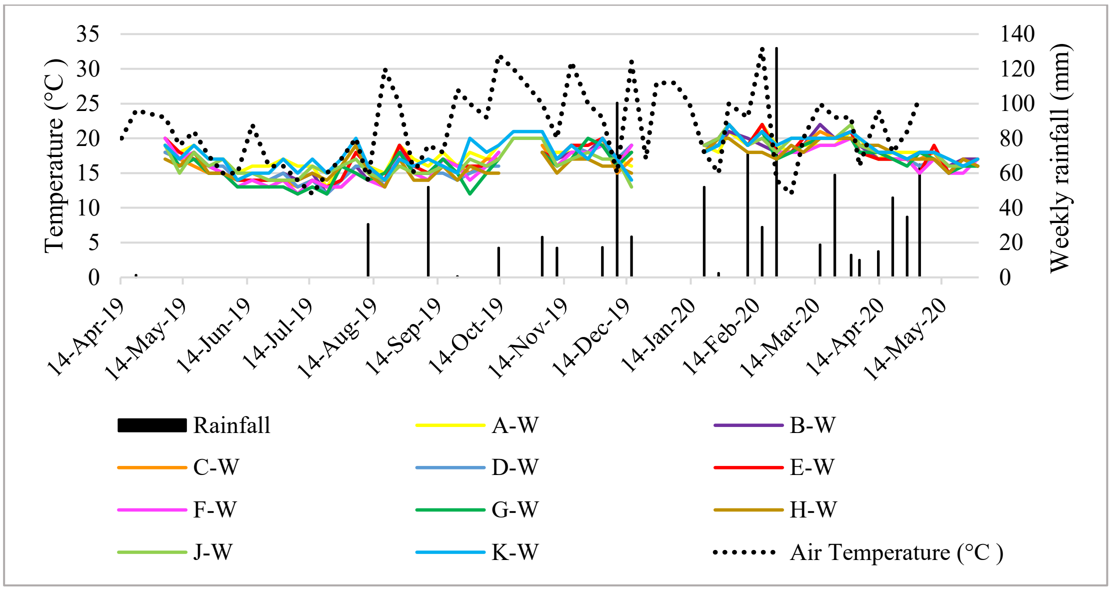


**Figure 4.12** Temporal variation of well water temperature, air temperature and rainfall from 14 April 2019 to 31 May 2020. Letters A to K represent the monitoring point and W indicates that this is well data only.

Figure 4.12 suggests that well water temperature fluctuates in relation to the air temperature. This is to be expected as the temperature of water below the ground largely depends on its temperature at recharge. A linear regression was undertaken to assess the relationship between air temperature and well water temperature. Table 4.13 presents the results of the regression model. All but three southern wells showed a significant regression of water temperature to air temperature and these wells were in close proximity to the stream. Variations in well water temperature are therefore likely to be related to the air temperature and water recharge.

**Table 4.13** Linear regression between well water temperature and air temperature ($r^2$ is the coefficient of determination and $p < 0.05$ indicates that the correlation is significant (shaded))

| Well | $r^2$ | p-value |
|---|---|---|
| A-W | 0.08 | 0.04 |
| B-W | 0.16 | 0.00 |
| C-W | 0.17 | 0.00 |
| D-W | 0.10 | 0.03 |
| E-W | 0.15 | 0.01 |
| F-W | 0.15 | 0.00 |
| G-W | 0.17 | 0.00 |
| H-W | 0.02 | 0.38 |
| J-W | 0.02 | 0.31 |
| K-W | 0.04 | 0.16 |

In an effort to test whether or not the rainfall received had an impact on the water temperature, a simple linear regression analysis was undertaken. All wells did not show a significant regression of water temperature on weekly rainfall. However, data was tested for time lag and the results suggest the presence of a lag time ranging from one to four weeks. The analysis could explain the greatest variation in water temperatures in the wells when a lag time of four weeks was applied. At four weeks, all wells showed a significant regression of water temperature on rainfall, even though rainfall could only account for a small percentage of the variation in the data. This allows for the inference that well water temperature probably has a lag time ranging from one to four weeks compared with air temperature, depending on the amount of rainfall received during that period.

Focussing attention on the water temperature in the piezometers (Table 4.14), a very slight seasonal variation in piezometer water temperature can be observed, with higher temperatures documented in summer and lower temperatures recorded in winter. Water temperatures ranged from 11-22°C. Piezometer temperatures decreased during the June/July 2019 winter period. Mean water temperatures ranged from 16-17°C, with a slight variation in the range of values. All of these values were similar to those recorded from wells. This is further evidence that a spatial variation in water temperature is minimal. Water temperatures recorded from the shallower piezometers were similar to those recorded from the deeper piezometers. This implies that temperature does not vary significantly according to depth. Figure 4.13 displays the temporal variation of piezometer water temperature, air temperature and rainfall from 14 April 2019 to 31 May 2020. The graph shows that depth had no influence on the water temperature recorded from the piezometers.

**Table 4.14** Descriptive statistics for piezometer water temperature from April 2019 to May 2020

| Piezometer | Number of observations | Mean temperature (°C) | Standard deviation | Minimum value (°C) | Maximum value (°C) |
|---|---|---|---|---|---|
| A-P1 | 51 | 17.69 | 1.59 | 13 | 21 |
| B-P1 | 51 | 16.84 | 2.28 | 13 | 22 |
| B-P2 | 51 | 16.80 | 2.23 | 13 | 21 |
| B-P3 | 51 | 17.00 | 2.14 | 13 | 21 |
| C-P1 | 51 | 16.55 | 2.28 | 11 | 21 |
| E-P1 | 51 | 16.82 | 2.27 | 12 | 22 |
| E-P2 | 51 | 16.84 | 2.09 | 13 | 21 |
| F-P1 | 51 | 16.73 | 2.09 | 13 | 22 |
| F-P2 | 51 | 16.73 | 1.96 | 13 | 21 |
| F-P3 | 51 | 16.78 | 1.98 | 13 | 21 |
| G-P1 | 52 | 16.44 | 2.47 | 12 | 22 |
| G-P2 | 51 | 16.55 | 2.20 | 13 | 21 |
| H-P1 | 51 | 16.22 | 1.97 | 13 | 21 |
| H-P2 | 51 | 16.29 | 1.84 | 13 | 21 |
| I-P1 | 51 | 16.47 | 2.35 | 12 | 22 |
| J-P1 | 52 | 17.02 | 2.08 | 13 | 21 |
| K-P2 | 45 | 17.87 | 1.79 | 14 | 22 |

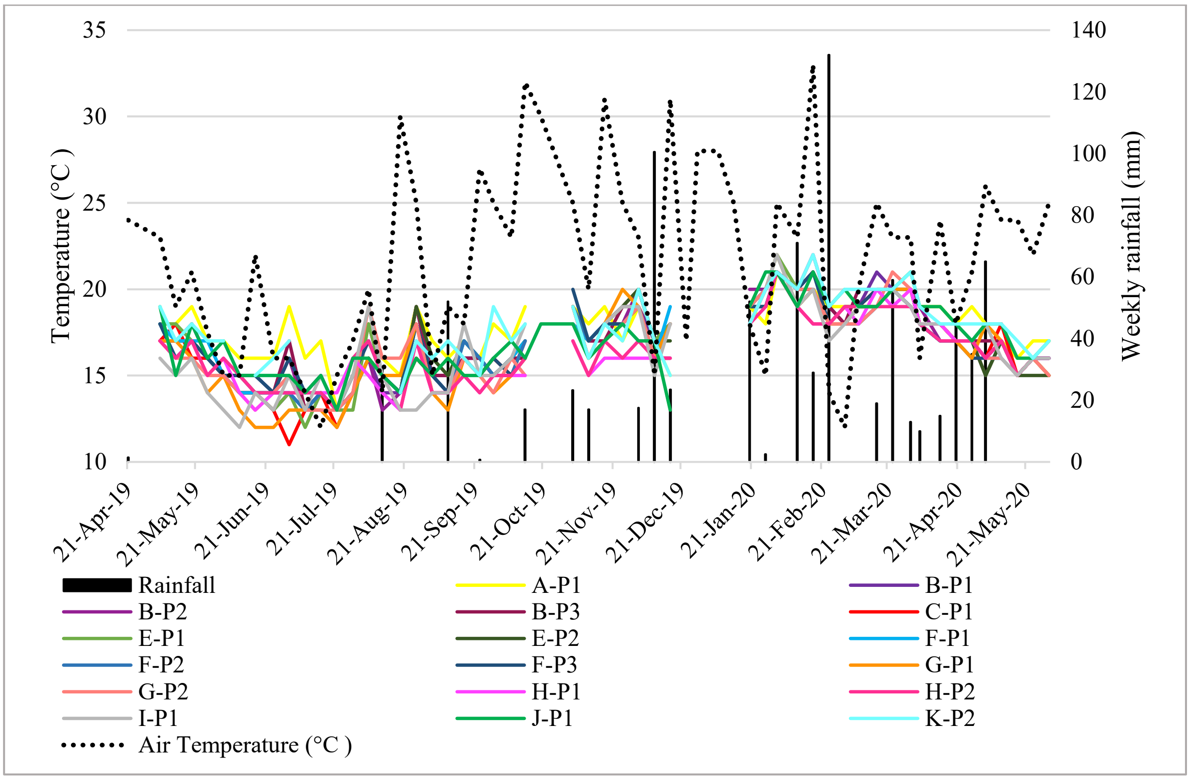


**Figure 4.13** Temporal variation of piezometer water temperature, air temperature and rainfall from 14 April 2019 to 31 May 2020. Letters A to K represent the monitoring points and P1, P2, P3, etc. show the different piezometers per site.

A Kruskal-Wallis analysis was undertaken to test for spatial differences in water temperature. Even though the analysis showed that water temperatures varied significantly ($H = 33$, $df = 16$, $p = 0.007$), the multiple comparison of mean ranks in Table 4.14 showed that the differences in temperature were minor. As observed from the wells, the peripheral piezometers had slightly higher water temperatures than the central wells (Figure 4.13).

The temporal variation of stream and air temperatures recorded from 14 April 2019 to 17 May 2020 is displayed in Figure 4.14. Temperatures were recorded at a depth of approximately 15 cm. Water temperatures ranged from 10-20°C, with a mean temperature of 16°C ($n = 56$). There were seasonal variations in water temperature, with cooler temperatures recorded in winter and warmer temperatures recorded in summer. Analysis of the graph in Figure 4.15 suggested that air temperature had an influence on the stream temperature, with stream temperatures warming when the ambient air temperatures were higher. As expected, the stream did show a significant regression of water temperature on air temperature ($r^2 = 0{,}135$; $p = 0.005$). The analysis shows that air temperature is one of the important factors determining stream temperature. The correlation is therefore accepted because they both react to the cycles of solar energy. The stream also showed a significant regression of temperature on weekly rainfall ($r^2 = 0.137$; $p = 0.005$).

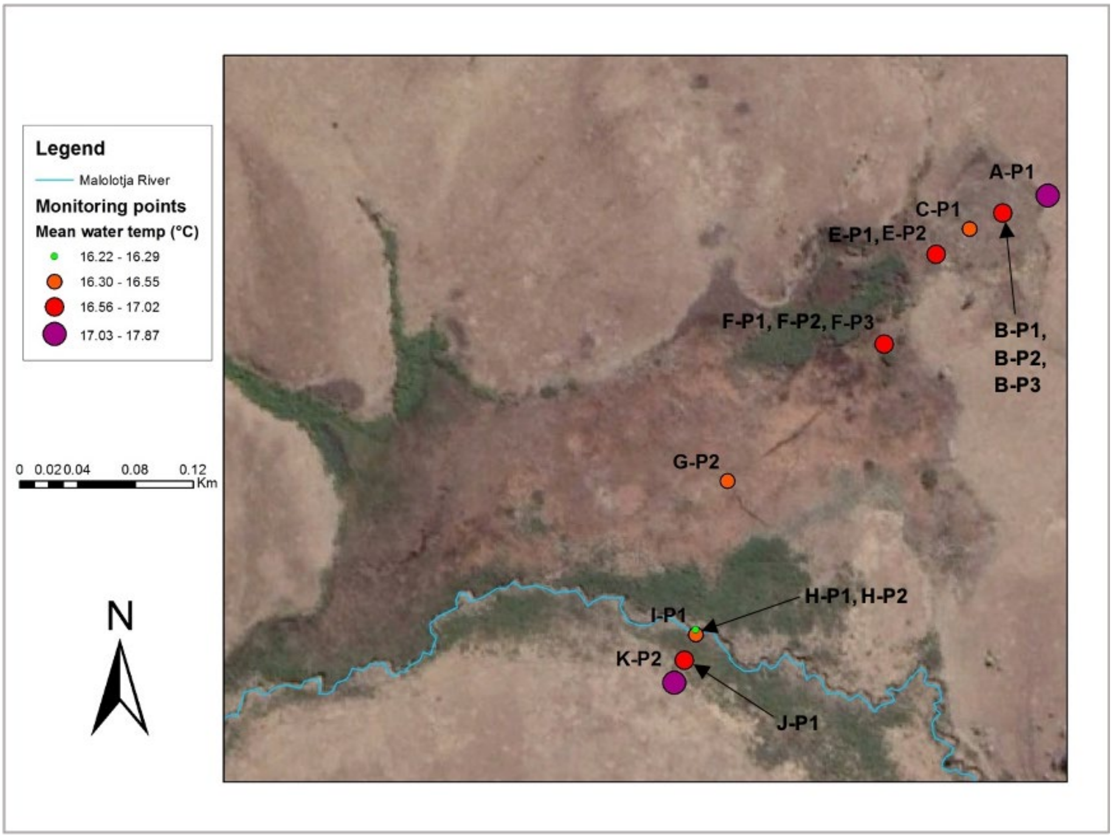


**Figure 4.14** Map showing the variation of water temperature in the piezometers from 14 April 2019 to 31 May 2020.

The relationship between piezometer water temperature and air temperature was again tested with a simple linear regression which showed that, even though the model was generally weak, it can be concluded that air temperature does have an influence on the water temperature, as might have been expected.

It was also investigated whether rainfall had any influence on water temperature. Most of the piezometers did not show a significant relationship of water temperature to rainfall. The regression model for air temperature and water temperature was much stronger than the one for weekly rainfall and water temperature – a relationship that might have been different had it been possible to use actual rainfall event data.

Given that delayed responses ranging between one and four weeks were observed for the wells, this was also explored for the piezometers. As was to be expected, water temperatures in the piezometers had a lag time of between one and four weeks. The regression model was at its strongest when a lag time of four weeks was considered, at which time all the piezometers showed a significant regression of water temperature to rainfall.

The temporal variation of stream and air temperatures was also recorded for the duration of the project (Figure 4.15). Stream temperatures were recorded at a depth of 15 cm. Water temperatures ranged from 10-20°C, with a mean temperature of 16°C (n = 56). There were seasonal variations in water temperature, with cooler temperatures not surprisingly being recorded in winter while warmer temperatures were recorded in summer. Analysis of the graph in Figure 4.15 suggests that air temperature has an influence on the stream temperature, with stream temperatures warming when the ambient air temperatures were higher. As expected, the stream did show a significant regression of water temperature on air temperature ($r^2 = 0{,}135$; $p = 0{,}005$). The analysis confirms the intuitive expectation that air temperature is one of the important factors determining stream temperature.

