The hydrogeomorphic distribution of the wetlands in Swaziland, and their prediction.

by

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ABSTRACT

Swaziland became a signatory to the Ramsar Convention on the 15th of June, 2013. To date, the country does not have a national wetland inventory. This study aimed to apply the newly developed wetland probability mapping technique developed in South Africa to Swaziland, in order to provide potential baseline information on the distribution of wetlands across the country. Prior to this study commencing, there was little understanding of this wetland probability mapping technique. Results of this study show that when applying the mapping technique as it was applied in South Africa, other watercourses (rivers, drainage lines, and riparian zones) are more frequently mapped than true wetlands. Given that Swaziland currently uses the broad Ramsar definition of a wetland, the wetland probability map is well suited to identify wetlands falling under such definition. However, it does not suffice as a wetland map in countries such as South Africa that use a more specific definition for wetlands. In order to improve the initial wetland probability map, this study further made use of attribute data, obtained from 2000 randomly distributed points across the initial wetland probability map, to improve the latter through refining it to distinguish wetlands from other types of watercourses. It also classified areas of the map with the highest probability of being true wetlands into hydrogeomorphic units. This resulted in three types of wetland probability maps being produced.

The initial wetland probability maps developed here can be used used to identify watercourses across Swaziland, which includes wetlands, drainage lines, riparian zones and rivers. The refined wetland probability map, which partially distinguishes wetlands from other types of watercourses, acknowledges the dynamic nature of wetlands and that the distinction between wetlands and other watercourses is not always exact. The refined wetland probability map also allows the government of Swaziland to locate watercourses with a highest probability of being wetlands. Furthermore, the classified wetland probability map provides the government of Swaziland with the baseline information needed to understand the relationship between organisms and the environment, as well as how the wetland is connected to the drainage network and how water moves through the landscape. The three wetland probability maps produced in this study also indicate that the location and distribution of the larger wetland systems across Swaziland are controlled by topography, soils, as well as the contact zones between different geologies.

Declaration

I, Jason le Roux, Declare that the thesis, which I hereby submit for the degree of Master of Environmental Management at the University of Pretoria, as my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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List of Acronyms

ARC-ISCW:	Agricultural Research Council- Institute for Soil Climate and Water (South Africa)
COP:	Conference of Parties
CFR:	Cape Floristic Region
DEM:	Digital Elevation Model
DRDLR:	Department of Rural Development and Land Reform (South Africa)
DWAF:	Department of Water and Forestry (South Africa)
ENTC:	Eswatini National Trust commission
FAO:	Food and Agricultural Organization (United Nations)
NFEPA	National Freshwater Ecosystem Priority Area
FGDC:	Federal Geographic Data Committee
HGM:	Hydrogeomorphic
IUCN:	International Union for Conservation of Nature
MCP:	Maputaland Coastal Plain
NWM:	National Wetland Map (South Africa)
NWA:	National Water Act (South Africa)
REMA:	Rwanda Environmental Management Authority
SAIIAE:	South African Inventory for Inland Aquatic Ecosystems
SRTM:	Shuttle Radar Terrain Mission
USA:	United States of America
USDA:	United States Department of Agriculture
UNFPA:	United Nations Population Fund
WMD:	Wetlands Management Department (Uganda)

Chapter 1: Introduction

1.1 Wetlands in southern Africa

Wetlands of southern Africa are estimated to cover 4.7% of the continental area (Lehner and Döll, 2004). This is in line with the global wetland area estimate of 4-6% of the land surface of the Earth (Rebelo *et al*., 2010). Despite covering such a small percentage of land, wetlands are known for their ecosystem services (Mitsch and Gosselink, 2000a), especially the in developing countries where people's livelihoods, particularly rural populations, tend to be more directly dependent on wetlands, as opposed to developed countries (Kotze *et al*., 2007; Rebelo *et al*., 2009; 2010). However, apart from South Africa, there is little information on wetlands in the resource-poor countries of sub-Saharan Africa (Rebelo *et al*., 2010; Marambanyika and Beckedahl, 2017).

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 and Jones, 1995). Wetlands are commonly described as areas that are periodically or continually inundated by shallow water or have saturated soils where plant growth and other biological activities are adapted to wet conditions (Mitsch and Gosselink, 2009). The value of wetlands depends on their size and placement within the landscape, as well as their relationship to adjacent water areas and their proximity to human settlements (Mitsch and Gosselink, 2000a; Galbraith *et al*., 2005). Although wetlands are primarily viewed as agriculturally rich land by many rural populations across Africa, they are complex and dynamic ecosystems that fulfill many other needs or ecosystem services (Mitsch and Gosselink, 2000b; Rebelo *et al*., 2010).

The ecosystem services provided by wetlands have been widely documented (Chen *et al*., 2009; Mitsch and Gosselink, 2009; Hester and Harrison, 2010; McLaughlin and Cohen, 2013). From a southern African perspective, the most comprehensive list of wetland ecosystem services is provided by Kotze *et al*. (2007) in an ecological assessment tool that acknowledges people with a high dependence on these natural resources. The direct benefits of wetlands include: provision of water for human use, harvestable resources, provision of cultivated foods, cultural heritage, tourism, recreation, education and research. Indirect benefits include: flood attenuation, streamflow regulation, provision of cultivated foods sediment trapping, phosphate assimilation, nitrate assimilation, toxicant assimilation, erosion control and carbon storage Kotze *et al*. (2007). Despite these benefits wetlands have been and continue to be degraded through various anthropogenic activities, which is especially the case in southern Africa (Galbraith *et al*., 2005 Marambanyika and Beckedahl, 2017).

In southern Africa, the degradation of wetlands is often attributed to a lack of management, which is a result of governments and landowners not having the resources and information needed to mitigate against the adverse impacts that humans have on wetlands (Mwendera, 2003; Masarirambi *et al*., 2010). Population expansion and the growing need for land has been a major driver of wetland loss (Jackson *et al*., 2016), especially through land use changes such as agriculture and urban expansion which result in many wetlands being drained and drying out (Madebwe and Madebwe, 2005). Wetlands also face increased sedimentation from erosion, pollution from urban runoff as well as agricultural fertilizers and pesticides which have adverse impacts on the natural biota of wetlands (Rebelo *et al*., 2010).

The increased consumption of surface and groundwater resources, along with the altering of the natural flow of water, results in wetlands not receiving sufficient water to sustain their hydrological balance. This is specifically the case in drier climates and where precipitation is more variable from year to year (Brinson, 1993). For this reason, many wetlands in southern Africa are more dependent on relatively large catchment areas for providing sufficient supplies of water to maintain their integrity. Macfarlane *et al*. (2007) explain how this dependence leads to wetlands being impacted by activities that occur within the entire catchment and not just within the wetlands.

In order to combat degradation of wetlands, many governments have established specific laws and policies that aim to protect and govern the use of wetlands. In South Africa this includes the National Environmental Management Act (NEMA, 1998), The National Water Act (NWA, 1998), and the National Environmental Management Biodiversity Act (NEMBA, 2004). An overarching convention that steers many of these policies relating to wetlands is the Ramsar Convention. It was established in 1971 and currently has 170 contracting parties (Ramsar Homepage, 2019).

1.2 The Ramsar Convention

The Ramsar Convention is a voluntary intergovernmental treaty that obliges countries to aim towards the conservation and wise use of all wetlands through local, regional and national actions as well as international cooperation (Ramsar Convention Secretariat, 2010; 2018). The Convention's purpose is to contribute towards achieving sustainable development throughout the world and provides various guidelines concerning the wise use of wetlands. In practice the Conference of the Contracting Parties (COP) meets every three years with the aim of promoting policies and guidelines to advance the objectives of the Convention. The Standing Committee, made up of Contracting Parties representing the six Ramsar regions of the world, meets each year to guide the Convention between meetings of the COP. The Ramsar Convention also consists of a Scientific and Technical Review Panel that provides guidance on key issues for the Convention (Ramsar Convention Secretariat, 2016).

Once a country becomes a signatory of the Ramsar Convention, the country is required to designate an administrative authority that acts as implementers of the Convention. Countries are also encouraged to establish a broad-based National Wetland Committee and are mandated to identify at least one wetland in their respective country as a site of international importance (known as a Ramsar site). As of July 2019, there are over 2300 international sites recognized as wetlands of international importance around the world (Ramsar Homepage, 2019). Along with many recommendations, the Ramsar Convention specifically recognizes the importance of national wetland inventories and classification systems as a key tool for informing policies and other actions to achieve the conservation and wise use of wetlands (Ramsar Convention Secretariat, 2010).

1.2.1 Wetland inventories

Contracting parties of the Ramsar Convention, of which Swaziland is a signatory, are encouraged to base their national wetland policies on a nationwide inventory of the country's wetlands and their resources (Ramsar Convention Secretariat, 2010). The Ramsar convention defines a wetland inventory as the collection and/or collation of core information for wetland management, including the provision of an information base for specific assessment and monitoring activities (Ramsar Convention Secretariat, 2018) The Ramsar Convention's handbook on wetland inventories (Ramsar Convention Secretariat, 2010), emphasizes that national wetland inventories are an essential basis for the formulation of national wetland policy, identification of sites suitable for inclusion in the list of Wetlands of International Importance, quantification of the global wetland resource, documentation of wetlands suitable for restoration, as well as risk and vulnerability assessments.

The handbook (Ramsar Convention Secretariat, 2010) explains that there have been many agreements and implementation commitments concerning wetland inventories. This includes the 1st meeting of the Conference of the Contracting Parties in 1980 where Contracting Parties agreed that national wetland policies should be based on a nationwide inventory of wetlands. Resolution VII.20 urged all Contracting Parties who have not yet completed comprehensive national inventories of their wetland resources to give this highest priority and to include, where possible, wetland losses and wetlands with potential for restoration. Resolution VI.12 also encourages contracting parties to include all the wetlands in their respective countries when establishing and maintaining national scientific inventories (Ramsar Convention Secretariat, 2010).

Finlayson and Spiers (1999) explain that the objectives of a wetland inventory can vary depending on the type of information required and that wetland inventories are compiled for various reasons. This includes determining wetland status, providing background information for future monitoring, identifying important habitats for wildlife, and determining economic interests and other functions.

Scott and Jones (1995) explain how wetland inventories also aid in the identification of priorities for future action in research, protection and management of wetlands, establish the basis for monitoring the conservation status of wetlands, facilitate local, national and international comparisons between sites, and promote increased awareness of/interest in key wetland sites on the part of politicians, government officials, land-use planners, students and scientists.

1.2.2 Wetland classification systems

A fundamental component of a national wetland inventory is a wetland classification system (Finlayson and Spiers, 1999). However, many wetlands remain difficult to characterise and classify (Lisenby *et al*., 2019). Regional variations in a landscape's geology, geomorphology, hydrology, drainage and climate result in the development of specific wetland habitats where different types of wetlands occur (Smith *et al*., 1995; Ellery *et al*., 2008; 2016). Sieben *et al*. (2017) 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 also needed for different wetland types (Dini and Cowan, 2001). This requires that each wetland unit be described and classified according to its biophysical characteristics and functional attributes (Ewart-Smith *et al*., 2006; Ramsar Convention Secretariat, 2010).

Given that local topographical features influence the types of wetlands in a region, applying a classification system developed for a particular part of the world is not always possible. Scott and Jones (1995) argue how the classification of wetlands is extremely problematic, since the definition of the term varies considerably across different regions. As an example, they state that some parts of the world include land which may be completely dry for years, but which may support internationally important wetlands after periods of exceptional rainfall. This makes it difficult to apply the wetland classification system developed in one country to another (Scott and Jones, 1995).

1.3 Swaziland and the Ramsar Convention

The Kingdom of Swaziland (now Eswatini)[1] 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 and Hughes 1992), their Ramsar sites are all lacustrine systems (dams) with a combined surface area of 1,183 hectares and include:

[1] In April 2018, after this study had commended, it was announced by King Mswati III that the Kingdom of Swaziland would revert to its original name, the Kingdom of Eswatini. Whilst it is acknowledged that the country's name has changed, the following dissertation will refer to Eswatini by its former name of Swaziland. The reason for this is because literature refers to the country's previous name, and changing between the countries current and former name lead to confusion.

1. Van Eck Dam, Ramsar Site number 2123, 187 ha.
2. Hawane Dam and Nature Reserve, Ramsar Site Number 2121, 232 ha.
3. Sand River Dam, Ramsar Site number 2122, 764 ha.

Swaziland's wetlands have historically been heavily over-utilized and undermanaged (Mwendera 2002; Masarirambi *et al*., 2010). There is also a dearth of knowledge relating to the wetlands of Swaziland, with scattered pieces of literature in various international reports and reviews, as well as smaller contributions from academic institutions and local government organisations. In 2015, the Swaziland Ramsar committee reported to that its five greatest difficulties in implementing the convention are (Ramsar Convention, 2015):

1) Delayed ratification of the Ramsar Convention by the Swaziland Government.

2) Lack of cooperation and enforcement by the institutions with responsibilities on wetland issues.

3) Shortage of financial resources to support wetland management activities.

4) The absence of a national wetland policy and legislation.

5) The absence of a land tenure policy for the country.

Unlike most signatory countries, Swaziland does not have its own definition for wetlands and has subsequently adopted the definition of the Ramsar Convention. There have also 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 inventory. Swaziland also does not have or use a classification system, apart from the three Ramsar sites that are classified according to the Ramsar system. However, the Ramsar Classification System is intended to be used for sites of international importance and not at a national level (Kabii, 1998). This calls for Swaziland to develop their own wetland classification system, or to adopt one that is suited to the wetlands found in the country. Given that Swaziland is mostly bordered by South Africa, there is a high likelihood that the wetland mapping techniques developed in South Africa are applicable to Swaziland.

1.4 South Africa

In the process of updating their national wetland inventory, South Africa has recently released their fifth version of their national wetland map (van Deventer *et al*., 2018a). Instead of using remote sensing techniques to map wetlands, which were used for previous versions of South Africa's national wetland map (Nel *et al*., 2011), van Deventer *et al*. (2018b) used a different approach for mapping wetlands based on fine-scale on-screen digitizing, using high resolution imagery. In addition to the on-screen digitizing of wetlands, South Africa also explored the use of a wetland probability mapping technique (Collins, 2018).

The use of a hydrogeomorphic wetland type classification system has become widespread in South Africa (Ollis *et al*., 2015). The current classification system of Ollis *et al*. (2013) is the result of collaborative research efforts and various field testing's between a number of wetland/aquatic scientists from numerous regions and institutions across South Africa (Ollis *et al*., 2015). Grundling *et al*. (2014a) and Grundling (2014b) explain that the current hydrogeomorphic classification system is based on the underlying assumption that aquatic ecosystems function slightly differently in different landscape settings and that wetlands belonging to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes. However, Grundling *et al*. (2014a) also add that this underlying assumption has yet to be fully tested. Further research is therefore required to test the recently developed wetland probability mapping technique (Collins, 2018), as well as the widely used classification system of Ollis *et al*. (2013).

1.5 Rationale for the study

Swaziland shares many strategic water sources with South Africa (le Maitre *et al*., 2018). The boundaries between the two countries are also political, rather than physical. It is therefore likely that the wetland mapping and classification techniques used in South Africa are applicable to Swaziland. In line with Swaziland's commitments to the Ramsar Convention, the country will drastically benefit from a national wetland inventory that will contribute to further policy development and conservation of wetlands (Scott and Jones, 1995; Finlayson and Spiers, 1999; Ramsar Convention Secretariat, 2010). In addition to determining the extent and distribution of wetlands in Swaziland, a classification system that distinguishes between different wetland types is fundamental to the compilation of a national wetland inventory (Ewart-Smith *et al.,* 2006). The Eswatini National Trust Commission (ENTC) is also currently in the process of drafting a Concept Note towards the development of a National Wetland Policy on behalf of the Swaziland Government (Gumedze, Personal Communication, 2019).

The following research intends to apply the wetland mapping and classification techniques used in South Africa to the wetlands of Swaziland, and determine the distribution of wetland types in the country. The outcomes of this research can provide a baseline data set for the Swaziland National Trust Commission when applying Swaziland's National Wetland Policy, and can be used as baseline data for fulfilling the countries obligations to the Ramsar Convention.

The mapping technique used here is based on the methods developed by Collins (2018). The technique is, however, in its infancy and the limited testing of its capabilities have led to a narrow understanding of where it can be used (van Deventer *et al*., 2018c). The research can thus also contribute towards the further development and understanding of wetland probability mapping and future South African Wetland Inventories. An attempt is also made to develop a new technique to automate the hydrogeomorphic classification of the wetland probability map, since automating the classification of a national wetland map to hydrogemoprhic units is also a challenge currently facing the South African Wetland Inventory (Nel *et al*., 2011; van Deventer *et al*., 2016; 2018b).

1.6 Aims and Objectives

This study aims to predict the areas of probable wetland occurrence in Swaziland through applying the Wetland Probability Mapping technique of Collins (2018), and adapting it to more accurately identify wetlands. The research also attempts to aid the development of both the South African wetland inventory as well as the development of wetland inventories for other countries that require them. Two objectives are identified:

Objective 1- To map areas where wetlands could occur in Swaziland and analyze the results
Objective 2- To improve the initial wetland probability map and analyze the results

1.7 Thesis outline

The thesis begins with this introduction chapter that highlights Swaziland's need for a wetland inventory and a corresponding wetland classification system. Chapter 2 consists of a literature review that outlines international, and African wetland mapping and classification techniques, as well as wetland related research in Swaziland. Chapter 3 provides the environmental setting of Swaziland, with an emphasis on its physical geography.

Chapter 4 is the application of the wetland probability mapping technique to Swaziland, based on the methods developed by Collins (2018), as well as an accuracy assessment of the initial wetland probability map. Chapter 5 explains the methodology and results of using attribute data to improve the initial wetland probability map produced in Chapter 4. Chapter 6 is a discussion chapter that focuses on the capabilities and limitations of the different wetland probability maps created for Swaziland, and where they can be of use. Chapter 7 concludes this research by summarizing the relevant findings identified in this dissertation.

Chapter 2: Review of wetland literature

The following chapter will start by explaining why different types of wetlands develop. The chapter will then review several wetland classification systems used to distinguish between different wetland types. This includes the Ramsar Convention's classification systems, the Classification of Wetlands and Deepwater Habitats (Cowardin *et al*., 1979; FGDC, 2013) and two hydrogeomorphic classification systems of the United States of America (USA) (Brinson, 1993; Smith *et al*., 1995). The reason for including classification systems developed in the USA is that they have been cited internationally and used as precedence for many others around the world, including South African (Ollis *et al*., 2013). The chapter will then shift towards Africa, where the mapping and classification methods for three African countries will be reviewed.

Uganda, Rwanda and South Africa are all signatories of the Ramsar Convention (Ramsar Homepage, 2019), have conducted a national wetland inventory and developed their own wetland classification systems. Uganda is also widely recognised as a leading African country in terms of wetland policy, Rwanda has had wetland mapping exercise performed with very good results (see Nyandwi *et al*. 2016). South Africa is already on their fifth version of a national wetland map (van deventer *et al*., 2018a) and uses a classification system that is widely accepted (Ollis *et al*., 2013). Swaziland is near enclave within South Africa, and therefore the section below on South Africa will go into more detail explaining their continuous methods of wetland mapping and classification. It is these methods developed in South Africa that will be applied to the wetlands of Swaziland.

Wetland studies in Africa have mainly focused on extensive wetland systems that are unique to respective countries (Ellery *et al*., 2008). Although not directly related to wetland inventories, such studies have all contributed towards understanding the formation of wetlands. This is important when classifying and describing their functionality (Ellery *et al*., 2016), which is also fundamental when creating an inventory of a country's wetlands (Ewart-Smith *et al*., 2006). For southern Africa this includes among many: the wetlands of Maputaland (Ellery *et al.*, 2012; Grundling *et al.*, 2013b; Grundling *et al*., 2014a; Faul *et al.*, 2016; Kelbe *et al*., 2016; and Gabriel *et al*., 2018), the Palmiet systems in the Western Cape (Pulley *et al.*, 2017; Rebelo *et al.*, 2018a; Rebelo *et al.*, 2018b), the Okavango Delta in Botswana (Ellery *et al.*, 1990; McCarthy *et al.*, 1998; Ellery *et al.*, 2003) and the Lesotho Highland peat systems (Grundling *et al.,* 2015). Elsewhere in Africa, there have also been several studies on wetlands which include the classification and characteristics of small wetlands in Kenya and Tanzania Sakané *et al.* (2011), and an analysis of the carbon and nitrogen gaseous fluxes for sub surface water flows in Ugandan wetlands (Bateganya *et al.*, 2015). The sedimentation of freshwater wetlands in Kenya was also assessed (Ashley *et al.,* 2004), along with the contamination of wetlands in Victoria Lake Basin (Nyangababo *et al.*, 2005) and greenhouse gas emissions following rewetting in Drakensberg wetlands (Kruger *et al*., 2014).

2.1 The formation of wetlands

Wetlands are areas where saturation with water is the dominant factor that determines both the nature of substrate development and the types of plant and animal communities (FGDC, 2013). Wetlands form when there is a surplus of water and the water table is at, or close to surface level (Ellery *et al*., 2008). 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, 2017).

Wetlands in southern Africa occur in diverse settings, ranging from coastal plains to the highlands of the escarpment. Ellery *et al*. (2008) explain that southern Africa has a mean annual rainfall that is generally much less than its potential evapotranspiration, which means that the majority of the larger wetland systems in southern Africa are linked in some way to streams or groundwater. Ellery *et al*. (2008) reason that wetlands generally occur in geomorphic settings where a river's transport capacity is less than or equal to load which results in wetlands frequently forming at the heads of streams, floodplains, the downstream reaches of a river as well as in association with lakes or dams. Tooth and McCarthy (2007) also found that stream flows which combine with factors that serve to impede drainage or reduce infiltration, including faulting, rock outcrops, and swelling soils, are needed to maintain most moderate to large wetlands in the drylands of southern Africa.

Wetland hydrology is governed by a mass balance equation that is based on the change in the volume of water storage in a wetland that is equal to the balance of the inflows and outflows. Water sources include precipitation, surface inflows and groundwater inflows (Mitsch and Gosselink, 2000b). Water losses include evapotranspiration, surface water outflows and groundwater outflows. The formula is given as follows (Mitsch and Gosselink, 2000b):

$\Delta V / \Delta t = Pn + Si + Gi - ET - So - Go$ where;

V= Volume of water in storage in wetland
t= time
$\Delta V / \Delta t$ = change in volume of water storage in wetland over time
Pn= Gross precipitation directly onto the wetland
Si= Surface inflows via streams or overland flow
Gi= groundwater inflows
ET= evapotranspiration
So= surface outflows
Go=groundwater outflows

2.2 International classification systems

A fundamental part of a classification system is the definition of a wetland (Scott and Jones, 1995). In order to classify wetlands, they are grouped according to several features, ranging from vegetation structure to geomorphic setting. Numerous wetland classifications have been developed throughout the world and vary in scale from international to local classification systems. The wetland classification systems discussed in this section include those that have been applied internationally, and have also been used as the basis for various national classification systems around the world.

2.2.1 The Ramsar Convention's classification system.

The Ramsar Convention on wetlands is an intergovernmental treaty, formed in 1971, whose mission is "the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world" (Ramsar Convention Secretariat, 2010: i). Due to the variety of wetlands found across the world, the Ramsar definition of a wetland is deliberately broad. A definition was adopted in 1971 and is commonly used as a foundation for national wetland inventories. Article 1 of the Convention states that "wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar Convention Secretariat, 2010 i).

In 1990, the Ramsar Convention adopted a recommendation approving an information sheet and hierarchical classification of wetland types (following Scott, 1989), which was based on the Classification of Wetlands and Deepwater Habitats of the United States (discussed in Section 2.2.2) by Cowardin *et al.* (1979). The Ramsar wetland classification serves as a broad framework to aid rapid identification of the main wetland habitats represented at each Ramsar Site. The system also provided broad units for mapping and comparability of concepts and terms for national or regional wetland inventories (Ramsar Convention Secretariat, 2010). Wetlands are divided into three main categories of marine and coastal wetlands, inland wetlands, and man-made wetlands. The categories have further subdivisions, which give a total of 40 wetland types (Ramsar Convention Secretariat, 2010).

Like all classifications, the Ramsar wetland classification system is a compromise as it focuses on broad generic categories to be used as a simple tool for describing Ramsar sites (Kabii, 1998). It was acknowledged, at its establishment, that the Ramsar Classification was not meant to be used for national wetland inventories since a more detailed classification would need more information and data (Scott and Jones, 1995).

One of the Ramsar Conventions contracting parties that possesses detailed classification systems is the United States of America. The United States Fish and Wildlife Service (USFWS) already conducted the first quantitative national inventory of American wetlands in the mid-1950s (Martin *et al*., (1953). The country has since produced many other classification systems (Cowardin *et* al., 1979; Brinson, 1993; Smith *et al*., 1995; FGDC, 2013), thereby setting the precedence for others around the world.

2.2.2 Wetland classification systems developed in the United States of America.

The Classification of Wetlands and Deepwater Habitats of the United States was produced in 1979 with the objective being to "impose boundaries on natural ecosystems for the purposes of inventory, evaluation, and management" (Cowardin *et al*., 1979: 3). The classification was adopted by the Federal Geographic Data Committee (FGDC) as a National Standard in 1996 and was the governing document until the Second Edition was published in 2013 (FGDC, 2013).

2.2.2.1 The Classification of Wetlands and Deepwater Habitats of the United States

The Classification of Wetlands and Deepwater Habitats of the United States (Cowardin *et al*., 1979) has been applied internationally, cited extensively in scientific literature, and also used as the basis for numerous other classification systems, including the Ramsar Convention's Classification system and the Asian wetland inventory (Finlayson and Spiers, 1999; Ramsar Convention Secretariat, 2010; FGDC 2013). The classification is applied through remote sensing technology and was designed for use over a broad geographic area (the entire U.S.A and its Territories).

Wetlands are specifically defined as "lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water" (Cowardin *et al*., 1979: 3). The definition of a wetland in this classification delimits the biological extent of wetlands, as influenced by substrate properties and the hydrologic characteristics at each site (FGDC, 2013). Hydric soils that have been drained and that are currently incapable of supporting hydrophytes, due to a change in water regime, are therefore not considered wetlands by this definition. The Ecoregions of Bailey's (1976) for the United States of America was applied by Cowardin *et al*. (1979) to this classification system to accommodate regional variations in climate, geology, soils, and vegetation which are important in the development of different wetland habitats.

The American Federal Geographic Data Committee (FGDC) updated the Cowardin *et al*. (1979) system in 2013, as the scientific foundation upon which the original classification was established had advanced (FGDC, 2013). However, the structure of the classification system remains largely the same and follows a hierarchical structure where Systems form the highest level. Systems refer to wetlands and deepwater habitats that share the influence of similar hydrologic, geomorphologic, chemical, or biological factors. Five Systems are defined, namely: Marine, Estuarine, Riverine, Lacustrine, and

Palustrine. The next level of the classification classifies Systems into more specific categories called Subsystems. Marine and Estuarine Systems each have two Subsystems (Subtidal and Intertidal), the Riverine System has four Subsystems (Tidal, Lower Perennial, Upper Perennial, and Intermittent); the Lacustrine has two Subsystems (Littoral and Limnetic) whilst the Palustrine system has no Subsystems.

Subsystems are then further classified into Classes, Subclasses and Dominance Types (Cowardin *et al*., 1979; FGDC, 2013). The Class describes the general appearance of the habitat in terms of either the dominant life form of the vegetation or the physiography and composition of the substrate features that can be recognized without the aid of detailed environmental measurements. Subclasses are named on the basis of the specific life form of the vegetation or finer distinctions in substrate material. Dominance Types are determined on the basis of dominant plant and animal species. Modifiers are then applied to the classification system in order to fully describe the wetlands and include water regime, water chemistry, and soil type. Special Modifiers can also be used to describe human and beaver alterations to wetlands.

Given the broad applicability of this classification system, it lacked the ability to differentiate between the functionality of wetlands. This resulted in the development of a hydrogeomorphic (HGM) approach to classifying wetlands (Brinson, 1993), which has served as the foundation for various HGM wetland classifications around the world (FGDC, 2013).

2.2.2.2 A Hydrogeomorphic approach to wetland classification

Brinson (1993) developed an approach to wetland classification based on the abiotic features of wetlands and focused on the underlying principles that explain wetland functions to reduce errors of interpretation. This classification emphasised hydraulic and geomorphic controls of wetlands rather than structure and species composition of plant communities which were often focus points for other classification systems, including the Cowardin *et al*. (1979) system. It anticipated that by using a hydrogeomorphic approach (HGM), it would lead to a better understanding of the relationship between organisms and the environment. The reason for this is that hydraulic and geomorphic controls of wetlands are responsible for maintaining many of the functional aspects of wetland ecosystems, including the wetlands' chemical characteristics of water, habitat maintenance, as well as water storage and transport (Brinson 1993).

Brinson (1993) explained two reasons for a HGM classification system. The first is to simplify the concept of wetlands by recognizing that each wetland may be unique, and should therefore be placed into categories in which they share functional properties. The focus of the HGM classification is therefore on the processes that are fundamental to the sustained existence of the respective wetland ecosystems. The other function of the HGM classification system is to foster the development and the redevelopment of paradigms that clarify the relationship between ecosystem structure and function. The reason for this is because there is a need for indicators that can highlight the sensitivity and thresholds of a wetland to certain changes.

Brinson's (1993) HGM classification was based on an open structure which allows for adaptation in various types of wetlands and geographic regions. The core of the classification system has three components, namely geomorphic setting, water source and its transport, and hydrodynamics. The geomorphic setting of a wetland refers to its landscape position, where water flow and wetland position are inextricably linked. Therefore, the landscape setting of a particular wetland is implicit in its hydrology through accommodating and governing the flows and storage of water. From a geomorphic perspective, Brinson (1993) listed four main geomorphic settings where each category tends to have a distinctive combination of hydroperiod, dominant direction of water flow, and zonation of vegetation. The first three geomorphic settings are elaborations of the depressional, riverine and fringe categories originally developed for mangroves by Lugo and Snedaker (1974). The fourth category added by Brinson was extensive peatlands.

Depressional wetlands frequently occur high in drainages and are more dependent on atmospheric exchanges than other wetland types (Brinson, 1993). In dry climates, depressions are either dry much of the time, or they are dependent on groundwater sources. Riverine wetlands form as linear strips throughout the landscape and have predominately unidirectional flow. The hydroperiod of a riverine system ranges from short and flashy in headwater streams to long and steady in higher order streams. Fringe wetlands occur in estuaries where tidal forces dominate or in lakes where water moves in and out of the wetland from the effects of wind, waves, and seiches. The hydroperiod is dominated by bidirectional flow, largely across the surface, as the result of the cumulative frequency of many flooding events. The fourth category is extensive peatlands, where Brinson (1993) used the description of Moore and Bellamy (1974) to describe extensive peatlands as large areas of land such that the peat substrate dominates the movement and storage of water as well as the mineral nutrition of the plants and patterns in the landscape itself (Moore and Bellamy, 1974).

Water sources are broken down into three categories: precipitation, groundwater discharge, and surface or near surface inflow (ranging from flooding, overbank flow to interflow and overland flow). Brinson provided three categories of hydrodynamics (the motion of water allowing it to do work) and explained that while the three components are treated separately, there is considerable interdependence between them:

a) vertical fluctuations of the water table that result from evapotranspiration and the subsequent replacement by precipitation or groundwater discharge into the wetland,
b) unidirectional flows that range from strong channel-contained currents to sluggish sheet flow and,
c) bidirectional, surface or near-surface flows resulting from tides or seiches.

Brinson (1993) emphasized that his classification is a generic approach meant to interface logically with existing regional classifications, and that this approach can provide a convenient template upon which to build a locally or regionally useful system for countries without a classification system. From this basis, Smith *et al*. (1995) developed an approach to wetland classification to be used for assessing wetland function. Brinson's (1993) classification was expanded to include seven HGM Classes along with functional assessments of the respective HGM units. The objective of this classification was to identify a group of wetlands that are relatively homogeneous in terms of structure, process, and ultimately function.