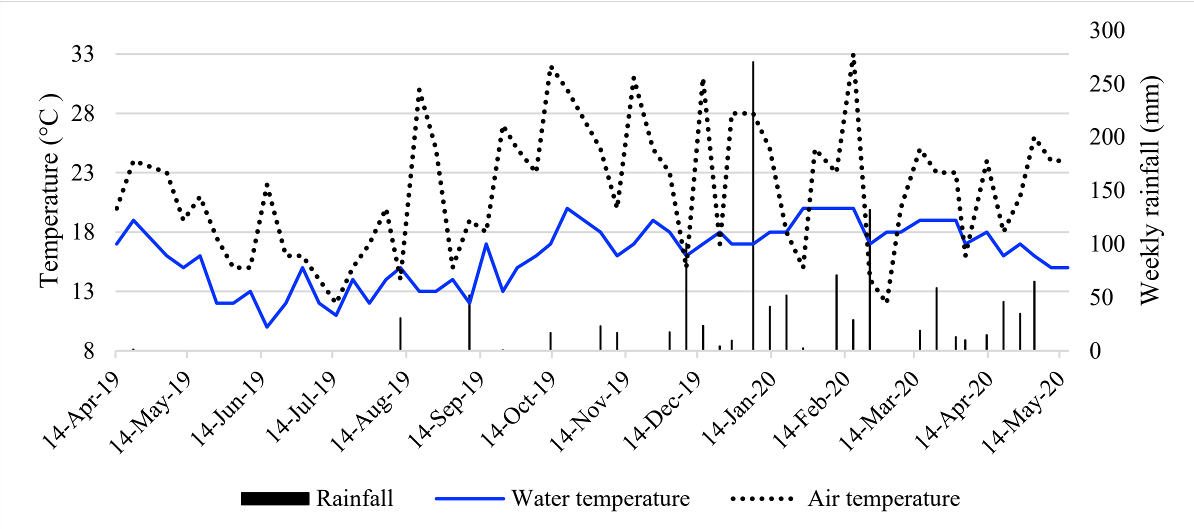


**Figure 4.15** Temporal variation of stream temperature, air temperature and rainfall from 14 April 2019 to 17 May 2020.

A comparison between piezometer, well and stream water temperatures suggests that water temperatures do not differ significantly between wells, piezometers and the stream. On average, the stream temperatures varied more on a weekly and seasonal basis when compared to well and piezometer water, which in turn corresponds with the findings of Lowry *et al*. (2007).

Analysis of the data shows that temperatures dropped slightly from April until the June/July period. This is assumed to be a consequence of the cooler winter season. Water from wells and piezometers averaged a mean temperature between 16-17°C, while temperatures as low as 10°C were recorded from the stream in winter. The greater responsiveness of surface waters to temperature is also supported in the findings of MacIntyre *et al.* (2002), who observed surface water temperatures to even be cooler in the morning and warmer in the afternoon. It is perhaps important to note here that for logistical reasons, monitoring and measurement at the Malolotja peatland was always undertaken between 08h00 and 09h00 each week.

## 4.5 INVESTIGATING THE INTERRELATIONSHIP BETWEEN THE VARIABLES PRESENTED THUS FAR USING MULTIVARIATE ANALYSIS

Multivariate analysis of the data presented thus far was performed using a principal component analysis (PCA). The PCA was performed to reduce the large dataset into a few factors or principal components which could then be interpreted to reveal the underlying data structure. The PCA was performed on a set of five parameters for the wells and piezometers (water level, water temperature, EC, rainfall and air temperature) and a set of four parameters for the stream (water temperature, EC, rainfall and air temperature). Table 4.15 shows the loading varimax rotated factor matrix, the Eigen values, the percentage of variance, as well as the cumulative percentage of the rotated variance associated with each other. For this study, factor loadings exceeding 0.4 were considered significant.

For wells, piezometers and stream, two significant principal factors explain 61.6%, 64.9% and 63.8% of the total variation in the hydrology, respectively. For the wells and piezometers, these variances are contained under Factor 1, which comprises water level and rainfall, and thus Factor 1 may be interpreted as representing water level for the wells and piezometers. This corroborates what was stated in section 4.4.1, that a relationship exists between rainfall and water levels in wells and piezometers. Factor 2 in the wells and piezometers could be interpreted as the temperature factor, again confirming that stated in section 4.4.2.

For the stream, the variation is also contained under Factor 1 but is associated with the variables air temperature, water temperature and EC. This factor could be interpreted as the water quality factor. A linear regression had already established a relationship between the stream temperature and ambient air temperature. In fact, air temperature is one of the most important factors that influences stream temperature. It is not surprising that EC is correlated with temperature because conductivity often rises as the temperature increases. EC does not appear as strongly in the multivariate analysis for the wells and piezometers, probably as a result of the buffering influence of the lag time already noted. Had it been possible to monitor the variables on a daily basis (or better still an hourly basis through autographic recorders), the results of the multivariate analysis might well have been somewhat different.

**Table 4.15** Rotated component matrix of hydrological parameters for wells, piezometers and the stream (shaded cells show factor loadings > 0.4)

| Variable | Wells | | Piezometers | | Stream | |
|---|---|---|---|---|---|---|
| | Factor | | Factor | | Factor | |
| | 1 | 2 | 1 | 2 | 1 | 2 |
| Water level | 0.852 | -0.058 | 0.879 | -0.051 | - | - |
| Rainfall | 0.767 | 0.235 | 0.768 | 0.145 | -0.186 | 0.886 |
| Air temperature | -0.394 | 0.803 | -0.306 | 0.872 | 0.837 | 0.100 |
| Water temperature | 0.273 | 0.789 | 0.353 | 0.691 | 0.496 | 0.676 |
| EC | -0.267 | -0.372 | -0.423 | -0.372 | 0.564 | -0.060 |
| Eigen values | 1.689 | 1.390 | 1.901 | 1.342 | 1.498 | 1.056 |
| % variance | 33.785 | 27.804 | 38.017 | 26.848 | 37.449 | 26.394 |
| % cumulative | 33.785 | 61.589 | 38.017 | 64.865 | 37.449 | 63.843 |

## 4.6 DISCUSSION OF THE DATA DERIVED FROM THE MALOLOTJA PEATLAND

The findings of this section of the study dealing with the Malolotja peatland, presented thus far, have indicated a spatial and a temporal differentiation of the water table in the main peatland complex of the Malolotja wetland. The northern and central areas maintained water levels that were close to or within the root zone (i.e. within -0.3 m) even during the dry winter season. Conversely, water in the peripheral region was infrequently found in the root zone, with water levels decreasing progressively during the dry 2019 winter period. Peatlands that occur under "favourable conditions" are likely to have a water table perpetually close to the ground surface. Due to the absence of many anthropogenic pressures at the Malolotja Reserve (and hence the peatland), water loss mainly occurs via evaporation or diffuse overland or near surface flow, from the central region of the peatland towards the peripheral regions.

Water level measurements displayed a delayed response to rainfall. The southern points appeared to have a lag time of about one to two weeks while the northern and central points might have a longer lag time of up to four weeks. Hydromorphic soils and a higher clay content were observed on the northern and central points, which might explain why the downward movement of water was slower. Mots'ets'e *et al*. (2017) argued that a delayed response in water level was indicative of high runoff during rainfall (or towards the end of rainfall events) as well as the presence of an additional source of water such as subsurface flow (or some form of base flow). The persistence of the water levels close to the ground surface in the central region of the Malolotja peatland (even in rain-free periods), the upward movement of water observed from piezometers in the dry season, and the correlation between rainfall and water level, suggest that there may be other important sources of water for the peatland apart from direct rainfall itself.

The data suggest that there may be strong linkages between the stream water and the water level in the wells and piezometers, either through surface stream flow, or subsurface (i.e. base) flow, or both. It is unfortunate that stream flow could not be closely monitored as the rules governing the reserve prohibited the installation of the appropriate monitoring equipment. Mekiso *et al*. (2013) were able to monitor the stream flow as well as rainfall and peatland water level elsewhere and reported that variations in water levels appeared to be strongly correlated to stream flow instead of rainfall, and it is hypothesized that the same may be occurring here. The permeable soils of the system studied in the cited study allowed very rapid movement of water both in the lateral and vertical directions and therefore rainfall was likely to be able to flow rapidly away from the site after most rainfall events.

Statistically, the electrical conductivity of the southern points and of the stream were not significantly different, further suggesting that the stream contributes to the hydrology of the peatland system in the southern area. This is likely to be through subsurface movement in the form of base flow. Another likely source of water for the Malolotja peatland is slope seepage due to the surrounding relief of the peatland, especially the slopes defining the northern border. Support for this hypothesis are the highly permeable valley slopes of the Matlabas Mire in the Limpopo Province of South Africa, which act as recharge areas that enable the flow of groundwater towards the wetland (Grundling *et al*., 2017). A more detailed understanding of the geological setting of the Malolotja peatland as well as the adjacent landscape and its geohydrology will allow for a better understanding of how water enters and flows within the system. In addition, the elevation profile of the peatland shows a gradual downward slope from the north to the centre; therefore it can be hypothesized that water moves towards the centre of this peatland.

In a separate study, Cole *et al*. (1997) concluded that the lack of a strong relationship between rainfall and water level for one of the wetland systems was indicative of the system's dependence on groundwater recharge as opposed to rainfall. The water table is likely to be found within the root zone for the better part of the year for sites in which the groundwater is a major water source. Sites influenced by both surface and groundwater tend to have a less stable hydrological regime, with the water table within the root zone less frequently by comparison with the groundwater dominated sites, as were observed in several of the sites in the Malolotja peatland. It is therefore hypothesized that slope-related groundwater input also influences the hydrology of the Malolotja peatland complex, particularly in the northern and central areas.

Overall, the data suggests that there is a consistent downward movement of water in the system. This is supported by more negative than positive vertical hydraulic gradients being observed during the 13-month monitoring period. Consistent down-welling implies that the peatland serves as a recharge area for an underlying aquifer. While the high clay content of the peatland soil is capable of slowing down the downward movement of water, it cannot prohibit aquifer recharge. The findings also suggest that down-welling mostly occurs in the dry winter season whereas frequent up-welling episodes were observed in the wet summer season. Following a heavy rainfall event in February 2020, gaining vertical gradients were observed from more piezometer nests than before this event.

Even though the EC of precipitation was measured from the rain gauge for comparative purposes, the data could not be used with any reliability as this water was often contaminated by bird droppings, making the measurements untrustworthy. The northern and central monitoring points in the peatland had relatively higher conductivities by comparison to the southern points. The EC in the north-east was higher in the dry winter season of 2019 and lower in summer, once rainfall was received. This may be due to groundwater-dominated flow during the dry season (and a related increase in solutes from the underlying geology) and rainwater-dominated flow in the wet season.

The EC can also be used as a means to determine where the boundary between the precipitation-dominated and the groundwater-dominated conditions of the peatland lies, and is considered further evidence that the northern and central areas are likely to have localized connections with groundwater flow. This might also explain why the EC in these areas does not appear to be responsive to rainfall. Differences in peat composition (as a result of differences in vegetation communities), accumulation and mineralization can also result in spatial differences in conductivities, and need to be investigated in the future. The northern and central regions of the peatland also appear to have a higher organic matter content than the peripheral areas, offering a further explanation for the high EC. The EC of the stream was very low, especially when compared to other rivers in the country. For example, the EC range of the Great Usuthu River is between 86.9 µS $cm^{-1}$ and 1244 µS $cm^{-1}$ (Nkambule, 2016) while that of the Malolotja River was only 20.8 µS $cm^{-1}$ to 34.7 µS $cm^{-1}$. It is unfortunate that comparable information on river chemistry in north-western Eswatini is limited, but it could potentially be explained by anthropogenic influence.

Water temperature was the most stable variable throughout the monitoring period with all wells and piezometers averaging a water temperature between 16 and 17°C. There were, however, slight spatial variations observed in water temperature, with the peripheral monitoring points exhibiting higher temperatures in comparison to the central peatland, likely due to the cool groundwater inputs at the centre. Water temperature also fluctuated in response to air temperature and this was evidenced by a significant relationship between the two. A principal component analysis confirmed the positive effect of air temperature on water temperature.

## 4.7 CONCLUSION FROM THE MALOLOTJA PEATLAND

A joint reconnaissance undertaken in 2018 led to the documentation of a peatland within Malolotja Nature Reserve. Due to the uncertainty regarding the true extent of peatlands in Eswatini, this is assumed to be the first official record of peatlands within the country. While it is widely acknowledged that the primary characteristic of peatlands is their high organic content, their ability to retain water and thus their hydrological properties control their existence and development. Therefore, in order to characterize the hydrology of the peatland, a network of 10 wells, 18 piezometers and a rain gauge was installed at specific monitoring points within the peatland. Monitoring of various hydrological parameters was initiated on 14 April 2019 until 31 May 2020. Monitoring of water levels, electrical conductivity, water temperature, rainfall and air temperature was conducted weekly.

The findings suggest that the northern and central areas of the peatland have a shallow water table with high EC and low water temperatures, while the peripheral areas have a deeper water table, lower EC and higher water temperatures. The dominant water sources for the peatland appear to be rainfall, groundwater, the stream and slope seepage.

It is recommended that long-term and detailed monitoring of peatland hydrology be undertaken within Eswatini to allow for a comparison of such results with similar parameters in southern Africa and elsewhere.

# 5. EXTENT, DISTRIBUTION AND DESCRIPTION OF WETLANDS IN KGASWANE MOUNTAIN RESERVE

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## 5.1 INTRODUCTION

Wetlands are important systems within our landscape. The formation of different types of wetlands is due to local variations in climate, geology, topography and soils and the way in which these factors control hydrology (Tooth, 2018). Since southern Africa has a mean annual rainfall that is generally much less than its potential evapotranspiration, a majority of the larger wetland systems that occur in southern Africa are linked in some way to streams or groundwater (Ellery *et al*., 2008). In addition, factors that serve to impede drainage or reduce infiltration, which are often related to geology and geomorphology, are needed to maintain most moderate to large wetlands in southern Africa (Tooth and McCarthy, 2007). The Kgaswane Mountain Reserve, located at Rustenburg in the North West Province, hosts a variety of interesting wetlands ranging from seeps to peatlands (e.g. Waterkloof Spruit peatland) in geomorphological diverse landforms such as alluvial fans, synclines and incidental wetlands.

## 5.2 AIMS

1) The first aim of the project was to map the different hydrogeomorphic wetland types in the Kgaswane Mountain Reserve, South Africa.
2) The research aim is to determine the relationships between the distribution of wetlands types, underlying geology and related processes including hydrology, geomorphology and vegetation in Kgaswane Mountain Reserve, South Africa and illustrate this with conceptual hydrological/geomorphology response diagrams.

## 5.3 OBJECTIVES

### 5.3.1 Kgaswane Mountain Reserve wetland map (Catchment scale)

The objectives for this part of the study were to:
1. Map the extent of wetland areas in the Kgaswane Mountain Reserve.
2. Classify these wetland areas as hydrogeomorphic wetland types.

### 5.3.2 Kgaswane Waterval peatland conceptual hydrological/geomorphology response diagram (Catchment scale)

The objectives for this part of the study were to:
1. Describe the geomorphology template.
2. Describe the hydrology: water source and flow paths.

## 5.4 METHODS

### 5.4.1 Kgaswane Mountain Reserve wetland map (Catchment scale)

Wetland mapping, based on the definition in the National Water Act (RSA, 1998), began by using a variety of Geographical Information System (GIS) techniques to identify potential wetlands in the Kgaswane Mountain Reserve. This included deriving morphometric parameters from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) and scanning the study area using Google Earth Pro (Google Earth Pro Inc., 2021) in order to gain an understanding of the study area. Throughout various field visits conducted during the course of this project, areas identified as potential wetlands were verified based on the guidelines and procedures of DWAF (2005). These guidelines state that a wetland delineation must identify the outer edge of the temporary zone of the wetland, as this marks the boundary between the wetland and adjacent terrestrial areas. This is because the temporary zone remains flooded, or saturated, for long enough to develop anaerobic conditions and determine the nature of the plants growing in the soil.

Verification points were used to determine the change in vegetation gradient and elevation change associated with the presence of a wetland in the Kgaswane Mountain Reserve. These points were then used to map the edges of the wetlands located within the study area using the imagery of different years in Google Earth Pro (Google Earth Pro Inc., 2021). Wetlands were thereafter classified into the hydrogeomorphic units of Ollis *et al*. (2013) using data derived from both desktop and field-based mapping exercises.

### 5.4.2 Kgaswane waterval peatland conceptual hydrological/geomorphology response diagram (Catchment scale)

#### *5.4.2.1 Geology and geomorphology*

Geological and geomorphological controls were determined using ArcMap (ESRI, 2018) with satellite imagery and geological maps obtained from the University of the Free State. The satellite images and geological maps were compared and possible fault lines identified. To supplement the identification of possible fault lines, a detailed description of the Rustenberg Fault by Bumbly (1997) was used to digitize the geological features contributing to the morphology of the wetland. GIS was used to identify geomorphic features such as changes in elevation, changes in slope, stream characteristics and alluvial deposits. The identified geological and geomorphological control points were subsequently verified in-field. In-field observations were based on landscape position, landform characteristics, wetland morphometry, hydrology and substrates. In addition, hydrogeomorphic units and wetland extent were used as reference for field observations and GIS analysis. A particle size analysis was performed on the bottom sediments of the peatland in order to understand the forming environment of the wetland (Hjulstrom, 1935; Hugget, 2011).

Peat cores were collected using a Russian peat corer. This is an auger specifically manufactured by Eijkelkamp to extract half-cylindrical cores that allow for easy identification and preservation (Gabriel *et al*., 2018). The cores were used to identify substrates and the resulting holes were used to construct wells and piezometers. Peat cores were classified according to the proposed classification system developed by Gabriel *et al*. (2018). Some peat properties were determined to aid in the classification thereof. Organic matter was determined with the loss of ignition method, whereby samples were dried for 24 hours, weighed and placed in a furnace at

550°C for one hour then weighed again, with the pre- and post-ignition weights being used to calculate carbon content (Schulte & Hopkins, 1996). Degree of decomposition was determined using the in-field squeezing method outlined by Von Post (1922).

#### *5.4.2.2 Hydrology (Rainfall, water monitoring readings and isotopes analysis)*

***Rainfall***

Rainfall data for the Kgaswane Mountain Reserve was acquired from the NW Parks Board.

***Water monitoring readings***

Numerous linear transects were installed along various wetlands within the study site (Figure 5.1). Cole *et al*. (1997) gives the procedures for studying wetland hydrology using wells and piezometers. This method provides the basis on which other wetland studies are built today, when studying water table fluctuations, seasonal changes or subsurface flow (Cao *et al*., 2012; Montalto *et al*., 2006). Locations for wells and piezometers were determined by looking at the direction and length of the hydraulic gradient. Each point identified consisted of a well and a piezometer, which were constructed using a 5 cm diameter PVC (polyvinyl chloride) pipe. The wells were slotted in full length and the piezometers were only slotted at the bottom 20 cm. This allowed water to enter the wells throughout the PVC pipe, thereby revealing an accurate representation of groundwater level, whilst water could only enter the piezometers from the bottom, thus giving a good indication of groundwater flow and pressure in the wetland. The wells and piezometers were typically placed 1 m apart and after they were installed, the top of the hole was grouted using clay to prevent water flowing into the borehole. They were then capped and marked for identification. After the installation of the wells and piezometers, water depth was determined by measuring the depth to water from the top of the PVC pipe and subtracting the length of the protruding end. By doing this, the height of the water table was revealed as well as the height of the pressure head.

Cole *et al*. (1997) also provided a description of the data that will be gathered. The main feature that stood out was that groundwater levels were measured relative to site-specific ground level. Data gathered from piezometers revealed the potential source of water for the wetland. When there is a positive head differential between the well and piezometer, there is a good possibility that groundwater discharge is a source at that specific site (Cole *et al*., 1997).

The wells and piezometers were used to monitor water levels with a Solinst water level meter from 2019 to 2021 (Table 5.1). Electrical conductivity (EC) and temperature of the water were also recorded using a handheld EC and temperature sensor.

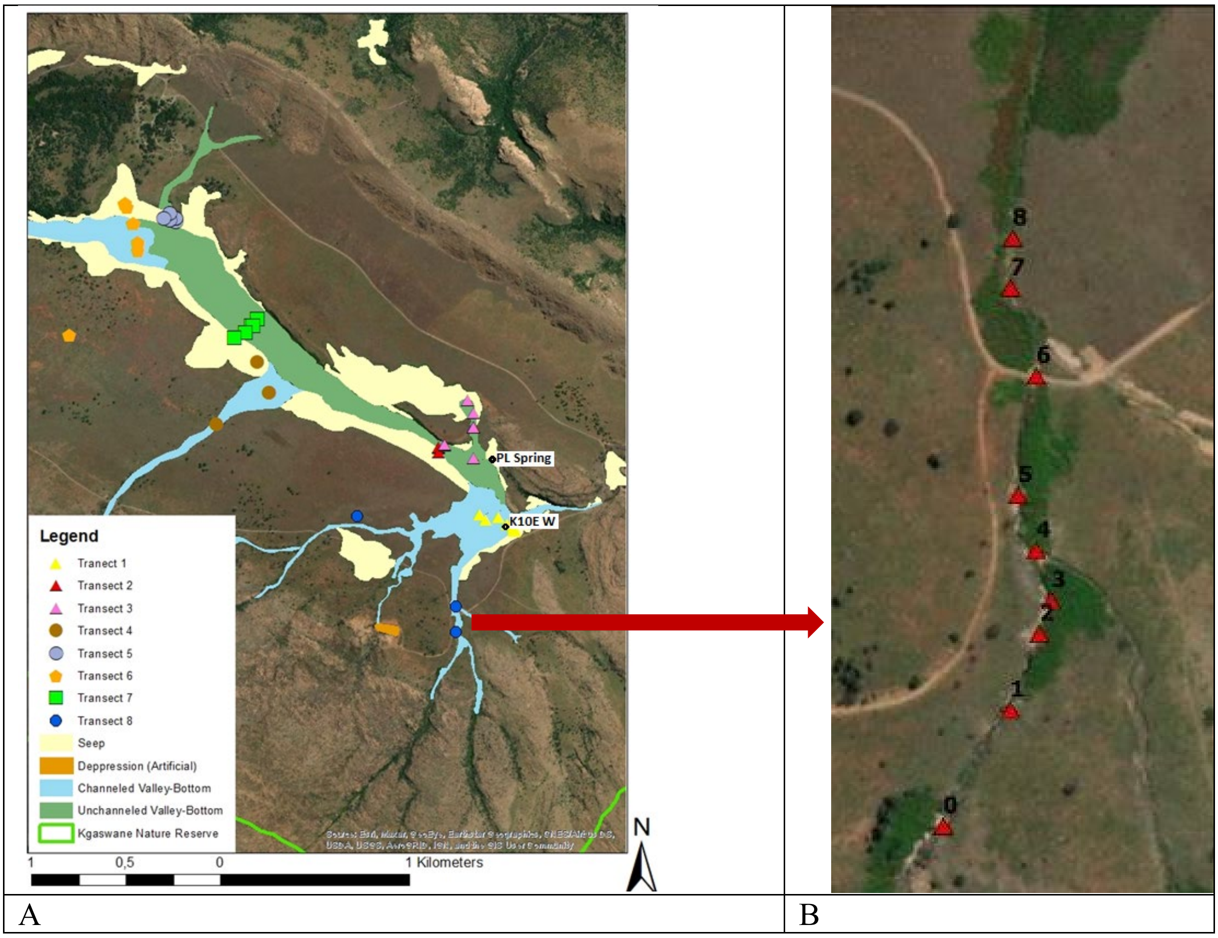



**Figure 5.1** A) The Kgaswane Mountain Reserve study area. Water level monitoring being done along eight transects and points indicated on the map. B) Enlarged view of the rehabilitation structures along the first tributary.

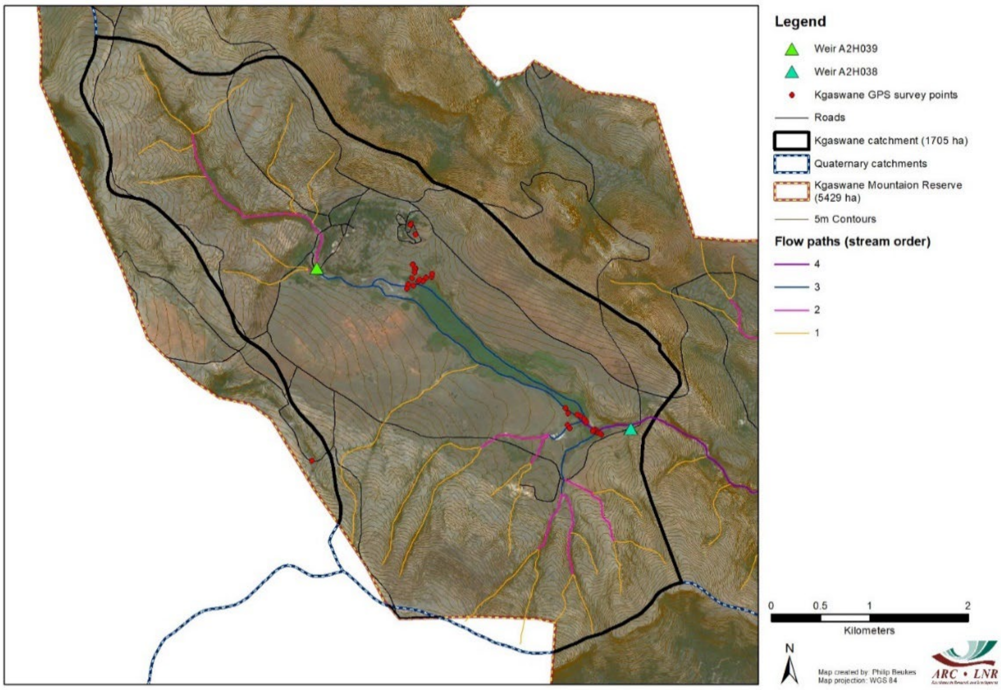



**Figure 5.2** Stream orders and Department of Water Affairs upper (A2H039) and lower weir (A2H038) locations in Kgaswane Mountain Reserve.

**Table 5.1** Dates on which the water monitoring was done

| WATER MONITORING SITES | 23-Mar-19 | 26-Apr-19 | 02-May-19 | 08-May-19 | 10-May-19 | 23-May-19 | 28-May-19 | 05-Jun-19 | 18-Jul-19 | 06-Aug-19 | 23-Oct-19 | 28-Nov-19 | 14-Jan-20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transect 1- Drainage Line 1 | x | x | x | | | x | | x | x | | x | | |
| Transect 2 - Narrow Reeds | x | x | x | | | x | | x | x | x | x | x | x |
| Transect 3 - Seepage | x | | | | | x | | x | x | | | | |
| Transect 4 - Drainage Line 2 | | | x | | | x | | x | x | | x | x | x |
| Transect 5 - Picnic Site | | | x | | | x | | x | x | | x | x | |
| Transect 6 – Interaction Zone | | | x | | | x | | x | x | | x | x | x |
| Transect 7 - Broad Reeds | | | | | x | | x | x | x | | x | x | x |
| Transect 8 - Rehabilitation | x | x | | x | x | | x | x | | | | | |
| Peat Site | | x | | | | x | | x | | | x | x | x |
| Upper Weir | | | | | x | x | | x | | | | x | |
| Lower Weir | | | | | | | | | | | | x | |

### *Isotope analysis*

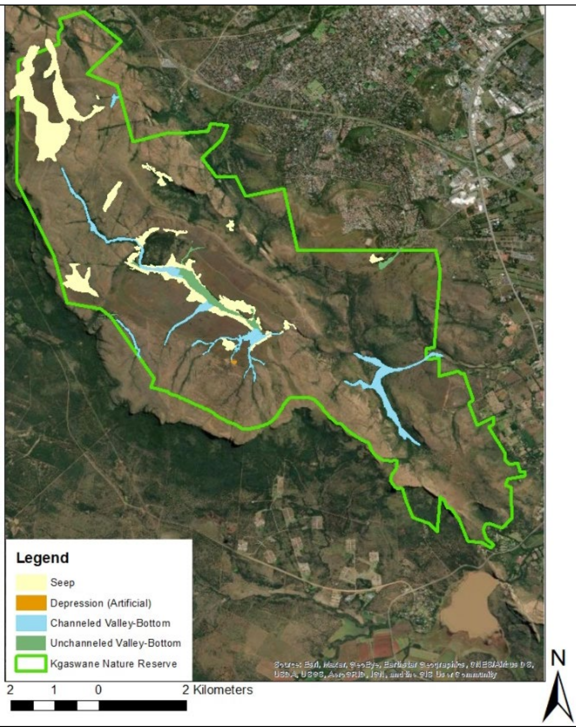
Water samples were collected on 4 and 5 February 2021 for isotope analysis. D/H (2H/1H) and 18O/16O ratios were determined by the Environmental Isotope Laboratory of iThemba Labs in Johannesburg using a Los Gatos Research liquid water isotope analyser. Laboratory standards, calibrated against international reference materials, are analysed with each batch of samples. The analytical precision is estimated at 0.5‰ for O and 1.5‰ for H, which applies to D/H (2H/1H) accordingly. These delta values are expressed as per mil deviation relative to a known standard, in this case standard mean ocean water (SMOW).

## 5.5 RESULTS

### 5.5.1 Kgaswane Mountain Reserve wetland map (Catchment scale)

Results of the mapping exercise are displayed in Figure 5.3A. Hydrogeomorphic wetland types (Ollis *et al*., 2013) identified in the reserve include channelled and unchannelled valley bottoms, seeps, as well as an artificial depression that is most likely associated with an old road quarry. Results indicate that wetlands occupy 370.42 ha of Kgaswane Mountain Reserve. Seep wetlands occupy the largest surface area of 244 ha, with 22 natural seeps and one incidental seep (discussed in Grundling *et al*., 2020) being identified. Fourteen channelled valley bottoms were identified with a total surface area of 86 ha, whilst six unchannelled valley bottoms were identified with a total surface area of 40 ha. The largest wetland that occurs in the reserve is the Waterkloof Spruit peatland, an unchannelled valley bottom with a surface area of 28.4 ha, which forms part of the 40 ha comprising unchannelled valley-bottom wetlands. The size of the artificial depression is 0.42 ha.

A




B

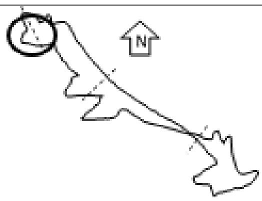
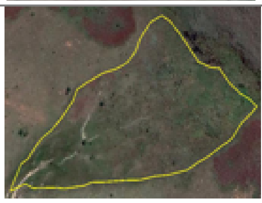
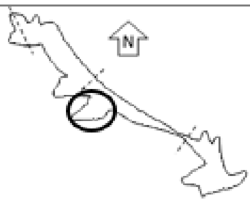
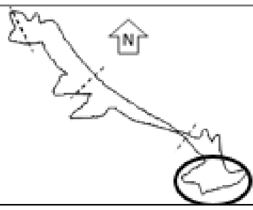
| Alluvial Fan | Shape | Location | Perimeter | Area |
|---|---|---|---|---|
| 1. Upstream alluvial deposits from the Waterkloofspruit. |  |  | 830m | $32.2m^2$ |
| 2. Middle reaches alluvial deposit from tributary. |  |  | 900m | $40.2m^2$ |
| 3. Downstream alluvial deposit from tributary. |  |  | 1460m | $78.9m^2$ |

**Figure 5.3** A) Hydrogeomorphic wetland units mapped in the Kgaswane Mountain Reserve and B) extent, location and size of alluvial fans providing sediment buffers.

### 5.5.2 Kgaswane Waterval peatland conceptual hydrological/geomorphology response diagram (Catchment scale)

#### *5.5.2.1 Geology and geomorphology of the Kgaswane Mountain Reserve*

This section provides a broad overview of the geomorphology of the Kgaswane headwater wetland system, located on the Waterkloof Spruit in the Kgaswane Mountain Reserve, south-east of Rustenburg. Upstream, Waterkloof Spruit is a closed system with a drainage area of approximately 17 km$^2$ and a flow length of approximately 6 km up to the outlet of the main headwater wetland. The source of the main channel is 1645 m a.m.s.l., from where it descends into a valley where the main headwater wetland is located, ranging from 1485-1435 m a.m.s.l. (Smakhtin & Batchelor, 2005). The wetland is located within the Magaliesberg Mountain Range at an altitude 330 m higher than Rustenburg. The main headwater wetland has a surface area of approximately 4.2 $km^2$ and a length of approximately 3 km. Since the formation and functioning of the headwater wetland is influenced by various geological and geomorphological controls, description of the geomorphology is preceded by a general description of the geology.