2.2.2.3 A hydrogeomorphic classification to assess wetland functions

This classification system begins with classifying wetlands into Classes, and then subsequently additional Subclasses along with various Modifiers. Classes include Riverine, Depressional, Slope, Mineral Soil Flats, Organic Soil Flats, Lacustrine Fringe and Estuarine Fringe. Subclasses are then used to further characterise wetlands based on site-specific hydrogeomorphic characteristics. The purpose of the Subclass is to provide insight into the major hydrologic inputs and outputs as well as other attributes that can explain wetland functioning. Smith *et al*. (1995) explained that Subclasses are not limited to a rigid, predeveloped set of established terms, nor are they restricted in the amount of subclasses used. Depending on the intended use of the classification effort, HGM subclasses can be single phase (depression) or multiphase (depression/flow-through/groundwater influenced), thereby highlighting the flexibility of the characterisation.

The United States Department of Agriculture (USDA) provides a few examples of terms that can be used as subclasses. It is also recommended that, at a minimum, the subclass should be reflective of the primary hydrologic influence on a wetland (USDA, 2008). These terms are:

- landscape—alluvial plain, basin, lowland
- landforms—arroyo, barrier flat, bog, Carolina Bay, fen, floodplain, meander scar, open depression, oxbow lake, slough, terrace
- microfeatures—closed depression, interdune, mound, gilgai, hummocks, mini mounds, pothole, swale, vernal pool
- anthropogenic features—borrow pit, pond, quarry, rice paddy

- tidal, nontidal, upland, bottomland
- ponded, flooded, saturated, open
- groundwater influenced
- leveed, incised
- flow-through, recharge, discharge, connected (USDA, 2008)

Smith *et al*. (1995) explained that the level of variability within a hydrogeomorphic class can be considerably great, based on numerous environmental factors. In order to overcome this problem, wetlands are grouped into regions that are defined as geographic areas that are relatively homogenous with respect to climate, geology, and other large-scale factors that influence wetland function. Applying the classification for different regions, with user specified sub-classes, allows the user to characterise the wetland based on site specific attributes.

2.3 Wetland mapping and classification in selected African countries

This section focuses on Uganda and Rwanda. The definitions used by these two countries outside of southern Africa to describe and define their wetlands, as well as the mapping and classification approaches used for their national wetland inventories will be presented.

2.3.1 Uganda

Uganda became a signatory to the Ramsar Convention in 1988, has twelve wetlands of International Importance (Ramsar Sites), and in 2005 became the first African country to host the Meeting of the Ramsar Convention Conference of the Parties (Ramsar Convention, 2013). Uganda was the first African Country to develop a wetland policy (in 1995) and has subsequently prepared a wide range of technical guidelines for the management of wetlands which includes the country's Wetland Sector Strategic Plan for 2011-2020, which is funded under various international cooperation schemes (Government of Uganda, 2016).

In Uganda, wetlands are commonly referred to as swamps and are defined differently in literature and policies of the country. The Wetland Atlas of Uganda explains that wetlands are an area of land that is permanently or seasonally saturated with water that includes marshes, swamps and bogs (Government of Uganda, 2016). Uganda's National Policy for the Conservation and Management of Wetland Resources (Government of Uganda, 1995) explains that wetlands are areas where plants and animals have become adapted to temporary or permanent flooding. The Uganda National Environment Act Cap. 153 defines wetlands as "areas permanently or seasonally flooded by water where plants and animals have become adapted by saline, brackish or fresh water" (Government of Uganda, 2015). Kalanzi, (2015) defined Uganda's wetlands as shallow, seasonally or permanently water-logged areas that support hydrophytic vegetation. In contrast the Wetlands Management

Department (WMD) of Uganda (WMD, 2009) described Uganda's wetlands as including permanently flooded areas with papyrus or grass swamps, swamp forests or high-altitude mountain bogs, as well as seasonal floodplains and grasslands.

2.3.1.1 Wetland mapping in Uganda

Uganda began mapping their wetlands in 1994 in collaboration with the National Biomass Study Project, which led to their first wetland inventory in 1997 (WMD, 2009). The wetland inventory was updated in 2008 using methods based on remotely sensed data (SPOT Imagery at 1: 50 000), topographic map analysis and ground surveys (Ramsar Convention Secretariat, 2010). Data on different wetland uses, the extent of use, and the impact of these uses on wetland systems is contained within the Ugandan National Wetlands Information system, maintained by the Wetlands Management Department of Uganda.

The Wetlands Management Department found that wetlands in Uganda cover between 10-13 % of the total land area of the country (23,599 km^2) where there are reportedly 7,000 individual wetlands spreading over 170 wetland systems (WMD, 2009). Seasonal wetlands cover 7.7%, permanent 3.4% and swamp forests <0.1% of the total land area in Uganda. *The* Ugandan Wetland Atlas Version II, highlights a key wetland in each of the eight wetland management basins of Uganda and also discusses the most common impacts on these respective wetlands as well as recommendations for environmental managers (Government of Uganda, 2016). However, the country's wetlands are first classified in order to aid in the appropriate management of each these valuable ecosystems (WMD, 2009).

2.3.1.2 Wetland classification in Uganda

The Wetlands Management Department of Uganda (WMD) (WMD, 2009) characterises the country's wetlands based on three basic characteristics, namely the permanence and seasonality of their moisture regime, the main vegetation and land cover types, and the resource pressure from human use. The WMD (2009) defines Seasonal wetlands as wetlands that are not flooded for part of the year, where the dry period extends over most of the year. Vegetation classes used to characterise wetlands include tropical high forest, woodland, bushland, grassland, papyrus (including other sedges, reeds, and floating plants), and small and large-scale farmland. Resource pressure from human use is based on land cover and whether the wetlands are seasonal or permanent.

The type of wetland (moisture regime and vegetation) and extent of use (land use) in turn determines how vulnerable each wetland is to becoming permanently degraded (WMD, 2009). Examples include grasslands that are commonly used for livestock grazing, or growing crops if the wetlands has the desirable soil and water regime. Woodland and papyrus wetlands that provide raw materials are deemed very vulnerable to over-harvesting especially if they are close to high demand centre or located along major transport routes. Additional indicators used to determine the potential for a wetland to be degraded is the area per capita which assumes the more numerous the population in an administrative area, the more vulnerable the wetland will be.

2.3.2 Rwanda

Rwanda signed the Ramsar convention in 2006 and has one Ramsar Site at Rugezi-Burera-Ruhondo (Ramsar Convention, 2014). The government of Rwanda promotes the sustainable development of wetlands, especially for agriculture, but has acknowledged that wetlands have many other services to offer such as hydrological functions, biodiversity reservoirs, peat reserves, mitigation of climate change, leisure, tourism and cultural value (REMA, 2015). In Rwanda, many rural households face poverty and food insecurity, and therefore rely heavily on wetlands for their livelihoods. Large tracts of the country's marshlands have been converted to agricultural fields to grow rice, cereals, vegetables and other crops, which in turn have a great role to play in the national economy (Nabahungu, 2012).

In *The Law Determining the Use and Management of Marshlands in Rwanda* the term "marsh" means an area between hills or mountains with water, high biodiversity, and vegetation associated with marsh environments (REMA, 2009). Nabahungu (2012) explains that for the English language version of this law, the term "marsh" is considered to be synonymous with the term "wetland".

2.3.2.1 Wetland mapping in Rwanda

The Rwanda Environment Management Authority (REMA) is the National Administrative Authority for the Ramsar Convention and published a national inventory and mapping of all wetlands, lakes and rivers (REMA, 2008). The project's purpose was to identify wetlands requiring special attention for protection (REMA, 2008). Using MODIS, Landsat and SPOT imagery, the inventory showed that Rwanda has 860 marshlands and 101 lakes covering a total surface of 278,536 ha (10, 6%) of the Rwandan surface area as well as 861 rivers totaling 6,462 km in length (REMA, 2008). The inventory found that 41% of the country's marshlands are covered by natural vegetation, 53% are under cropping and about 6% are fallow fields. The delineation and classification accuracy of the 2008 inventory was, however, questioned as numerous inconsistencies were identified during the nationwide land registration process. Therefore, Nyandwi *et al*. (2016) performed a mapping exercise on Rwanda's wetland's using a probability mapping approach rather than a static delineation (mapping) technique.

Nyandwi *et al.* (2016) favoured a probability mapping approach over a static delineation approach as wetland bodies are changeable over time due to wetter years resulting in more wetland area existing than during 'drier' years. Wetland location probability was determined using topographic (elevation, slope), hydrological (contributing area) and climatic (temperature and rainfall) location factors. Wetland locations were analyzed and statistically modeled using their location factors with logistic regression. The probability map obtained a validation accuracy of 86.2% using an independently collected dataset. The map also reached a calibration accuracy of 87.9% to the existing inventory at a national level and up to 98 % of wetlands being mapped correctly at a subnational level.

2.3.2.2 Wetland classification in Rwanda.

The 2008 REMA wetland inventory classified Rwanda's wetlands into seven types based on relief, altitude, soil type, vegetation, hydrology and size of the marsh, slope of the watershed (catchment) and population density of the area. The seven types include:

- High altitude swamps
- Volcanic Swamps
- Central Plateau swamps
- Swamps of Kanyaru- Nyabarongo and Akagera Basins
- Swamps in the East
- Swams of the Bugarama depression
- Swamps on the edge of Lake Kivu (REMA, 2008)

Another wetland classification was performed through The Rwanda Irrigation Master Plan (Malesu *et al*., 2010) which classified the country's marshlands according to their altitude, as follows:

High-altitude marshes: Typically, these have narrow shapes and develop organic soils that ultimately become peat. These marshes serve as buffer zones, facilitating water retention and storage. Some of them are cultivated or exploited for tea plantations; and

Medium-altitude marshes: These are often large, extending over the central plateaus. Traditional agriculture is practiced in these areas;

Low-altitude marshes: These are known as collecting marshes. They are the largest and occur in the central and eastern parts of the country and extend along the country's main rivers. These wetlands act as buffers, filling up during the rainy season and promoting a constant outflow rate during the following dry season. They are covered by papyrus and are scarcely exploited for agriculture.

2.4 South Africa

South Africa became a signatory to the Ramsar Convention in 1975 and has 23 sites designated as wetlands of International Importance (Ramsar Sites), totalling a surface area of 557, 028 hectares. In South Africa, wetlands are included in the National Water Act (NWA, 1998) under the definition of a watercourse as:

(a) a river or spring;
(b) a natural channel in which water flows regularly or intermittently;
(c) a wetland, lake or dam into which, or from which, water flows; and
(d) any collection of water which the Minister may, by notice in the Gazette, declare to be a watercourse, and a reference to a watercourse includes, where relevant, its bed and banks (NWA, 1998).

Wetlands in South Africa are specifically 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” (NWA, 1998). According to the South African wetland and Riparian habitat delineation manual, wetlands must have one or more of the following attributes (DWAF, 2005):

- hydromorphic (wetland) soils that display characteristics resulting from prolonged saturation,
- The presence, at least occasionally, of water loving plants (hydrophytes), or
- A high water table that results in saturation at or near the surface, leading to anaerobic conditions developing in the top 50cm of the soil.

A piece of land can thus be classified as a wetland when the period of saturation is sufficient to allow for the development of hydric soils which in normal circumstances support, or would support hydrophilic vegetation. Collins (2005) explains that it is important to note that from the South African wetland definition, even drained wetlands of which the water table is no longer at, or near, the surface, or of which the land is no longer periodically covered with shallow water, are still considered to be wetlands.

The South African Water Act (Act No. 36 of 1998), also defines Riparian habitats as the physical structure and associated vegetation of the areas associated with a watercourse which are commonly characterised by alluvial soils, and which are inundated or flooded to an extent and with a frequency sufficient to support vegetation of species with a composition and physical structure distinct from those of adjacent land areas. The wetland and riparian delineation guidelines for south Africa (DWAF, 2005), explain how riparian habitats/areas are associated with a watercourse, contain distinctively different plant species adjacent areas, contain species similar to adjacent areas but exhibiting more vigorous or robust growth forms, and may have alluvial soils. Riparian areas may not be saturated for long enough or as often enough to develop wetland characteristics, however, the guidelines (DWAF, 2005) reason that some areas display both wetland and riparian indicators and can accordingly be classified as both.

2.4.1 Wetland mapping in South Africa

The South African government began investigating the diversity of inland aquatic ecosystems in the 1970s, which resulted in a directory (list and map) of the locations of some of these systems (Noble and Hemens, 1978; O'Keeffe, 1986). The South African National Wetland Map 1 (NWM1), made publically available in 2006, was derived from the National Land Cover 2000 (Thompson *et al*., 2002) using multi-season Landsat imagery where wetland polygons were described as 'Wetland' or 'Waterbody'. After an upgrade to the National Land Cover which included the National Wetland Map (Van den Berg *et al*., 2008), the 2011 National Biodiversity Assessment and the National Freshwater Ecosystem Priority Areas (NFEPA) projects led to the development of National Wetland Map 4 (NWM4)/NFEPA (Nel *et al*., 2011).

Over the years where the NFEPA wetlands data/NWM4 (Nel *et al*., 2011) was used for government planning and environmental impact assessments, many users noted the number of errors in the data (Grundling *et al*., 2013a, 2014a; Grundling, 2014b; Mbona *et al*., 2015; Rebelo *et al*., 2017; Collins, 2018). These errors were attributed to National Land Cover 2000 map which used Landsat 4-5 Thematic Mapper (TM) imagery with a 30m spatial resolution (van Deventer *et al*., 2018d). Van Deventer *et al*. (2018b) explained that the errors can be attributed to the reflectance values of inland wetlands being as diverse as their nature across the country, as well as that the broad bands of older generation sensors being incapable of distinguishing these systems adequately. The following issues of NWM4 were reported on by van Deventer *et al*. (2018b):

- Up to 46% estimated omission errors of wetlands in several landscapes when compared to wetlands mapped at a fine scale (e.g. Mbona *et al*., 2015; Schael *et al*., 2015; van Deventer *et al*., 2016; Melly *et al*., 2016),
- Polygons mapping artificial wetlands, fire scars and shadows of mountains as wetlands (commission errors, estimated at 30% of the data set),
- Horizontal shifts of polygons in comparison to more recent space-borne Imagery;
- Zig-zag boundaries between HGM types which resulted from using a raster-derived landforms data set for typing wetlands (van Deventer *et al*., 2014; 2016);
- Errors in HGM wetland types as a result of automated modelling (van Deventer *et al*., 2014; 2016) of some of these units;
- Areas mapped around dams were initially thought to be natural palustrine and seep wetlands however upon closer inspection after NWM4, agreed to have rather be classified as artificial for the purpose of a national map, and

- Slivers of inland wetland polygons, which resulted from a number of overlays and editing processes.

2.4.1.1 The South African Inventory of Inland Aquatic Ecosystems (SAIIAE).

Due to errors identified in the National Freshwater Ecosystem Priority Areas (NFEPA)/NWM4, the South African National Biodiversity Institute (SANBI) upgraded the National Wetland Map in 2018 (van Deventer *et al*., 2018a). It was decided that no wetlands mapped through remote sensing techniques would be used for National Wetland Map 5 which would be used as the South African Wetland Inventory of Inland Aquatic Ecosystems (SAIIAE) (van Deventer *et al*., 2018b). Rather the mapping approach for National Wetland Map 5 (NWM5) was based on fine-scale mapping through manual digitizing of selected parts of the country. Various data sources were used when creating NWM5 which included previously mapped hydrological features (from 2006 and 2016) that were issued as provincial geodatabases from the Department of Rural Development and Land Reform (DRDLR), wetlands data of four metropolitan districts, wetlands data mapped for the purpose of NWM5 at a scale of below 1:10 for nine district municipalities of South Africa, along with an additional three districts mapped by external parties. The wetland mapping for the nine districts was done by trained interns (not wetland specialists), using 50 cm spatial resolution orthophotography, through the ArcGIS online viewer, as well as SPOT Imagery. Except for a selected number of floodplains, eight limnetic depressions and wetlands within the majority of South Africa's Ramsar sites, no data capturing was done in the remainder of South Africa's provinces.

Confidence ratings were developed and assigned to the sub-quaternary catchments of South Africa based on the source of the various fine scale mapped wetland data received for SAIIAE (van Deventer *et al.,* 2018b). Most of the country (69%) was assigned a low confidence rating (where wetlands were mapped by non-wetland specialists of the DRDLR). A low to medium rating was assigned to areas mapped and classified by interns (24% of the country). Mapping done by wetland specialists (7% of the country) and was assigned a medium confidence rating. None of the mapped areas were assigned a high confidence rating since none of the field verifications considering the long-term hydrological cycles of the respective wetlands. This resulted in only 16 of the 52 districts (31%) of South Africa having been mapped at a fine-scale at a low-medium/medium confidence (van Deventer *et al*., 2018b).

It was recommended that areas mapped with a low confidence rating, where omission errors are estimated at 50% and commission errors <10%, be used at a scale of 1:50 000. Areas that were mapped at a low to medium confidence rating should be used at a scale of 1:10 000, where omission errors are estimated at <30% and commission errors <10%. After testing if wetlands mapped for

NWM4 could be used to supplement NWM5, it was decided that NWM4 polygons would need careful evaluation before being integrated and should rather be used during the improvement of National Wetland Map 6 (NWM6) (van Deventer *et al*., 2018c).

Concurrently to the creation of NWM5, Collins (2018) developed a wetland probability mapping technique in order to improve on the wetland mapping in the Free State Province of South Africa. Van Deventer *et al*., (2018b) explain how the preliminary results of the wetland probability map were impressive and that it had the ability to contribute to the future fine-scale mapping of South Africa. This resulted in the wetland probability map being released along with wetlands mapped at a fine scale to be used to supplement the South African Wetland Inventory in 2018 (van Deventer *et al*., 2018a).

2.4.1.2 Wetland probability map for South Africa (Collins, 2018)

The initial objective of Collins (2018) when developing the wetland probability map for South Africa was to rapidly map extensive areas with minimum data, skill and cost requirements. Collins (2018) emphasized that previous methods to mapping wetlands based on remote sensing resulted in poor contiguity of wetlands, as was also identified by Nel *et al*. (2011) and van Deventer *et al*. (2018c). Collins (2018) pointed out that another disadvantage of only using multispectral imagery is that wetlands that no longer support hydrophytic vegetation (due to various impacts) will not be mapped whereas the modelling approach assumes such areas to be wetlands, thereby allowing the original wetland extent to be mapped and hence determine wetland loss.

The wetland probability mapping technique is based on a Digital Elevation Model (DEM), meeting the landscape position criterion for identifying and delineating wetlands in South Africa (DWAF, 2005). This is based on the assumption that water will accumulate in the lowest positions of the landscape which are likely the areas of highest probability for wetland occurrence (Collins, 2018). Mapping aims to selectively identify areas, based on the subjective identification from aerial imagery. Collins (2018) explained that although wetlands are most likely to develop within these low-lying areas, watercourses other than wetlands may also be present and subsequently mapped. This is due to the fact that these low lying areas may also not always contain wetlands, as their development not only requires the presence of low lying areas, but also numerous other factors including, mean annual precipitation, slope and soil depth (Collins 2018). These watercourses, include rivers, wetlands, lakes, dams, springs and natural areas in which water flows regularly or intermittently, which all fall under the definition of a watercourse following the National Water Act (NWA, 1998; DWAF, 2005). The mapping technique is similar to onscreen mapping, but instead of identifying each individual wetland, the modelled approach simultaneously maps all the wetlands identified within a mapping region using an ‘overall best fit’ approach according to user defined parameters.

Data used for creating the wetland probability map for South Africa includes (Collins, 2018):

- Remotely sensed aerial imagery: SPOT 5 national mosaic coverage (SANSA, 2013)
- Digital Elevation Model (DEM): The 30 meter Shuttle Radar Topology Mission (SRTM) layer (NASA, 2000).

The probability mapping process of Collins (2018) began by subdividing South Africa into provincial boundaries in order to overcome computational limitations. Provincial boundaries were then further subdivided into ‘mapping regions’, which are areas that share similar factors pertaining to wetland development, including relief, mean annual precipitation and generalized geology. Users need to determine a certain set of parameters based on flow accumulation and percentile filters within each mapping region. Flow accumulation parameters are determined through trial and error where the threshold value represents the number of cells that surface water will flow through towards a particular cell. The ‘percentile filter’ tool of Whitebox GIS (Lindsay, 2014) was applied to perform a percentile analysis on the DEM, which expresses the value of each cell as a percentile (0%-100%) of the range of cells within a moving window.

Wetlands that are still not accurately mapped using the above mentioned tools can be manually digitized. Ancillary data (i.e. data from other sources that can support wetland mapping) also has the option of being added to the probability map. Flow accumulation and percentile filter maps are subsequently merged and dissolved in order to produce a seamless wetland probability map. It is also important to note that the size of the mapping regions is based on the user and specific objectives, where the scale at which the regions are divided can be reduced in order to produce a more accurate map.

Preliminary findings, by Collins (2018), of the wetland probability map found that it has a high certainty that mapped areas are watercourses, however there is also a high uncertainty as to whether they represent wetlands (as defined by the South African National Water Act’s (NWA, 1998) definition of wetlands). The strength of the mapping approach does however allow for uncertainty in this regard as the extent to which wetlands, as well as different watercourses are mapped is attributed to the conscious decision of the user to include them or not. The mapping thresholds represent an average best fit for all wetlands within a mapping region and therefore do not result in a 100% spatially accurate map. Collins (2018) pointed out that expert knowledge of the user is key in producing an accurate map and that failure to accurately map wetlands does not necessarily represent a failure in the methods. Different users will likely produce different mapping results, depending on what they consider to be wetlands or not, which is also based on the imagery that they use (Collins, 2018).

Collins (2018) conducted a visual comparison as a first estimation to determine whether the wetland probability map provides any improvements to NFEPA/NWM4 (Nel *et al*., 2011). Significant differences were detected between the two maps where the wetland probability map showed a marked increase in the representation of wetland extent within the chosen mesic area where both methods were expected to perform optimally. In addition to the visual comparison, the ability of each mapping method to accurately indicate wetland occurrence was also tested. The wetland probability map and NFEPA/NWM4 (Nel *et al*., 2011) were tested against 93 points of confirmed wetland presence (Collins, 2018). The results showed that the wetland probability map out-performed NFEPA/NWM4 (Nel *et al*., 2011), both with and without buffers around confirmed wetland points.

The wetland probability map was also compared to NWM5 (van Deventer et al., 2018b) and three field based reference wetland map data. It was found that the reference data set outperformed all the above approaches and was subsequently decided that the wetland probability map would likely address shortcomings of NWM5, but due to time constraints of NWM5, it was recommended to be used as a guide for capturing wetlands for NWM6. However, it was also concluded that the limited number of reference data available for comparison led to a narrow view and understanding of where the wetland probability map can be of value (van Deventer *et al*., 2018c).

Accuracy of the map can be vastly improved by using: more percentile filter base maps, different moving window sizes, different DEM resolutions, and more time spent on testing modification options. Obtaining sources of known wetland location to use as 'training features', obtaining Imagery of different years and from different sensors, further subdivisions of mapping regions as well as the inclusion of environmental variables which can all lead to a more accurate wetland map (Collins, 2018).

2.4.1.3 Fine scale wetland mapping studies in South Africa

Before National Wetland Map 5 (NWM5) (van Deventer *et al*., 2018a) was released, National Wetland Map 4 (NFEEPA) (Nel *et al*., 2011) was the wetland map used for South Africa at a national scale. Due to the various shortcomings of the NFEEPA wetlands data set, more accurate mapping exercises were needed for specific wetland studies. Included in these more accurate wetland mapping exercises are wetlands mapped through remote sensing e.g. Grundling *et al*. (2013a) and Rebelo *et al*. (2017), as well as wetland location modelling approaches e.g. Hiesterman and Rivers-Moore (2015) and Rebelo *et al*. (2017). The following section highlights the methods used by these authors.

Hiesterman and Rivers-Moore (2015) showed the possibility of using topological and climatic variables as the basis for predicting the probability of wetland occurrence over a large spatial domain. The authors noted that current approaches to mapping wetlands through the classification of satellite imagery typically under-representing actual wetlands. In order to overcome this, the authors recognised the importance of ancillary data to improve the accuracy in mapping wetlands and compared two modelling approaches (Bayesian Networks (BN) and Logistic Regression (LR)) to predict the likelihood of wetland occurrence in KwaZulu-Natal (KZN), South Africa.

Using the existing KZN wetland layer of Scott-Shaw and Escott (2011) as the basis for establishing wetland presence/absence, Hiesterman and Rivers-Moore (2015) extracted environmental parameter statistics to be used as training and test wetland data sets and generated a spreadsheet of wetland presence and absence. The authors used principle component analysis (PCA) to evaluate whether there were high levels of inter-correlation between the input predictor variables in order to derive an optimal predictor data set by eliminating redundant variables for the original list of 19 possible variables.

Results obtained by Hiesterman and Rivers-Moore (2015) indicated that the predicted probabilities of the BN model were 0.853 and for the LR model were 0.840. Although there was a marginal difference in the results for the BN and LR models, the authors found that the difference was not conclusive that one model outperformed the other in predicting wetland occurrence and that both models predicted wetland occurrence relatively similarly and compared well with the current regional wetland layer and literature highlighting regional priority wetland areas.

Grundling *et al*. (2013a) demonstrated the capability of using Landsat remote sensing imagery with ancillary datasets to establish wetland extent and permanence. The study assessed the distribution of wetlands over wet and dry periods for the Maputaland Coastal Plain (MCP) in north eastern KwaZulu-Natal, South Africa. The study used Landsat TM and ETM imagery acquired for two dry years (1992 and 2008) and one wet year (2000), as well as ancillary data to determine the spatial extent and distribution of wetlands during wet and dry years. The ancillary datasets were only used as guidelines, together with known verification sites, to create areas of interest to classify the different land-cover classes.

In order to describe the extent and wetness types (permanent or temporary) of wetlands and open water in the MCPs after creating a land cover classification map, Grundling *et al*. (2013a) compared the respective maps for the three years. A script was used to calculate the sum value for the three years with each pixel value equal to one. The wetland or open water area was considered to be a permanent system if the total value for the three years was 3. If the total value for the three years was 2 or 1, it was considered to be a temporary wetland or open water area. The overall land-cover mapping accuracy for the entire MCP dataset was 80%, whilst the wetland class was assigned 76% accuracy.

Rebelo *et al*. (2017) investigated the best technique to detect, map and determine historical changes of valley-bottom palmiet wetlands in the Cape Floristic Region (CFR) of South Africa. The authors applied three techniques namely: (i) multispectral remote sensing techniques, (ii) maximum entropy distribution modelling and (iii) aerial photograph analysis. Landsat8 images were used to determine whether multispectral remote sensing was a suitable technique to map small wetlands (both in terms of detection, and accurately mapping extent). Habitat suitability modelling was used to construct a probability map of the possible occurrence and extent of palmiet wetlands. Geology, soil and climate data was used as input data for the MaxExtent distribution model (Rebelo *et al*., 2017) which is a general-purpose machine learning method based on the principal of maximum entropy and the ecological niche concept.

It was found by Rebelo *et al*. (2017) that the Landsat8 classification produced reasonable results for the current occurrence of palmiet wetlands within the CFR region of South Africa, with a mapping accuracy of 76%, whilst Landsat5 and Landsat1-3 were not able to detect the historical occurrence of Palmiet wetlands. The MaxExtent distribution model was able to successfully identify some fragments of existing palmiet wetland patches as 'suitable habitat'. It produced results of 0.81 under the receiver-operating characteristics curve (0.5 is considered no better than random, whilst 1 is considered good model performance). However, it was found that the MaxExtent distribution model was not able to predict the historical occurrence of palmiet wetlands when compared to aerial photographs used to digitize palmiet wetland fragments for three times slices (1940/50s, 1980s and 2010s).

This section on wetland mapping in South Africa has shown that there are a variety of techniques used to map wetlands at both national and smaller scale levels, each having their advantages and disadvantages. Although Grundling *et al*. (2013a) and Rebelo *et al*. (2017) used remote sensing to relatively accurately map wetlands, results from using remote sensing at a national scale for South Africa were less favourable (Nel *et al*., 2011). The wetland probability mapping of Hiesterman and Rivers-Moore (2015) also showed relatively accurate results, but the environmental attributes used to train the model were based on a map produced through remote sensing (Scott-Shaw and Escott, 2011). This makes their methods of predicting wetland occurrence heavily based on the accuracy of the map used to extract environmental parameters, of which an accurate map is not always available for data scarce countries. The wetland probability mapping technique of Collins (2018) is therefore seen as a favourable approach, given that it is based on open source data, and does not require a pre-existing map to extract environmental attributes. It is also not as time-consuming and costly as manually digitising wetlands, as was done for NWM5 (van Deventer *et al*., 2018b).

2.4.2 Wetland classification in South Africa

In South Africa, the use of Hydrogeomorphic (HGM)-based classification systems has become widespread and aims to provide a common language and consistent terminology to be able to distinguish between the different types of wetlands that occur in South Africa (Ollis *et al*., 2015). The HGM approach to wetland classification was first introduced to South Africa by Kotze *et al.* (1994) and has undergone numerous adaptations (Dini *et al*., 1998; Kotze, 1999; Dini and Cowan, 2000; Ewart-Smith *et al*., 2006; Ollis *et al*., 2009, Sieben *et al.,* 2011; Ollis *et al*., 2013). The final version, and the classification currently in use in South Africa was produced by Ollis *et al*. (2013) and is the result of collaborative research efforts and various field testings between a number of wetland/aquatic scientists from numerous regions and institutions across South Africa (Ollis *et al*., 2015).

2.4.2.1 Classification system for wetlands and other aquatic ecosystems in South Africa

Ollis *et al*. (2013) use a hierarchical approach, with increasing amounts of detail added at each successive level. This approach allows the classification system to be applied at a variety of spatial scales depending on the purpose of the classification and the information available (Ollis *et al*., 2013, 2015). The classification system is six-tiered in structure, where the first four levels are based on primary descriptors that distinguish between different types of aquatic ecosystems.

Level 1 distinguishes between systems at the broadest spatial scale (Marine vs Estuarine vs Inland). Level 2 of the classification system identifies the Regional Setting of the wetland using an existing spatial framework which provides an understanding about the broad context within which the wetland occurs (Ollis *et al*., 2015). Level 3 of the classification categorises the landscape unit of an aquatic ecosystem in order to provide the topographic context for each HGM unit. The classification distinguishes between four landscape units, namely; Valley Floors, Slopes, Plains and Benches. Benches are further divided into Hilltops, Saddles and Shelfs. Level 4 is the focal point of the classification system and identifies the HGM unit (Table 2.1).

Table 2.1 Hydrogeomorphic (HGM) Units (Ollis *et al*., 2013).

HGM Units	Description
River	- A linear landform with clearly discernible bed and banks. - Permanently or periodically carries a concentrated flow of water. - Taken to include both the active channel and the riparian zone as a unit. - Concentrated, unidirectional flow within a distinct active channel.
Floodplain	- A wetland area on the mostly flat or gently-sloping land adjacent to and formed by an alluvial river channel, under its present climate and sediment load. - Subject to periodic inundation by overtopping of the channel bank. -Generally occur on a Plain and are typically characterised by a suite of geomorphological features associated with river-derived depositional processes.
Channelled Valley-Bottom	- A mostly flat wetland area located along a valley floor with a river channel running through it. - Characterised by being positioned on a Valley Floor and the absence of characteristic floodplain features. - Dominant water inputs are from the river channel flowing through the wetland, either as surface flow resulting from flooding or as lateral seepage, and/or from adjacent valley-side slopes.
Unchannelled Valley-Bottom	- A mostly flat wetland area located along a valley floor without a river channel running through it. - Characterised by being positioned on a Valley Floor. - An absence of distinct channel banks and the prevalence of diffuse flows. - Water inputs are typically from an upstream channel and seepage from adjacent valley side-slopes.
Depression	- An inland aquatic ecosystem with closed (or near-closed) elevation contours, which increases in depth from the perimeter to a central area of greatest depth, within which water typically accumulates. - May be flat-bottomed (in which case they are often referred to as 'pans') or round-bottomed, and may have any combination of inlets and outlets or lack them completely. A variety of potential sources of water input but hydrodynamics are typically dominated by (primarily seasonal) vertical fluctuations. - Natural lakes (including coastal lakes) and dams (i.e. artificial lakes), which are typically drowned valley floors, are considered to be depressions for purposes of the classification system.
Seep	- A wetland area located on gently to steeply sloping land and dominated by the colluvial (i.e. gravity-driven), unidirectional movement of water and material downslope. - Water inputs are primarily via subsurface flows from an up-slope direction.
Flat	- A level or near-level wetland area that is not fed by water from a river channel, and which is typically situated on a Plain or a Bench. - The primary source of water is generally precipitation, with the exception of Wetland Flats situated on a coastal plain where groundwater may rise to or near the ground surface. - Horizontal water movements within the wetland are typically weak and multidirectional, if present at all.

HGM units defined by Ollis *et al*. (2013) are based on the HGM classification of Brinson (1993), where landform, hydrodynamics and hydrological characteristics are used to distinguish between different wetland types. Level 4A distinguishes Primary HGM Units of which there are seven in the classification system namely: River, Floodplain, Channelled Valley Bottom, Unchannelled Valley Bottom, Seep, Depression, and Flat (Ollis *et al*., 2013). This is also the level at which South African wetland inventories have classified their wetlands (Nel *et al*., 2011; van Deventer *et al*., 20018b). Level 4B and 4C of the classification system further divide the respective HGM Types. Rivers are divided on the basis of the longitudinal geomorphological zonation of Rowntree and Wadeson (2000). Floodplain Wetlands are divided into Floodplain Depressions and Floodplain Flats based on the wetlands localised landforms. Depressions and Seeps are further classified based on their drainage characteristics.

Level 5 of the classification system describes the hydrological regime of an HGM unit. The hydrological regime of rivers uses perenniality, whilst the Hydrological Regime of wetlands' uses inundation and saturation period. Level 6 of the classification is included for optional application and is based on descriptors that allow the user to categorise the structural, chemical and or biological characteristics of an HGM Unit (Ollis *et al*., 2015). Descriptors include Salinity, Geology, Vegetation cover, Substratum type, pH and whether the wetland is natural or artificial (Ollis *et al*., 2013).

2.4.2.2 The Application of Hydrogeomorphic Wetland Classification in South Africa.

With regards to a National Inventory that identifies the types of wetlands across a country, hydrogeomorphic units were first incorporated into the South African National Wetland Map 4, however, few of the data sets available had typed wetlands to HGM units (Nel *et al*., 2011). This led van Deventer *et al*. (2016) to model landforms as an attempt to automate the classification of wetlands to HGM units. Van Deventer *et al*. (2016) primarily used standard deviation from the average elevation, calculated from both small and large neighbourhood distances using the TPI tool (Weiss, 2001) and the Landform Tool of Jenness (2006) and Dilts (2009) to derive and classify primarily four landform classes, namely valley floors, slopes, plains and benches. The authors used the boundaries of the Geomorphic Provinces of South Africa (Partridge *et al*., 2010) and the sub-quaternary catchments of South Africa when defining search distances (Nel *et al*., 2011). The results showed a 42% accuracy and it was decided that the data-set was acceptable as a general reference framework at a national scale, but improvements would be essential for fine scale wetland classifications (van Deventer *et al*., 2016). The current wetland inventory of South Africa (van Deventer *et al*., 2018a), used manual classification to classify wetlands to level 4A of Ollis *et al*. (2013) using ArcGIS and Google Earth Imagery.

Although the South African wetland classification system (Ollis *et al*., 2013) is widely used throughout South Africa for wetland environmental impact assessments, the only research based application of the South African wetland classification system is by Grundling *et al*. (2014a) and Grundling, 2014b). It is for this reason that the rest of this section focuses on the methods used by these authors, as it is the only reference that applying the HGM classification of Ollis *et al*. (2013) to Swaziland can be related to.

Grundling *et al*. (2014a) initially created a wetland map through remote sensing for the Maputaland Coastal Plain (MCP), in KwaZulu-Natal, South Africa. In order to classify hydrogeomorphic units, as per Ollis *et al.* (2013), Grundling *et al.* (2014a) used an elevation map, percentage slope (Weepener *et al*., 2012) and a terrain unit map (van den Berg *et al*., 2009). The terrain Unit map (Van den Berg *et al*., 2009) used curvature morphology to define terrain units (Figure 2.1).

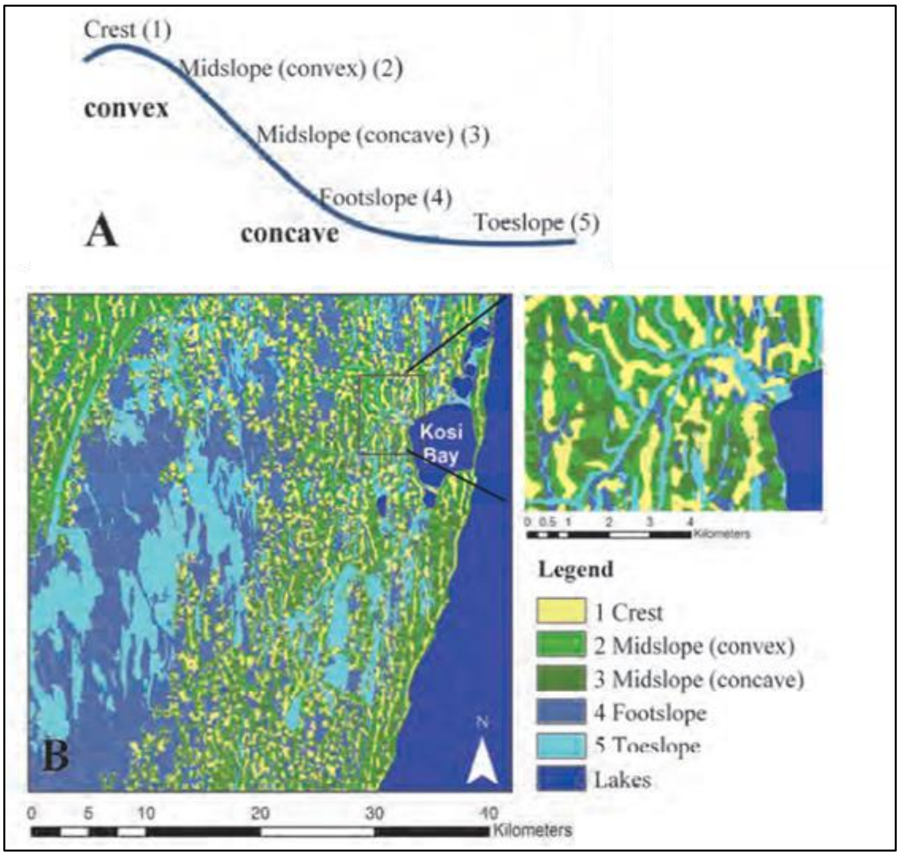


Figure 2.1: The Terrain unit map of Van den Berg *et al*. (2009), used by Grundling *et al*. (2014) to classify the wetlands of Maputaland Coastal Plain.

Grundling *et al.* (2014a) used a semi-automated approach to apply the hydrogeomorphic wetland classification for inland hydrogeomorphic wetland units at level 4A of the Ollis *et al.* (2013) classification system. Using a process of elimination through ArcMap 10 software (ESRI 2012), the wetness map was classified to assign respective wetland's an HGM class. Table 2.2 shows the wetland classes and the criteria used to define them.

Table 2.2: Criteria used by Grundling *et al*. (2014a) to classify the wetlands of the Maputaland Coastal Plain according to the hydrogeomorphic units of Ollis *et al*. (2013).

HGM Type	Criteria
Floodplain	All wetland polygons that fall in terrain unit 5 (toeslope) and are characterised by distinct meandering channels and oxbow depressions with secondary channels, indicated by the digitized SPOT 2010 channel layer or from the 1:50 000 river layers.
Channelled valley bottom	All wetland polygons that occurred in terrain unit 5 (toeslope) and that intersect with defined stream channels digitized from the SPOT 2010 channel layer or from the 1:50 000 river layer (NGI, 2012a).
Unchannelled valley bottom	All wetland polygons that occurred in terrain unit 5 (toeslope) lacking a well-defined stream channel.
Depression	All polygons were classified as such using the 1:50 000 Inland Water Layer category depressions (NGI, 2012b).
Seep	Polygons that include permanent and temporary open water areas from the wetness map with modal slope values of 1-2%; typically concave midslopes characterised by seepage.

2.5 Wetland Research in Swaziland.

The following section presents the relevant work and research pertaining to wetlands in Swaziland. The review is in chronological order and is split into two sections. The first section focuses on earlier wetland research beginning with the wetland map produced in 1973 as part of a survey of national protection worthy areas (Grimwood, 1973). The second section looks at work that has been done in the last decade and ends with the Malereo project (Franke *et al*., 2013) that mapped wetlands in parts of South Africa, Swaziland and Mozambique that are prone to hosting malaria carrying mosquitoes.

2.5.1 Early wetland research in Swaziland.

Research on the wetlands of Swaziland began in 1973 where a survey on national protection worthy areas of Swaziland produced a location map of wetlands within these areas (Figure 2.2) (Grimwood, 1973). The map only showed point locations, with a majority of the identified wetlands being lacustrine systems. A table containing the names, location and types of wetlands was also produced.

The survey on nationally protection worthy areas found that the wetlands in Swaziland have very little protection from trampling stock and human interference (Grimwood, 1973). This impacts negatively on the country's waterbird resources due to breeding habitats being limited. The largest natural waterbird habitat in Swaziland has long since been destroyed by cultivation and drainage, stock intrusion and human disturbance (Grimwood, 1973).

Several studies followed, including Dlamini (1981), who studied the local uses for different types of flora found in Swaziland, and identified the many uses that the people of Swaziland have for wetland plants. The main uses for wetland plants in Swaziland was found to be clothing, mats, baskets, medicine as well as cultural significance (Dlamini, 1981). The location, origin and geomorphological significance of closed depressions (pans) in the Lubombo Mountains of Swaziland were identified by Watson (1986). Fifty-three closed depressions, ranging from 50m to 400m in diameter and up to 5m deep were identified, with a density of 0.3km^2 (Figure 2.3).

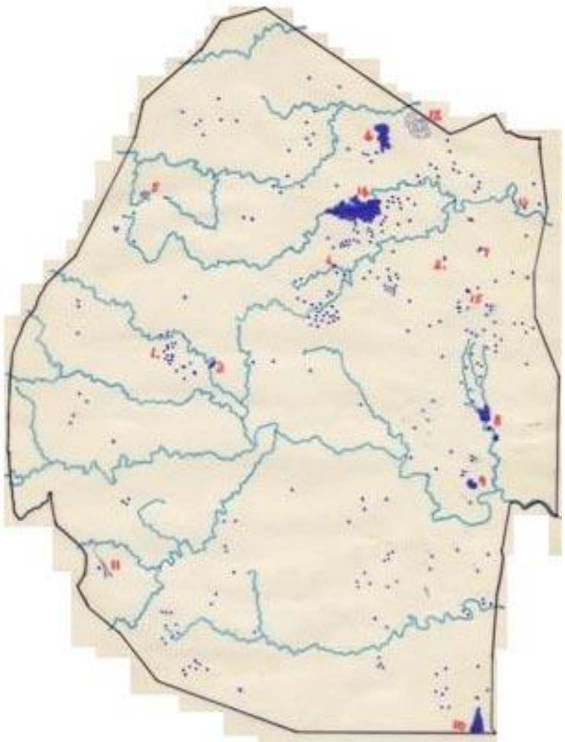


Figure 2.2: The location map of wetlands within the protection worthy areas of Swaziland (Grimwood, 1973).

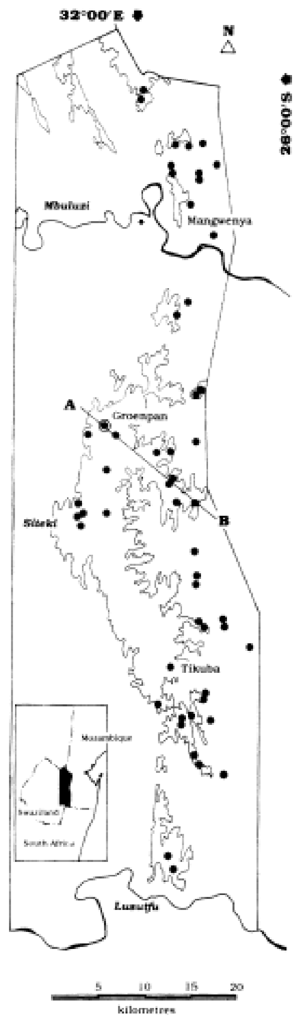


Figure 2.3: Figure 2.3: The depressions on the Lebombo Mountain range within Swaziland, identified by Watson (1986).

Watson (1986) found that the pans frequently occurred in groups on the geomorphological remnants of the tilted African Planation Surface. The preservation of the pans were attributed to the Jurassic rhyolites which are less susceptible to erosion than the surrounding basaltic and sedimentary rocks that were exposed since the Miocene. Watson (1986) reasoned that the depressions developed on the tuffaceous horizons within the acid volcanic sequence and are the result of the local surface lowering from the dissolution of plagioclase weathering products. This resulted in the origin of the pans being described as karstic.

Hughes and Hughes (1992) in "A Directory of African Wetlands" reported on the wetlands of Africa and commented that there are no major wetlands in Swaziland and of those that occur, the most important are sponges found at elevations 1400-1800m on the summits of the mountainous western parts of the country. The authors explained that these wetlands formed above springs or below seepages from clefts and discontinuities in the bedrock and provide perennial reservoirs for the headwaters of countless streams, upon which much of the population of Swaziland depends directly. The authors went on to explain that there are also small swamp and peat bog areas as well as numerous pools that occur along these streams wherever they traverse flat areas. Many streams flow underground, even on steep slopes, where boulders and soil have collapsed into their channels. The courses of these streams are visible as shallow depressions lined by tree ferns where some arborescent vegetation is usually clustered. Small reed swamps occur on the margins of numerous farm ponds and dams and along the courses of rivers. The authors also isolated saline pans that occur in the Lowveld of Swaziland.

In terms of human impact and utilisation, Hughes and Hughes (1992) also found that Irrigation schemes have led to the disappearance of several swampy areas adjacent to rivers in the middle and the Lowveld areas. The hillsides of the Highveld are heavily overgrazed and burnt during the winter, where small bogs and sponges are heavily trampled and tend to dry and erode. Most bog pools, which are used as water holes, had been degraded and their banks broken down so that they drain by streams rather than a gentle over-welling over their lips through bog vegetation. Hughes and Hughes (1992) also identified two substantial herb swamps in the valleys of the Malolotja Nature Reserve, which were described as areas of extensive and relatively flat undisturbed sponge and peat bog.

In 1997, a wetland conservation report through the International Union for the conservation of Nature (IUCN), found that Swaziland has riverine, lacustrine, and palustrine wetland systems, with the riverine system as the most common type (IUCN, 1997). The riverine wetlands were described as well-developed in the lower Middleveld and Lowveld regions, consisting mainly of small flood plains and swamps along rivers and streams. In the Highveld, Middleveld and Lubombo regions, the high rainfall and constant flow of water from seepage resulted in the development of numerous vleis (i.e. wetland) and swamps (IUCN, 1997).

Frenken and Mharapara (2002) reported to the FAO that in Swaziland, wetland areas are often referred to as 'sponges' or 'bog systems'. The name 'vlei', borrowed from the Afrikaans language, is also commonly used to refer to wetlands. The Swaziland report highlighted the descriptive definition of wetlands from Mitsch and Gosselink (1993), where wetlands were described as being distinguished by the presence of water at the surface or within the root zone, commonly have soil conditions that differ from the adjacent uplands, support vegetation adapted to wet conditions and conversely are characterized by the absence of flooding intolerant vegetation. In addition, an unnamed survey outside of the protected areas of Swaziland led to wetland identification in Cibidze, Gege, Lushikishini and Motjane in the Highveld region, Tondozi in the Middleveld region, and Balekazulu and Wesselrode in the Lowveld region (Frenken and Mharapara, 2002).

The report to the FAO (Frenken and Mharapara, 2002) stated that the country is endowed with different types of wetlands that have various natural and socio-economic functions and values, which could be enhanced if the wetlands were developed and managed properly. The authors stated that the potential of utilizing some of the wetlands for sustainable agricultural production could also be realized once all the wetlands are mapped and their hydro-ecological processes fully understood. It was also mentioned that the various policies that address natural resources mention wetlands in passing and that most of the policy and legislation frameworks that touch on wetlands are contained in blanket statements that treat wetlands simply as riverine systems. Frenken and Mharapara (2002) added that there is a general perception that agricultural activities lead to wetland degradation, hence there is nothing in the report to suggest deliberate strategies and efforts to promote wetland cultivation in Swaziland.

As observed earlier by Dlamini (1981), given the levels of poverty in Swaziland, many of its people directly depend on these wetland systems. Mwendera (2002, 2003), found that the wetlands of Swaziland are an important water supply for many people and provide important grazing resources that can be used for dry season cropping. Mwendera (2003) highlighted that many women in Swaziland see wetlands as an important economic resource and earn a living off using plants found in wetlands to make various crafts. These include food mats, sleeping mats, bags and baskets as well as handcrafts. Cultural ceremonies, including the maiden reed dance also make use of wetland vegetation.

2.5.2. Recent research on the wetlands of Swaziland

Masarirambi *et al*. (2010) analysed the distribution and utilization of wetlands in Swaziland. The objective of the study was to develop an inventory of the wetlands found in Swaziland and to review the legislation and policies applied to effectively utilise and conserve wetlands. The authors found that Swaziland does not have a clear policy on wetland use and management and went on to explain that the overall management of wetland resources is on an *ad hoc* basis through several uncoordinated pieces of legislation, which are spread out across various ministries as well as institutions outside government. The authors produced a list of the principle pieces of legislation and boards of authority governing wetlands in Swaziland which are summarised in Table 2.3.

Table 2.3: Principle pieces of legislation and respective governing bodies of wetland related management across Swaziland, extracted from Masairambi et al. (2010).

Legislation (Government of Swaziland)	Governing body	Tasks related to wetland management
The natural resources Act no. 71 of 1951	The Natural Resources Board	Oversee the conservation of wetlands in all areas outside of Swazi Nation Land (therefore excluding national parks, reserves and monuments) where its function is to supervise and manage natural resources.
Swaziland National Trust Commission Act no. 9 of 1972	Swaziland National Trust Commission	Custodian of wetlands in all nationally declared parks, reserves and monuments.
The Environmental Management Act no. 5 of 2002	the Swaziland Environment Authority	Oversee the enhancement, protection and management of natural resources. Provide approvals to any person who undertakes a project that may have adverse effects on the environment, and may request environmental Impact assessments and mitigation plans before granting permission for a specific development.
The Water Act no.7 of 2003	National Water Authority	Responsible for advising the Minister responsible for water affairs on matters related to water use and management. Is also tasked with preparing a Water Resources Master Plan that includes the generally accepted principles of river basin management

Although Masarirambi *et al*. (2010) highlighted the main pieces of legislation acting upon wetlands in Swaziland, the mapping and distribution of wetlands was insufficient to suffice as a national wetland inventory. The methods in the study state that the authors analysed satellite images and used field surveys to create a map showing the distribution of wetlands. The authors state that “A representative number of the wetlands were selected from the four ecological zones [of Swaziland] for detailed survey. The information sought during the detailed field survey included the area covered by the wetlands, flora and fauna within the wetlands, dominant land use, management strategies and impacts of using the wetlands” Masarirambi *et al*. (2010, p.148). It was also stated that a questionnaire on the utilization and management of wetlands was also prepared and administered to users of the wetlands, however, Masarirambi *et al*. (2010) do not mention the results of the questionnaires. Furthermore, the study provided as wetland map as the only map displayed in the article is the 1973 map of wetlands in the protected areas of Swaziland (Grimwood, 1973). In another study focusing on the ecosystem services of wetlands in Swaziland, Zwane *et al.* (2011) highlighted the importance of the natural fibre plant resources used by local communities.

The most recent and comprehensive wetland map for Swaziland was performed in 2013 through the European Commission Seventh Framework Programme (Franke *et al*., 2013). The authors produced a land cover map of the malaria prone areas of South Africa, Mozambique and Swaziland. However, only 66% percent of Swaziland was covered by the MALEREO project (Figure 2.4). The project was titled *MALEREO* and used RapidEye satellite images with a resolution of 5m. The *MALEREO* land cover/use classification of the RapidEye data was conducted through the application of an object-based image analysis with a predefined hierarchical rule-set (supervised classification) using eCognition software (Franke *et al*., 2013). Eleven classes were produced, with waterbodies being divided into three classes of flowing water, standing water and wetland. Overall the land cover maps produced an accuracy of 81% with the respective wetland layers reaching an accuracy of: wetland (78%), standing water (93%) and flowing water (100%). However, Franke *et al*. (2013) did not provide a definition of what they deemed to be a wetland.

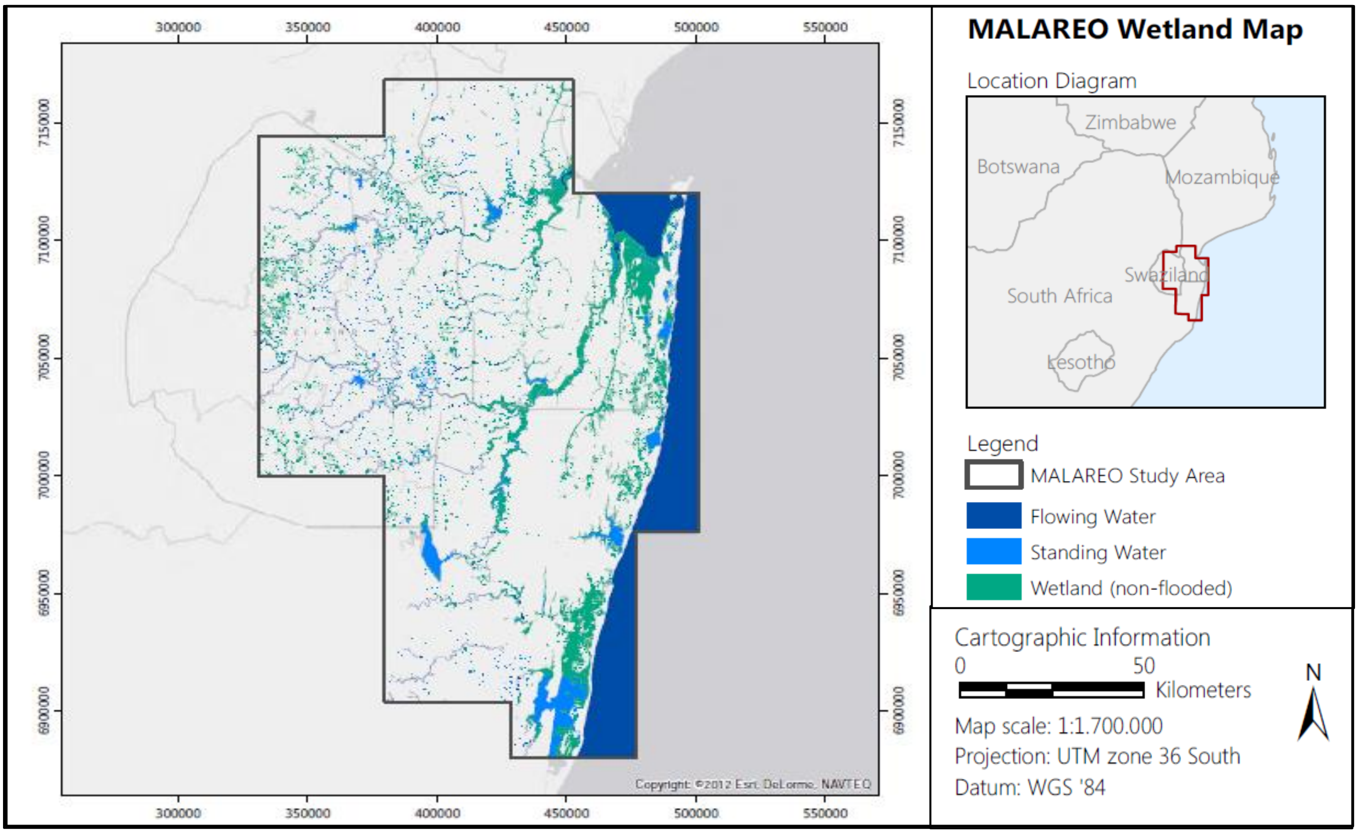


Figure 2.4: MALEREO project wetland map (Franke et al., 2013).

2.5.3 Summary of wetland research in Swaziland

The section on Swaziland's wetland research has shown that there has been very little research on the types of wetlands across the country. The descriptions by Hughes and Hughes (1992) provide a brief summary on wetland types, whilst the detailed work by Watson (1986) is restricted to only depressional wetlands on the Lubombo summit. The section has also shown that there have been incomplete attempts to map the wetlands of Swaziland which includes Grimwood's (1973) location map of wetlands in protected areas, the work done by Massarambi *et al*. (2010) and the Malereo wetland map that only mapped wetlands for approximately 66% of Swaziland (Franke *et al*., 2013). Since then, there has been no published research on wetlands in Swaziland. The Website for the Eswatini National Trust Commission (said to have been updated in 2014), only makes reference to the 1973 Map (Grimwood, 1973) as the available wetland map for Swaziland (ENTC, 2014).

Although the wetlands of Swaziland have been shown to provide basic services for many rural people of the country (Dlamini, 1981; Zwane *et al*., 2011), the wetlands are being over utilized and are under threat (Mwendera 2002; 2003). This can be attributed to the country not having adequate policy relating to wetland management (Massarambi *et al*., 2010) as well as not having the resources and means to identify and locate wetlands across the country that would be achieved with a national wetland inventory.

The following chapter describes the environmental setting of Swaziland with a focus on the physical geography of the country that will have an influence on wetland occurrence and distribution.

Chapter 3- The environmental setting of Swaziland

The following section provides an overview of the Kingdom of Swaziland and begins with the natural factors. It ranges from the location of the country to environmental characteristics which include the geology, soil and climate of the country. These attributes govern the types of wetlands occurring in a region and were therefore used in this research. Furthermore, the chapter describes the physiographic zonation of Swaziland, which was used as a fundamental data set when classifying Swaziland's wetlands and explaining their distribution across the country. The anthropogenic factors of Swaziland are also briefly discussed.

3.1 Location

Swaziland is bordered by South Africa in the north, west and south, and by Mozambique in the east. The country covers 17, 364km^2 between 25^o 43' and 28^o 19' South and 30^o 47' and 32^o 08' East (Figure 3.1), is 130 km wide and 180 km long. Elevation ranges from over 1800 m.a.s.l. in the west to under 100 m.a.s.l. in the east (Figure 3.2). Swaziland is located at the transition of the central South African Plateau and the Eastern Coastal plains (Remmelzwaal, 1993). The high level plateau in the west consists of an escarpment complex with steep slopes between eroded plateaux at subsequent levels, whilst the lowveld plains occur in the eastern part of the country and are separated from the Mozambique coastal plains by the Lebombo Mountain range that rises to 600 m.a.s.l. (Remmelzwaal, 1993).

3.2 Water resources

Swaziland has five main river systems which flow from the west to the east of Swaziland and discharge into the Indian Ocean along the Mozambique coastline (Government of Swaziland, 2015). Main river systems include the Lomati, the Nkomati, the Mbuluzi, the Great Usuthu, and the Ngwavuma Rivers (Manyatsi *et al*., 2013)(Figure 3.3). In total, 42% of Swaziland's annual renewable water resources originate in South Africa (Mwendera, 2002). The Komati and Lomati Rivers which originate in South Africa, flow through the northern part of Swaziland, back into South Africa, and then enter Mozambique. The Mbuluzi River arises in Northern Swaziland before flowing into Mozambique, whilst the Great Usuthu River, along with a number of major tributaries which originate in South Africa, flow through the center of the country before flowing into Mozambique. The Ngwavuma River, located in the south, arises in Swaziland and flows into South Africa before entering Mozambique, along with the Pongola River (Manyatsi *et al*., 2013).

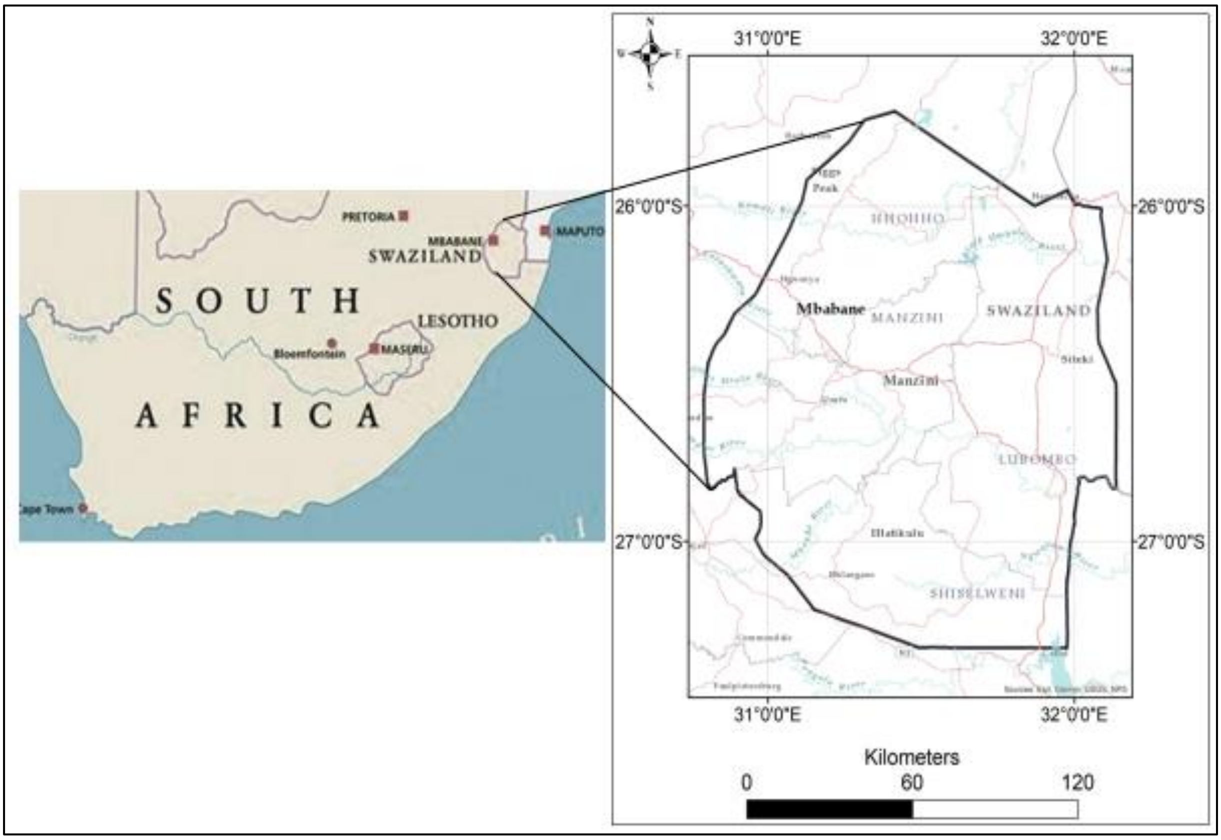


Figure 3.1: Location of Swaziland relative to other Southern African countries.