***Geology***

The underlying geology of the wetland consists of recrystallized Magaliesberg Quartzite of the Transvaal System. In addition, Norite intrusions from the Bushveld Igneous Complex occur in the reserve (Nel, 2000). Faulting 2000 million years ago resulted in the folding of Magaliesberg and Silverton formations to the west of the fault line. Fold arrangements consist of an anticline to the north and a syncline to the south, where Silverton shales are exposed along the eroded anticline (Bumbly, 1997). It is postulated that vertical dipping of the Rustenburg fault line is a major geological control to the existence of the wetland. The Rustenburg fault line created inferred fault lines to the south-west of the syncline. Along the syncline, downward folded beds created a valley with a gradual slope in which water accumulated (Carruthers, 2000). A valley formed along a line of weakness that was created when a diabase dyke intruded into the quartzite during the development of the Bushveld Igneous Complex, which resulted in vertical displacement of the quartzite (Carruthers, 2000). Two erosion-resistant key points, consisting of Magaliesberg Quartzite, were created during faulting with the wetland in between. The erosion-resistant key point to the south-east end of the wetland was created by inferred faults that interrupted the planar nature of the valley by displacing the formations in a north-easterly direction (Carruthers, 2000). This erosion-resistant key point created conditions for flow accumulation, sediment to fill the valley bottom and gentle gradients to form, in turn promoting low energy flow conditions, organic sedimentation and ultimately peat formation. Below the key point is a gorge and waterfalls as the river continues to exploit the line of weakness formed during faulting (Smakhtin & Batchelor, 2005). Therefore, the Rustenburg fault line is a major geological control, by creating a syncline to the south-west in which the wetland is situated (Bumbly, 1997). Geology provided a blueprint for the onset of geomorphological controls.

***Geomorphology***

The geomorphology of the headwater wetland system is relatively complex despite being nested/confined between two outcrops of Magaliesberg Quartzite. The headwater wetland system consists of three HGMs including seeps, channelled and unchannelled valley bottoms, as well as a main source zone, 15 well defined drainage lines, four alluvial fans, an uncertain number of artesian springs, and a waterfall downstream. These features (total surface area of approximately 4.2 $km^2$) will be discussed in sequence, as they occur upstream to downstream.

As mentioned above, upstream Waterkloof Spruit catchment is a closed system with a drainage area of approximately 17 $km^2$. The source of the main channel is located to the north-west of the reserve at an altitude of 1645 m a.m.s.l., from where the channel, after a flow length of 3060 m, descends to 1485 m a.m.s.l. into a valley where the main wetland system is located (Smakhtin & Batchelor, 2005). The main channel is defined as a channelled valley-bottom wetland with a surface area of 136.574 $m^2$. Here, the valley is V-shaped and relatively steep, conveying water via a bedrock channel. The average slope of the bedrock channel is 5% with a total length of 2.7 km. Relatively high energy water flows from the V-shaped valley, via a bedrock channel with an average slope of 5%, into an alluvial channel with a surface area of 106.972 $m^2$ and an average slope of 1.1%, which in turn flows into the main headwater wetland.

The headwater wetland is not only fed by the main channel, but also by approximately 15 other drainage lines or (sub-) tributaries ranging between 370 and 1200 m in length. Thirteen of these drainage lines are located to the south-west of the main wetland and the other two are to the north-east. Three of the drainage lines mentioned above feed directly into channelled valley bottoms in the south-west of the main system. Profiles of three prominent drainage lines indicate that soil erodes in the channels and is deposited along the drainage channels; however, fine sediment seems to be transported and deposited further downstream into the main unchannelled valley-bottom wetland. The tributaries thus act as geomorphological controls to the wetland as they not only feed water but also sediment to the main peatland system. Sediment profiles across the respective alluvial fans confluencing with the peatland gave an indication of deposition along the interaction zones. The presence of coarse sediment in the profiles infers previous water flow towards the peatland, which supports the notion that drainage lines are important geomorphological controls.

The channelled valley bottoms, in turn, feed into three individual alluvial fans in the south-west of the system, which then feed into the main system (Figure 5.2B). More specifically, the first alluvial fan is located at the head of the peatland, the second is located in the middle reaches and a third is located near the outlet of the peatland. Alluvial fans 1, 2 and 3 have surface areas of 5.88, 8.85 and 8.28 ha respectively. As mentioned above, the alluvial fans are supplied by water and sediment by drainage lines on the western slope of the reserve. They form at a break of slope between a tributary and valley floor, where steep tributaries deposit sediment (Rowntree, 2013). Alluvial channels are no longer in contact with the hillslopes and the gradual slope reduces flow velocity, which allows for sediment deposition and a reduction in connectivity. Alluvial fans act as sediment buffers. Where the tributary stream diverges across the alluvial fan it loses power and forms a sedimentological and hydrological buffer between a tributary and channel, in this case a wetland (Rowntree, 2013). As a result of continuous sediment deposition, an elevational increase of 1 m is observed where the stream dissipates to subsurface flow at the first alluvial fan created by the Waterkloof Spruit. Furthermore, incised channels and banks occur in alluvial fan 1, created by the Waterkloof Spruit, suggesting interaction between high energy and low energy flows. Alluvial fan 3 has noticeable incised channels which, along with alluvial fan 1, represents increased sedimentological and hydrological connectivity. Partial explanation for the occurrence of incised channels in alluvial fan 1 and 3 could be attributed to the steeper slopes occurring upstream of the Waterkloof Spruit and the lower tributary. Alluvial fan 2 has no incised channels, therefore reducing sedimentological and hydrological connectivity fulfilling the role as a sediment buffer. A fourth alluvial fan is located in the north-east directly above a hillslope seep that also feeds into the main system.

The main wetland system is described as an unchannelled valley-bottom peatland, due to peat encompassing approximately 31.5 ha or 95% of the area (the remaining 5% is a transition zone from the main channelled valley-bottom wetland to the unchannelled valley bottom). The unchannelled valley-bottom peatland descends from 1485 to 1435 m a.m.s.l. with a flat slope between 0 and 1 degrees. Dense populations of reeds (*Phragmites australis*) and sedge (*Cyperaceae*) occur within the peatland, which exhibits a high hydraulic resistance to flow. Vegetation occurring on slopes allows for the stabilization of soil and interception of runoff (Jackson *et al*., 2019). Establishment of vegetation after sediment deposition and water accumulation dramatically reduced flow velocity, creating optimal conditions for a peatland to develop (Grundling *et al*., 2015).

More than 20 hillslope seeps occur throughout the wetland system, with a total surface area of approximately 244 ha (Figure 5.1 and Figure 5.3). Eighteen of these seeps are directly adjacent to the main system whilst five seeps are located higher up on the hillslopes. On these hillslopes, the average slope is moderately steep at between 4 and 12°. It is postulated that artesian springs feed the main system. These artesian springs are associated with (i) a fractured aquifer related to the Quartzite outcrop on the left bank, in the lower part (downstream) of the main system; or (ii) an alluvial fan (opposite of the Quartzite outcrop) that is most likely linked to semi-confined preferential flow path along the gravel embedded in peat towards the confluence. Within the main peat system there is artesian pressure (piezometers with higher pressure head than the water table). This is where the system narrows so it could be linked to a semi-fractured aquifer that forces the water to the surface or upwelling of old sump.

We also observed groundwater discharge (seepage flow) upstream of the main peatland. Finally, water exists in the main wetland with a waterfall directly downstream of the lower weir (A2H038) (Figure 5.2). An abrupt slope change to 12° can be attributed to a 5 m cliff on the eastern bank of the wetland, followed by a mire with a low slope downstream of the waterfall.

In summary, the morphology of the peatland is a result of sediment movement and accumulation that reflects a balance between the drainage geomorphology and geological resistance. The fundamental control to the origin of the peatland is the development of an erosion-resistant rock band, which initiated a valley fill cycle. Peatland formation was strongly influenced by geological features including the Rustenburg fault line and erosion-resistant key points near the peatland outlet, which allowed for water and sediment accumulation. The establishment of vegetation created a strong feedback on valley filling, allowing for water accumulation and adequate conditions for peat to form. Grenfell *et al*. (2009) found similar results, highlighting the effect of underlying dolerite intrusions when studying cut and fill cycles of valley-bottom wetlands. The wetland itself is a sediment buffer that filters energy. The headwater filling creates a buffer that reduces longitudinal sediment connectivity (Grenfell *et al*., 2009). This can clearly be observed where the incised Waterkloof Spruit terminates in an alluvial fan, flows into an unchannelled valley-bottom peatland, then reappears at the outlet of the wetland.

#### 5.5.2.2 *Hydrology (Rainfall, water monitoring readings and isotopes)*

***Rainfall***

Rainfall data obtained from the NW Parks Board (Figure 5.4) indicates that the annual rainfall ranges from a below-average 607 mm in 2018 to 701 mm in 2020 (Table 5.2). The 2019 rainfall figure of 743 mm compared to the long-term annual average with the rainfall measured during the study period from 1 March 2019 to 7 March 2020 at 697 mm (Table 5.2).

**Table 5.2** Annual rainfall measured at Kgaswane Mountain Reserve

| Year | Rainfall (mm year$^{-1}$) | Average (mm year$^{-1}$) |
|---|---|---|
| 2018 | 607 | |
| 2019 | 743 | |
| 2020 | 701 | |
| 1 Mar 2019 to 7 Mar 2020 | 697 | |
| Average 2018 and 2019 | | 675 |
| Average 2018 to 2020 | | 684 |
| Long-term average | | 670 (Smaktin and Bachelor, 2005)<br>600-750 (Mucina and Rutherford, 2006)<br>850 (Phillips, 2020) |

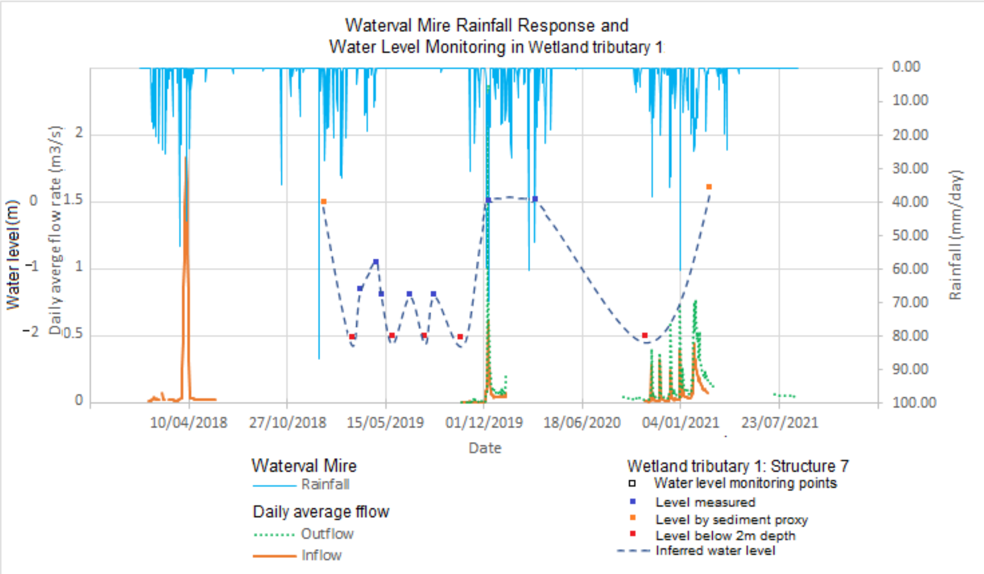



**Figure 5.4** Rainfall data for the Kgaswane Mountain Reserve from 2018 to 2021 with hydrographs for the inflow and outflow of the Waterval mire with inferred water level fluctuations for a tributary (wetland tributary 1). Note: the hydrograph data received from DWS were incomplete.

***Water monitoring readings***

Kgaswane hydrological monitoring: 1 January 2018 to 20 August 2021

Water levels as recorded in the wells installed at structure 5 and structure 7 located in wetland tributary 1 (see Figure 5.1A transect 8 and Figure 5.1B) delivered mixed results as recorded in Table 5.3. Presence of water was not observed in the 1-m deep well upstream of the spillway of structure 1. Water levels as depicted in Figure 5.4 in the 2-m deep well at structure 7 varied from 90 to 130 cm below the height of the spillway. Water was flowing 1 cm deep over both structures during the wet season of 2019/2020. The spillway heights of both structures were increased by 20 cm between March and October 2020 and the sediment level evident at the top of the elevated spillway was used as a proxy of water level. As such it is estimated that water flow was 20 cm higher than the original spillway (or 104 cm above the apron – representing the downstream streambed level). Therefore, water levels in the stream, as measured at structure 7, varied from 200 cm below the original spillway level to 20 cm above it (a fluctuation range of at least 220 cm) (Figure 5.4).

**Table 5.3** Water level recordings in the wetland tributary 1 (see Figure 5.1B)

| Date | **Water level (in cm)** Relative to top of spillway (relative to apron = streambed) | | Comment |
|---|---|---|---|
| | **Structure 5** Pipe length: 100 cm Pipe depth: 100 cm (16 cm) | **Structure 7** Pipe length: 200 cm Pipe depth: 200 cm (116 cm) | |
| 07-Mar-19 | Dry -1 (+83) | Dry -1 (+83) | Sediment height behind spillway = proxy of water level |
| 24-Mar-19 | Dry | -122 (-38) | |
| 26-Apr-19 | Dry | -90 (-6) | |
| 08-May-19 | Dry | -130 (-46) | |
| 23-May-19 | Dry | Dry | |
| 06-Jun-19 | Dry | -130 (-46) | |
| 18-Jul-19 | Dry | Dry | |
| 05-Aug-19 | Dry | -130 (-46) | |
| 19-Oct-19 | Dry | Dry | |
| 16-Dec-19 | +1 (+85) | +1 (+85) | Water flowing over spillway |
| 07-Mar-20 | +1 (+85) | +1 (+85) | Water flowing over spillway |
| 29-Oct-20 | Dry | Dry | |
| 19-Mar-21 | Dry +20 (+104) | Dry +20 (+104) | Spillway height was increased by 20 cm. Sediment height behind spillway = proxy of water level |

***Isotopes***

The monitoring readings from the wells and piezometers along transects agree (Table 5.3) with the isotope analysis (Figure 5.5). These were all incorporated into the conceptual model (Figure 5.4; see discussion section). The local monitoring water level (LMWL) line is parallel to but slightly offset from that of the ground monitoring water level (GMWL) (dD = +0.2 from the GMWL). Interestingly the two recent rainfall events do not align with the LMWL line but most of the values taken from surface and GW flows do, except for the SE spring (K10E W Spring) (dD = -0.3 from the LMWL). Two groupings of values are apparent. The surface inflow and outflow are both in the lower grouping with the outflow not reflecting any significant offset from the LMWL. Most peat points fall in the upper grouping except the shallow piezometer at the wide peat transect (probably indicating contamination by surface water through a leaking pipe). The springs do not plot in any particular pattern with two in each grouping. However, K10E W falls on an evaporation path.

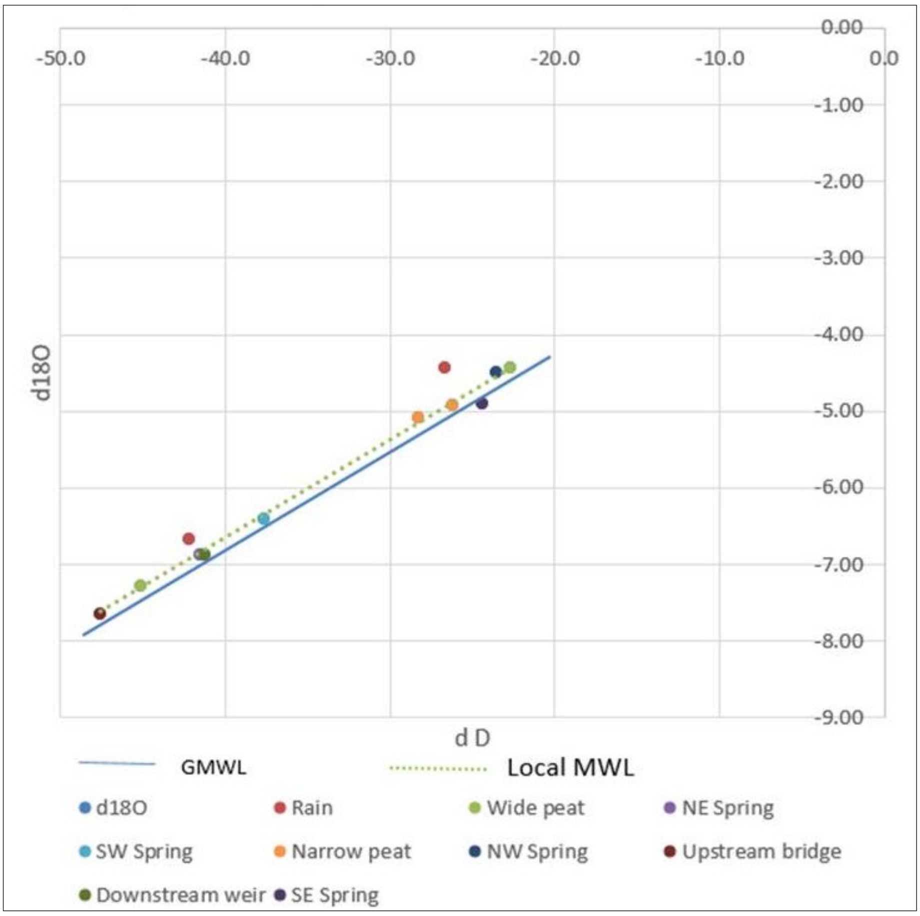



**Figure 5.5** Isotope readings from water samples taken on 4 and 5 February 2021.

## 5.6 DISCUSSION

Wetland degradation follows decadal droughts in drier climates impacted by land use change (Grundling *et al.,* 2020). Erosion within wetland tributary 1 resulted in an incised channel and excess sediment due to erosion in its catchment. This impacted on the ability of the wetland to deliver ecosystem services such as flood attenuation, sediment control and base flow maintenance. Rehabilitation focussed on building structures in the incised channel to raise the water level in the wetland and to increase the base level of the channel by trapping excess sediment (Grobler, 2014).