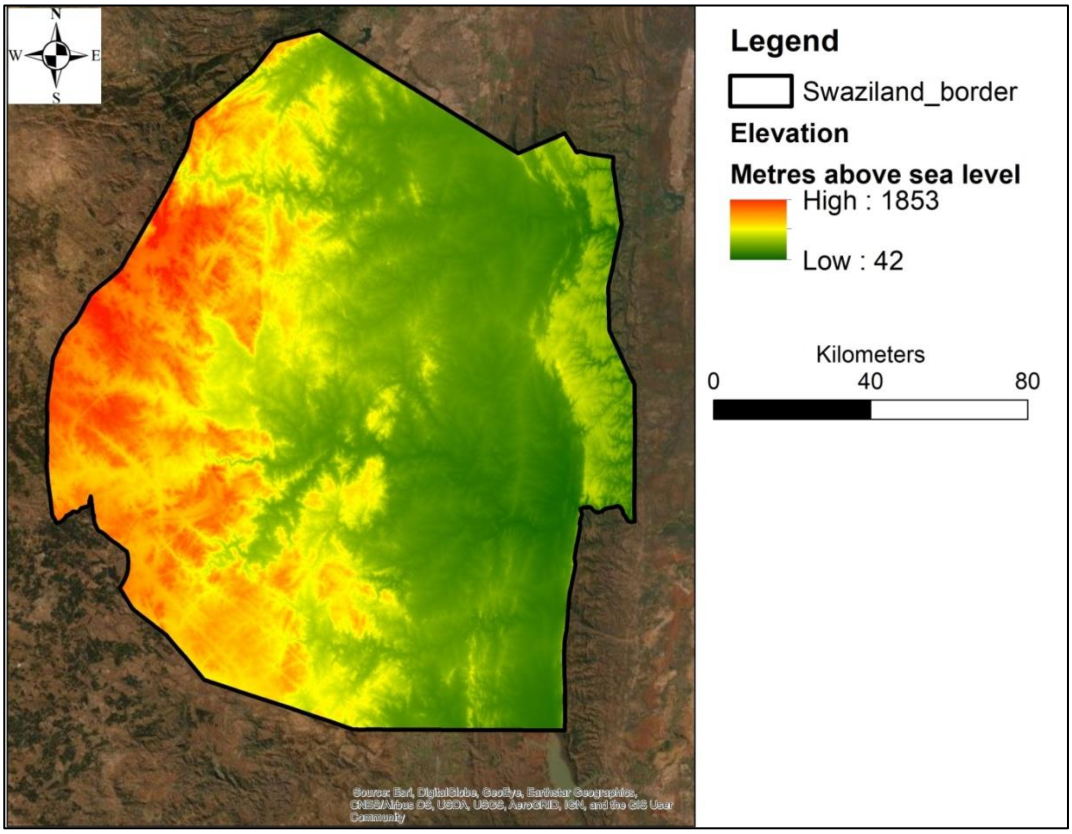


Figure 3.2: Elevation map of Swaziland (NASA, 2000)

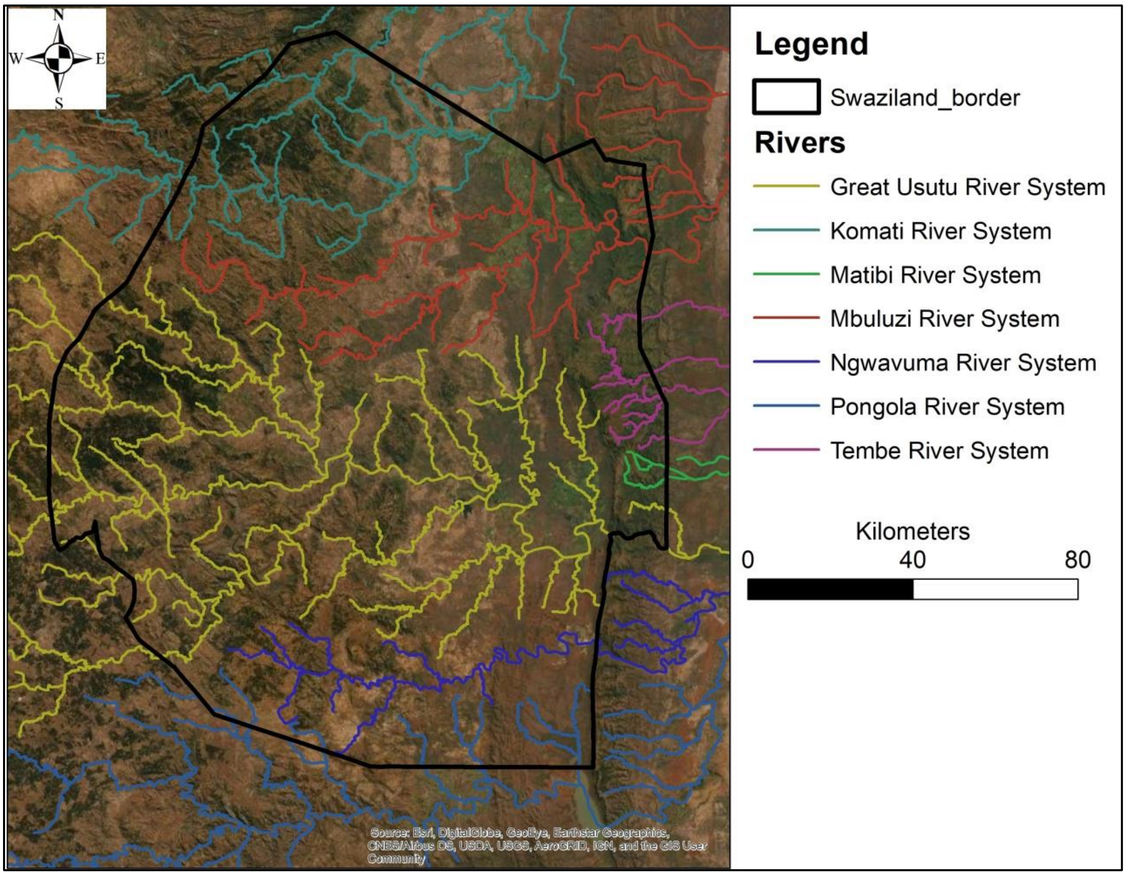


Figure 3.3: River systems of Swaziland (ENTC, 2017).

3.3 Climate

Swaziland has a sub-tropical climate, with warm wet summers and cool dry winters (Government of Swaziland, 2015). Most of the rains (75%) fall in the summer months (October–March) and about 25% falls 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 characterised by wet summers and dry winters with an average annual rainfall of 1500mm and mean temperatures between 16^{0}C and 22^{0}C (Figure 3.4). Central Swaziland and the Lubombo regions of Swaziland receive between 800-1200mm of rain annually with mean annual temperatures of 20^{0}C and 22^{0}C respectively. The Low lying eastern plains receives on average 450mm of rain annually, with temperatures reaching over 30^{o}C in the summer (Matondo *et al*., 2005).

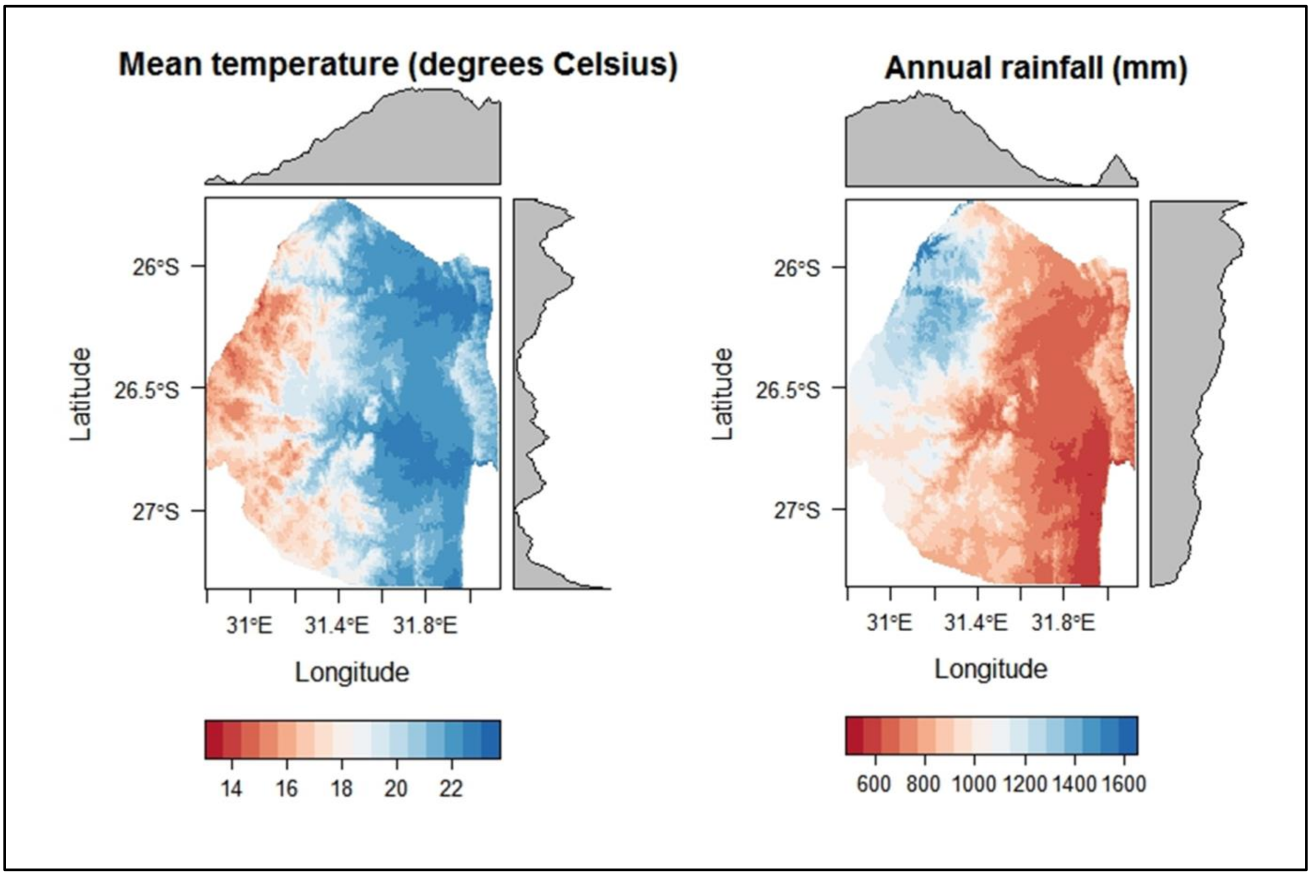


Figure 3.4: Temperature and Rainfall maps for Swaziland (extracted from Dlamini, 2017)

3.4 Geology

Wilson (1982) constructed a Geological map of Swaziland, drawing on earlier work from Hunter (1961), Hunter (1968), Hunter *et al.* (1978) Clarke (1975) and Tankart *et al*. (1982). Swaziland's geology (Figure 3.5) is dominated by rocks of the Precambrian (mostly Archean Age) in the west, and sedimentary and volcanic rocks of Karoo age in the East (Wilson, 1982; Schlüter, 2008). Swaziland's geology consists of the ancient Ngwane Gneiss dykes, 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).

The Ngwane Gneiss dykes (> 3.6Ga), which predate the Onverwacht Group (3.55Ga-3.25Ga) Schlüter, 2008), occur in the center of Swaziland and compromise of felsic to mafic gneisses that were metamorphosed and deformed and include subordinate and concordant thin amphibolites that have been cut by mafic intrusions (Hunter *et al*., 1978).

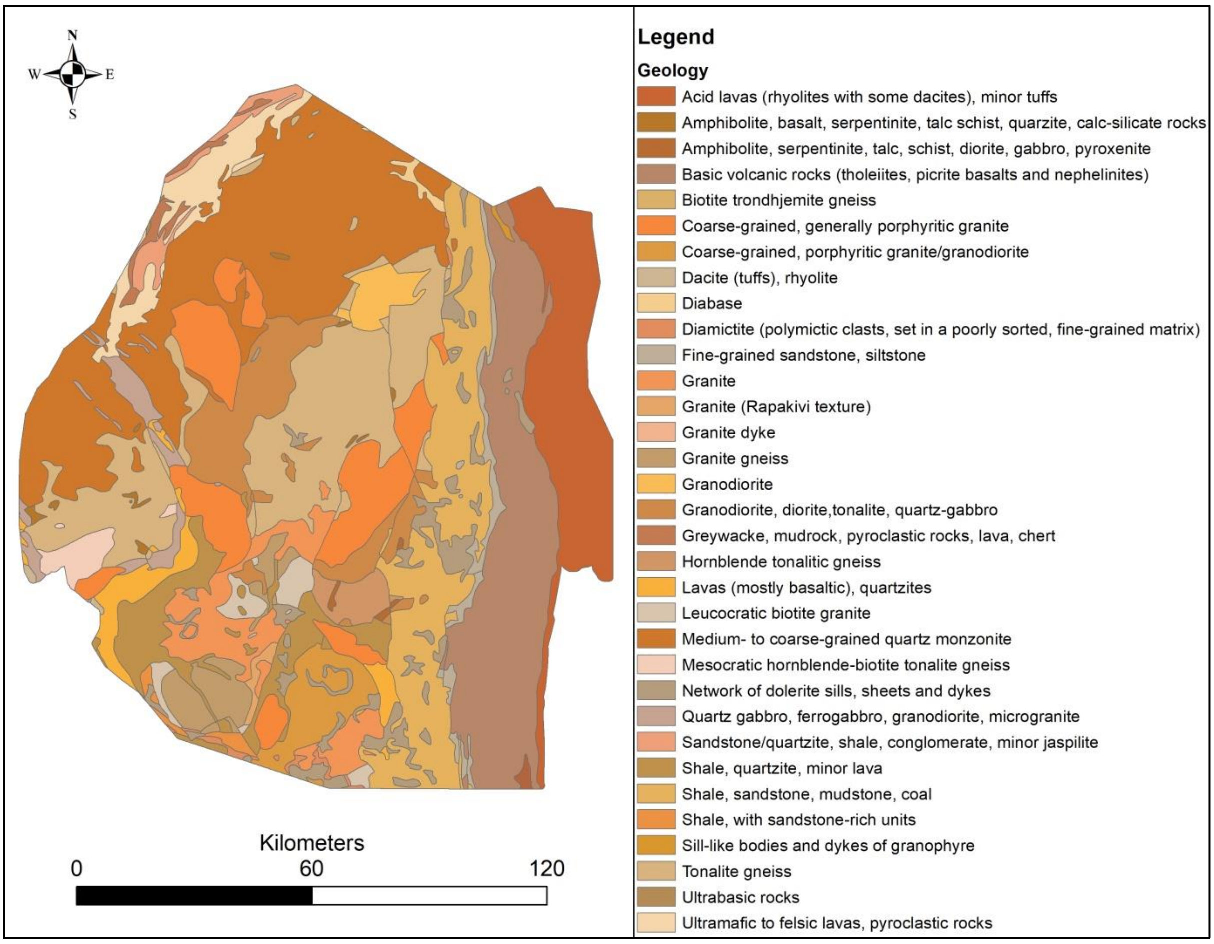


Figure 3.5: Geology of Swaziland, adapted from (Wilson, 1982).

The Barberton Supergroup, referred to by Wilson (1982) as the Swaziland Supergroup, consists of the Onverwacht, Fig Tree and Moodies Groups. The Swaziland supergroup lies on the eastern edge of the Kaapvaal craton and crops out within the Barberton Greenstone Belt in the northwest of Swaziland. The lowermost units of the Onverwacht Group comprise komatiites and mafic to silic fine grained metasediment and volcaniclastic rocks. The upper Onverwacht Group consists of komatiitic to basaltic metavolcanics and interlayered siliciclastic units, cherts, banded iron formations, and tuffs (Schoene *et al*., 2008). The succeeding Fig-Tree Group is made up of fine-grained shales, siltstones, cherts and silicic to intermediate volcanics that coarsen upward into the Moodies group that consists of quartzites and chert conglomerates that lie below the coarser-grained quartzose sandstones and conglomerates (Schoene *et al*., 2008). The Dwalile Metamorphic Suite is found in southwest Swaziland, and is lithologically similar to the Onverwacht Group and occurs as refolded synclinal fold keels and other minor patches within the Ngwane Gneiss outcrop (Hunter *et al*., 1984).

The Mahamba Gneiss in southern Swaziland consists of high-grade semi-pelitic garnetiferous gneisses (Wilson, 1982). Subsequent to the development of the greenstone belt the Ngwane Gneiss was intruded by the Tsawela and Mhlatuzane Gneisses (Kröner *et al*., 2014) and by the sheetlike Mponono Anorthosite Suite (Hunter, 1968). The post-greenstone intrusive phase continued with the emplacement of the composite Usutu Intrusive Suite in the center of Swaziland. The western parts of Swaziland are dominated by the Lochiel Granite, which intruded in a number of pulses to form a major hood-like batholith, over the subjacent gneisses (Mfana, 1992). A screen of leucocratic gneisses also occurs intermediately along the contact between the greenstone belt and the Lochiel Granite, and also outcrops at the Komati River as well as near Pigs Peak (Wilson, 1982).

Lavas and sediments of the Pongola Supergroup were laid down in the mid-Archean, within a cratonic basin, which lay across the eroded top of the Lochiel batholith. The Insuzi lavas, which form the lower half of the supergroup, were overlain disconformably by Mozaan sediments and lavas. The Shiselweni Amphibolites, which crop out in southern Swaziland, contain flattened, amygdale-like quartzose blebs and are believed to be lavas (Wilson, 1982).

The basic intrusion of the Usushwana Complex, made up of microgranites and gabbros (Scholten, 1997) followed the deposition of the Mozaan sediments near the western parts of the country (Wilson, 1982). The Nhlangano Gneiss dome in the south west of the country is the central core among a series of mantled gneiss domes which formed from an increase in the geothermal gradient which remobilised the respective basement and together with its Pongola cover rose diapirically (Schlüter, 2008).

The Mkhondo Valley Metamorphic Suite and adjacent outcrops were deformed into a series of dome-and-basin interference folds. The Kwetta and Mtombe Granites in southern Swaziland are rapakivi granites and belong to a formerly continuous post-deformation intrusion. The coarse grained Mswati Granitic plutons outcrop in different locations near the center of Swaziland and represent the youngest magmatic phase of the Archean in Swaziland (Scholten *et al.*, 1997).

The main Karoo outcrop in Swaziland is confined to and draped over the eastern edge of the Kaapvaal Craton, with other outcrops occurring in the southwest of the country (Wilson 1982). The patchy development of the Dwyka Group of glacigenic sediments reflects deposition within an area of considerable relief (Wilson, 1982). The widespread Lower Ecca claystones, deposited in a shallow marginal-marine basin, were overlain by a prograding fluviodeltaic sequence. Continental deposition of the Nkondolo Group included braided stream deposits intercalated with aeolian sediments. The eastern Lowveld consists of Olivine-poor tholeiitic Sabie River basalts which flooded most of the landscape in this part of the country (Schlüter, 2008).

The Lebombo mountain range, consisting of rhyolites, forms the eastern boundary of Swaziland (Scholten *et al*., 1997), and forms a cuesta mountain range which separates the main sequence of basic and acidic volcanic rocks. These mountains represent the main phase of folding along the Lebombo Monocline, and together with its associated volcanic pile, are believed to have developed in response to the breakup of Gondwanaland (Wilson, 1982).

3.5 Geomorphic evolution of Swaziland

The mountainous, western, parts of Swaziland are part of the Great Escarpment of southern Africa (Partridge *et al*., 2010). The Great Escarpment formed during the fragmentation of Gondwanaland in the late Jurassic and early Cretaceous, though it is also suggested that the great escarpment was accentuated by the arching of the crust prior to rifting (McCarthy and Rubidge, 2005). Partridge and Maud (2000) explain that rifting created a steep marginal escarpment which was eroded back by rivers during the Cretaceous period which resulted in most scarp recession happening during this period as well as during the uplift of the Neogene.

Rivers flow off the Great Escarpment towards the east in steep valleys, and are also orthogonal to many ridge features and valleys (King, 1967). Two post-Cretaceous epeiroegenic uplift events during the Neogene (Partridge and Maud, 1987) amplified the relief of the area to the east of the Great Escarpment and caused a steepening of the lower courses of many rivers. This created broad, upwardly convex, longitudinal profiles in most rivers and rapid down cutting of pre-existing meander systems which resulted in many rivers in central Swaziland being deeply incised in their middle and lower reaches Partridge *et al*. (2010). The low-lying eastern parts of Swaziland have been excavated by erosion between resistant uplands to the west (Escarpment) and east (Lebombo) (McCarthy and Rubidge, 2005). Partridge and Maud (1987) explain how planation occurred mostly during the Post-African I cycle, whilst the area immediately west of the Lebombo Range represents the Post-African 2 surface. The Lebombo Range is attributed to its geology of Rhyolites, which are more resistant to weathering than the basalts to the west of it (Partridge *et al*., 2010). The geomorphic evolution of the various geologies of Swaziland, along with the substantial difference in elevation has resulted in different physiographic zones developing across the country.

3.6 Physiographic divides

Remmelzwaal (1993) adapted and elaborated on preexisting physiographic zones for Swaziland by redefining the boundaries and adding further subdivisions. The six physiographic zones are shown in Figure 3.6 with descriptions shown below in Table 3.1 and their characteristics listed in Table 3.2.

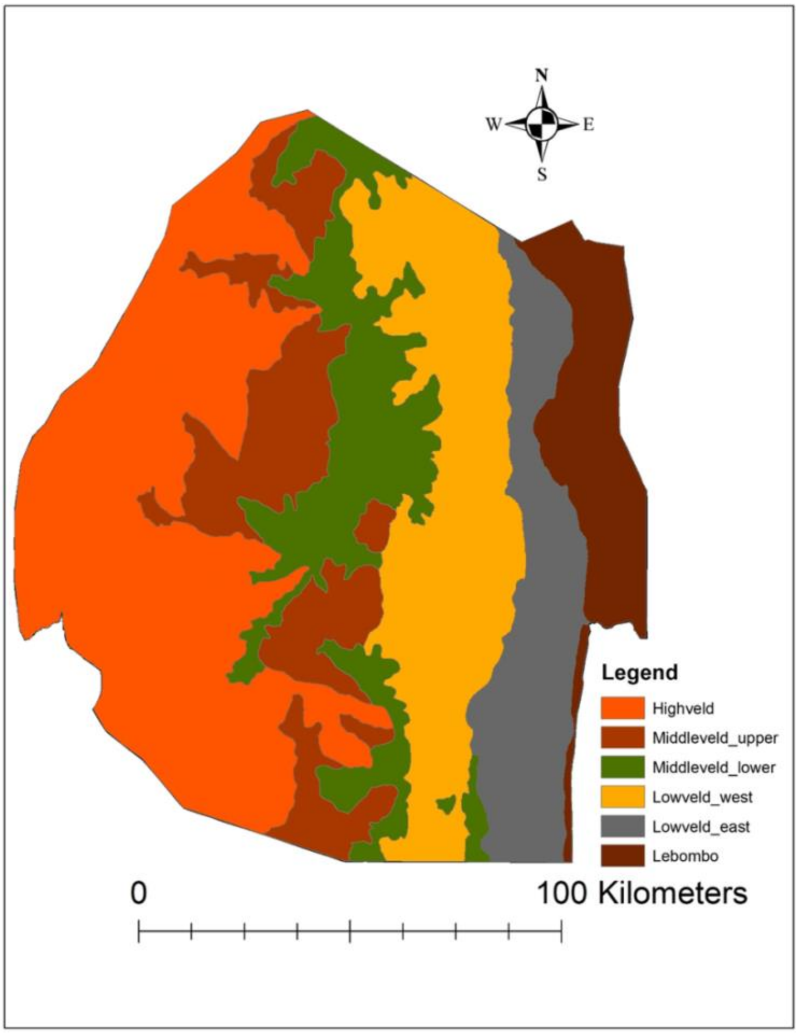


Figure 3.6: Physiographic zones of Swaziland (adapted by Remmelzwaal, 1993).

Table 3.1: The physiographic zones of Swaziland modified from Remmelzwaal (1993)

Physiographic zone	Description
Highveld	The upper part of the overall escarpment, consisting of a complex of steep slopes between low and high levels, dissected plateau, plateau remnants, and associated hills, valleys and basins.
Upper Middleveld	Strongly eroded plateau remnants and hills at an intermediate level of the overall escarpment. It also contains structurally defined basins in relatively protected positions, which are only weakly eroded.
Lower Middleveld	The piedmont zone of the escarpment characterised by generally strongly eroded footslopes. Although the Lower Middleveld contains hilly parts, the overall slopes are predominantly moderate and the zone classifies as the first level of the plain.
Western Lowveld	A Plain which has gradual transition from the Lower Middleveld, characterised by sedimentary rocks of sandstone and claystone.
Eastern Lowveld	A plain characterised by basalt.
Lebombo Range	A cuesta with a steep escarpment bordering the Eastern Lowveld with a gradual dipslope of about 5% descending east. The Lebombo qualifies a plateau and is quite strongly dissected with a geology (Rhyolite) different to that of other zones.

Table 3.2: Attributes of the physiographic zones of Swaziland modified from Remmelzwaal (1993)

Physiographic zone	Surface area	Altitude: Average (min-max)	Landforms	Topography	Geology
Highveld	5.68km2 (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	2.42km (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	2.42km (14%)	400-600 (250-800)	Plains associated with low hills	Rolling piedmont, undulating basins and isolated hills	Gneiss, Granite, Granodiorite
Western Lowveld	3.41km (20%)	250-400 (200-500)	Plain	Undulating part rolling	Sandstone, claystone with dolerite intrusions
Eastern Lowveld	1.96km (11%)	200-300 (200-500)	Plain	Gently undulating part rolling	Basalt
Lebombo Range	1.48km (8%)	250-600 (100-750)	Plateau dissected	Undulating cuesta, part hilly and steeply dissected.	Rhyolite, Ignimbrite

Remmelzwaal (1993) further subdivided Swaziland into second level physiographic zones primarily based on landforms and elevation levels along with geology and soils as subordinate factors. The map was constructed using topographical maps with contour lines at scales 1: 250 000 and 1: 50 000 as base maps for the elevation. Landforms were identified and delineated using Landsat and SPOT colour composite images. The standard lithological nomenclature of the 1: 250 000 Geological Map of Swaziland (Wilson, 1982) and the 1: 125 000 soil map of Swaziland (Murdoch, 1970) were used as base maps. However, this study focuses on the six physiographic zones shown in Figure 3.6.

3.7 Soils

In 1970, soil and land capability maps for Swaziland were published at a scale of 1: 125 000 (Murdoch 1970). Soil mapping aimed to define agricultural potential for several important crops across Swaziland. The soil classification used in the map is referred to as the “Murdoch classification system” and has two levels of classification, namely sets and series, with the ‘set’ being the superior class and ‘series’ the subordinate and includes 107 soil series in 34 sets (Appendix 1). Murdoch (1970) adopted the Kellog (1951) standard soil ‘series’ definition which explains that a soil series is a group of soils having soil horizons similar in differentiating characteristics, arrangement in the soil profile and have developed from a particular type of parent material. Murdoch (1970) based his classification according to the Legend for the soils of Africa of D'Hoore , (1964) in order to introduce a reference framework.

Nixon (2006) correlated the Murdoch (1970) classification to the South African Binomial System (Soil Classification Working Group, 1991) for the Swaziland Sugar Industry, as the South African Binomial System had fully incorporated the identification and management of soils in the sugar industry. Van Waveren and Nhlengetfwa (1992) identified many shortcomings and practical problems of the Murdoch soil classification system, mainly around the classification definitions of soil sets, descriptions of soil properties, subdivisions of sets into series, as well as mapping only being done to set level for the national map. It was often found that more than one set or series would fit a particular soil profile and that in quite a few locations the mapped soil units were found to correspond with other sets. However, van Waveren and Nhlengetfwa (1992) still acknowledge that the soil map produced by Murdoch (1970) is an important set of information.

There is a clear spilt in the soil distribution of Swaziland with regards to the higher and lower parts of the country (Remmelzwaal and Masuku, 1994). The soils typical of the Highveld and Middleveld are characterised by intense weathering and leaching with very deep soil formation. Soils of the Lower Middleveld and Lowveld are characterised by moderate weathering and soil formation (pedogenesis). Remmelzwaal and Masuku (1994) explain that the major soil boundary of Swaziland coincides with the major boundary between the main Tertiary and Quaternary erosion cycles. The higher part of the country has been influenced by Tertiary cycles of geological erosion, but remained relatively unaffected by the major Quaternary cycle, which has progressed approximately as far as the boundary between Upper and Lower Middleveld.

The general status of geological erosion explains why the extensive occurrence of old and deeply weathered soils is mainly confined to the Highveld and Upper Middleveld whilst in the Lower Middleveld and Lowveld most of the older soils have disappeared. The soil and erosion cycle boundaries correlate with the current major climatic boundary in Swaziland where the upper part has relatively high rainfall and moderate temperatures, whereas the lower parts have low rainfall and high temperatures (van Waveren and Nhlengetfwa, 1992).

3.8 Vegetation.

Swaziland is unique in the southern African region for the diversity of vegetation types that it supports in a comparatively smaller area (Dlamini, 2011). The Highveld is dominated by man-made forests of *Pinus* and *Eucalyptus* as well as sour grassland in unforested areas. Tall grassland with scattered trees occupy the Middleveld, whilst the Lowveld (which is extensively used for sugar cane) contains sweet grassland. The Lebombo plateau mainly consists of hillside bush and savannah (Masariambi *et al*., 2010).

The vegetation map of Swaziland was developed by Dobson and Lötter (2004), whilst the sixteen vegetation units that occur in Swaziland are described in Mucina and Rutherford (2006) and include: Ironwood Dry Forest, Lowveld Riverine Forest, Northern Mistbelt Forest and Scarp Forest. Three grassland types: Barberton Montane Grassland, Itala Quartzite Sourveld, KaNgwane Montane Grassland. Nine savannah types: Delagoa Lowveld, Granite Lowveld, Kaalrug Mountain Bushveld, Lebombo Summit Sourveld, Northern Zululand Sourveld, Southern Lebombo Bushveld, Swaziland Sour Bushveld, Tshokwane-Hlane Basalt Lowveld and Zululand Lowveld. Boycott *et al*. (2007) aggregated the above vegetation units into five vegetation types or habitats, which are illustrated in Figure 3.7.

The wetland flora of Swaziland were outlined in Hughes and Hughes (1992) and includes, in addition to many grasses and sedges : *Anoiganthus breviflorus*, *Brunsvigia natalenis*; *Hypoxis acuminate*, *H. filiformis*, *H. gerrardii*, *H. angustifolia*; *Aristea woodii*, *Dierama medium*, *Gladiolus papillo*, *Hesperantha lacteal*, *Anthericum haygarthii*, *Bulbine stenophylla*, *Drinia nenniformis*, *Drimiopsis maculate*, *Eriospermum cooperi*, *Eucomis poleevansii*, *Kniphofa multiflora*, *K. porphyrantha*, *K. praecox*, *K umbrina*; and *Disa versicolor*, *Disperis tysonii*, *S. crisatum*, *S macrophyllum*, *S. ocellatum* and *Schizochilus strictus*, *Agrostis barbuligera*, *Andropogon appendiculatus*, *Helictotrichon turgidulum*, *Hyparrhenia drageana*, *Pennisetum macrourum*, *P. spacelatum*, *P. thunbergii*, *Setaria rigida* and *Stiburus alopecuroides.*

3.9 Demographics

The latest population data, although now outdated, indicates that Swaziland has a population of just over 1.09 Million people, with 78% living in rural areas and 22% in urban areas (Swaziland Ministry of Economic Planning and Development, 2007; UNFPA, 2017). The two major cities are Mbabane and Manzini. The official unemployment rate in 2007 was 28.3%, although it is estimated that the actual figure was over 40% with over 69% of the total population below the poverty line of $1 per day (Swaziland Ministry of Economic Planning and Development, 2007). Subsistence agriculture therefore provides an important food source, with 80% of the population being engaged in agriculture (Manyatsi *et al*., 2013).

3.10 Land use

Swaziland has a dual system of land tenure comprising Swazi Nation Land (SNL), which is communal land held in trust by the King, and Title Deed Land (TDL). Title deed Land (TDL), which covers 46% of the country is privately owned land used mainly for ranching, forestry (8%) and commercial agriculture (6%) which includes crops such as vegetables, sugarcane, citrus, and pineapples (Manyatsi *et al*., 2013). The remaining land is held in trust by the king for the Swazi people, where the main land uses include 50% extensive communal grazing and 12% small-scale subsistence farming (Manyatsi *et al*., 2013).

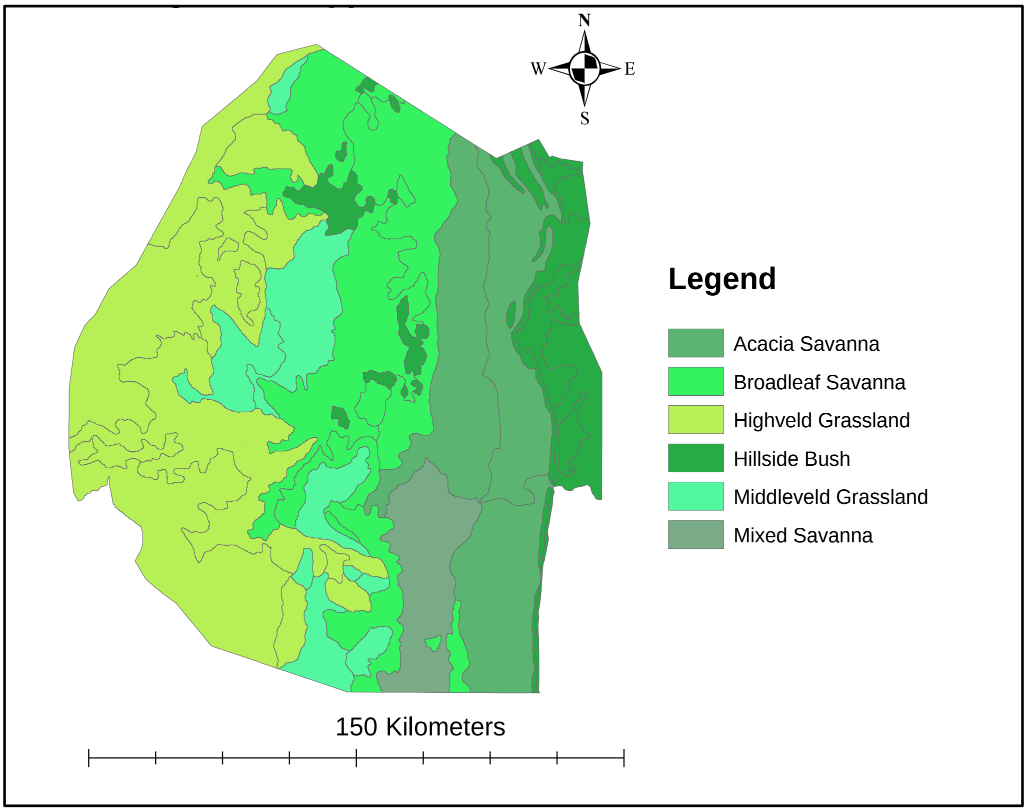


Figure 3.7: Vegetation types of Swaziland (Boycott *et al*., 2007)

Many of the above listed species are listed in the South African wetland delineation guidelines (DWAF, 2005), as well as van Ginkel *et al*. (2011), who provide an identification guide for various wetland plants across South Africa. The similarity between the wetland vegetation in Swaziland and South Africa is further evidence that the wetlands of Swaziland have much in common with those in South Africa.

This chapter has shown that Swaziland possesses a wide range of physical landscapes with numerous types of rocks, soils, climate and topography. These different landscapes are grouped into physiographic zones (Remmelzwaal, 1993), which lay a foundation for the wetlands of Swaziland to be characterised. The following chapter applies the wetland probability mapping technique of Collins (2018), whilst Chapter 5 uses the attribute data listed in this section, including the physiographic zones of Swaziland, to improve on the initial wetland probability map produced in Chapter 4.

Chapter 4- The methodological approach used to map the probable location of wetlands of Swaziland and an assessment of its accuracy

This chapter explains the methodology used to map probable areas of wetland occurrence across Swaziland. The chapter begins by explaining the reasons for using the wetland probability mapping technique of Collins (2018) and also includes the results of a field, and desktop accuracy assessment of this initial wetland probability map.

4.1. Motivation

As indicated in the literature review, Swaziland is mostly bordered by South Africa with the boundaries being merely politically established. It was therefore decided that South Africa's methods for mapping wetlands would be the most applicable to Swaziland. Van Deventer *et al*. (2018c) recently updated the South African wetland inventory using alternative methods to remote sensing, as users of the previous South African wetland map, produced by Nel *et al*. (2011), noted many problems with its accuracy (Grundling *et al*., 2013a; 2014a; 2014b; Mbona *et al*., 2015; Rebelo *et al*. 2017; Collins, 2018; van Deventer *et al*., 2018c). Van Deventer *et al*. (2018b) used on-screen digitizing at a fine scale to map and classify the wetlands of South Africa for the country's latest national wetland inventory. However, only 31% of the mapped wetlands were assigned a moderate and above confidence rating as they were mostly mapped by interns, and a limited number by wetland specialists (van Deventer *et al*., 2018b).

Due to the time and budget constraints of this study, it was not practical to digitize the wetlands for the entire Swaziland. This led to alternative methods being required. The wetland probability mapping technique of Collins (2018) was determined to be an alternative to on-screen digitizing, considering the short comings of mapping techniques based on Remote Sensing. As the wetland mapping technique of Collins (2018) is relatively new, there is a limited understanding of how and where it can be of use (van Deventer *et al*., 2018c). Therefore, there is a need to test its applicability in a country that contains a wide range of physiographic landscapes, such as Swaziland (Dlamini, 2017).

There are two limitations to using the technique of Collins (2018). The first is that it does not map depressional wetlands which have been previously identified in Swaziland. Depressional wetlands of the Lebombo were located and documented by Watson (1986), whilst Hughes and Hughes (1992) stated that isolated pans occur in the Lowveld of Swaziland. However, the IUCN (1997) stated that Riverine wetlands are the most common wetland type in Swaziland. This is also the type of wetland that the wetland probability mapping technique of Collins (2018) is best suited to map. The second downfall to the wetland probability map is that it also includes watercourses that are not necessarily wetlands, as defined in South Africa (NWA, 1998). However, these watercourses are recognized as wetlands according to the Ramsar definition of a wetland (Ramsar Convention Secretariat, 2016). Watercourses that are mapped by the probability mapping approach include rivers, riparian areas, wetlands, lakes, dams, springs and natural areas in which water flows regularly or intermittently.

4.2 Methodology used to map probable areas of wetland occurrence in Swaziland

The wetland probability mapping technique requires remotely sensed imagery (either aerial photographs or satellite imagery) and a Digital Elevation Model (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 orthorectified 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 "Breach depression" tool of Whitebox GIS (Lindsay, 2014) to be consistent with the methods of Collins (2018).

The 2008 SPOT images were the highest quality available from the Agricultural Research Council-Institute for Soil, Climate and Water (ARC-ISCW) and were of a dry year. A dry year was preferable because it shows areas that have a sustained water source and are most likely to be wetlands, in contrast to an image of a wet year where more areas would show signs of wetness. The SRTM DEM was used because it is a freely available DEM and was also used by Collins (2018) for the wetland probability map of South Africa, as well as by Grundling *et al*. (2013a; 2014a) to classify the wetlands of Maputaland.

The mapping process includes combining parameters for flow accumulation (ESRI, 2018) and percentile filter maps (Lindsay, 2014) for each mapping regions. The mapping regions were identified through an algorithm developed by Collins (2018), and is based on factors pertaining to wetland development and includes rainfall, relief and generalized geology. The DEM was then pre-processed in order to hydrologically correct it, using the 'Breach Depressions tools of Whitebox GIS, and then exported to ArcGIS. Parameters were then determined for each mapping region based on trial and error in order to include all areas on the respective image that were low lying and had a change in vegetation with respect to immediate surrounding areas. These two sets of parameters were then combined to produce a layer of wetland probability. Swaziland was initially divided into 122 mapping regions using the algorithm of Collins (2018). Mapping regions were further split into 180 regions in order to improve the accuracy of the predictive map. This was due to mapping parameters not matching all the probable areas of wetland occurrence within an entire mapping region, which resulted in those specific regions being split, with different parameters applied to each respective region.

4.2.1 Flow accumulation

Flow accumulation thresholds are determined using the SRTM DEM (NASA, 2000) for each mapping region in ArcGIS (ESRI, 2018). Thresholds represent the number of cells that surface water will flow through in order for it to reach a low lying area that displays a distinct change in vegetation. For example, a flow accumulation of 100 means that 100 or less cells flow into a particular cell. The Flow accumulation maps focus on the narrower wetland systems that connect broader wetland systems along with those on adjacent slopes and include features such as rivers valley bottom wetlands and seeps (Collins, 2018). Figure 4.1 shows how different flow accumulation parameters are tested until they adequately pick up features that have a high probability of being wetlands due to the landscape's change in vegetation. Flow accumulation parameters used included values that ranged from 650-2000 cells.

4.2.2 Percentile filters

The 'percentile filter' tool of Whitebox GIS (Lindsay, 2014) was used to perform a percentile analysis on the DEM in order to map the broader valley floor systems that include floodplains as well as channelled and unchannelled valley bottom wetlands. Using Whitebox GIS (Lindsay, 2014), a percentile value (0%-100%) is expressed for each cell that represents the range of that particular cell in relation to the range of cells within a user defined moving window.

Using a trial and error approach, the size of the moving window was specified according to the relief of a particular mapping region. The size of the moving window determines how many cells are used to calculate the relationship between the elevation of particular cell (the cell in the middle of the moving window) in relation to the range in elevation of the cells covered by the moving window. Along with specifying the size of the moving window for each mapping region, a threshold value that identifies cells lower than the specified range within the moving window needed to be determined for each mapping region. This allowed for cells to be selected with a percentile value that is equal to or lower than the specified threshold value. Selected cells are then subsequently mapped as probable wetlands.

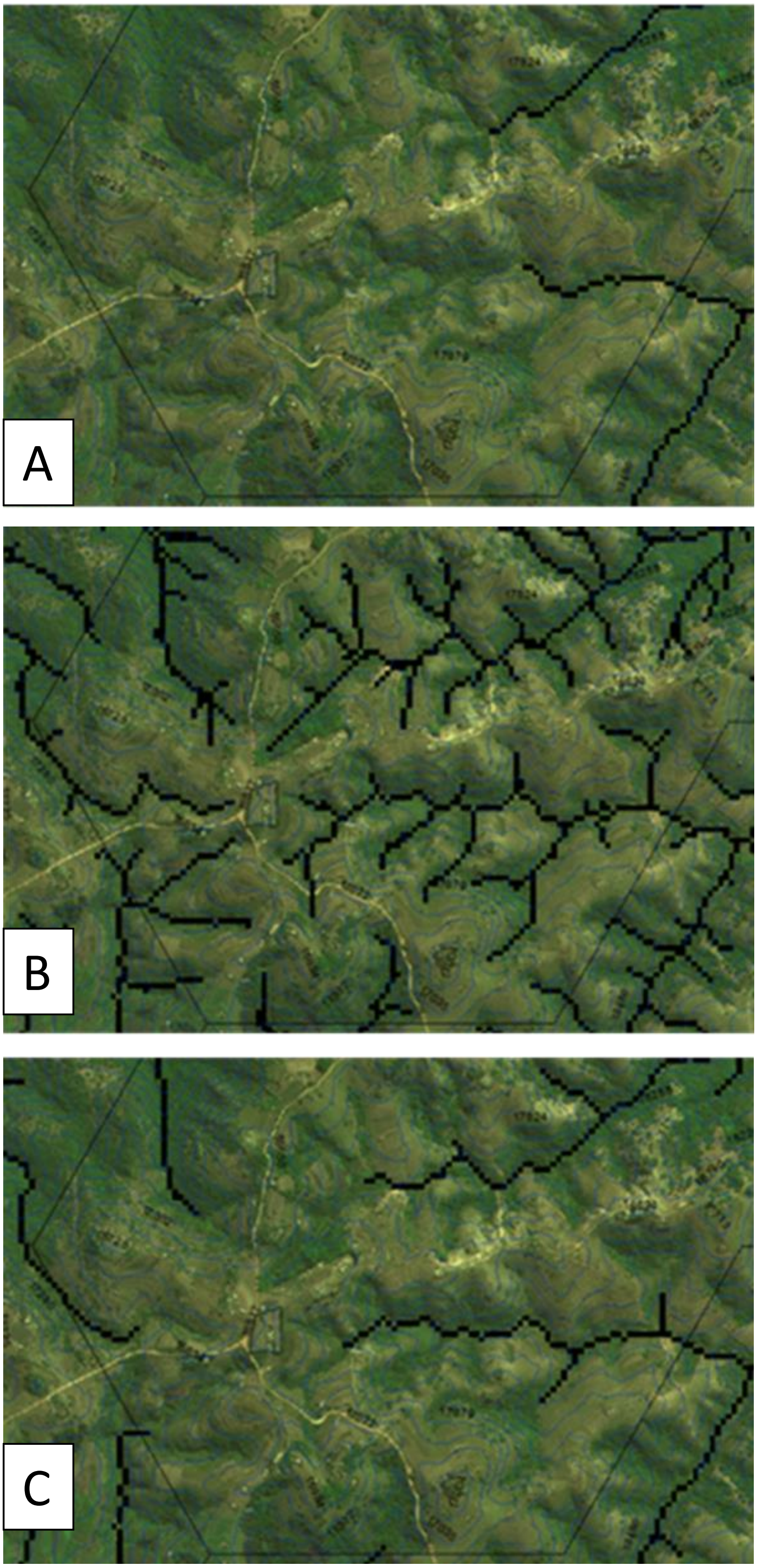


Figure 4.1: Different flow accumulation parameters used to detect low-lying areas with a change in vegetation, showing areas that have a high probability of being wetland. Figure 4.1A had a flow accumulation of 600, Figure 4.1B had a flow accumulation of 800, and Figure 4.1C has a flow accumulation of 1000.

Collins (2018) determined that in addition to the above-mentioned thresholds, the accuracy of mapped areas was increased by iteratively expanding and shrinking cells or vice versa (Collins 2018). These modified percentile filter maps were created through a python script. It was found that the wetlands in many mapping regions are best mapped when using a combination of more than one modified percentile filter map, which allowed for the accurate mapping of wetlands of different shapes and sizes within that respective mapping region. Flow accumulation and percentile filters parameters for every mapping region were subsequently combined and integrated to produce a wetland probability map for Swaziland. Figure 4.2 indicates different percentile filters along with flow accumulation parameters.

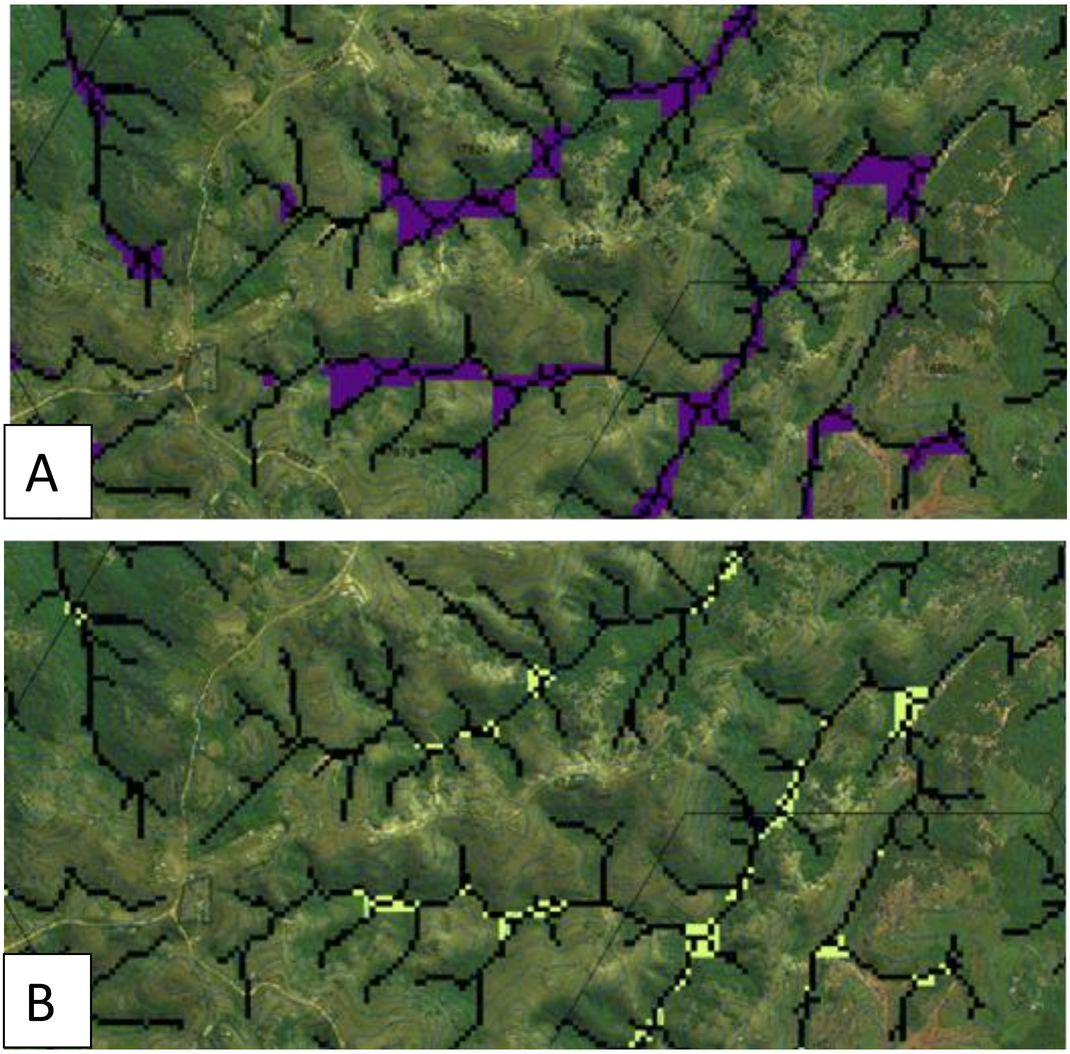


Figure 4.2: Percentile filter maps (yellow and purple) on top of flow accumulation maps (black) used to detect probable areas of wetland occurrence. Figure 4.2 A used a larger moving window (15x15), compared to Figure F.2B which used a smaller moving window (9x9).

4.3 The Initial wetland probability map

Figure 4.3 displays the initial wetland probability map of Swaziland that was created using the methods of Collins (2018). Figure 4.4 shows various examples of possible wetlands mapped in different landscape settings across Swaziland.

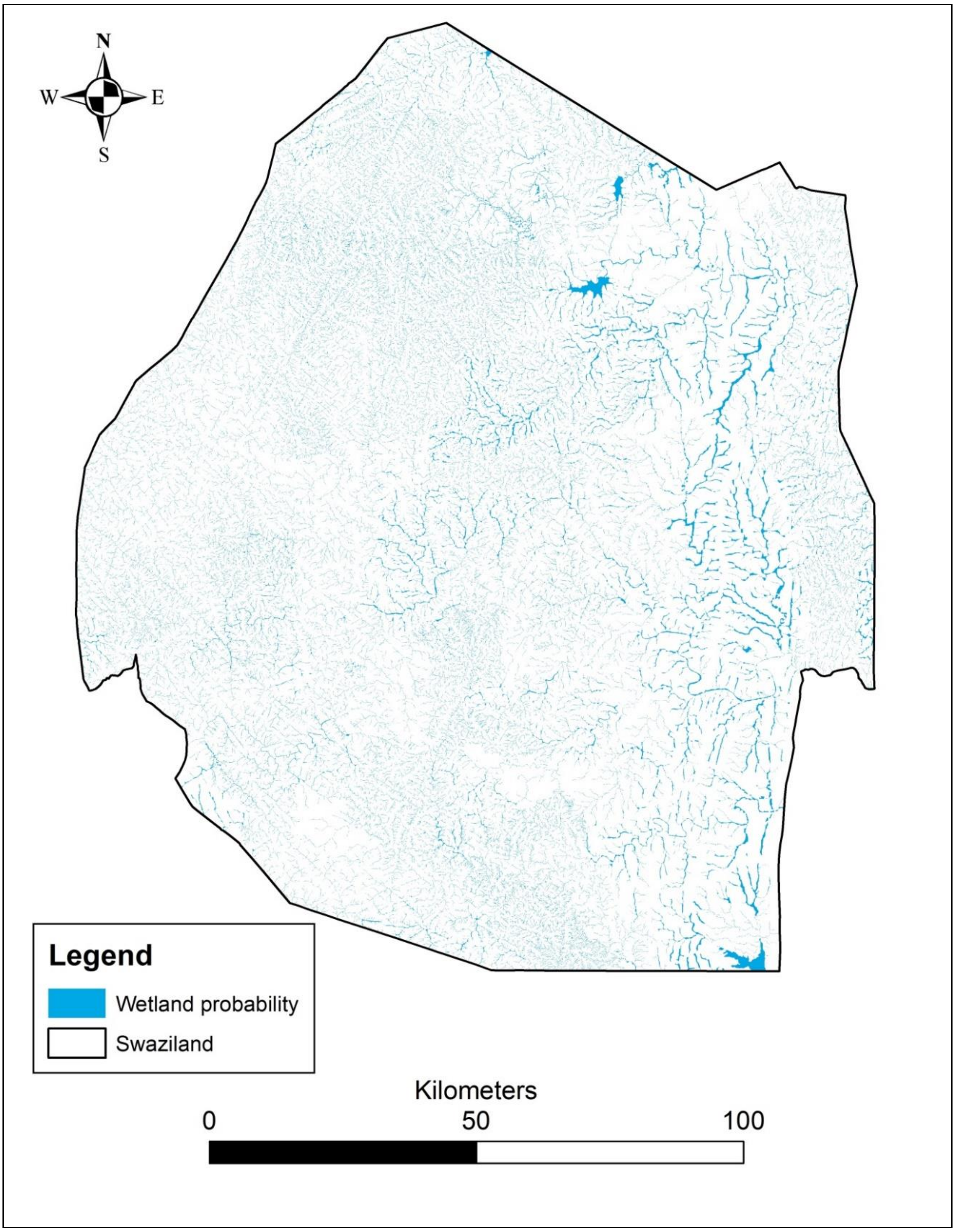


Figure 4.3: Initial prediction map showing probable wetland locations in Swaziland.

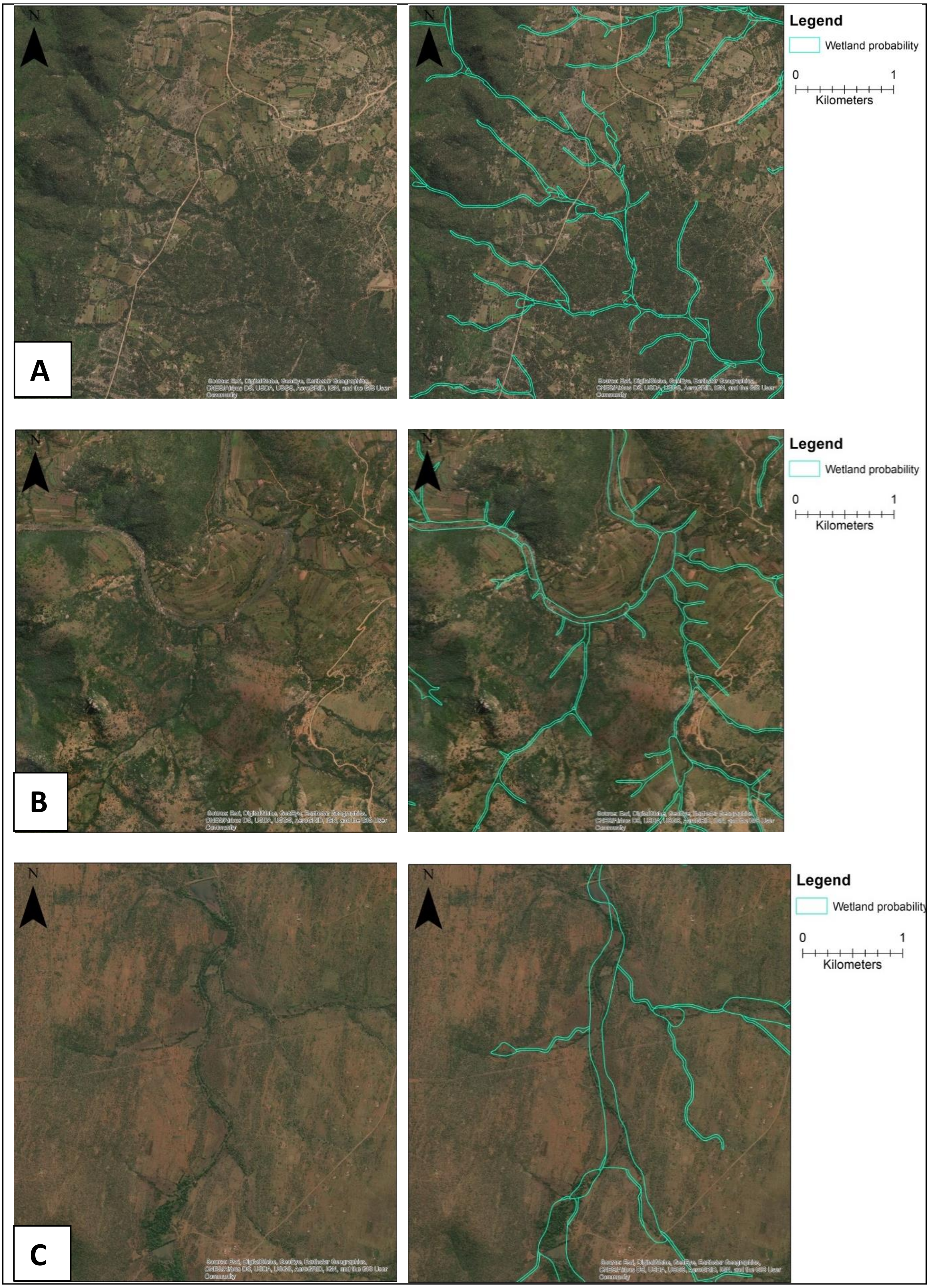


Figure 4.4: Examples of the wetland probability map in different landscape settings. Figure 4.4A is where the mountains of the Middleveld extends into the plains of the Western Lowveld, Figure 4.4B is a river in the Mountainous Highveld, and Figure 4.4C is in the Eastern Lowveld plains.

4.4 Preliminary field based accuracy assessment of the wetland probability map

A field based, preliminary accuracy assessment of the initial wetland probability map was conducted to determine whether the wetland probability map correctly identified areas that have a likelihood of wetland occurrence. Due to the wetland probability map locating areas where wetlands could occur, and not just true wetlands as defined in South Africa (DWAF, 2005), every watercourse that could potentially be wetland was identified. Furthermore, because Swaziland uses the Ramsar definition of a wetland, which includes all types of watercourses, the points located during this accuracy assessment included true wetlands, riparian zones, drainage lines and rivers.

In total, 510 kilometers were travelled through Swaziland on both tarred and dirt roads. Each watercourse that intersected the road, or was situated close enough to be identified, was marked using a Garmin 62 GPS and was briefly described based on its HGM unit and vegetation structure. The vegetation used to identify wetlands included those identifiable from a moving car and included *Phragmites australis, Phragmites mauritianus, Typha capensis,* as well as *Juncus* and *Cyparacea sp*. Riparian zones and drainage lines were identified through a change in vegetation density, and a visible flow path. The points collected (369) was used in the accuracy assessment. Watercourse locations obtained during the field visit were imported into ArcGIS (ESRI, 2018) and overlaid with the wetland probability map. Results of the mapping errors are shown in Table 4.1, with Figure 4.5 illustrating the types of mapping errors.

Table 4.1: Results of the preliminary, field based accuracy assessment.

Description	Number of points	Percentage (%)
Mapped and located in field (successful)	303	82
Mapped but no point located in field (commission)	44	12
Point located in field but not mapped (omission)	22	6

The accuracy assessment showed that 82% of the points were successfully mapped and identified in the field. However a majority of the points were described as drainage lines or riparian zones, even though the Ramsar definition of wetlands includes all these types of watercourses. Only 47% of the identified points were described as having vegetation characteristics of a wetland that would be classified as such under the South African wetland delineation guidelines (DWAF, 2005). Using the

Ramsar definition of wetland, the wetland probability map can be seen as a suitable tool to locate wetlands.

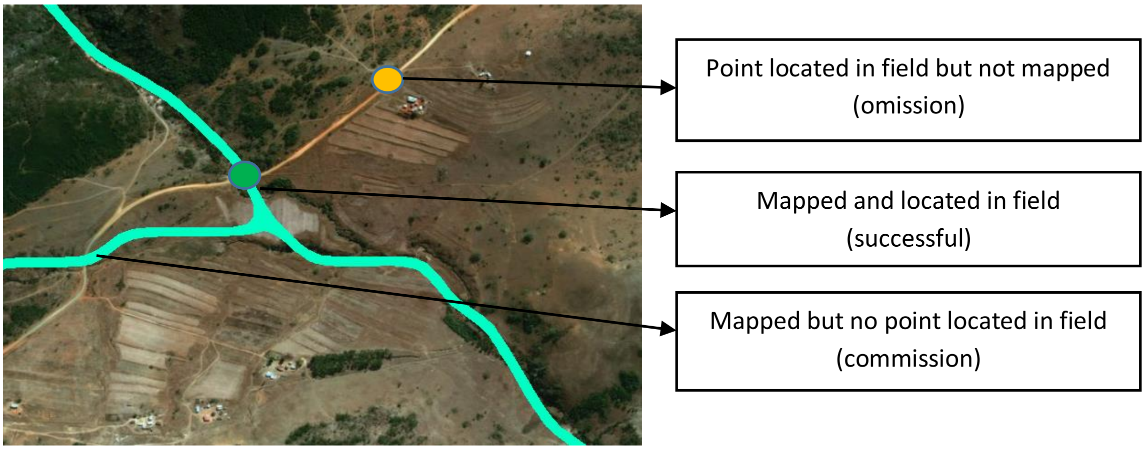


Figure 4.5: Examples of errors encountered during the preliminary accuracy assessment.

The limitation of taking field reference points whilst driving in a car through Swaziland is that large proportions of the country is mountainous and that roads are often located on the crests of various hills and mountains. This resulted in a biased sampling approach, since it is expected that drainage lines are more frequent along the slopes of a mountain when compared to true wetlands that are usually located in the lower lying areas of a landscape. Therefore, the preliminary field based accuracy assessment of the wetland probability map did not provide a comprehensive understanding of its accuracy in respect to identifying true wetland. This lead to another accuracy assessment approach being required. Due to time and budgetary constraints, a desktop approach was followed for the secondary accuracy assessment.

4.5 Desktop accuracy assessment of the wetland probability map of Swaziland

Random points were distributed across Swaziland along the wetland probability map, using the ArcGIS random point's tool (ESRI 2018). In total, 2000 points were distributed across Swaziland. The number of points chosen was found to be the smallest number of points that adequately covered the surface area of the country. Although more points would have added to a more accurate assessment, the duration of this study did not allow for more random points to distributed. These random points 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. Figure 4.6 displays the 2000 random points across the physiographic zones of Swaziland.