Following the decadal drought of 2014 to 2016 in southern Africa (Malherbe *et al.*, 2016), the Kgaswane wetlands received only 607 mm rainfall in 2018 (Table 5.2) compared to the long-term average of up to 750 mm annum$^{-1}$ (Mucina & Rutherford, 2006). Furthermore, although average rainfall of about 743 mm was received during 2019, the rainfall during the main monitoring period for this study was only 646 mm from 1 March 2019 to 7 March 2020 with significant precipitation (20 mm and more) occurring during only four rainfall events (6 & 7, 10 & 11 December 2019, 25 & 26 January and 28 February to 1 March 2020) towards the end of the fieldwork season (Figure 5.4).

The hydrograph for the Waterval mire indicates a continuous low flow even during dry periods into and from the mire (Figure 5.4), but wetland tributary 1 exhibits a water level fluctuation of at least 220 cm. Figure 5.4 suggests that it is seasonal in character and only flowing above the surface during episodes of continuous rainfall events.

The level of sediment behind structures, especially within one consecutive wet season, is evidence of the effectiveness of these trapping measures. By comparison, the effectiveness in lifting the water table is seasonally bound due to the episodic (ephemeral) nature of the tributary. However, the presence of springs just upstream of the confluence with the Waterval mire suggests that the coarse nature of the sediment within wetland tributary 1 (transect 8; Figure 5.1A) allows for sufficient recharge of the underlying groundwater table during the wet seasons to allow sustained groundwater exfiltration downstream at the confluence.

### 5.6.1 Kgaswane Mountain Reserve conceptual model (Catchment scale)

The conceptual model of the Kgaswane Mountain Reserve (Figure 5.6) coupled with the profiles of the transects (Figure 5.7) were used to explain the interaction dynamics of the system. The surface flow and groundwater values on the LMWL line indicate that rainfall events are an important driver of flow regimes in the wetland with the recent heavy events flushing the system, and good correlation between groundwater and surface flows indicating rapid recharge of the aquifers and discharge to streamflow. The similar surface and inflow values indicate that little evaporation took place, most likely as a result of relatively effective infiltration from upper catchment recharge surfaces into the groundwater and short resident times in the wetland (with probably well shaded dispersed flow in the acrotelm amongst tall reeds). The evaporation signal in the alluvial fan spring (K10E W; Figure 5.1A) indicates that water was flowing on the surface in the alluvial fan's feeder channel before dipping subsurface and then discharging as a spring on the edge of the peatland. The artesian spring (PL spring) plot is in the same grouping as the peat piezometers and therefore one can conclude that there is deeper groundwater feeding into the main peat basin.

The Waterval mire is, amongst others, fed by groundwater through fractures, as evident from various artesian springs, intermediate groundwater flow (depicted by seep lines), surface stream inflow from the upper plateau, and various smaller tributaries. Some of these tributary wetlands also play a key geomorphological role in the development and functioning of the mire. Primarily, they act as classic sediment pathways into the valley-bottom basin in the form of alluvial fans, creating sub-basins within the valley bottom. Within these sub-basins, low energy and permanent saturated conditions prevail which are ideal for the accumulation of peat. The sequence of clastic and organic layering within the distal reaches of the alluvial fans provides preferential intermediate/groundwater flow paths towards the basin downstream of the fan.

The position of the fan will determine the functional contribution of the fan to the system. For example, the fan at the inflow provides mainly hydrological preferential flow paths; the fan in the middle forms a major sub-basin feature with seasonal hydrological flows itself; whilst the hydrological contribution of the lower fan is less towards the mire than to the Waterval stream directly. The value of the lowest alluvial fan is more in the form of its geomorphological contribution at its outflow by raising the base level of the mire through the continuous clastic sediment input. This creates a continuous elevated base level, upstream of which peat can then keep developing. In addition, the continuous supply of sediment negates erosion of the stream channel.

Given the current erosion and outflow of sediment in the mire, the following question arises: Is the current phase of sediment control structures that are placed within the tributary detrimental to the mire?

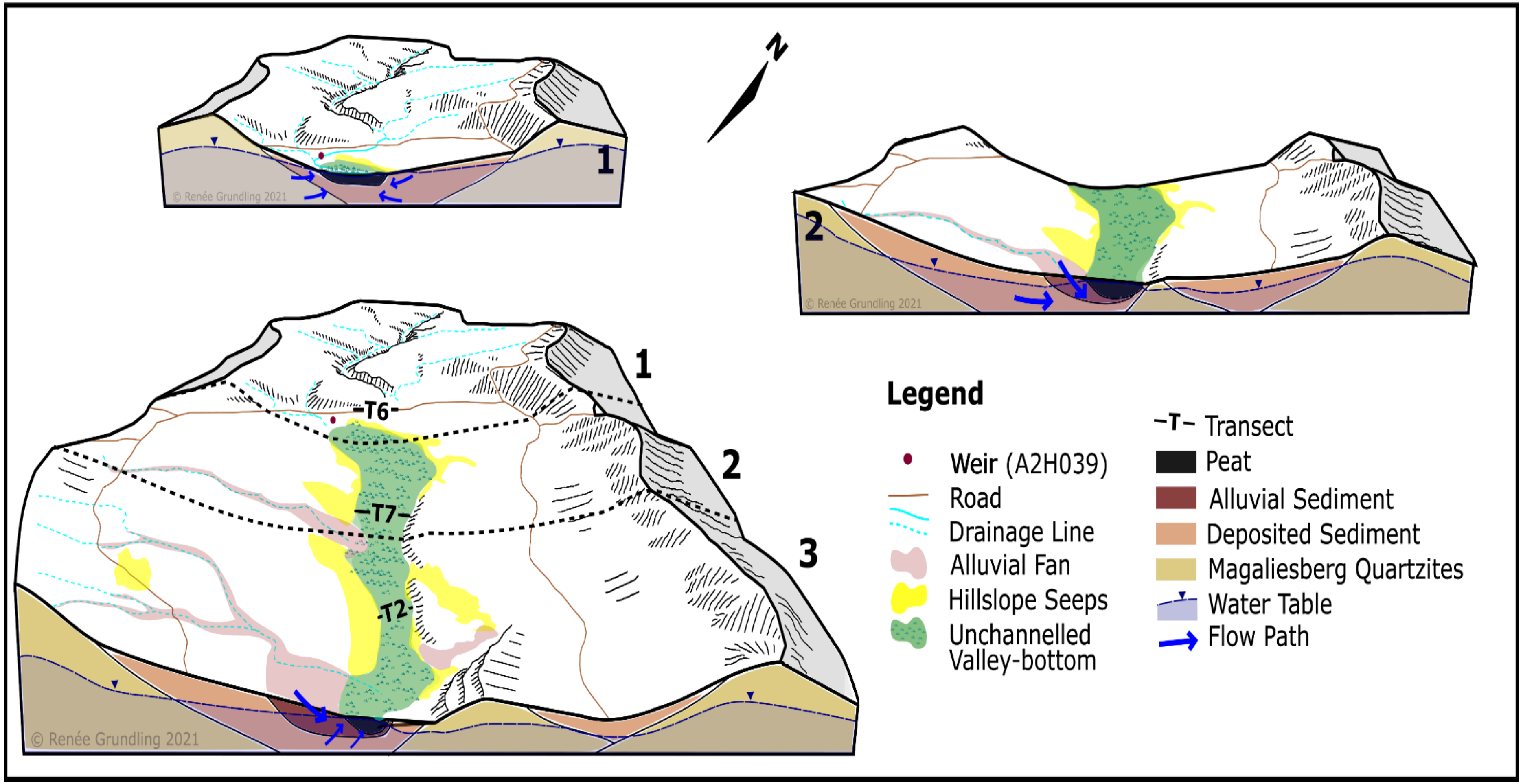



**Figure 5.6** Conceptual model of the Kgaswane Mountain Reserve catchment study area (production and illustration by Renée Grundling, 2021).

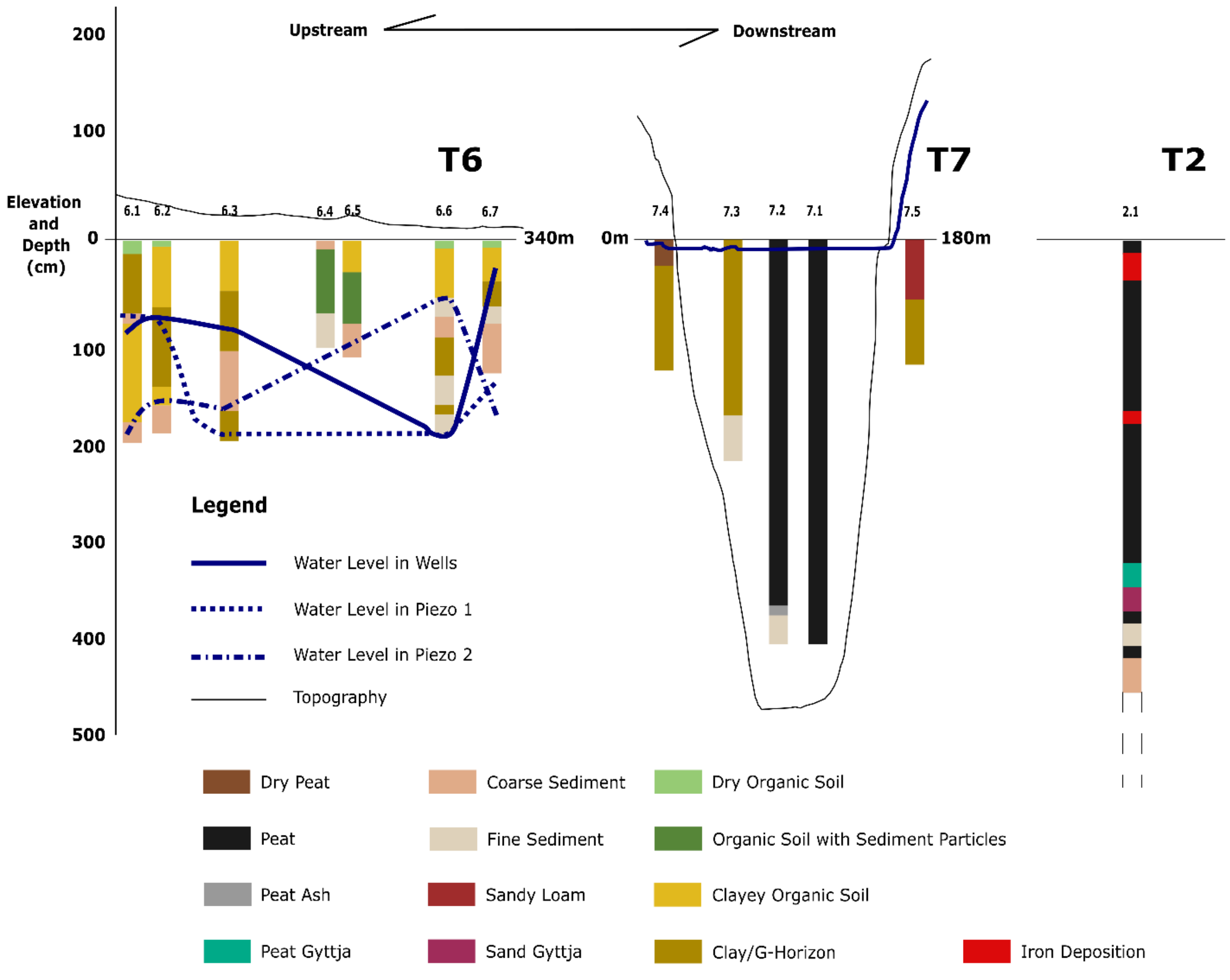



**Figure 5.7** Profiles along transects (top, middle and bottom) of the main wetland system (illustration by Renée Grundling, 2021).

## 5.7 CONCLUSION

In conclusion, the morphology of the peatland is a result of sediment movement and accumulation that reflects a balance between the drainage geomorphology and geological resistance. The fundamental control to the origin of the peatland is the development of an erosion-resistant rock band, which initiated a valley fill cycle. Peatland formation was strongly influenced by geological features including the Rustenburg fault line and erosion-resistant key points near the peatland outlet, which allowed for water and sediment accumulation. The establishment of vegetation created a strong feedback on valley filling allowing for water accumulation and adequate conditions for peat to form. Grenfell *et al*. (2009) found similar results, highlighting the effect of underlying dolerite intrusions when studying cut and fill cycles of valley-bottom wetlands. The wetland itself is a sediment buffer that filters energy. The headwater filling creates a buffer that reduces longitudinal sediment connectivity (Grenfell *et al*., 2009). This can clearly be observed where the incised Waterkloof Spruit terminates in an alluvial fan, flows into an unchannelled valley-bottom peatland, and then reappears at the outlet of the wetland.

# 6. CONSERVATION AND WISE USE OF WETLANDS

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## 6.1 INTRODUCTION

Wetlands are among the most important and productive ecosystems in the world. They are the main suppliers of fresh water for human use, and provide water, habitat and refuge to thousands of animal and plant species. One such example is the Ntondozi wetlands in Eswatini (Kotze, 2010; Marambanyika and Beckedahl, 2017; Hussien *et al*., 2018; Kunene, 2020).

## 6.2 SUSTAINABLE WETLAND UTILIZATION? THE NTONDOZI CASE STUDY, ESWATINI

The people of rural Eswatini source important elements of their livelihoods from wetlands such as those at Ntondozi (Figure 6.1). There are a number of plant species found in wetland areas which are important for the local community, such as *Cyperuslatifolius* (***Likhwane***) and *Phragmites australis* (***Umhlanga***) (Seswati name in bold).