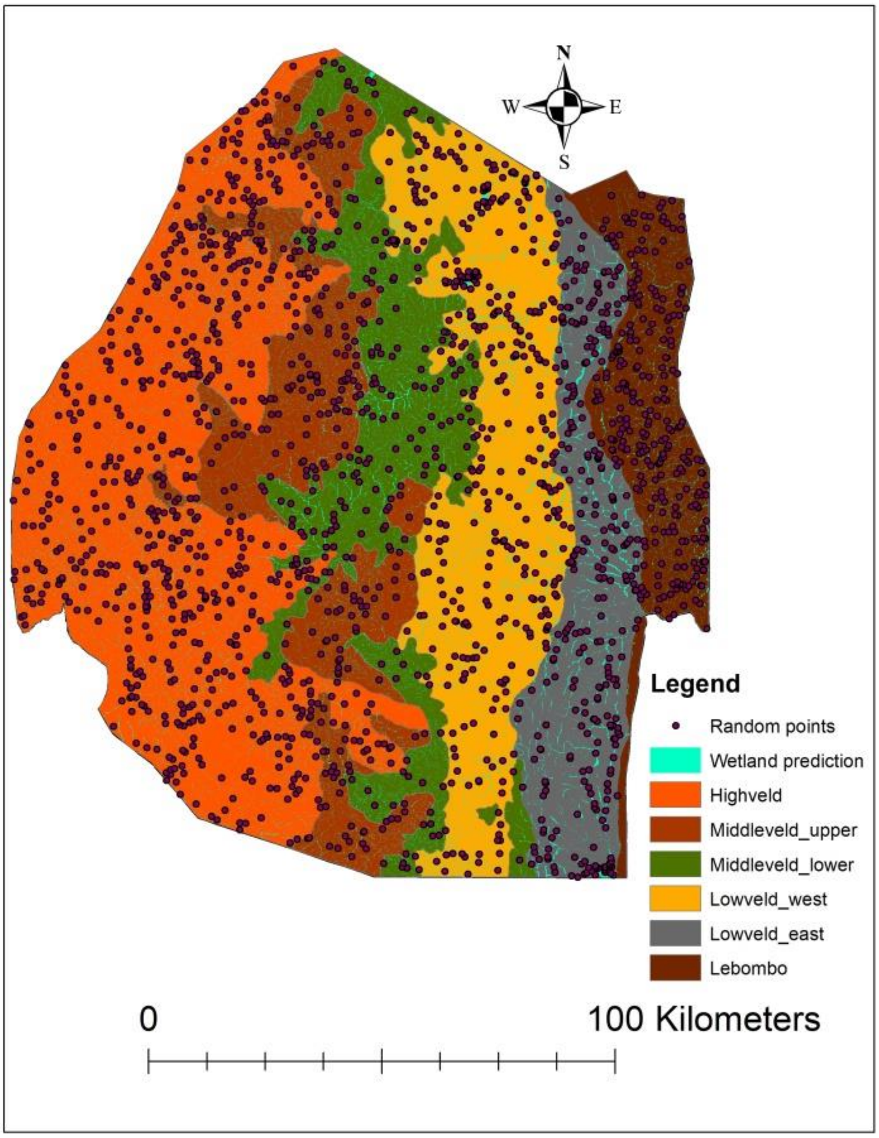


Figure 4.6: **The 2000 random points distributed across the wetland prediction map based on stratified sampling was overlayed on the Physiographic zones of Swaziland.**

These points were then converted to kml format and imported into Google Earth Pro (Google Earth Pro Inc, 2019). Each point was classified as: "wetland", "other watercourse excluding wetlands" and "not a watercourse". The reason that Google Earth Pro (Google earth Pro Inc, 2019) was used is because it allows the location of each point to be viewed in multiple years, scales and perspectives. In cases where the boundary of the wetland varied over different years (due to wet and dry years), and the point was located in this variable temporary zone, the point was classed as a wetland based on the South African Delineation guidelines, where the edge of a wetland is based on the edge of its temporary zone (DWAF, 2005). 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 due to forestry and sugar cane plantations, as well as dams and urbanization. In total, 265 points were being classed as 'disturbed', which resulted in 1735 points remaining that were used to calculate the accuracy of the initial wetland probability map. However, this accuracy assessment only tested for errors of commission. The reason for this is because wetlands occupy such a small percentage of surface area across a country (Lehner and Döll, 2004), it was not practical to distribute random points outside of the wetland probability map. The few wetlands that would have been identified as omission errors would have resulted in a similar sample size to the field based accuracy assessment, and added little value to the overall assessment of the maps accuracy. A desktop accuracy assessment was also not used to test the accuracy of the new South African wetland map (van Deventer *et al*., 2018a).

Table 4.2 shows the results of using the Ramsar definition of a wetland, which equates to the South African definition of a watercourse. Results indicate that 93% of the areas mapped using the initial wetland probability map were classified as wetland based on the Ramsar definition of a wetland, with a commission error of only 7%. However, when applying the South African definition of a wetland, wetlands only made up 31% of the initial wetland probability map, whilst other watercourses that exclude wetlands (rivers, drainage lines and riparian zones) made up 62% (Table 4.3)

Table 4.2: Results of the desktop accuracy test when using the Ramsar definition of a wetland (Ramsar Convention Secretariat, 2010).

Physiographic zone	Ramsar wetland (%)	Not Ramsar wetland (%)	Total count of points
Highveld	96	4	563
Upper Middleveld	93	7	178
Lower Middleveld	89	10	156
Western Lowveld	86	14	325
Eastern Lowveld	93	7	248
Lebombo	98	2	265
Total	**93**	**7**	**1735**

Table 4.3: Results of the desktop accuracy test when using the South African definition of a wetland (NWA, 1998; DWAF, 2005).

Physiographic zone	South African Wetland (%)	Watercourses excluding wetland (%)	Not a watercourse (%)	Total count of points
Highveld	50	46	4	563
Upper Middleveld	49	44	7	178
Lower Middleveld	21	69	10	156
Western Lowveld	21	65	14	325
Eastern Lowveld	19	73	7	248
Lebombo	6	92	2	265
Total	**31**	**62**	**7**	**1735**

Based on the above results of both the field and desktop based accuracy tests, the wetland probability map is well suited to identify possible wetlands using the Ramsar definition of a wetland, or when identifying watercourses. But, it does not suffice as a wetland map for identifying true wetlands, as defined in South Africa. The following chapter attempts to use ancillary data to improve the wetland probability map, both through differentiating between wetlands and other watercourses, as well as through classifying wetlands into HGM units.

Chapter 5: Improving the accuracy of the wetland probability map in Swaziland.

Both the field based and the desktop accuracy assessments showed that the wetland probability map adequately locates watercourses, and wetlands when using the Ramsar definition of a wetland. However, not all of these watercourses are necessarily wetlands when using the South African definition of a true wetland (NWA, 2002). The following chapter shows how ancillary data was used to improve the accuracy of the initial wetland probability map. This included refining the map to differentiate true wetlands from other watercourses, as well as classifying these true wetlands into the hydrogeomorphic units of Ollis *et al*. (2013).

5.1 Attribute data used to improve the accuracy of the wetland probability map

The 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 Swaziland (Murdoch, 1970). Morphometrics included Slope, Curvature, Plan Curvature, Profile Curvature, and Elevation. The soil map of Swaziland (Murdoch, 1970) contained 32 soil sets that were mapped at a national scale (1:250 000). For the purpose of improving the initial wetland probability map, the sets of Murdoch (1970) were grouped into classes according to their hydrological functioning and degree of saturation, using two pre-existing soil classifications currently used in South Africa. This includes the hydrological soil types of Van Tol *et al.* (2013), also referred to as hydropedological classes, which was used to group soils with similar hydrological functions (Figure 5.1) and the wetness regimes of soil forms listed in the South African wetland delineation guidelines (DWAF, 2005). Included is this classification are soil forms that occur due to being permanently saturated, or seasonal/temporary saturated. Soil forms not listed in the delineation guidelines were classed as terrestrial soils. The two soil classifications were then subsequently merged in order for soils to belong to only one of the newly classified soil classes (Table 5.1).

Before the soil sets of Murdoch (1970) could be classified according to wetness regimes listed in the South African delineation guidelines, the soil sets needed to be classified according to the South African classification system (Soil Classification Working Group, 1991; 2018). A previous attempt was made by Nixon (2006) to classify the soils sets of Murdoch (1970) to the South African system (Soil Classification Working Group, 1991).

Hydrological soil type	Description	Symbol
Recharge	Soils without any morphological indication of saturation. Vertical flow through and out of the profile into the underlying bedrock is the dominant flow direction. These soils can either be shallow on fractured rock with limited contribution to evapotranspiration or deep freely drained soils with significant contribution to evapotranspiration.	
Interflow (A/B)	Duplex soils where the textural discontinuity facilitates buildup of water in the topsoil. Duration of drainable water depends on rate of ET, position in the hillslope (lateral addition/release), and slope (discharge in a predominantly lateral direction).	
Interflow (soil/ bedrock)	Soils overlying relatively impermeable bedrock. Hydromorphic properties signify temporal build of water on the soil/bedrock interface and slow discharge in a predominantly lateral direction.	
Responsive (shallow)	Shallow soils overlying relatively impermeable bedrock. Limited storage capacity results in the generation of overland flow after rain events.	
Responsive (saturated)	Soils with morphological evidence of long periods of saturation. These soils are close to saturation during rainy seasons and promote the generation of overland flow due to saturation excess.	

Figure 5.1: Hydrological soil types, extracted from Van Tol et al. (2013)

Table 5.1: Combined soil classifications 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 occur 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).

Although it was found that most of Nixon’s (2006) correlations were correct, errors were noted in some of the conversions, as well as that some soil sets were not included in his correlation. Minor changes were therefore made to Nixon’s (2006) conversion of the Murdoch system (1970) and the sets not included by Nixon (2006) were then also included. Changes made to Nixon’s Conversion were confirmed by Van de Waals (personal communication, 2019).

South Africa has recently updated their soil classification system (Soil Classification Working Group, 2018), but the South African delineation guidelines (DWAF, 2005), were based on the former soil classification system (Soil Classification Working Group, 1991). When classifying the soils of Murdoch (1970), preference was thus given to the former classification system. The full list of Soil sets and their classification into wetness regimes (DWAF, 2005) and hydropedology classes (Van Tol *et al*., 2013) are listed in Appendix 1.

Morphometric and Soil class data were extracted for every random point (2000 points) that was distributed across Swaziland during the desktop accuracy test in Chapter 4. These points were also classified according to their HGM unit (Ollis *et al*., 2013) as well as their watercourse type (Table5.2) using Google Earth (Google Earth Pro Inc. 2018).

Table 5.2: Watercourse and HGM types used to classify the 2000 Random Points, based on DWAF (2005) and Ollis *et al*. (2013).

Type of watercourse	HGM/ Other watercourse type.
Wetland	Channelled valley bottom Unchannelled valley bottom Floodplain Seep
Other watercourse (excluding wetland)	Riparian habitat Drainage line River
Not any type of watercourse	Not a watercourse

Statistical analysis was then performed to determine if significant differences existed in the attribute data of the different types of wetlands and other watercourses. If statistically significant differences existed, then these attributes (soil and morphometrics) could be used to distinguish true wetlands from other watercourses. Before this was done, preliminary statistical tests were performed on the soils and morphometrics of the different physiographic zones of Swaziland (Remmelzwaal, 1993), to determine if the attribute data of wetland and watercourses were consistent across the entire Swaziland, or if they were unique to each physiographic zone.

5.2 Testing the statistical difference between different physiographic zones

If it proved to be statistically significant that physiographic zones of Swaziland (Remmelzwaal, 1993), discussed in Chapter 3, hosted wetlands with the same attributes across Swaziland, then the refining and classification process could be done on Swaziland as a whole. But, if the different physiographic zones hosted wetlands with different attributes, then each physiographic zone would need to be analysed separately in order to assign certain attributes to the types of wetlands and watercourses in each physiographic zone. For example, *is the slope of wetlands in the Highveld, the same as the slope of wetlands in the Lowveld, and are the soils in the Highveld the same as those found in the Lebombo?*

5.2.1 Testing if and how soils can be used to improve the wetland probability map

Two types of statistical tests were performed on the soil data (Murdoch, 1970). Due to the map being produced at a landscape scale of 1: 250 000, it cannot be assumed to be accurate enough to improve the initial wetland probability map. The first statistical test therefore determined if the soil map of Murdoch (1970) could be used to improve the wetland probability map. The purpose of this test was to determine whether certain soils occurred more, or less frequently in association with wetlands or other watercourses across the different physiographic regions. The second statistical test, tested if the proportions of soil types per physiographic region are the same across Swaziland, in order to determine whether soils classes needed to be treated separately by physiographic region, or applied to Swaziland as a whole.

The statistical tests performed for both tests were two-proportions z-tests, which were anaylzed using the *prop.test* function in R(R Core Team, 2013). The first test to determine if the soil map could be used made use of the 2000 random points that were part of the desktop accuracy assessment (Section 5.3) and can be referred to as a trend analysis. The frequency that a point classed as "wetland" or "other watercourse" landed on a type of soil in each physiographic region was compared to the size of that soil in that physiographic region. This showed whether "wetlands" or "other watercourses" occur statistically more or less on the different soil types for each physiographic region. Specifically, the test aimed to answer the following question: *If 60% of wetlands landed on a type soil in a region, does it mean anything?* The answer can then be: *If 60% of the wetlands landed on a type of soil, but that type of soil covers 60% of that region, then no it does not mean anything*. *But, if 60% of the wetlands landed on a type of soil in a region, and that soil only makes up 5% of the soils in that region, then yes it does mean something*.

Table 5.3A and 5.4A show whether there was a statistical difference, where green represents a statistical difference while red does not. Table *5*.3B and *5*.4B show whether these differences were due to there being more (up arrow) or less (down arrow) occurrences of wetlands or other watercourses on that particular soil class. Values were tested for a 95% confidence rating, meaning that values smaller than *0, 05* are statistically different.

Table 5.3: A Trend analysis showing whether wetland and other watercourses occurred significantly more or less on the different wetness regime of the South African Delineation guidelines. Table 5.4A shows the value derived from the Z test where green is a significant difference and red is not. Table 5.4B shows whether the difference was due to wetlands and other watercourses occurring more (up-arrow), or less (down-arrow) on the different soils.

SA Wetness Regime	Permanent soils	Seasonal soils	Terrestrial soils
	Wetlands		
Highveld	7,67E-05	0,9858	2,2E-16
Lower Middleveld	0,09645	0,2336	2,2E-16
Upper Middleveld	0,7103	0,3842	2,2E-16
Western Lowveld	1,377E-15	0,0003116	2,2E-16
Eastern Lowveld	0,07974	7,524E-08	2,2E-16
Lebombo	0,05615	0,002756	2,2E-16
	Other Watercourses		
Highveld	0,0009658	0,00001382	2,2E-16
Lower Middleveld	0,5121	0,7915	2,2E-16
Upper Middleveld	0,01586	0,4341	2,2E-16
Western Lowveld	0,0005144	0,002051	2,2E-16
Eastern Lowveld	0,4346	0,0002445	2,2E-16
Lebombo	0,3505	2,2E-16	2,5E-16

A

SA Wetness Regime	Permanent soils	Seasonal soils	Terrestrial soils
	Wetlands		
Highveld	↑		↓
Lower Middleveld			↓
Upper Middleveld			↓
Western Lowveld	↓	↓	↓
Eastern Lowveld		↓	↓
Lebombo		↓	↓
	Other Watercourses		
Highveld	↓	↓	↓
Lower Middleveld			↓
Upper Middleveld	↓		↓
Western Lowveld	↓	↓	↓
Eastern Lowveld		↑	↓
Lebombo		↑	↓

B

Table 5.4: Trend analysis showing whether wetland and other watercourses occurred significantly more or less on the different wetness regime of the South African Delineation guidelines. Table 5.4A shows the value derived from the Z test where green is a significant difference and red is not. Table 5.4B shows whether the difference was due to wetlands and other watercourses occurring more (up-arrow), or less (down-arrow) on the different soils.

Hydrological Soil Types	Wetlands			
	Interflow AB	Interflow rock	Recharge	Responsive
Highveld	0,5452	1,76E-05	2,2E-16	7,269E-06
Lower Middleveld	0,02366	4,606E-16	2,2E-16	0,8854
Upper Middleveld	0,8145	0,001862	2,2E-16	0,08458
Western Lowveld	2,2E-16	2,2E-16	3,35E-15	0,2402
Eastern Lowveld	0,001548	2,2E-16	2,2E-16	0,0006733
Lebombo	0,01341	1,506E-11	2,2E-16	1
	Other Watercourses			
Highveld	0,09795	3,894E-13	2,2E-16	0,0007829
Lower Middleveld	0,8752	0,003378	0,000006352	1
Upper Middleveld	0,8145	0,001016	2,2E-16	0,01204
Western Lowveld	0,006028	3,338E-11	0,0002254	0,2402
Eastern Lowveld	0,8062	0,00019	2,331E-16	2,557E-07
Lebombo	0,3254	2,39E-11	2,2E-16	2,2E-16

A

Hydrological Soil Types	Wetlands			
	Interflow AB	Interflow rock	Recharge	Responsive
Highveld		↓	↓	↑
Lower Middleveld	↓	↓	↓	
Upper Middleveld		↓	↓	
Western Lowveld	↓	↓	↓	
Eastern Lowveld	↓	↓	↓	↓
Lebombo	↓	↓	↓	
	Other Watercourses			
Highveld		↓	↓	↓
Lower Middleveld		↓	↓	
Upper Middleveld		↓	↓	↓
Western Lowveld	↓	↓	↓	
Eastern Lowveld		↓	↓	↑
Lebombo		↑	↓	↑

B

*The values in Tables 5.3A and 5.4A are not rounded to specific number of decimal places, thereby allowing the true value of the z test to be portrayed. This can however lead to a false sense of accuracy, given that the decimals in the tables extent to the 16^{th} decimal, and the data going into the z test was limited to 3 decimals.

When using wetness regime soil classes (Table 5.3) the trend analysis showed that 66% of the points that were classified as wetland, and 72% of the points classified as watercourse occurred on certain soils significantly more or less when compared to the soils in that respective region. Results of the hydrological soil type classes were similar to those of the wetness regimes. The frequency that wetlands and other watercourses landed on hydropedology classes with statistical significant difference to the soils found in that respective region were 75% for wetlands and 71% for other watercourses. Although very few wetlands and watercourses were found to occur statistically more on a certain type of soil, many were found to occur statistically less on certain types of soil. Specifically, this included terrestrial and recharge soils where wetlands and other courses are not expected to occur.

The second statistical test determined whether different types of soils occur across the respective physiographic zones of Swaziland (Table 5.5). The null hypotheses of *H_0:p_region=p_Swaziland* was tested, where the area of a soil class (combined South African South African Wetness regimes (DWAF, 2005) and hydrological soil types (Van Tol *et al*., 2013) by physiographic region was compared to the total area of that soil class across Swaziland.

Table 5.5: Results of the proportions z test to determine whether combined soil classes per physiographic region occurred equally across the whole of Swaziland (hydrological soil types and wetness regime). Cells in green represent a significant different, and cells in red do not.

InterflowAB Permanent		**InterflowAB Seasonal**		**InterflowAB Terrestrial**	
Highveld	2,2E-16	**Highveld**	2,605E-12	**Highveld**	N/A
Upper Middleveld	2,2E-16	**Upper Middleveld**	0,9919	**Upper Middleveld**	2,2E-16
Lower Middleveld	0,6901	**Lower Middleveld**	1,07E-03	**Lower Middleveld**	1,12E-05
Eastern Lowveld	2,056E-09	**Eastern Lowveld**	0,4708	**Eastern Lowveld**	5,28E-11
Western Lowveld	2,2E-17	**Western Lowveld**	9,85E-05	**Western Lowveld**	2,2E-16
Lebombo	6,709E-13	**Lebombo**	0,1073	**Lebombo**	1,04E-13
Interflow Rock Seasonal		**Interflow Rock Terrestrial**		**Recharge Seasonal**	
Highveld	0,1793	**Highveld**	2,2E-16	**Highveld**	2,106E-08
Upper Middleveld	0,6772	**Upper Middleveld**	4,52E-03	**Upper Middleveld**	0,493
Lower Middleveld	3,74E-05	**Lower Middleveld**	2,2E-16	**Lower Middleveld**	0,02594
Eastern Lowveld	0,7089	**Eastern Lowveld**	2,2E-16	**Eastern Lowveld**	0,01417
Western Lowveld	2,76E-04	**Western Lowveld**	6,973E-07	**Western Lowveld**	2,53E-06
Lebombo	0,08329	**Lebombo**	9,613E-11	**Lebombo**	0,01312
Recharge Terrestrial		**Responsive Permanent**		**Responsive Seasonal**	
Highveld	2,2E-16	**Highveld**	3,315E-12	**Highveld**	2,2E-16
Upper Middleveld	2,2E-16	**Upper Middleveld**	8,68E-06	**Upper Middleveld**	1,797E-09
Lower Middleveld	2,2E-16	**Lower Middleveld**	8,44E-03	**Lower Middleveld**	1,214E-07
Eastern Lowveld	2,2E-16	**Eastern Lowveld**	N/A	**Eastern Lowveld**	2,2E-16
Western Lowveld	2,2E-16	**Western Lowveld**	1,127E-12	**Western Lowveld**	0,3361
Lebombo	2,2E-16	**Lebombo**	0,06841	**Lebombo**	3,75E-04

Table 5.5 illustrated that the majority of soil classes per physiographic region exhibited statistically different soils when compared to the soils of Swaziland as the overall population. Therefore, the results of the statistical tests above warrant that the soils can be used to improve the initial wetland probability map, as well as that the soils need to be analysed separately for each physiographic region.

5.2.2 Testing the statistical differences between Morphometrics across the physiographic zones of Swaziland

One-way analysis of variance (ANOVA)(R Core Team, 2013) was used to test the equality of the different morphometric values across the physiographic zones of Swaziland. Morphometrics, all derived from the SRTM DEM (NASA, 2000), include Slope, Curvature, Plane Curvature, Profile Curvature as well as Elevation. Examples of these are displayed in Figure 5.2.

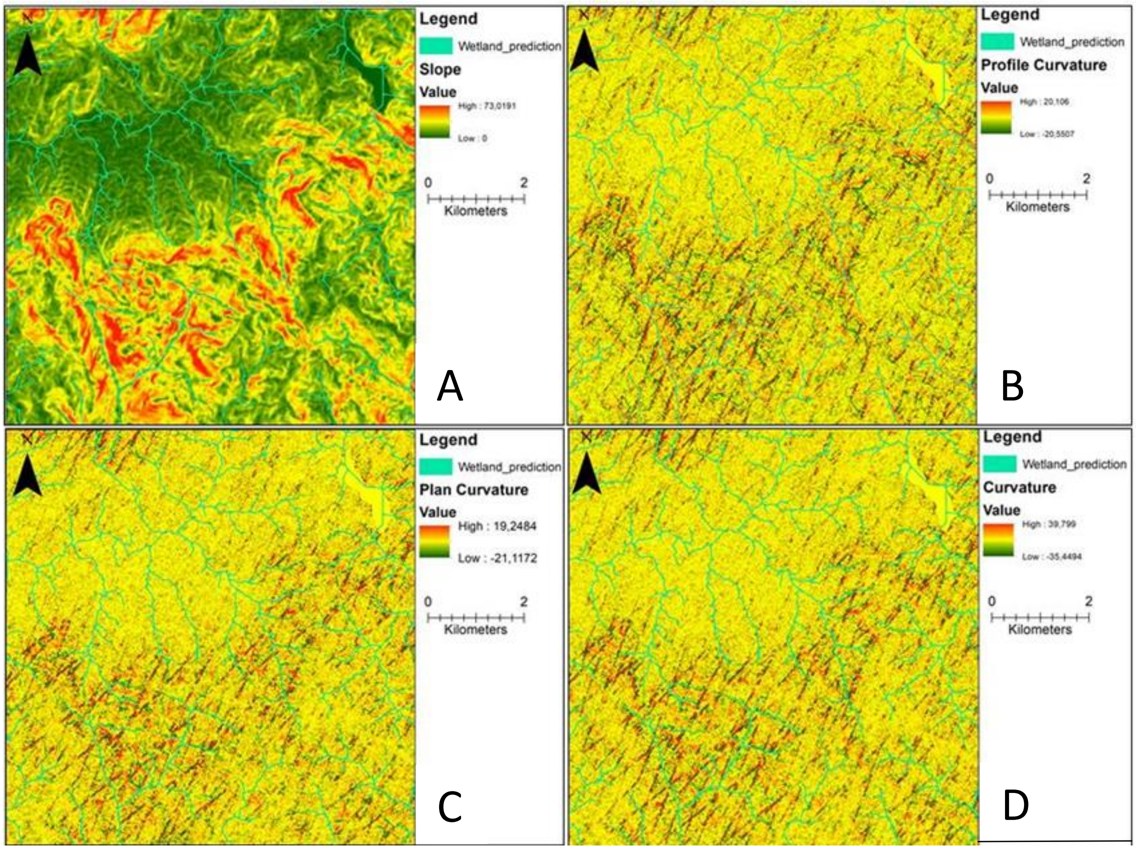


Figure 5.2: Examples of different Morphometrics including Slope (A), Profile Curvature (B), Plan Curvature (C), and Curvature (D).

To use ANOVA there are two assumptions about the data that should be met: The population is (1) normally distributed with (2) equal variance (homogenous) (Swanepoel *et al*., 2009). The assumption of normality was first tested using Shapiro Wilk's test for normality and Levene's test for equality of variance. If both criteria for the respective tests were met, one-way ANOVA was performed. When the assumption of normality is violated, The Kruskal Wallis test was used as the alternative to ANOVA.

When the assumption of normality was met, but the assumption of equal variances was not, then the ANOVA test without the assumption of equal variance was used, also known as Welch's ANOVA. Table 5.6 illustrates the results of the statistical tests that were used to determine if the morphometrics (Slope, Curvature, Plan Curvature and Profile Curvature) were the same, or differed across the physiographic regions. Values were tested for a 95% confidence rating, meaning that values smaller than *0, 05* are statistically different.

Table 5.6: Results of the ANOVA tests used to determine if the morphometrics are statistically similar, or differ across the physiographic regions.

Slope	**Highveld**	**Upper Middleveld**	**Lower Middleveld**	**Western Lowveld**	**Eastern Lowveld**	**Lebombo**
Highveld	x					
Upper Middleveld	0,0268	x				
Lower Middleveld	2,2E-16	2,2E-16	x			
Western Lowveld	2,2E-16	2,2E-16	0,0154	x		
Eastern Lowveld	2,2E-16	2,2E-16	1,20E-05	0,0154	x	
Lebombo	2,2E-16	2,2E-16	4,60E-06	0,005	0,8055	x
Curvature	**Highveld**	**Upper Middleveld**	**Lower Middleveld**	**Western Lowveld**	**Eastern Lowveld**	**Lebombo**
Highveld	x					
Upper Middleveld	0,87	x				
Lower Middleveld	2,2E-16	2,2E-16	x			
Western Lowveld	2,2E-16	2,2E-16	2,2E-16	x		
Eastern Lowveld	2,2E-16	2,2E-16	2,20E-16	2,2E-16	x	
Lebombo	2,2E-16	2,2E-16	2,2E-16	2,2E-16	0,45	x
Plan Curvature	**Highveld**	**Upper Middleveld**	**Lower Middleveld**	**Western Lowveld**	**Eastern Lowveld**	**Lebombo**
Highveld	x					
Upper Middleveld	0,878	x				
Lower Middleveld	2,2E-16	2,2E-16	x			
Western Lowveld	2,2E-16	2,2E-16	5,6E-11	x		
Eastern Lowveld	2,2E-16	2,2E-16	1,30E-07	0,024	x	
Lebombo	2,2E-16	2,2E-16	1,3E-09	0,493	0,164	x
Profile Curvature	**Highveld**	**Upper Middleveld**	**Lower Middleveld**	**Western Lowveld**	**Eastern Lowveld**	**Lebombo**
Highveld	x					
Upper Middleveld	0,7588	x				
Lower Middleveld	1,40E-06	1,40E-03	x			
Western Lowveld	1,40E-06	1,40E-03	0,0637	x		
Eastern Lowveld	1,40E-06	1,40E-03	1,20E-01	0,8226	x	
Lebombo	1,40E-06	1,40E-03	0,0637	0,956	0,8226	x

Results of the above statistical tests indicate that the vast majority of physiographic regions have statistically different morphometric values when compared to the morphometrics of other physiographic regions. Based on the above, morphometrics were assessed separately for every physiographic region.

5.3 Refining the wetland probability map.

The statistical analysis in Section *5*.2 established that morphometrics and soil classes have statistically significant differences between the physiographic regions of Swaziland. Therefore, these attributes of each physiographic region were analysed separately to determine the parameters that could differentiate true wetlands from other watercourses.

5.3.1 Soil classes used to refine the wetland probability map

Table 5.7 shows percentages of randomly distributed points that were classified as “wetland”, “other watercourse”, or “not a watercourse” that occurred in each soil class for each physiographic region. Soil classes where over 75% of the points were classed into one of the above categories and were subsequently classed as “probably wetland”, “probably other watercourse”, or “probably not a watercourse” soils. Soil classes that did not fulfil the criteria of having over 75% of their points falling into one of the wetland probability classes were classed as “either wetland or other watercourse”. The cut-off value of 75% was based on the intended accuracy of the refined wetland probability map.

There were instances where the number of sampled points for a soil class within a region where very little or no points were assigned to that class. In these instances, various samples of the initial wetland probability map that intersected these soils were manually examined until a conclusion could be drawn as to whether the respective soil should be classed as “probably wetland”, “either wetland or other watercourse”, or “probably other watercourse”. These soils have a star next to their respective wetness regimes in Table 5.7.

Table 5.7: The percentages that points, per physiographic region, were classed as "wetland", "other watercourse", and "not a watercourse" by physiographic region. Soil classes in Green represent those that are mostly associated with wetlands, red is those associated with other watercourses, yellow is soil classes that can either be "wetland" or "other watercourse", and blue are those classes that were manually changed due to not enough sample points falling on those types of soils. Soils with a star next are those which had little, or no, sampling points assigned to them. These soils were manually classed.

Highveld					Middleveld upper				
Hydrological soil type	**Wetness regime**	**Not a watercourse**	**Other watercourse**	**Wetland**	**Hydrological soil type**	**Wetness regime**	**Not a watercourse**	**Other watercourse**	**Wetland**
Interflow AB	Seasonal	0	0	100	Interflow AB	Seasonal	0	50	50
Interflow rock	Seasonal	8	23	69	Interflow rock	Seasonal	0	45	55
	Terrestrial	3	42	55		Terrestrial	12	44	44
Recharge	Seasonal	0	25	75	Recharge	Seasonal	0	25	75
	Terrestrial	4	54	42		Terrestrial	7	50	43
Responsive	Permanent	4	13	83	Responsive	Permanent	0	0	100
	Seasonal	0	0	100		Seasonal	0	0	100
Middleveld Lower					**Western Lowveld**				
Interflow AB	Permanent	0	71	29	Interflow AB	Permanent	18	73	10
	Seasonal	0	29	71		Seasonal	0	71	29
	Terrestrial	0	100	0		Terrestrial	15	72	13
Interflow rock	Seasonal	18	50	32	Interflow rock	Seasonal	20	60	20
	Terrestrial	12	72	16		Terrestrial	14	56	30
Recharge	Seasonal	0	78	22	Recharge	Seasonal	0	43	57
	Terrestrial	11	77	13		Terrestrial	18	65	18
Responsive	Permanent*	20	40	40	Responsive	Seasonal*	0	50	50
	Seasonal	0	100	0					

Eastern Lowveld					Lebombo				
Hydrological soil type	**Wetness regime**	**Not a watercourse**	**Other watercourse**	**Wetland**	**Hydrological soil type**	**Wetness regime**	**Not a watercourse**	**Other watercourse**	**Wetland**
Interflow AB	Permanent*	0	100	0	Interflow AB	Permanent*	0	100	0
	Seasonal	0	83	17		Seasonal	0	80	20
Interflow rock	Seasonal	33	67	0		Terrestrial	0	100	0
	Terrestrial	11	71	19	Interflow rock	Seasonal	0	100	0
Recharge	Seasonal	0	73	27		Terrestrial	1	93	6
	Terrestrial	13	65	21	Recharge	Seasonal	8	92	0
Responsive	Seasonal*	1	79	20		Terrestrial	4	90	6
					Responsive	Seasonal*	2	91	7

5.3.2 Morphometrics used to refine the wetland probability map

An ANOVA test, using the same methods as those in Section 5.2.2, was performed on points classed as "wetland", "other watercourse" and "not a watercourse" to determine whether these classes showed differences in their morphometric values that can be used to differentiate between them. The results are shown in Table 5.8, where significant differences are represented in green, whilst those where there was no difference are in red.