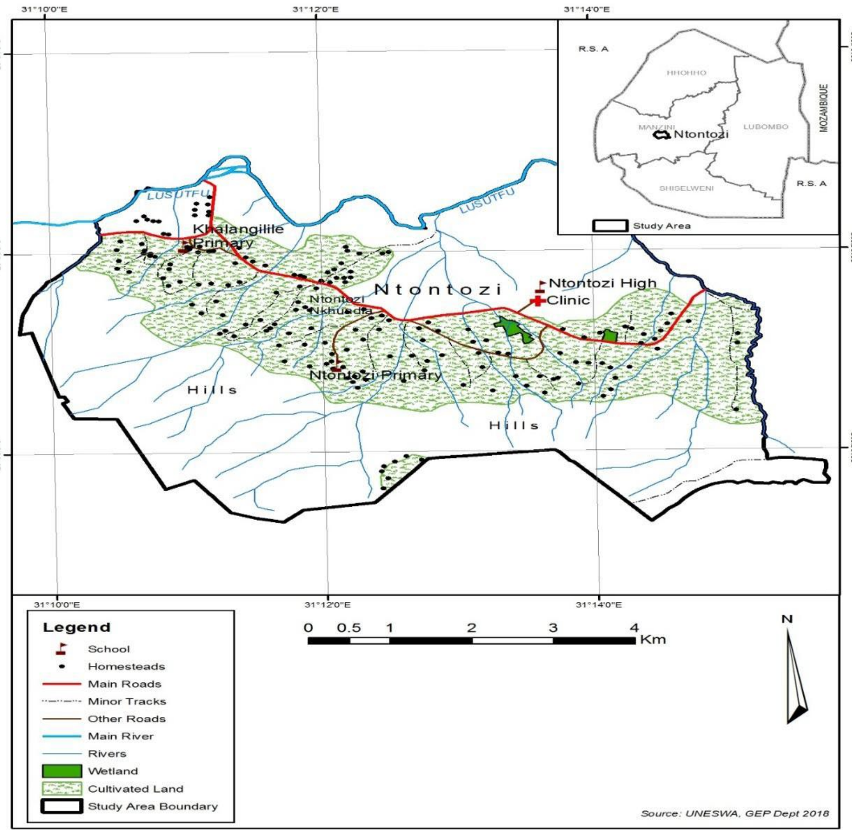



**Figure 6.1** The Ntondozi area and primary wetlands in Eswatini (source: UNESWA, 2019).

These plants are used for making food mats, sleeping mats, bags and baskets; hence, they are of economic value to many women in the Ntondozi area. Community members also use wetlands for crop production, collection of building material, edible fruits and livestock grazing in some areas. This shows how important the wetlands are in rural areas (Kotze, 2010). Wetlands often supply fresh borehole water, which is pumped to most of the community. The local school at Ntondozi (Mvimbeko High School) also sources agricultural water from the wetlands. Most importantly for the local community is that people are able to collect medicinal plants from the wetland for curing various ailments.

The interactions and relationships between land, water, atmosphere and people, as well as the contribution to global change are poorly understood, hence the need to scrutinize these relationships (Grenfell *et al.*, 2016). According to Macfarlane *et al.* (2007), wetlands are among the world's most prolific natural environments. They support biological diversity, provide water and primary productivity upon which numerous species of plants and animals depend for survival (Grenfell *et al.*, 2016). Therefore, they should not be disturbed since they are home to many macro and micro-organisms. Wetlands are also important storehouses of plant genetic material; for example, rice, which is a common wetland plant, is the staple diet of more than half of humanity. Inputs to the soil around wetland areas such as chemical fertilizers affect the water quality and living things in the wetlands since they introduce more nutrients (WHO and UNICEF, 2013; EPA, 2006; Ramsar Convention Secretariat, 2013). These wetland environments are important since they provide an extensive range of uses in and around them such as grazing (domestic and wild animals), food production (e.g. fish, fruits and crops), extracting wood for cooking and construction, a source of medicine and water, enshrining religious values, as well as providing ecological services such as water purification, climate regulation, nutrient transfers and flood attenuation (Marambanyika, 2015). However, all these functions have negative effects on the wetlands, thus compromising their health and making them to be less productive in terms of the goods and services they provide.

Wetlands are important because of the functions and values that they provide which benefit humankind. These benefits can be either direct or indirect. Until recently, the benefits of wetlands to society were often not recognized and many wetlands have been destroyed or poorly managed (Marambanyika & Beckedahl, 2017, Kotze, 2010). Wetland benefits refer to those functions, products, attributes and services provided by the ecosystem that have value to humans in terms of worth, merit, quality or importance (Kotze *et al.,* 2007).

## 6.3 FUNCTIONS OF WETLANDS AND THE BENEFITS DERIVED FROM THEM

Wetlands play an essential role in the ecology of watersheds. The combination of shallow water, high levels of nutrients and primary productivity is ideal for the development of organisms that form the base of the food web (Kotze, 2010). Many species of birds and mammals rely on wetlands for food, water and shelter, especially during migration and breeding. Wetland specialists need a broad understanding of the biophysical environment if they are to conserve and manage wetlands wisely, so this is the mandate that we have to live up to (Ellery *et al.*, 2008). Wetlands are cradles of sustainable livelihoods in arid and semi-arid environments but, according to Kotze *et al*. (2007), the functioning of wetlands is mainly affected by human activities such as fire, draining and damming. On the same note, Turpie (2010) highlights that the functioning of wetlands is also affected by factors taking place in the surrounding catchment such as a change in land cover from natural grassland to a gum tree plantation, which would decrease the amount of water reaching the wetland. In view of their importance, the Environmental Protection Agency (EPA, 2006) regards wetlands as biological supermarkets since they produce great quantities of food that attract many animal species. According to Masarirambi *et al.* (2010), many plant species that are found in Eswatini wetlands are important economic resources for women in Eswatini. These include *Cyperusarticulatus* and

*Schoenoplectus corymbosus* plants which are used for making food mats, sleeping mats, bags and baskets, hence providing an economic livelihood to many women (Zwane & Masarirambi, 2009; Manyatsi *et al*., 2013). Communities also use wetlands for irrigation of crops, collection of reeds for building material (*Adiriami crocephala*), edible fruits (*Syzygium cordatum*) and livestock grazing in some rural areas (Edje, 2006; Marambanyika & Beckedahl, 2016a).

According to the Ramsar Convention Secretariat (2013), the relations of physical, biological and chemical mechanisms of a wetland enable it to perform many vital functions for both living and non-living things. These functions include water storage, storm protection and flood mitigation, shoreline stabilization and erosion control, groundwater recharge and discharge, water purification, retention of nutrients, sediments and pollutants, and stabilization of local climate conditions (particularly rainfall and temperature), which directly and indirectly benefit the community (Macfarlane *et al.*, 2007). Kotze *et al.* (2007) state that wetlands provide both direct and indirect benefits. The direct benefits include water purification, sustained stream flow, flood reduction, groundwater recharge/discharge, hydrological benefits, erosion control, biodiversity conservation, integrity and irreplaceability. Indirect benefits include chemical cycling, water supply, provision of harvestable resources, socio-cultural significance, tourism, recreation, education and research (Marambanyika, 2015). Hussien *et al*. (2018) state that wetlands have helped many people in improving water quality in nearby rivers and streams, and thus have considerable value as filters for future drinking water. When water enters a wetland, it slows down and moves around wetland plants. According to Marambanyika & Beckedahl (2016a), plant roots and micro-organisms on plant stems and in the soil absorb excess nutrients in the water from fertilizers, manure, leaking septic tanks and municipal sewage. While a certain level of nutrients is necessary in water ecosystems, excess nutrients can cause algae growth that is harmful to fish and other aquatic life. A wetland's natural filtration process can remove these nutrients before the water leaves the wetland, making it healthier for drinking and supporting plants and animals (EPA, 2006).

## 6.4 THREATS TO WETLANDS AND RESOURCE MANAGEMENT IN AFRICA

In Africa, community-based natural resource management (CBNRM) seeks to integrate local communities into the protection of their immediate environment in an endeavour to accomplish ecological and social goals on both local and global scales (Government of Swaziland, 2005). Roe *et al*. (2009) describe CBNRM as formal or informal management of resources such as land, forests, wildlife and wetlands by communal local institutions for local and regional benefit. Kotze (2010) and Grenfell *et al*. (2016) argue that wetlands are found where the landform (topography) or geology slows down or obstructs the movement of water through the catchment (for example, where the landform is very flat), or where groundwater surfaces causing the surface soil layers in the area to be temporarily, seasonally or permanently wet. This provides an environment where particular plants (hydrophytes) that are adapted to wet conditions tend to grow in large quantities. The plants in turn affect the soil and hydrology, for example, by further slowing down the movement of water and by producing organic matter that may accumulate in the soil (Collins, 2005). The main threats to wetlands are over-exploitation of faunal and floral resources, shrinkage of habitat due to conversion of wetlands for agriculture, aquaculture and human settlements in rural areas (Ellery *et al*., 2008). Typical examples of threatened wetlands in Africa include the Congo River Swamps, Inner Niger Delta, Sudd of the Upper Nile and the Okavango Delta in sub-Saharan Africa (Hussien *et al*., 2018; Marambanyika & Beckedahl, 2016a). In southern Africa, as in other regions in Africa, many communities depend on wetlands for multiple benefits, including social, economic, ecological and aesthetic values (Grenfell *et al.*, 2016, Marambanyika & Beckedahl, 2017). In such semi-arid to arid conditions, wetland agriculture delivers a means to reduce crop yield losses related to low and unpredictable rainfall and frequent droughts and thus improves food security and returns of poor agriculture dependent communities (Marambanyika & Beckedahl, 2016a). Whilst wetlands play a key role in supporting the livelihoods of many communities in the region, their continuous use for cultivation and grazing has the potential to degrade their fragile ecosystems and undermine their capacity to provide services in future (Ramsar Convention Secretariat, 2018; Breen *et al.,* 1997).

The existence of many wetlands in Eswatini is under threat due to alarming degradation taking place as a result of human activities. Studies estimate that more than 50% of the global wetlands were lost over the last century (Kotze, 2010; Marambanyika, 2015). Although there is no consolidated figure on the rate of wetland loss, rapid degradation dating back to the colonial period has been reported in different parts of southern Africa. Wetland degradation and loss is attributed mainly to human activities such as agriculture, industrial development, urbanization, pollution and human settlements (Ramsar Convention Secretariat, 2010a). This explains why policies restricting wetland use in most developing countries are based on the known effects of development activities, in particular, commercial agriculture which is the predominant land use (Marambanyika & Beckedahl, 2016a).

Hydrophytes have acted as sources of livelihoods in rural poor communities. Native fibre plants found in different geographical wetlands in Eswatini include *Cyperuslatifolius* (***Lukhwane***) and *Phragmites australis* (***Umhlanga***), which have been supporting rural households for centuries. Various products are made from these plants (Dlamini, 1981; Manyatsi *et al*., 2013; Marambanyika & Beckedahl, 2016a). Tourists place great value on natural products made from indigenous fibre plants of the wetlands and are often the biggest buyers of these handicrafts in markets of Eswatini such as eZulwini, Swazi Candles, Manzini market and many more (Masarirambi *et al*., 2010). However, global warming due to climate change is threatening the biodiversity of these wetlands and their plants as far as continued survival and contribution to the next generation is concerned (Zwane *et al*., 2011; Manyatsi *et al*., 2013, Government of Swaziland, 2005). Poor rural, and nowadays poor urban communities, derive a source of revenue from these indigenous plants which may be threatened with extinction if they are not conserved and taken care of (Marambanyika & Beckedahl, 2016a). The biggest challenge in Eswatini is that there is a dearth of knowledge when it comes to wetland studies in both ecology and process geomorphology, while neighbouring countries like South Africa are far ahead in wetland studies.

## 6.5 COMMUNITY-BASED NATURAL RESOURCE MANAGEMENT (CBNRM)

Marambanyika (2015) argues that a number of strategies on wetland use and management have been developed and implemented at various scales in response to wetland degradation and loss in Africa. These strategies include community-based natural resource management which is a term used to describe the management of resources such as land, forests, wildlife and water collectively for local benefit (Roe *et al*., 2009). CBNRM takes many different forms in different locations and socio-political and bio-physical contexts, such that it is important in light of institutional conflicts arising from divergent or different priorities and objectives of many findings from different studies as well as institutional negligence as some instrumental factors behind wetland loss (Marambanyika, 2015). It is on this basis that Marambanyika & Beckedahl (2017) argue that the capacity of indigenous institutions in natural resource management was weakened by interference and institutional disruptions introduced by colonial governments. For instance, in most developing countries, including Zimbabwe, it was discovered that a colonial legacy (that was later inherited by post-colonial governments) set up a resource governance system, which largely disregarded indigenous knowledge and common practice (Marambanyika & Beckedahl, 2017). Notably, the notion of engaging the local people in the management of natural resources is a fundamental aspect of good governance (Rozwadowska, 2011). Thus, if successful, CBNRM programmes can be simulations of local empowerment bestowing communities with greater authority over the use of natural resources (Goemeone *et al.,* 2018). According to Roe *et al*. (2009), CBNRM varies from one location to another and also depends on the basis of different socio-political and bio-physical contexts. For instance, it may either be based on commercial uses of natural resources, such as managing wildlife for local tourism or hunting enterprises, or on primarily subsistence uses of resources such as wetlands (Roe *et al*., 2009).

## 6.6 BENEFITS COMING FROM THE WETLANDS

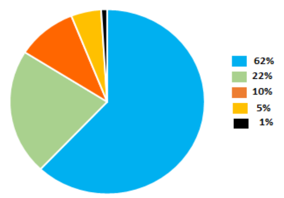
Wetland ecosystems in southern Africa present plentiful goods and services that have a significant value, not only to local people living on their periphery but also to communities living outside the wetland area. They are important sources of food, fresh water and building material, and provide priceless services such as water treatment and soil erosion control. Marambanyika & Beckedahl (2016a) argue that benefits coming from wetlands are realized through a broad range of goods and services that they provide. However, the significance of the value attached to wetlands differs from wetland to wetland, as shown by the response to community survey questionnaires at Ntondozi. It is worth noting is that in one case (wetland 2, Ntondozi) there is a groundwater pump which was constructed in 2013. This is a community water project that was sponsored by Micro Projects (a Rural Development Agency in Eswatini) in order to supply the community with a reliable source of water. This borehole pumps water from the wetland to two tanks which are each 10 000 litres in capacity, and it is pumped three times a week depending on usage. This water is used by five sub-areas of Ntondozi, which indicates that water is one of the main benefits derived from the wetlands.

The five sub-areas of Ntondozi that benefit from the water pumped from the wetland are Nqudvula, Mahlabatsini (or Emvileni), Sibovu, Ndvonsamlomo and Mlandvo. The pump uses electricity, so in order to buy units for pumping water into the tanks, all beneficiaries are supposed to pay E30.00 a month, which helps in maintaining the pump and buying electric units. The pump uses approximately 230 units of electricity to fill the tanks if they are empty. Some users are allowed to have water meters in their homesteads; they are charged E7.00 per unit and are only allowed to use the water for domestic use and backyard gardens. Mlandvo community has been removed from the scheme due to members' failure to pay the monthly subscriptions for maintaining the pump and purchasing electric units. A large number of the respondents expressed their disappointment in the water scheme, stating that it was expensive for them and the water is not always available since it was only pumped three times a week and is supplying a vast population. This project has thus to some extent perpetuated views to undervalue the scheme since they further complained that the water also does not reach some parts of their area and the pipeline is not managed properly in case of leakages. This has led to a large number of the people in the community near the wetlands preferring to fetch 'free' water direct from the wetlands and continuing with their daily activities such as washing clothes in the wetland and polluting the wetland water with detergents. This is the same reason why Mlandvo sub-region was removed from the scheme, because they undermined it by failing to pay the monthly fees used for maintenance of the scheme. Some members still believe that the project sponsor must continue to maintain the pump (in other words, perpetuating a development-dependency relationship, detrimental to the conservation ethos). They argue that they were not told of any fiscal related issues when the project was implemented. This may be an indication that the people will not easily adapt to the operations of the project because they do not want to be charged. In addition, the community water committee does not hold frequent meetings to update itself and the community on the needs of the people and the operation of the project. This is seen as an indication that the wetlands are still utilized heavily and that current management is unsustainable.

The Ntondozi study mainly focussed on household heads or any household member who makes a decision in the absence of the head of household. The findings reflect that most of the respondents were males (65%) which tells us that most decisions are influenced by males in Ntondozi. The percentage of males versus females also gives an idea of how gender differs in terms of sustainable resource utilization. The continued existence of wetlands, including benefits obtained, largely depends on people's attitude towards resource utilization which basically impacts on the existing management and conservation approach (Marambanyika & Beckedahl, 2016a). There are a number of benefits derived by the community from the wetlands. Since 1988, the land use has been changing as a result of cultivation, community development and settlements. Annual average temperatures and annual rainfall amounts have indicated that there is a continuous increase in temperatures and a decrease in total rainfall. This has resulted in a decline in terms of the benefits derived from the wetlands. Generally, the area under cultivation, settlements and pastures has been increasing from 1988 to 2018 towards the wetlands. It should be noted that the main interest of the research is the area within and close to the wetlands rather than the whole community, thus resulting in less attention to settlement patterns but more attention focussed on land cover around the wetlands. From the wetlands, the people get benefits such as *Phragmites australis* (***Umhlanga)***, *Cyperus articulates* (***Incoboza***), medicinal plants (herbs), water, hunting and even building materials in the form of reeds and grass. This shows that these people are dependent on the benefits that come with wetlands and the rainfall received over the years directly influences the performance of the wetlands. This calls for the wise use of wetlands since they play a key role in the livelihoods of the people. For instance, about 62% respondents fetch water from the wetlands and thus regard them as water sources (Figure 6.1). On the other hand, 22% of the respondents regard the wetlands as a source of income because they sell some of the benefits derived from them. Sources of income include *Phragmites australis* (***Lukhwane***) and *Cyperus articulatus* (***Incoboza***) which are used to make food mats, brooms and sleeping mats for sale in the community and in Manzini market. Some also sell incense (10%) and use it for traditional purposes. Traditionally, they believe that burning incense can drive away evil spirits and bring good fortune to the household. This further indicates that the community benefits from the wetland, and thus these features need to be sustained. The uses and importance of wetlands as cited by the Ntondozi community are shown in Table 6.1.