The results indicate that most morphometric values between "wetlands", "other watercourses" and "not a watercourse" do not have significantly different morphometric values. Of the few that did, the slope in the Highveld and Upper Middleveld had a significant difference between wetlands and other watercourses, as well as between wetlands and points that were classed as not a watercourse. The slope of the remaining four physiographic regions showed no statistically significant differences. The Highveld and Upper Middleveld also showed differences in the elevation between wetlands and other watercourses. The only other two morphometrics across the physiographic zones that showed a difference was the curvature between other watercourses and not a watercourse in the Lower Middleveld, and wetland and other watercourse in the Highveld.

Due to the small number of the morphometrics in each physiographic region having statistical differences between the wetland probability classes of "wetlands", "other watercourses" and "not a watercourse", morphometrics could not be used, like the soil classes, to differentiate between true wetlands and other watercourse types in wetland probability classes. The reason why morphometrics do not show many statistical differences between wetlands and other watercourses is because of the landscape position of the different types of watercourses. Valley-bottom wetlands (both channelled and unchannelled), rivers and riparian zones predominantly all occur in the same valley bottom landscape position, which explains why their morphometrics do not differ significantly. Reasons as to why the Highveld and Upper Middleveld showed differences in their slope (Table 5.8), is because of the many steep drainage lines (first and second order drainage lines) that occurred in the mountainous terrain are significantly steeper than most wetlands that occur in valley-bottom positions.

Table 5.8: Results of the ANOVA test used to determine whether morphometrics could be used to distinguish wetlands from other watercourses.

Highveld	Slope			Curvature			Curvature_plane			Curvature_profile			Elevation		
	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse
Wetland	x						x						x		
Other Watercourse	2E-16	x			0,1279		0,0014	x			0,6261		0,0005574	x	
Not a Watercourse	0,0057	0,5084	x				0,8993	0,592	x				0,8499585	0,1218581	x
Upper Middleveld	Slope			Curvature			Curvature_plane			Curvature_profile			Elevation		
	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse
Wetland	x												x		
Other Watercourse	0,0115	x			0,371			0,065			0,983		0,0003964	x	
Not a Watercourse	0,0048	0,0519	x										0,1320753	0,999324	x
Lower Middleveld	Slope			Curvature			Curvature_plane			Curvature_profile			Elevation		
	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse
Wetland															
Other Watercourse		0,704		0,9979323				0,143			0,0753			0,625	
Not a Watercourse				0,1083746	0,0499724										
Western lowveld	Slope			Curvature			Curvature_plane			Curvature_profile			Elevation		
	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse
Wetland															
Other Watercourse		0,11			0,2036			0,101			0,872			0,434	
Not a Watercourse															
Eastern Lowveld	Slope			Curvature			Curvature_plane			Curvature_profile			Elevation		
	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse
Wetland															
Other Watercourse		0,284			0,241			0,145			0,5671			0,771	
Not a Watercourse															
Lebombo	Slope			Curvature			Curvature_plane			Curvature_profile			Elevation		
	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse	Wetland	Other Watercourse	Not a Watercourse
Wetland															
Other Watercourse		0,882			0,355			0,241			0,5194			0,715	
Not a Watercourse															

Statistical analysis of morphometric values was also performed between the different hydrogeomorphic and watercourse types listed in Table 5.2, following the same methods previously outlined in Section 5.2.2. The full table of results are presented in Appendix 2, with a section of the Appendix, displayed in Table 6.9 below which illustrates that Slope values varied significantly between different HGM and other watercourse types in the Highveld. Most of the morphometrics across the other physiographic regions did not have such favourable results, making morphometrics difficult to use when differentiating between wetlands and other watercourses, as well as HGM units.

Table 5.9: An extract of Appendix 2, showing the results of the ANOVA test between the morphometric (slope) values for the different HGM units and watercourse types identified in the Highveld.

Highveld	Slope						
	Channeled valley-bottom	First/Second Order drainage line	Not a watercourse	Riparian zone	River	Seep	Unchanneled valley-bottom
Channeled valley-bottom	x						
First/Second Order drainage line	2E-16	x					
Not a watercourse	0,0012	0,94674	x				
Riparian zone	0,00263	2,2E-09	0,01705	x			
River	0,28185	3,30E-05	0,01312	0,60409	x		
Seep	0,00000013	1,8E-15	0,01977	0,69507	0,45343	x	
Unchanneled valley-bottom	0,59817	2E-16	0,00091	0,00171	0,19784	5,00E-06	x

Although watercourses could not be differentiated from true wetlands using morphometrics, the slope values for first and second order drainage lines differed significantly enough from wetlands which allowed it to be used to further refine the wetland probability map. The reason for this is because first order drainage lines do not share the same landscape position as wetlands, and therefore have different slope values, particularly in the Highveld, Upper Middleveld and the Lebombo (Table 5.9, Appendix 2). However, the Lowveld contained few first or second order drainage lines and the slope of those identified did not differ from wetlands in those respective regions.

In order to do differentiate wetlands from first and second order drainage lines using slope values, the cumulative frequencies were determined for wetland and first and second order drainage lines along slope degree intervals. Due to wetlands having a lesser slope value than first and second order drainage lines, a cut-off slope value was identified where the most wetlands would be included below the value and as many as possible first and second order drainage lines above the value. Table 5.10

shows the cumulative values for the regions, whilst Figure 5.3 shows the graphs used to determine these values. Although only the Highveld and Upper Middleveld showed statistically significant differences in their slope values between wetlands and first order drainage lines, meaningful values were also extracted from the Lower Middleveld and Lebombo regions**.**

Table 5.10: Cut-off slope values (degrees) for the different physiographic regions used to differentiate between wetlands and first/second order drainage lines. The cut-off value was used to include the most wetlands and below the cut-off value, whilst excluding the most first and second order drainage lines.

Region	Cut-off value	Wetland		First/Second Order Drainage line	
		% less than cut-off	% greater than cut-off	% less than cut-off	% greater than cut-off
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

5.3.3 Combining soils classes and morphometrics to refine the wetland probability map

Soil classes (DWAF, 2005; Van Tol *et* al., 2013) were grouped per physiographic region into "probably wetland", "either wetland or other watercourse" and "probably other watercourse" classes, based on the results shown in Table *5*.7. The Initial wetland probability map was then selected into these respective soil classes. Slope raster layers were then reclassed into the respective cut-off values (Table 5.10) for each region and then converted to vectors. Sections of the initial wetland probability map that were included in the "probably wetland" class that fell above the respective cut-off slope value per physiographic region were then moved into the "either wetland or other watercourse" class. This resulted in the initial wetland probability map being split into three classes, namely: "probably wetland", "either wetland or other watercourse", and "probably other watercourse" Examples of the map are shown in Figure 5.4 and Figure 5.5.

The total surface area each layer is as follows:

- Probably wetland = 2127.41km^2 (15% of the initial wetland probability layer)
- Either wetland or other watercourse= 10956.18km^2 (75% of the initial wetland probability layer)
- Probably other watercourse=1467.57km^2 (10% of the initial wetland probability layer)

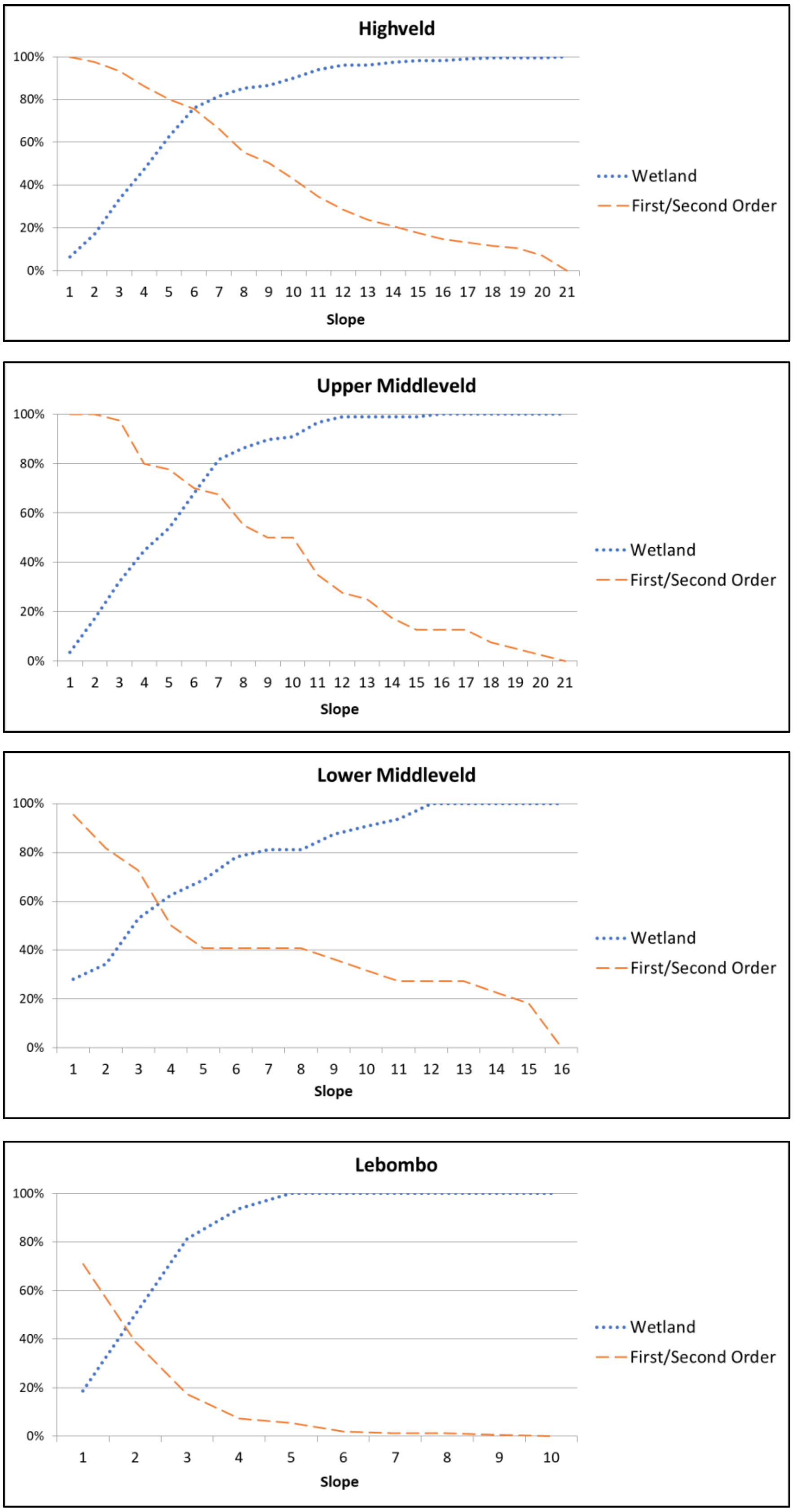
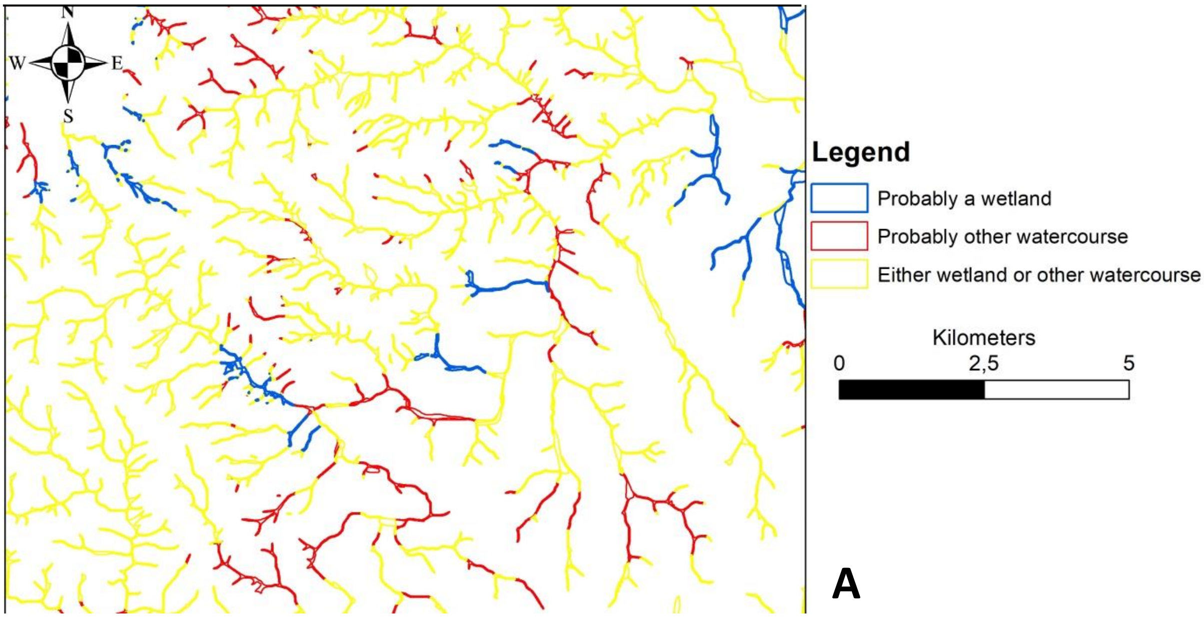


Figure 5.3: Graphs showing the cumulative frequencies of slope values for wetland and first/second order drainage lines. The values of first/second order drainage lines are plotted inversely. The slope value where the lines of wetland and first/second order drainage lines intercept is the slope value that includes the most wetlands whilst excluding the most first/second order drainage lines.



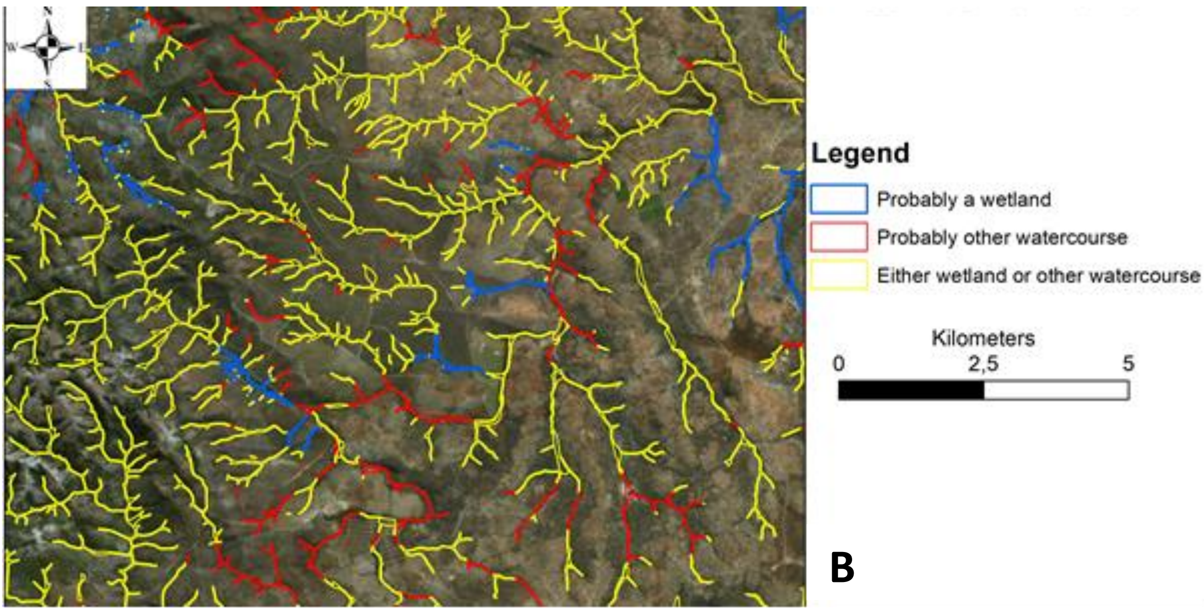


Figure 5.4: A zoomed out example of the refined wetland probability map without an image overlay (A), and with an image overay (B)

The total surface area each layer is as follows:

- Probably wetland = 2127.41km^2 (15% of the initial wetland probability layer)
- Either wetland or other watercourse= 10956.18km^2 (75% of the initial wetland probability layer)
- Probably other watercourse=1467.57km^2 (10% of the initial wetland probability layer)

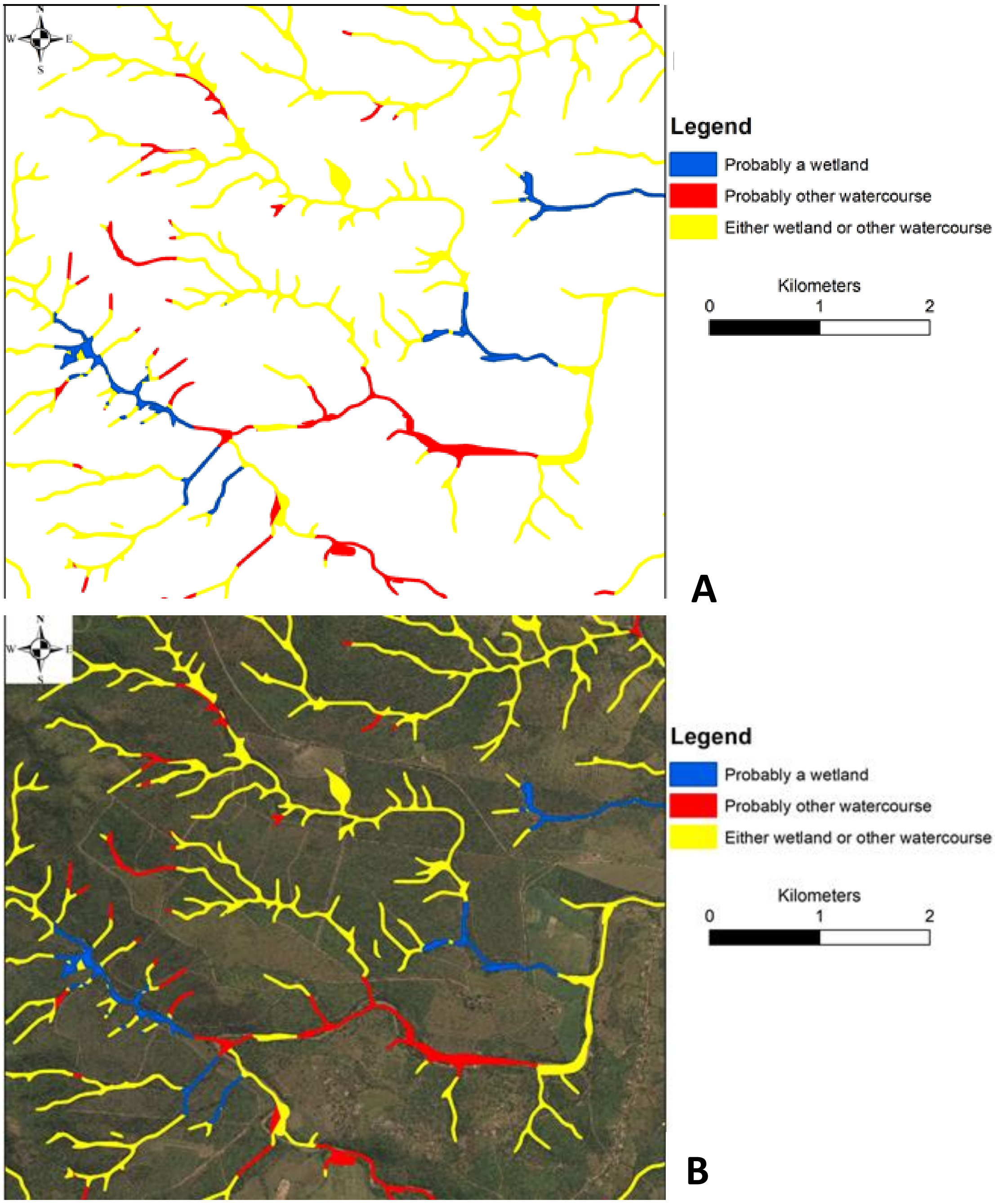


Figure 5.5: A zoomed in image of the refined wetland probability map without an image overlay (A), and with an image overay (B)

5.4 Classifying the wetland probability map

The initial wetland probably map that was classed as "probably wetland", was further classified into the hydrogeomorphic units applied in South Africa, based on the classification of Ollis *et al*. (2013) using the methods outlined below. Wetlands were classified up 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*., 2018a; 2018b).

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 2000 random points, were used to differentiate these valley bottom wetlands from seeps, using the same methodology that differentiated between wetlands and first/second order drainage lines in Section 5.3. This included plotting the cumulative slope degree frequencies of valley bottom wetlands and seeps against each other to determine a cut-off value (Table 5.11) that includes the most valley bottom wetlands below the value, and the most seeps above the value (Figure 5.6). As in previous sections, slope values were determined separately for each physiographic zone. Due to the small number of seeps identified with the random points in the Lowveld, as well as the gentle slopes in the region, the Western and Eastern Lowveld physiographic zones were combined and the horizontal axis bin size of the slope values made smaller.

Table 5.11: Cut-off slope values for the different physiographic regions used to differentiate valley bottom wetlands from seep wetlands. The cut-off value was used to include the most valley bottom wetlands below the cut-off value, whilst excluding most seep wetlands.

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

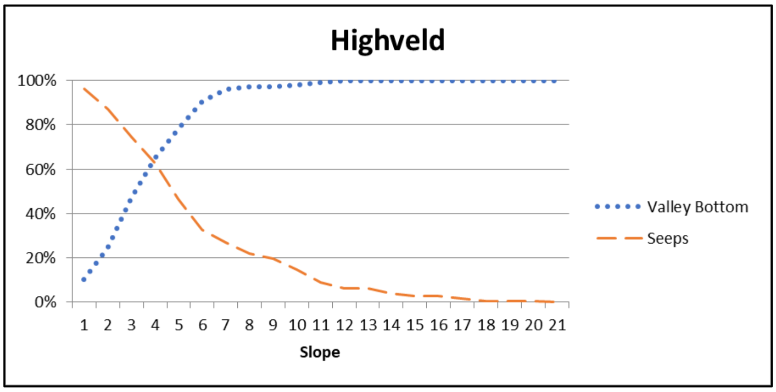


Figure 5.6: Graphs showing the cumulative frequencies of slope values for valley bottom wetlands and seep wetlands by physiographic region. The values of seeps are plotted inversely. The slope value where the lines of valley bottom wetlands and seeps intercept, is the slope value that includes the most valley bottom wetlands whilst excluding the most seeps wetlands.

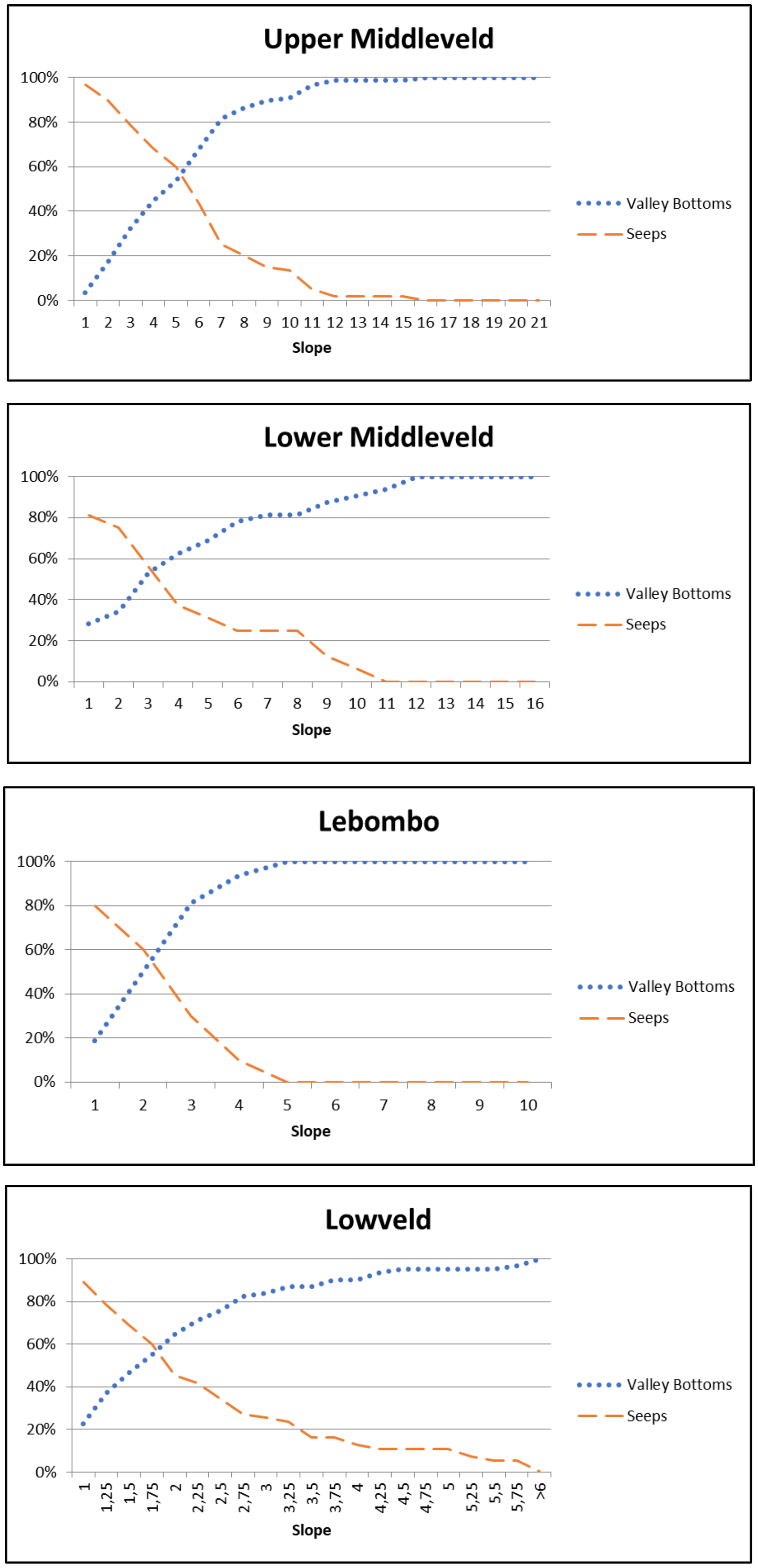


Figure 5.6: Graphs showing the cumulative frequencies of slope values for valley bottom wetlands and seep wetlands by physiographic region. The values of seeps are plotted inversely. The slope value where the lines of valley bottom wetlands and seeps intercept, is the slope value that includes the most valley bottom wetlands whilst excluding the most seeps.

To distinguish valley bottom wetlands from each other, the river layer of ENTC (2017) was used to differentiate channelled, from unchannelled valley bottoms. The "probably wetland" layer was intersected with the Rivers layer (ENTC, 2017) to extract channelled valley bottom wetlands. Buffers of 100m were used to account for misalignment of the rivers layer with imagery that was noticeable below a scale of 1: 60 000. 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 Swaziland 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, rather than overbank flooding which is the major driver of channelled valley bottom wetlands (Ollis *et al*., 2013). In order to identify floodplain HGM Units in Swaziland, the major rivers in Swaziland were scanned in Google Earth Pro (Google Earth Pro Inc, 2019) at roughly a scale of 1; 50 000, to identify the features that are characteristic of a floodplain HGM Unit according to Ollis *et al*. (2013). This includes geomorphological features associated with river-derived depositional processes and includes point bars, scroll bars, oxbow lakes and levees. However, none of these features were identified when scanning Google Earth Pro, and therefore no floodplain wetlands were included in the classified wetland probability map.

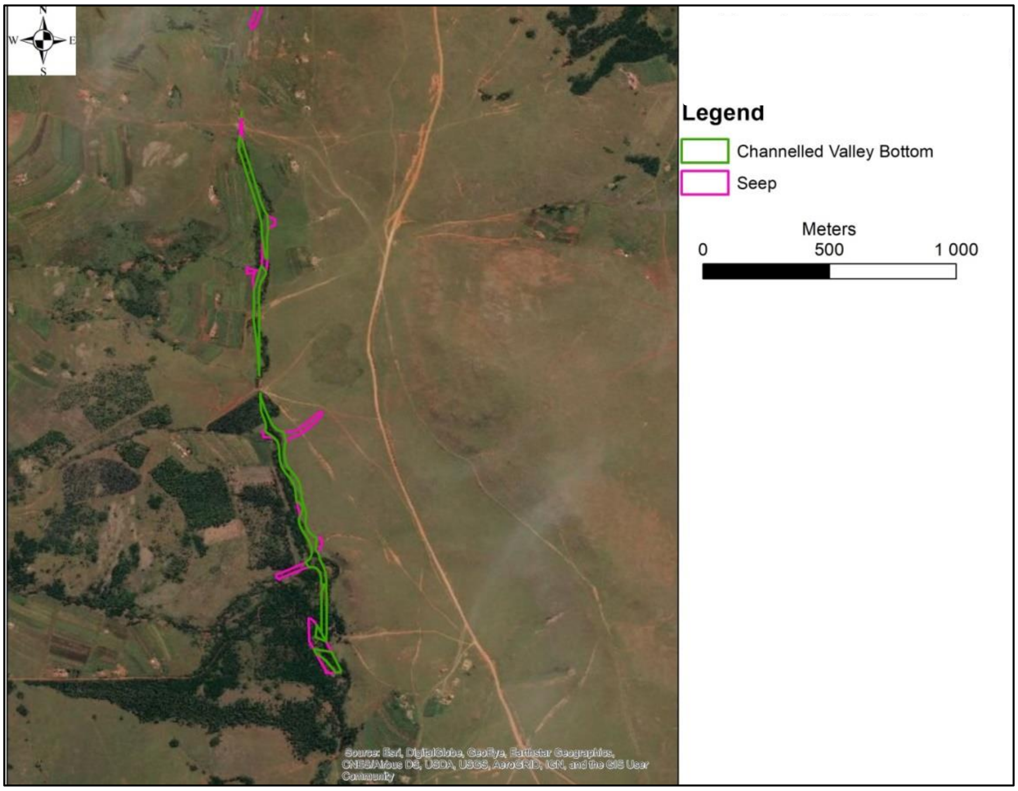


Figure 5.7: An example of the classified wetland probability map showing a channelled valley bottom wetland and various seep wetlands.

5.5 Testing the accuracy of the improved wetland probability map.

The field verification points previously used to test the accuracy of the initial wetland probability map (Section 4.2) were used to test the accuracy of the refined and classified wetland probability map. Field points were classified as "wetland" or "other watercourse", as well as into HGM units (channelled/unchannelled valley-bottoms, and seeps) and other watercourse types (river, riparian zone and first/second order drainage line).

Accuracy assessments based on the methods of Story and Congalton (1986) produced an error matrix that allows one to determine the producers, and user's accuracy of the map. User's Accuracy represents the probability that the refined and classified map actually predicts the correct type of watercourse on the ground, and tests for errors of commission. Producer's accuracy is the probability that a field sample will be correctly classified on the map, and tests for errors of omission.

5.5.1 Accuracy of the refined wetland probability map

Two approaches to the standard accuracy assessment, as well as an informal accuracy test were used to determine the accuracy of the refined wetland probability map. The reason for this is that the initial wetland probability map was classed into three classes namely: "probably wetland", "either wetland or other watercourse", and "probably other watercourse" to create the refined wetland probability map. Whilst the reference data consisted of two classes of: wetlands and other watercourses. Due to the error matrix requiring an equal amount of vertical and horizontal columns, having three wetland probability classes for the classed data and two classes for the reference data lead to an uneven number of columns and rows.