**Table 6.1** Wetland use by the Ntondozi community

| **Wetland Use Category** | **Percentage** |
|---|---|
| Water | **62%** |
| *Phragmites australis & Cyperus articulatus* | **22%** |
| Traditional herbs | **10%** |
| Hunting fowl & small mammals | **5%** |
| Building material (e.g. grass) | 1% |




The results of the survey are an indication of the value of wetlands to the local community. Water is regarded as the main benefit as flora, fauna and human beings rely on it to sustain themselves. Change in and around the wetlands can affect the benefits coming from them. Marambanyika (2015) stated that wetlands are known to provide direct and indirect benefits to societies through both ecosystem goods and services, thus the way they are utilized must tally with their productivity. In areas highly reliant on natural resources, especially many rural parts of sub-Saharan Africa (including Eswatini and South Africa), direct usage of wetlands for cultivation, grazing and aquaculture is customary. These activities are at the core of livelihood strategies of primarily subsistence rural communities in these areas and as such are responsible for the degradation of this valuable natural resource (Dahwa *et al*., 2013). The Ntondozi area is one case that presents a well-structured setup on how rural communities benefit from wetlands and their reliance on other natural resources.

The findings also gave us the estimated amount of income received by the respondents from the benefits they derive from the wetlands like *Phragmites australis* (***Lukhwane***), *Cyperus articulatus* (***Incoboza***) and wild herbs. These goods were priced at local market value. From the findings, 24.4% of the respondents regarded the wetlands as a source of income. Out of those, 14% received up to R500 annually, 8.1% received between R500 and R1000, and 2.3% received over R2000.

The respondents who have seen the largest scale changes in and around the wetlands are those who have been in the area for more than 20 years. Household heads that have been in the area for less than 20 years have seen less change regarding practices in and around the wetlands. About 38% of the respondents who have been in the area for more than 20 years have seen a huge change around the wetlands in terms of agricultural activities. In addition, 31% of them have also seen settlements encroaching around the wetlands. This basically proves that the wetland size has decreased due to the increase in agricultural activities and settlements. Satellite images of 1988 show the wetlands with a full reflectance of NDVI but in 2013 there is less water, indicating that there is degradation in the wetlands. Whilst this may have been caused by the low annual rainfall received in 2012 (864 mm), it may also be due to unsustainable utilization of the wetland by the community members.

When it comes to changes observed over time, community development (2%) has resulted in a change to the wetlands. This development includes road construction and services next to the roads like shops. Households that have been established in the area for about 15-20 years have seen changes in agricultural activities and settlements increasing around the wetlands. About 13% of them have seen changes in agricultural activities and only 8% have seen an increase in settlements. Respondents who have been in the area for 10-15 years (1%) indicated that they have seen an increase in agricultural activities and only 2% have seen a change in settlements. From those who responded that they have been in the location for 5-10 years, 2% have seen increasing settlements in the wetlands and only 1% observed agricultural change. From the results, it was gathered that respondents who have established themselves in the area for a long period of time has seen major changes in and around the wetlands in terms of agricultural activities, settlements and community development projects.

The wetlands have been heavily degraded by what is called ‘tragedy of the commons’ (i.e. if there is only communal responsibility, no one tends to take responsibility). Livestock and human beings have been sharing the same sources of water and there is a high rate of farming around the wetlands, thus contributing to eutrophication. To verify whether there is any water pollution, the study tested water quality in both wetlands. These tests proved that there were agricultural activities influencing the quality of water. This was reflected by high levels of nutrients mainly observed in wetland 2. In wetland 1 the nitrate level was within the recommended range of 2.3 mg $L^{-1}$ $NO_3^-$, while in wetland 2 the level was at 5.6 mg $L^{-1}$ $NO_3^-$ which, according to the EPA (2006), indicates that the water in wetland 2 is likely to be contaminated either by fertilizers, animal waste, or septic tank and pit latrine wastes as a result of runoff (Table 6.2 and Table 6.3).

**Table 6.2** Water quality test results for wetland 1 and wetland 2 in summer

| Wetland 1 | | Wetland 2 | |
|---|---|---|---|
| **Parameter** | **Measurement** | **Parameter** | **Measurement** |
| Water temperature | 23°C | Water temperature | 23.5°C |
| Ammonium ($NH_4^+$) | 0 mg $L^{-1}$ $NH_4^+$<br>0 mg $L^{-1}$ $NH_4^+$ N | Ammonium | 0.2 mg $L^{-1}$ $NH_4^+$<br>0.16 mg $L^{-1}$ $NH_4^+N$ |
| Carbonate hardness (ANC) | 1.5 mg $L^{-1}$ 4.2 od | Carbonate hardness | 1.3 mg $L^{-1}$ 3.6 od |
| Total hardness | 2.8 0d 45 mg $L^{-1}$ | Total hardness | 2.2 od 30 mg $L^{-1}$ |
| Residual hardness | Red violet 0.5 od (0.6oe) | Residual hardness | Red violet 0.5 od (0.6oe) |
| Nitrate ($NO_3^-$) | 10 mg $L^{-1}$ $N0_3^-$<br>2.3 mg $L^{-1}$ $NO_3^-N$ | Nitrate | 25 mg $L^{-1}$ $NO_3^-$<br>5.6 mg $L^{-1}$ $NO_3^-N$ |
| Nitrite ($NO_2$-) | 0 mg $L^{-1}$ $NO_2^-$<br>0 mg $L^{-1}$ $NO_2^-N$ | Nitrite | 0 mg $L^{-1}$ $NO_2^-$<br>0 mg $L^{-1}$ $NO_2^-N$ |
| Phosphate ($PO_4^{3-}$) | 0 mg $L^{-1}$ $PO_4{}^{3-}$ | Phosphate | 0 mg $L^{-1}$ $PO_4{}^{3-}$ |
| pH | 7.0 | pH | 7.0 |
| Oxygen ($O_2$) | 5 mg $L^{-1}$ | Oxygen | 4.7 mg $L^{-1}$ |

**Table 6.3** Water quality test results for wetland 1 and wetland 2 in winter

| Wetland 1 | | Wetland 2 | |
|---|---|---|---|
| **Parameter** | **Measurement** | **Parameter** | **Measurement** |
| Water temperature | 15°C | Water temperature | 15.5°C |
| Ammonium ($NH_4^+$) | 0 mg $L^{-1}$ $NH_4^+$<br>0 mg $L^{-1}$ $NH_4^+N$ | Ammonium | 0 mg $L^{-1}$ $NH_4^+$<br>0 mg $L^{-1}$ $NH_4^+N$ |
| Carbonate hardness (ANC) | 1.5 mg $L^{-1}$ 4.2 od | Carbonate hardness | 1.3 mg $L^{-1}$ 3.6 od |
| Total hardness | 2.8 0d 60 mg $L^{-1}$ | Total hardness | 2.2 od 45 mg $L^{-1}$ |
| Residual hardness | Red violet 0.5 od (0.6oe) | Residual hardness | Red violet 0.5 od (0.6oe) |
| Nitrate ($NO_3^-$) | 5 mg $L^{-1}$ $N0_3^-$<br>1.3 mg $L^{-1}$ $NO_3^-N$ | Nitrate | 5 mg $L^{-1}$ $NO_3^-$<br>2.9 mg $L^{-1}$ $NO_3^-N$ |
| Nitrite ($NO_2^-$) | 0 mg $L^{-1}$ $NO_2^-$<br>0 mg $L^{-1}$ $NO_2$-N | Nitrite | 0 mg $L^{-1}$ $NO_2^-$<br>0 mg $L^{-1}$ $NO_2^-N$ |
| Phosphate ($PO_4^{3-}$) | 0 mg $L^{-1}$ $PO_4{}^{3-}$ | Phosphate | 0 mg $L^{-1}$ $PO_4{}^{3-}$ |
| pH | 7.0 | pH | 7.0 |
| Oxygen ($O_2$) | 6 mg $L^{-1}$ | Oxygen | 4.2 mg $L^{-1}$ |

## 6.7 SUMMARY OF FINDINGS

The Ntondozi study investigated whether there are changes in wetlands as a result of community utilization over time and if such utilization is sustainable or not. From the findings it is evident that the people in the community rely heavily on the wetlands since they derive livelihoods in terms of the goods and services that they provide, either directly or indirectly.

Wetlands are sensitive to extreme temperature changes (Kotze, 2010). From the analysis of annual average temperatures and rainfall totals it is evident that temperatures are increasing each year, thus affecting the moisture content of the wetlands. This has compromised the size and productivity of the wetlands in terms of the goods and services they provide. Rainfall patterns from 1988 to 2018 have also shown a variation at Ntondozi, with the annual totals received decreasing over this period. In 2015 a low annual rainfall total of about 541 mm was recorded, indicating that the wetlands were almost dry and less productive. They would have been under massive usage that year because wetlands buffer fauna and flora during periods of high water stress and can therefore continue to provide goods and services for people as well as a unique habitat for water-loving animals (Hussien *et al.*, 2018).

There is a high level of negligent usage of the wetlands and, as stated by Hussien *et al*. (2018), many societies do not accord sufficient value to wetland resources (goods) and services, thus utilizing them unsustainably. In Zimbabwe, for instance, there is a missing link between wetland values and wetland awareness (Marambanyika & Beckedahl, 2017). Similarly, wetlands are perceived as a habitat for insects and as barriers to development in rural communities. This might be the reason why they were heavily polluted with detergents and plastics in Ntondozi. Schuyt (2005) argues that failure to understand the consequences of land use impacts such as pollution is a major threat to wetland degradation and the fact that wetland function has no market price is a sign of the unsustainable use of wetlands. This might be caused by resistance to change by individuals and failure to value wetlands as a resource with an economic value. Satellite images from 1988 to 2018 clearly showed changes in the wetlands as a result of community utilization over time. The area around the wetlands has been encroached by subsistence agriculture which, according to Marambanyika & Beckedahl (2016a), dominates rural land use in the area Ntondozi. In addition, the images indicated that in years which had less rainfall there was a lower moisture content in the wetlands. Since the fencing of the wetlands in 2017 they were seen to be improving, as shown by the differences when comparing the vegetation inside and outside the wetlands. The vegetation inside the wetlands was greener compared to the brownish outside vegetation, possibly due to differing degrees of disturbance by livestock and human beings inside and outside the wetlands. This will improve the benefits coming from the wetlands. Maintenance of the already established fencing will be helpful in preventing adjacent land use impacts.

The community members were concerned about the rapid decline in goods and services coming from the wetlands. The consequences of wetland depletion have increased dry land in and around the wetlands, posing threats to sustainable livelihoods (Gardner *et al*., 2015). The socio-economic benefits have decreased; for example, the reeds and grasses that they have been selling to sustain themselves is now insignificant and can no longer sustain their livelihood. Moreover, seasonal benefits like harvesting medicinal plants and building material have also decreased, with water remaining the major benefit from both wetlands. This suggests that unsustainable use of the wetlands has led to a decline in wetland resources such as thatching grasses, herbal plants as well as water supply in Ntondozi, which are a source of livelihoods to the rural society. This might be the reason why such wetland resource degradation led to Ramsar sites to guarantee wetland sustainability (Bridgewater, 2008). The satellite images indicated that from 1988 to 2018 the size of the wetlands in terms of moisture content was declining. This might be due to increase in wetland usage as more people source their livelihoods (especially water) from the wetlands. From the researchers' observation, invasive species like *Lantana camara* and guava trees were colonizing the wetlands. *L. camara* is a category 1b species in South Africa in terms of the Alien and Invasive Species Regulations, National Environmental Management: Biodiversity Act (Act 10 of 2004). These alien invasive plant species are a problem because they tend to dominate an area, preventing indigenous plants from growing and outcompeting them. They also consume a lot of water and can lead to the wetlands drying up.

From a comparison of the remotely sensed data of the wetlands, there is a massive change mainly due to temperature increase, decrease in annual rainfall totals, over-reliance on wetlands for their goods and services, and unsustainable utilization of the wetlands mainly as a result of 'tragedy of the commons'. No one is held responsible for wetland damage and pollution since everyone has access to the wetlands and harvesting what the wetlands can offer in that moment in time. Small wetlands in rural communities are mainly at risk of degradation since both animals and plants heavily depend on them, as is the case with the Ntondozi wetlands. This is the reason Hussien *et al*. (2018) argue that the overexploitation of wetland resources leads to unsustainable ecological and economic benefits. This shows us that wetlands in rural communities are one of the most threatened natural resources. This threat can mainly be caused by land use practices around the wetlands, the rate of change of which can determine the future of the wetlands. If the wetlands in Ntondozi are not governed, their future as providers of goods and services to the local community will be bleak (Kunene, 2020). The mobilization of stakeholders to actively participate in the management of wetlands is important because they gain knowledge and understanding of the value of the wetlands and how they are supposed to be utilized (as stated in the CBNRM document; Roe *et al*., 2009). There must be a change in mindset of the utilizers in terms of fully understanding the hydrological processes of the wetlands and their capability to be degraded over time.

Since water is the main benefit coming from the wetlands, it is essential to monitor water quality. It was noticed that anthropogenic activities might have a direct effect on water quality, as seen by the high rates of nutrients (nitrates of 25 mg $L^{-1}$ $NO_3^-$ and 5.6 mg $L^{-1}$ $NO_3^-N$) in Ntondozi wetland 2, which may come directly from chemical fertilizers used in the fields mostly in summer. Agricultural activities were evidently close to wetland 2, giving us an idea of nutrient pollution in this wetland. Generally, the water quality of both wetlands was within the standards of drinking water and the water was not yet heavily polluted by nutrients from fertilizers and livestock waste, except for the nitrate levels recorded in summer. Water levels in the wetlands are directly related to the amount of rainfall received. The water depth measurements showed that water levels in the wetlands were decreasing as autumn and winter approached. In January 2019 there were heavy rains that resulted in higher water levels, while towards the end of that month the levels began to decrease drastically since no significant rains were received. These observations enabled the prediction of further decreases in water levels as the dry winter season approached.

## 6.8 CONCLUSIONS

This study provided justification to wetland researchers, managers and environmentalists to shift towards an integrated style of wetland management, a condition that can ease effective and sustainable utilization of wetlands, and is currently lacking in Eswatini (Marambanyika & Beckedahl, 2016b). Wetlands are ecosystems which perform important ecological and socio-economic functions for the local people and should therefore be utilized sustainably. However, the results showed that there were no controls put in place to monitor how the wetlands should be utilized in a sustainable way, so consequently they were not used wisely. The Ramsar Convention recognizes the importance of national recognition of wetlands value as a key tool for informing policies and other actions to achieve the conservation and wise use of wetlands (Ramsar Convention Secretariat, 2010b).

The changes observed by remotely sensed images traced back to 1988 when the wetlands were fully covered by high levels of moisture and vegetation, but as the years progressed they became heavily degraded and shrank in terms of moisture coverage. The study further disclosed that the wetland system is facing challenges of human induced degradation resulting from intertwined poor land use practices. If nothing is done to address the current problems, it is clear that the ability of the wetlands to deliver ecological, economic, social and cultural benefits to the local community in Ntondozi is likely to be compromised. This might hit the rural poor hard, who depend on the wetland for essential resources such as medicinal plants, water and building material, since already the wetlands are degraded due to poor practices. The research study further indicated that the land use around the wetlands was approaching them, mainly due to cultivation. From the researchers' observation, there was a high unsustainability level in the wetlands but the fencing of the wetlands in 2017 might help them to recover slowly even though the people continue with their indigenous practices and there is no wetland governance. The benefits derived from the wetlands have declined and lost significance since only 24.4% of the respondents regarded the wetlands as a source of income and they have seen a major decline in these benefits over the last three decades (1988 to 2018). Fencing of the wetlands might help in re-establishing some of the benefits derived from them. The new shoots of *Phragmites australis* noticed in wetland 2 was an affirmative sign that the community would soon have the goods and services provided by the wetlands. Unfortunately there was also dense dry *P. australis* which can easily attract fire and destroy the new shoots, and at the same time decreasing the moisture content in the wetlands, especially in wetland 2. Water quality tests in relation to land use around the wetlands indicated that there are some nutrients from human activities such as agricultural fertilizers and pit latrine related waste; otherwise the water from the wetlands was not in a bad condition for human consumption since all the parameters tested were not alarming for local community consumption and the water was less polluted except for the nitrate levels in wetland 2 in summer. Water levels in the 8 weeks in summer and winter indicated a huge dependency on rainfall availability. Recordings that were done on days that received rainfall in the previous night recorded high water depths, while the opposite was true with days that did not receive rainfall. Winter level trends were constant in terms of water depths.

## 6.9 IMPLICATIONS OF THE FINDINGS TO EXISTING LITERATURE

The research presented here has clarified the significance of understanding the effects of both land use and linked utilization strategies in the justification of wetland ecosystems and their sustainable use. The results of this study have a number of implications for the current literature on factors affecting wetland utilization in Eswatini. It was revealed that if wetlands are not taken care of, they can be degraded at an unprecedented rate. Notably, there is lack of enforcement of resource governance in the country despite elaborate laws and policies on paper. The lack of enforcement of laws and policies governing wetlands is a serious issue regarding wetland utilization in the country. The study has shown that the institutional and the practical factors were the ones affecting the sustainability of the wetlands at Ntondozi and Eswatini at large. The indigenous practices including washing in the wetlands still existed. The wetland users do not have the knowledge and understanding of how the wetlands should be wisely used and sustained. All the users are competing to meet their needs from the wetlands and thus manipulating the strength of the wetlands in providing adequate goods and services. This study is a baseline for wetland sustainability and management in the country since it has discovered that there is a gap between wetland utilization and sustainability of wetlands resources in Eswatini, and that there is limited information based on wetland studies in the country.

## 6.10 RECOMMENDATIONS FOR ACTION

Based on the findings of the study, the following recommendations are made:

- The community must achieve sustainable utilization of the wetlands jointly as local institutions for local benefits as recommended by the CBNRM.
- All people utilizing wetlands must bear the costs of unsustainable utilization of the wetland resources. It was observed that some users were failing to pay their monthly subscription to maintain the water pump and leaving pollutants in the wetlands, which is totally unacceptable.
- If there is no shared understanding of the wetlands and they are left completely ungoverned, then they will be subject to depletion through a 'tragedy of the commons' scenario whereby all users compete to access and utilize/exploit the wetlands anyhow.
- The community must make fire breaks around the wetlands since there is thick dry grass, especially in wetland 2, which may compromise the health of the wetland in case of it catching fire.
- Conduct a comparative study on the factors affecting wetland sustainability in Eswatini in order to make an informed choice of wetland use, then strengthen the positives and fix the loopholes in the sustainable use of wetlands.
- Formulate wetland resources management frameworks based on an understanding of socio-economic and ecological processes in wetland utilization in Eswatini.

# 7. CONCLUSIONS AND RECOMMENDATIONS

Considering the scarcity of peatlands in South Africa and their global importance, it is critically important for site-specific investigations coupled with climate change projections to help us understand the potential impact of climate change on ecosystem processes, their functions and structure in order to inform decisions regarding the conservation and rehabilitation of peatlands.

This study set out to provide clarity on the ecosystem resilience of headwater wetlands by studying the morphological controls and hydrology of the Waterval peatland in the Kgaswane Mountain Reserve near Rustenburg, North West Province, and the Malolotja peatland in the Malolotja Nature Reserve near Mbabane, Kingdom of Eswatini (formerly the Kingdom of Swaziland). An ensemble of high resolution projections of future climate change over Africa and southern Africa supported these catchment-scale studies. The national-scale wetland prediction map of Eswatini made a significant contribution towards the baseline data for the Kingdom of Eswatini, which did not previously have a wetland map.

The results of this study add to the limited body of knowledge on the functioning of peatlands. Peatland formation was strongly influenced by geological features including fault line and erosion-resistant key points near the peatland outlet, which allowed for water and sediment accumulation. The geomorphological controls such the topography, steep to flat hillslopes and sediment buffers, promote saturated conditions for peat formation. Evidence in this study also confirms that groundwater input is an important factor for the maintenance of saturated conditions, thereby contributing to our understanding of the hydrological systems.

The research outcomes from this study provided additional information to support the conservation management of the Kgaswane Mountain Reserve and the Malolotja Nature Reserve. The studies done by Mr Jason le Roux, Ms Thandeka Ndlela and Mr Welile Kunene are important for inclusion into a draft wetland policy document for Eswatini because of the proposed future focus area of sustainability and wise use of wetlands. The results proved that there were no controls put in place to monitor how the wetlands should be utilized in a sustainable way, so consequently they were not used wisely.

The results from the three indicators (i.e. hydrology, sediment deposition and vegetation cover) have shown a positive response to the rehabilitation interventions. The wetland rehabilitation process should not end with the implementation of rehabilitation interventions such as erosion prevention structures, but should also incorporate the monitoring and evaluation of the functionality of the rehabilitation interventions as well as the intended (ecological) outcome of the rehabilitation process.

This international transboundary water research project is of importance and has laid the foundation for other international transboundary projects. The study also created various opportunities for capacity building (five MSc students and two Hons students completed their studies) and for future research.

Overall recommendations include the following:

- Further investigations are needed to quantify the volume of peat and carbon balance within both peatlands.
- The calculated water balance and more accurate hydrological and stratigraphic description for each of these systems will help to understand their vulnerability to environmental and climate change.

- Long-term and detailed monitoring of peatland hydrology (larger sample sizes and more transects) undertaken within Eswatini could allow for a comparison of such results with similar parameters in southern Africa and elsewhere.
- Determine whether soil and morphometric data at a finer scale and resolution, and other types of attribute data, would yield more accurate results in mapping probable areas where wetlands could occur.
- The community will only achieve sustainable utilization of the wetlands through a joint effort (e.g. community-based natural resource management).
- Conduct a comparative study on the factors affecting wetland sustainability in order to make an informed choice of wetland use, then strengthen the positives and fix the loopholes in the sustainable use of wetlands.

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# APPENDICES

**Appendix 1** Project deliverables

| | Title | Description | Target Date |
|---|---|---|---|
| **1** | Project Advance | Project Advance (20% of first year's budget). | 01/04/2018 |
| **2** | Project Inception Report | **Project Inception Report** documenting PhD Student registration, MSc student registration and student proposals. | 30/06/2018 |
| **3** | Field Survey Report | **Field Survey Report** on the respective study area imagery and water sample results. | 30/11/2018 |
| **4** | Interim Progress Report 1 | **Progress Report 1** Highlighting the progress to date, including relevant student progress and results. | 30/06/2019 |
| **5** | Information Dissemination Report | Report on the **Cross-cultural Wetland Workshop** and the presentations at a scientific conference. | 30/11/2019 |
| **6** | Interim Progress Report 2 | **Progress Report 2** Highlighting progress to date, including relevant student progress and results. | 30/06/2020 |
| **7** | Draft Final Report | **Draft Final Report** to the review committee for comments and edits. | 28/02/2021 (08/03/2021) |
| **8** | Final Print Ready Project Report | **Final Print Ready Project Report** submitted (final payment of 20% of the total project value). | 31/08/2021 (31/03/2022) |

**Appendix 2** Capacity building

The South African and the Eswatini students who formed part of the project are listed below. Two students were awarded their MSc degrees *cum laude* (Mr Jason le Roux and Ms Thandeka Ndlela) and both have registered for PhD degrees.

***South African students who formed part of the project team***

| | Name | University | Department | Degree | Student No. | Start | End |
|---|---|---|---|---|---|---|---|
| 1 | Yonwaba Atyosi | UFS | Geography, Environmental Science | PhD | 2017562154 | Jan 2018 | - |
| 2 | Lufuno Nemakhavhani | UFS | Centre for Environmental Management | MSc | 2016174704 | Jan 2018 | Feb 2022 |
| 3 | Jason le Roux | UP | Geography, Geo-informatics and Meteorology | MSc Environmental Management | 12022609 | Jun 2017 | Sep 2019 |
| 4 | Bernardus Bosman | UFS | Geography, Environmental Science | BSc Hons | 2014104448 | Jan 2019 | Nov 2019 |
| 5 | Ayabonga Gangathele | UFS | Geography, Environmental Science | BSc Hons | 2015230432 | Jan 2019 | Dec 2019 |

***Eswatini students who formed part of the project team***

| | Name | University | Department | Degree | Student No. | Start | End |
|---|---|---|---|---|---|---|---|
| 1 | Welile Kunene | UNESWA | Geography, Environmental Science & Planning | MSc (Environmental Resource Management | 137068 | Aug 2016 | Jun 2020 |
| 2 | Thandeka Ndlela | UNESWA | Geography, Environmental Science & Planning | MSc (Environmental Resource Management) | 144291 | Feb 2019 | Dec 2020 |
| 3 | Musawenkhosi Twala | UNESWA | Geography, Environmental Science & Planning | MSc (Environmental Resource Management) | 138049 | Aug 2016 | Feb 2022 |

**Appendix 3** Technology transfer

## CROSS-CULTURAL WORKSHOP

The Cross-cultural Wetland Workshop (Information Dissemination Report, Deliverable 5) was one of the project's aims, namely to facilitate discussion between role-players (wetland experts, government officials and students) from different countries on wetland types and their functioning. The Cross-cultural Wetland Workshop was held at *Miss Chrissies Country House* at Chrissiesmeer, Mpumalanga on 4-6 October 2019 and was attended by 17 participants representing the following countries: South Africa, Kingdom of Eswatini, The Netherlands and Australia. A mini-seminar session, where the students presented their research (and received feedback), was coupled with field trips to Tevrendenpan and Blinkpan. The focus of the field visits was to expose the students and the government officials from Eswatini to hydro-geomorphic wetland types (depressions) that are different from the peat wetland types studied at Kgaswane Mountain Reserve and Malolotja Nature Reserve.

## INTERNATIONAL MIRE CONSERVATION GROUP FIELD SYMPOSIUM

The International Mire Conservation Group (IMCG) had to postpone the Field Symposium and Scientific Congress that would have taken place in December 2021 due to the COVID-19 pandemic. The dates are now set for 13-30 March 2022 when international peat and wetland experts will visit South Africa and the Kingdom of Eswatini. The main purpose of this international Field Symposium is to visit unique peat systems in South Africa and in the Kingdom of Eswatini, to discuss the impacts on these systems and to come up with suggestions for further research and conservation. The IMCG offers hands-on practical training and opportunity for three ARC Professional Development Programme (PDP) students, who will also be able to meet and interact with the international experts. The Symposium makes provision for a Scientific Congress that will take place at the University of Eswatini, Manzini on 22 March 2022 and for a Mire Restoration Workshop at the Marakele National Park on 29 March 2022.

## CONFERENCES AND PUBLICATIONS

This section lists the presentations made at international and national conferences, sharing results and findings from this project.

❖ **International Conferences**

- Le Roux J, Beckedahl H, Grundling AT & Sumner P (2019). *The prediction and spatial distribution of wetlands in Eswatini (Swaziland)*. AG (Geomorphology), Greece 2019 (19-21 September 2019). https://rcg2019.com/

❖ **Global Sustainability Conference**

- Beckedahl H (2021). *Sustainability, or where does 'failing to plan' become 'planning to fail'?* Keynote address. 8 September 2021, Halle, Germany.

- Beckedahl H, Mabaso S, Singwane S & Mamba F (2021). *Community-based rehabilitation efforts in the Ngcanyini chiefdom of Eswatini*. Paper presented on 9 September 2021. Halle, Germany.

❖ **National Conferences**

- Grundling P & Grundling A (2019). *Peat fire - an erosion catalyst in southern African mires?* Southern African Geomorphology (SAAG) Conference, 16-17 September 2019.

- Le Roux J, Beckedahl H, Grundling A, Grundling P & Sumner P (2019). *The hydrogeomorphic distribution of wetlands in Eswatini*. Southern African Geomorphology (SAAG) Conference, 16-17 September 2019. Mr Jason le Roux was one of two students who received a prize for **best student presentation**.

- Nemakhavhani L, Grundling AT & Grundling P (2019). *Assessment of wetland rehabilitation interventions using hydrology, geomorphology and vegetation in Kgaswane mountain reserve.* National Wetlands Indaba, 7-11 October 2019.

- Gangathele AM, Grundling AT, Grundling P & Le Roux JJ (2019). *Comparing two main tributaries feeding a peatland system in Kgaswane mountain reserve, Rustenburg*. National Wetlands Indaba, 7-11 October 2019.

- Bosman BL; Grundling AT, Grundling P & Le Roux JJ (2019). *Geomorphological controls and hydrology of a peatland in the Kgaswane mountain reserve, Rustenburg*. National Wetlands Indaba, 7-11 October 2019. Mr Nardus Bosman was one of four students who received a prize for **best student presentation**.


*Mr Nardus Bosman (second from right) was one of four students who received a prize for best student presentation at the National Wetlands Indaba 2019.*

- Gangathele AM, Grundling AT, Grundling P & Le Roux JJ (2021). *Peatland response to degradation: A case study of Waterval peatland in Kgaswane mountain reserve.* Society of South African Geographers (SSAG) & Southern African Association of Geomorphologists (SAAG) 2021 Joint Biennial Conference online, 6-8 September 2021.

- Ndlela T, Beckedahl H & Grundling AT (2021). *Peatland hydrological processes in Malolotja nature reserve, Eswatini.* Society of South African Geographers (SSAG) & Southern African Association of Geomorphologists (SAAG) 2021 Joint Biennial Conference online, 6-8 September 2021.

- Beckedahl H & Thwala M (2021). *An assessment of the effects of human settlement expansion on wetlands in Eswatini: The case of the Matsapha peri-urban area.* Society of South African Geographers (SSAG) & Southern African Association of Geomorphologists (SAAG) 2021 Joint Biennial Conference online, 6-8 September 2021.

❖ **Masters Degrees**

- Kunene W (2020). *Towards sustainable community utilization of wetlands in Eswatini: The case of Ntondozi.* MSc thesis, Department of Geography, Environmental Science and Planning, University of Eswatini, Kwaluseni, Kingdom of Eswatini.

- Le Roux JP (2020). *The hydrogeomorphic distribution of the wetlands in Swaziland, and their prediction.* MSc thesis, Department of Geography, Natural and Agricultural Sciences, University of Pretoria.

- Ndlela T (2021). *Understanding peatland hydrology in the Malolotja nature reserve, Kingdom of Eswatini.* MSc thesis, Department of Geography, Environmental Science and Planning, University of Eswatini, Kwaluseni, Kingdom of Eswatini.

- Nemakhavhani L (2022). *Assessment of the effectiveness of wetland rehabilitation interventions at Kgaswane Mountain Reserve using hydrology, sedimentation, and vegetation as indicators*. MSc thesis, Centre of Environmental Management in the Faculty of Natural and Agricultural Sciences, University of the Free State.

- Thwala M (2022). *The effects of human settlements expansion on wetlands in Eswatini: The case of Matsapha peri-urban area.* Masters thesis, University of Eswatini, Kingdom of Eswatini.

❖ **Honours Degrees**

- Bosman BL (2019). *Geomorphological controls and hydrology of a peatland in the Kgaswane Mountain Reserve, Rustenburg, South Africa.* Report for Honours degree, University of the Free State.

- Gangathele AM (2019). *Comparing two tributaries associated with alluvial fans feeding a peatland system, Kgaswane Mountain Reserve, Rustenburg, South Africa.* Report for Honours degree, University of the Free State.

❖ **Peer-reviewed Publications**

- Le Roux JP, Beckedahl HR, Grundling AT & Sumner P (2022). *Determining the distribution of wetlands across Eswatini*. South African Geographical Journal. doi: 10.1080/03736245.2021.2021975.

- Ndlela T, Beckedahl HR, Grundling A & Grundling P (in review). *Spatio-temporal variation in groundwater at a Swati peatland.* Geoökodynamik.