The first approach to determine the maps accuracy introduced a third class to the reference data ("wetland" and "other watercourse" being the original two), namely "difficult to determine" to construct a 3x3 error matrix. The "difficult to determine" class included points taken in the field that were not easily classified as wetland or other watercourse (Table 5.12). This is due to wetland identifications actually requiring detailed field work, specifically soil samples, that cannot always be observed from a car. The second approach to the accuracy assessment ignored the "either wetland or other watercourse" probability class as well as the points that were difficult to determine while driving in a car, and only used the "probably wetland" and "probably other watercourse" probability classes of the map, and field points that could easily be classified as such (Table 5.13). A third, informal accuracy test (Table 5.14) was included to aid in the understanding of the accuracy assessment. The informal assessment shows the raw data, with simple calculations of how many reference points landed on each of the refined wetland probability map classes. Given the difficulties of a formal accuracy assessment, this method provides a more holistic and simple representation of how accurate the refined wetland probability map is. An interpretation of the results of the two formal accuracy assessments is presented in Table 5.15 which includes the reasons why certain results could be used and others not, based on the limitations described above.

Table 5.12: An accuracy assessment where a third reference data class of "Difficult to determine" was included in the accuracy assessment.

		Classified data Predicted (What the map said)			Total
		Probably wetland	Either wetland or other watercourse	Probably other watercourse	
Reference data (observed in the field)	Wetland	34	30	2	**66**
	Difficult to determine	4	37	3	**44**
	Other watercourse	10	87	25	**122**
Total		**48**	**154**	**30**	**232**

Producers accuracy
Probably wetland = 52%

Difficult to determine=84%

Probably other watercourse= 20%

Users accuracy
Probably wetland = 71%

Difficult to determine=24%

Probably other watercourse= 83%

Overall accuracy = 41%

Table 5.13: An Accuracy assessment that excluded the "either wetland or other watercourse" probability class as well as points that were difficult to class as wetland or other watercourse while travelling by car

		Classified data Predicted (What the map said)		Total
		Probably wetland	Probably other watercourse	
Reference data (observed in the field)	Wetland	34	2	**36**
	Other watercourse	10	25	**35**
Total		**44**	**27**	**71**

Producers accuracy
Probably wetland = 94%

Probably other watercourse= 71%

Users accuracy
Probably wetland = 77%

Probably other watercourse= 93%

Overall accuracy = 83%

Table 5.14: A simplified representation of the accuracy of the refined wetland probability map. The table shows the percentages of wetland and other watercourses that occur on each wetland probability class of the map. Field data points that were difficult to determine what type of watercourse they were, were excluded from the percentages.

Wetland Probability classes of the refined map	**Probably wetland**	**Either wetland or other watercourse**	**Probably other watercourse**
Percentages of points identified in the field that intersected the respective wetland probability map classes	Wetland=**77%** Other watercourse=**23%**	Wetland=**26%** Other watercourse=**74%**	Wetland=**7%** Other watercourse=**93%**

These accuracy assessments were able to identify different accuracies of the refined wetland probability map, using both formal and informal methods. Using the results of these assessments, as well as the relative size of each wetland probability layer, the accuracy of the different probability layers of the refined wetland map is put into context below, with Table 5.16 explaining the reasoning why these values can be used to determine the accuracy of the refined wetland probability map.

Probably wetland map layer

- The probably wetland map layer only makes up **15%** of the surface area of the initial wetland probability map, but includes **52%** of the identified wetlands and 3% of the identified other watercourses.
- Of the field points that landed on this layer, **77%** of the field points were wetlands and 23% were other watercourses.

Either wetland or other watercourse map layer

- This map layer makes up **75%** of the surface area of the initial wetland probability map, and includes **45%** of the wetlands, and **71%** of the other watercourses.
- Of the points that landed on this map layer **26%** were wetlands and **74%** were other watercourses.

Probably other watercourse map layer

- This map layer makes up **10%** of the surface area of the initial wetland probability map, and includes **20%** of the points classed as other watercourses and **3%** of the points classed as wetland.
- Of the field points that landed on this layer, **93%** were actually other watercourses and **7%** were wetlands.

Table 5.15: Interpretations of the results of the two formal accuracy assessments used to determine the accuracy of the refined wetland probability map, when introducing a third reference data column to create a 3x3 matrix, and when ignoring the either or wetland map layer and points that were difficult to determine

Refined wetland probability map layer	What do the results mean	Are the results of the assessment of any use to explain the accuracy of that layer?
When introducing a third reference data column to create a 3x3 matrix		
Producers accuracy		
Probably wetland	Of the field points identified as wetland, **52%** landed on the Probably wetland map layer.	Yes, even though it was only **52%,** the wetland probability map layer only makes up 15% of the surface area of the initial wetland probability map.
Difficult to determine	**84%** of the field points that were difficult to determine landed on the either wetland or other watercourse map layer.	No, the difficult to determine reference data does not relate to the "either wetland or other watercourse map layer".
Probably other watercourse	**20%** of the field points classed as other watercourse, landed on the probably other watercourse map layer.	No, a majority of the field points classed as other watercourse landed on the either wetland or watercourse map layer (71%).However it does show that 20% of the field points classed as other watercourses occur in the probably other watercourse map layer.
Users accuracy		
Probably wetland	**71%** of the field points that landed on probably wetland map layer were classed as wetland.	No, these results included field points that were classed as "difficult to determine" that landed on the probably wetland layer. The user's accuracy of Table 5.13 provides a more accurate result.
Difficult to determine	**24%** of the field points that landed on the either wetland or watercourse map layer were difficult to determine.	No, the difficult to determine reference data does not relate to the either wetland or other watercourse map layer
Probably other watercourse	**83%** of the points that landed on probably other watercourse class were other watercourses.	No, these results included field points that were classed as "difficult to determine" that landed on the probably wetland layer. The user's accuracy of Table 5.13 provides a more accurate result.
When ignoring the either or wetland map layer and field points that were difficult to determine		
Producers accuracy		
Probably wetland	**94%** of the field points classed as wetland landed on the probably wetland map layer.	No, it excludes all the field points classed as wetland that landed on the either wetland or watercourse map layer.
Probably other watercourse	**71%** of the field points classed as other watercourse landed on the other watercourse map layer.	No, it excludes all the field points classed as other watercourses that landed on the either wetland or watercourse map layer .
Users accuracy		
Probably wetland	**77%** of the field points that landed on the probably wetland layer were actually wetlands.	Yes, this calculation excludes points that were difficult to determine and provides an accurate user accuracy of the probably wetland map layer.
Probably other watercourse	**93%** of the field points that landed on the probably other watercourse map layer were actually other watercourses.	Yes, this calculation excludes points that were difficult to determine and provides an accurate user accuracy of the probably other watercourse map layer.

5.5.2 Accuracy of the classified wetland probability map.

Similar methods as those applied to the refined wetland probability map were applied to the classified wetland probability map (Story and Congalton, 1986). Two approaches to a formal accuracy assessment were applied. The first tested if a field point was classed as type of HGM unit, what HGM unit the classified map predicted it to be (Table 6.16). This resulted in an accurate producer's accuracy that tested for errors of omission. However, because only the "probably wetland" map layer was classed into HGM units, only those points that landed on this layer could be used to test the accuracy of the HGM classification. Therefore, this approach excluded errors of commission, which would test whether the classified HGM map correctly predicted the HGM type of wetland in the field, which would produce a user's accuracy. In order to overcome this, a second accuracy assessment included reference points that landed on the "probably wetland" map layer, but were classed as other watercourses in the field.

As was done in Section 5.5.1 for the refined wetland probability map, a simple table with basic calculations is shown that provides a more holistic view of how accurate the classified wetland probability map is, given the difficulties in presenting a standard accuracy assessment.

Table 5.16: An accuracy assessment for the classified wetland probability map that test's for errors of omission.

		Classified data Predicted (What the map said)			Total
		CVB	**UVB**	**Seep**	
Reference data (observed in the field)	**CVB**	8	2	0	10
	UVB	1	12	0	13
	SEEP	2	0	14	16
Total		11	14	14	51

**CVB= Channelled valley bottom; UVB= Unchannelled valley Bottom;*

<u>Producers accuracy</u>
Channelled valley bottom= 73%

Uncannelled valley bottom=86%

Seep= 100%

Table 5.17: An accuracy assessment for the classified wetland probability that tests for errors of commission.

		Classified data Predicted (What the map said)				**Total**
		CVB	**UVB**	**Seep**	**Other watercourse**	
Reference data (observed in the field)	**CVB**	8	2	0	**0**	10
	UVB	1	12	0	**0**	13
	SEEP	2	0	14	**0**	16
	Other watercourse	**0**	**7**	**2**	**0**	9
Total		11	21	16	0	51

**CVB= Channelled valley bottom; UVB= Unchannelled valley bottom; and Other watercourse = Other watercourse excluding wetlands*

Users accuracy
Channelled valley bottom= 73%

Uncannelled valley bottom= 57%

Seep= 88%

Table 5.18: A simplified representation of the accuracy of the classified wetland probability map that shows the percentages of hydrogeomorphic units identified in the field that occurred on each hydrogeomorphic class of the map.

Hydrogeomorphic classification of the classified wetland probability map	Channelled valley-bottom	Unchannelled valley-bottom	Seep
Percentages of points identified in the field that landed on each wetland hydrogeomorphic class on the map	CVB=8 (73%) UVB=1 (9%) Seep=0 Other=2 (18%)	CVB= 2 (10%) UVB=12 (57%) Seep=0 Other= 7 (33%)	CVB=0 UVB=0 Seep=14 (88%) Other=2 (12%)

**CVB= Channelled valley bottom; UVB= Unchannelled valley bottom; and Other = Other watercourse excluding wetlands*

Although the number of sample points used for the accuracy assessment of the classified wetland map was relatively small, the results have shown that the methods used to classify wetlands into HGM units were 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 classified map, which tests the percentage of field points 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 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%. Again

Seeps were the highest at 88%, unchanneleld valley bottoms the lowest at 57% and channelled valley bottoms at 73%.

As favorable as the results of the classified map were, various limitations were identified. These were attributed to both the mapping technique as a whole, as well as the methods used to classify wetlands into hydrogeomorphic units. These limitations, as well as those of the Initial and refined wetland probability map will be discussed in the following chapter. In addition, the various capabilities of the different wetland probability maps will also be discussed. Metadata for the wetland probability maps is attached in Appendix 3.

Chapter 6: Advantages and limitations of the wetland probability maps

To date, apart from this study, the capabilities of the mapping technique have not been extensively tested. The following chapter discusses the results obtained from this study and highlights the strengths and limitations of the mapping technique in general, as well as its application to Swaziland. Reference is also made to other wetland mapping techniques, where it is discussed how the wetland mapping technique of Collins (2018) can be used to compliment other wetland mapping methods. Furthermore, the chapter also discusses observations concerning wetland distribution across Swaziland and the controls responsible for the wetlands occurrence and development.

6.1 Factors influencing the wetland probability map

There are general factors that will influence how accurate the wetland probability map is, and the scale at which it can be used. These factors are adjustable, and can be changed based on the intended purpose of the map. Bearing in mind that the wetland probability mapping technique was originally produced with an initial objective of mapping extensive areas with minimum data, skills and cost requirements (Collins, 2018), using the map as an accurate wetland map was not its intended purpose. The results of this mapping exercise have shown that using attribute data derived from ancillary datasets (i.e. DEM and soil data as well as and river and stream layers) can improve the initial wetland probability map, with a possibility of it being able to stand alone as a wetland map for inventory purposes. The following factors, which vary based on every application of the wetland probability map, contribute towards the accuracy of the final product. Reference is made towards the current application in Swaziland that can be used to set a benchmark for other applications of the wetland probability map.

6.1.1 Definition of wetland used

A fundamental aspect when using and determining the accuracy of the wetland probability map is the definition one uses for a wetland. Although the desktop accuracy assessment identified that 93% of the initial wetland probability map was classified as a wetland, these results were based on the Ramsar definition of a wetland which includes other types of watercourses such as rivers, riparian zones and drainage lines (DWAF, 2005). When using the South African definition of a wetland (NWA, 1998), the initial wetland probability map identified that only 31% of the mapped watercourses were in fact true wetlands, and would be classed as such in South Africa (DWAF, 2005). Therefore, if one applies the deliberately broad definition of the Ramsar Convention (Ramsar Convention Secretariat, 2010; 2018), or aims to map a wider variety of watercourses, the map would result in high accuracy. Results of this research have also indicated that attribute data derived from ancillary datasets can be used to refine the wetland probability map to more accurately differentiate wetlands from other watercourses.

6.1.2 Purpose and producer of the wetland probability map

Applying the wetland probability map is a relatively simple process, however it is extremely subjective. It is based entirely on what the user expects to be a vegetation change associated with wetland conditions. A decision needs to be made whether one choses to use mapping parameters that include all watercourses that have a probability of including a wetland, or aims to just map potential wetlands. Given that the mapping technique is based on landscape setting, which assumes that wetlands occur in the lowest lying landscape positions, differentiating rivers from valley bottom wetlands is not always possible as both occur in relatively the same landscape position. However, a user of the map can choose not include steep drainage lines, but at the cost of excluding seep wetlands.

Since Swaziland uses the Ramsar definition of a wetland the option of including all possible watercourses that could contain wetlands was therefore chosen. This also explains why such a high percentage of the mapped watercourses turned out to not be true wetlands. Further research is needed to determine if a more conservative approach to expanding mapping parameters would increase the accuracy of the map, considering that this approach could result in a large amount of omission mapping errors.

6.1.3 Amount of time spent on producing the wetland probability map

The accuracy of the map is related to how much time is spent on the mapping process. This includes the amount of time used to determine the best flow accumulation and percentile filter for a specific mapping region, as well as how small the mapping regions are. If one were to divide a study area into many small mapping regions, the parameters are bound to be more accurate. However, if one increases the number of mapping regions substantially, the time required to assign mapping parameters would rival that of manually digitising the wetlands of the study area. A distinction therefore needs to be made whether the map aims to accurately map the boundaries of wetlands, identify broad areas that are probably wetland, or to find a balance between the two.

Based on discussions with Collins (2017; personal communication), the way the wetland probability map was applied to Swaziland was at a slightly finer detail than what it was applied in South Africa. This included splitting mapping regions where mapping parameters did not accurately map the entire region, often using more than one percentile filter per mapping region, and more time spent choosing the best mapping parameters.

6.1.4 Data used to produce the wetland probability map.

Two data sets are required to produce the wetland probability map: a DEM, and remotely sensed imagery. The accuracy of the map is therefore directly related to the quality and resolution of these data sets. This study used the SRTM DEM (NASA, 2000) which has a resolution of 30 m. Using a DEM with a higher resolution would increase the accuracy of the map. The reason for this is because using a 30 m DEM results in the map only being applied in 30 m increments. A DEM of a higher resolution, particularly when used for determining percentile filters which map the width of a wetland system, would help the probability map in mapping seeps more accurately, which were often noted to be smaller than 30 m.

The study made use of 2008 SPOT 5 satellite imagery (SANSA, 2013) to create the wetland probability map. The quality of the images was high enough to distinguish changes in vegetation, but not necessarily the type of vegetation. Having access to high resolution remotely sensed imagery would therefore improve the results of the map as the type of vegetation changes would be clearer to the user when zooming into the image. Although the ArcMap basemap (ESRI, 2018) is of high resolution, panning across mapping regions and testing different mapping parameters in ArcMAP is time consuming due to the maps loading speed, thereby making the use of these basemaps impractical. However, having access to a high powered computer/laptop would also overcome this limitation.

6.2 Capabilities of the wetland probability maps

This study produced three types of wetland probability maps which include 1) the Initial wetland probability map, which was directly based on the methods of Collins (2018); 2) a refined wetland probability map, which partially differentiated true wetlands from other watercourses; and 3) a classified wetland probability map which classified the areas of highest wetlands probability into the hydrogeomorphic units applied in South Africa. The following section will highlight the various advantages of these maps and discuss their potential application in Swaziland, as well as in South Africa where it has already been produced at a National scale by Collins (2018).

The various wetland probability maps produced in this study provide baseline data that can be used for various purposes, including the foundation of a national wetland inventory. Their purpose is to locate potential areas where wetlands and other watercourses can occur, as well as the potential types of wetlands that can be present. These maps are not intended to be used at a fine-scale level that accurately delineates wetlands. Finlayson and Spiers (1999) explain how wetland inventories can vary depending on the type of information required. Considering that Swaziland does not have a national wetland inventory, the wetland probability maps are able to fulfil some of the various functions of a national inventory that is required by the Ramsar Convention, of which Swaziland is a contracting party. Especially since the Ramsar Convention urges all contracting parties, who have not yet completed comprehensive national inventories of their wetland resources, to give this the highest priority (Ramsar Convention Secretariat, 2010). Furthermore, the convention also suggests that countries include wetland losses and wetlands with restoration potential. These are some of the functions of a wetland inventory that the wetland probability map can fulfil.

Other functions listed by the Ramsar Convention's Handbook on wetland inventories (Ramsar Convention Secretariat, 2010), that the wetland probability map can fulfil include: an information base for monitoring activities near a watercourse, formulating a national wetland policy (which Swaziland is currently in the process of developing), identifying more sites that are suitable for inclusion in the List of Wetlands of International Importance, quantification of Swaziland's wetland resource, identifying wetlands suitable for restoration, as well as risk and vulnerability assessments (Ramsar Convention Secretariat, 2010). The maps can also be used to increase the awareness and interest of wetlands for politicians, government officials, land use planners, students and scientists, which are criteria of a national wetland inventory as listed by Scott and Jones (1995). Furthermore, the different maps provide an important foundation for further research concerning wetlands in Swaziland. Each of the three wetland probability maps have capabilities unique to them and will be discussed below.

6.2.1 Capabilities of the initial wetland probability map produced in this study.

Although the initial wetland probability map does not distinguish wetlands from other watercourses, it does provide a map layer that includes the watercourses of the country. Due to Swaziland using the Ramsar definition of a wetland, which includes other watercourses/aquatic ecosystems (rivers, riparian zones and drainage lines), as a type of wetland; the initial wetland probability map can be used by Swaziland as a national wetland map because it includes everything that Swaziland currently defines as a wetland. Given that the field based accuracy assessment of the initial wetland probability map correctly identified 82% of the wetland reference points identified in the field (based on the Ramsar definition of a wetland), and only excluded 6% of these reference points in the form of omission errors, the map serves as a good foundation to identify areas where wetlands could occur in Swaziland. Commission errors were also relatively low at 12%. Therefore, this map layer is well suited to be used as a National Wetland Map of Swaziland.

Previous remote sensing exercises of mapping wetlands in South Africa (Nel *et al*., 2011; Scott-Shaw and Escott, 2011; Grundling *et al*., 2013a) did not include a riparian zones class in their image classifications. Given that riparian zones are often identified by dense, woody vegetation (DWAF, 2005), the likelihood that they would have been mapped as a wetland using remote sensing is small. Furthermore, the South African wetland delineation guidelines (DWAF, 2005) explain that riparian areas often perform important ecological and hydrological functions, some of which are the same as those performed by wetlands. It is for this reason that both wetlands and riparian areas be taken into consideration when making mandatory management decisions affecting water resources and biodiversity. The Initial wetland probability map therefore serves as an adequate tool to address these management objectives.

A wetland map that only maps true wetlands results in poor continuity between aquatic ecosystems. This is why many countries, especially South Africa, are shifting towards a catchment based management approach. The reason for this is because the country has realized that through merely conserving a wetland, and not the headwaters, recharge and interflow areas that provide wetlands with water, inevitably results in the destruction of the wetland (Roets, 2019). The initial wetland probability map consequently provides the data needed to determine the links between different watercourses due to the maps continuity between different wetland systems.

A fundamental benefit of the wetland probability map is that it acknowledges the dynamic nature of wetlands, where their presence and boundaries are not constant every year (DWAF, 2005). Although recent research has identified that Sentinel-2 can be applied to monitor wetland vegetation for a specific biome (van Deventer, 2019), many wetland mapping exercises in Africa are shifting away from static remote sensing techniques, towards probability mapping (Hiestermann and Rivers-Moore, 2014; Nyandwi *et al*., 2016; Rebelo *et al*., 2017; Collins, 2018). The various shortcomings of mapping wetlands using remotely sensed techniques are also the reason why South Africa sought to manually digitise wetlands for their National Wetland Inventory and not include those mapped through remote sensing (van Deventer *et al*., 2018b). Given the new method that South Africa is using to map their wetlands, the wetland probability map of Collins (2018) provides a good foundation to steer the manual digitisation of wetlands, as well as other watercourses.

6.2.2 Capabilities of the refined wetland probability map

Although true wetlands and other watercourses can perform similar ecosystem functions, wetlands have received significantly more attention regarding their importance and conservation (Mitsch and Gosselink, 2000b). Results of the methods used to improve the initial wetland probability map have highlighted how using attribute data derived from ancillary data sets at a national level is not able to definitively distinguish true wetlands from other watercourses (rivers, riparian zones and drainage lines), but can rather identify areas with a higher probability of being a true wetland. However, wetlands and other watercourses are not mutually exclusive and the technical distinction between the two is not always definitive.

The South African wetland and riparian zone guidelines (DWAF, 2005) state that many riparian areas display wetland indicators and should also be classified as both. This is why most soil classes were not exclusively associated with either wetlands or other watercourses, and why the types of watercourses were not specifically associated with certain slope values. Using attribute data of a finer scale would probably have resulted in wetlands and other watercourse being associated more often with specific soils and slope values, but it would not have been able to definitively distinguish the two from each other. Therefore, producing a map that definitively distinguishes between the two would lead to a false sense of accuracy, especially for this study that was performed using attribute data at national scale. Instead, the refined wetland probability map acknowledges the dynamic nature wetlands where in wet years, many drainage lines and riparian zones will display wetland characteristics and function as such, as opposed to dry years when they will not. It is for these reasons why the refined wetland probability map is split into three categories of "probably wetland", either wetland or other watercourse" or "probably other watercourse".

The likelihood of a watercourse being a true wetland therefore varies across the different classes of the refined wetland probability map. Although the "probably wetland" map layer only contains 52% of Swaziland's true wetlands, it has a 77% chance of being a true wetland, whilst those that fall under the "either wetland or other watercourse" and "probably other watercourse" map layers have a 26% and 7% likelihood of wetland occurrence whilst. These map layers respectively contain 45% and 7% of Swaziland's wetlands.

The refined wetland map therefore provides the relevant conservation authorities in Swaziland with a means to locate watercourses with a high probability of being wetlands, as well as the ability to identify other watercourses across Swaziland that can potentially also contain wetlands. Due to the soil map of Murdoch (1970) having a large influence in identifying watercourses with the highest probability of being a wetland, these wetlands are most likely the larger, unfragmented and more permanent wetland systems in Swaziland, that were identified during the nationwide soil survey (Murdoch, 1970). These types of wetlands often provide more ecosystem services (Kotze *et al*., 2007). The "probably wetland" map layer therefore provides the Swaziland government with the locations of the larger wetland systems across the country, thereby highlighting areas that should be considered for protection and restoration.

Considering that accurately delineating a wetland requires extensive fieldwork, desktop approaches to mapping wetlands merely serve to shorten fieldwork exercises through highlighting the relevant areas that should be located in the field. A static remote sensing approach that results in a *yes wetland* or *no wetland* answer will not be as beneficial as a probability map that shows where wetlands could, or used to occur is of greater use considering that many pieces of land in Swaziland are currently disturbed (Hughes and Hughes, 1992; Mwendera, 2002; Frenken and Mharapara, 2002; Masarirambi *et al*., 2010) and the respective vegetation would not be able to be classed as a wetland using remote sensing. This is of great importance to South Africa because from the definition that the country uses (NWA, 1998) , drained wetlands of which the water table is no longer at, or near, the surface, or of which the land is no longer periodically covered with shallow water, are still considered to be wetlands (Collins, 2005). The refined wetland probability map therefore allows the relevant authority (in Swaziland) to estimate the probability that pieces of degraded land used to be wetland, identify sites that can be rehabilitated, and provide an estimate of how many wetlands and other watercourses have been lost in the different areas across the country due to various land use changes. This will all contribute towards future water resource management in Swaziland.

6.2.3 Capabilities of the classified wetland probability map

The classified wetland map classified watercourses with the highest probability of being a wetland into hydrogeomorphic units. Hydrogeomorphic classification systems place emphasis on the hydraulic and geomorphic controls on wetlands, which can be used to identify the processes that are fundamental to the sustained existence of the respective wetland ecosystems (Brinson, 1993). It can therefore also be used to highlight the sensitivity of these various wetlands to certain changes, and establish mechanisms to mitigate against certain impacts (Smith *et al*., 1995).

The HGM classification system applied to Swaziland (Ollis *et al*., 2013) will therefore aid in the conservation of these wetlands. In addition, the use of an HGM classification system is useful for water resource planning through providing information about how the wetland is connected to the drainage network, identifying how water moves through the wetland, and superficially deriving the ecosystem services that a wetland unit provides at a broad-scale (Sieben *et al*., 2018).

However, the various wetland probability maps are not without their limitations. Before these limitations are discussed in Section 6.4, it is important to acknowledge the differences in the wetland probability maps compared to other mapping exercises. Limitations of the other wetland and classification mapping studies will also be highlighted with the aim of identifying potential opportunities for the wetland probability map and the semi-automated classification methods developed in this study, to compliment and help improve other wetland mapping techniques.

6.3 Advantages of the wetland probability maps when compared to other wetland mapping techniques

Although wetland probability mapping is not a new concept, previous exercises have only attempted to identify areas of wetland probability against terrestrial areas, and not against other watercourse types that can possibly be classified as wetland (Histermann and Rivers-Moore, 2015; Nyandwi *et al*., 2016). The main difference between the wetland probability maps produced in Swaziland, opposed to other predictive wetland modelling is that they include potential wetlands that are not always included in other wetland maps. This includes Riparian zones, and temporary wetlands/wetland boundaries.

6.3.1 Benefits over other wetland mapping exercises

Results of the predictive wetland modelling of Nyandwi *et al*. (2016) and Histermann and Rivers-Moore (2015), produced satisfactory levels of predictive accuracy, however both of their models were trained and tested on pre-existing wetland map layers, derived from remote sensing. Therefore some of the limitations experienced with remotely sense wetland maps, as noted by Nel *et al*. (2011); Rebelo *et al*. (2017); Collins (2018), and van Deventer *et al*. (2018c), will be carried over into the predictive models based on these maps. This includes amongst others not mapping areas that have been disturbed, poor continuity between wetland systems, and the mapping of artificial wetlands and dams. The initial accuracy assessment performed by Histermann and Rivers-Moore (2015) on the KZN wetland map was based on aerial photographs with no field verifications. In contrast, the wetland probability maps of Swaziland, produced in this study, will not include these mapping errors.

The definitions of a wetland used by Histermann and Rivers-Moore (2015) do also not include riparian zones. For example the metadata of the KZN wetland layer (Scott-Shaw and Escott, 2011) states that the main input into the layer was the KwaZulu-Natal Land Cover of 2008 which defined its wetland class as “All permanent, near permanent or daily freshwater, brackish or saline wetland areas.” The metadata of the land cover map does also not include a class for riparian zones, nor does it describe how they were classified (Scott-Shaw and Escott, 2011). Nyandwi *et al*. (2016), who based their predictive wetland model on the REMA wetland map (REMA, 2008) (the same map that they criticised for not acknowledging that wetland bodies are changeable over time), do not provide what definition of wetlands they used. The only indication of what definition of a wetland was used by the authors was in the introductory text of the article where a definition of Keddy (2010) was used to describe permanently saturated wetland systems. The definition of wetlands in Rwanda is also not very descriptive as it defines wetlands as areas with water, high biodiversity and vegetation associated with marsh environments (REMA, 2009).

A third mapping approach, which was based on remote sensing but acknowledged the variability of wetlands, like the wetland probability maps produced for Swaziland, is that of Grundling *et al*. (2013). To date this is the only remote sensing based map that attempted to create a wetness map with permanently and temporary wetlands and open water areas in Africa. The authors used *Landsat TM and ETM imagery acquired for 1992 and 2008 (dry) and Landsat ETM for 2000 (wet) along with ancillary data* to determine if wetlands were temporary or permanently wet and were able to create a wetland class with a user's accuracy of 80% and a producer's accuracy of 76%. These results are slightly higher than those achieved in Swaziland for the wetland probability map. However the study of Grundling *et al*., 2013a was applied on the Maputaland Coastal plain, which is a very different landscape setting to Swaziland which does not include the types of Riparian zones and steep drainage lines found in Swaziland (Grundling: Personal Communication, 2019). Further research is needed to determine whether the methods of Grundling*et al*., (2013) are applicable to other areas, like Swaziland.

Riparian zones have also not been included in South Africa's latest inventory of aquatic ecosystems (van Deventer *et al*., 2018c), making their documentation across South Africa limited. Mapping riparian zones is also difficult as they are often narrow strips of different vegetation that grows along a river (Grundling, Personal communication, 2019). The South African wetland inventory does also not provide a mapping accuracy determined from an accuracy assessment for the mapping and classification of HGM units across South Africa. Rather it provides a recommended scale to use the maps with estimated mapping errors. Van Deventer *et al*. (2018c) recommended that areas mapped by non-wetland specialists with a low confidence rating, where omission errors are estimated at 50% and commission errors <10%, be used at a scale of 1:50 000. Areas that were mapped at a low to medium confidence rating by interns should be used at a scale of 1:10 000, where omission errors are estimated at <30% and commission errors <10%.

6.3.2 Benefits over other wetland classification exercises in South Africa

A large benefit of digitising the wetlands for the national wetland map (van Deventer *et al*., 2018b) is that wetlands could be manually classified according to the hydrogeomorphic classification of Ollis *et al*. (2013). The reason why this is such as benefit is because applying the HGM classification at a national scale in South Africa has not previously been very favourable, where van Deventer *et al*. (2016) only achieved a 42% classification accuracy. Although classifying wetlands whilst manually digitising them will result in a more accurate classification than an automated approach, wetlands classified for the South African wetland inventory were digitised in 2D in ArcMap (ESRI, 1999-2018). This makes it difficult to distinguish Seep wetlands from Valley bottom wetlands. Rather, using a 3D mapping programme, for example Google Earth (Google Earth Pro Inc. 2019), allows the mapper to more easily distinguish Seeps from other wetlands. However, a downfall to using Google Earth is that it is very time consuming to align adjacent wetland polygons of different HGM units, whereas in ArcMap (ESRI, 2018) this is very simple to do. The semi-automated methods applied to the classified wetland map of Swaziland partially overcomes this, but it is also not without its limitations, which will be discussed in Section 6.4.

The only wetland classification approach to apply HGM types to wetlands at a sub-national level in South Africa is that of Grundling *et al*. (2014a). The following section will compare this classification to the classified wetland probability map produced in this study. Based on the wetness map of Grundling *et al*. (2013a), Grundling *et al*. (2014a) used a terrain unit map based on curvature morphology (van den Berg *et al*., 2009), along with slope values to identify hydrogeomorphic wetland types on the Maputaland Coastal Plain, KwaZulu-Natal, South Africa. The authors classified valley bottom wetlands as those occurring on terrain unit 5 (toe slope areas). Channelled valley bottoms were distinguished from unchannelled valley-bottom wetlands, as polygons in the toe slope terrain unit that intersected the national 1: 50 000 river channel layer (NGI, 2012B) and digitised distinct channels across the study area. Seeps were identified as wetland polygons with a modal slope value of 1-2%, which typically occurred on concave midslope terrain units.

The methods to distinguish channelled from unchannelled valley-bottom wetlands in Swaziland were similar to that of Grundling *et al*. (2014a) and Grundling (2014b). However, the latter manually digitised river channels for their study site which resulted in them achieving a higher classification accuracy for these valley-bottom wetlands. The classified map in Swaziland therefore relied heavily on the accuracy of the Swaziland River Layer and the buffer applied to it to account for misalignment when zooming in past a scale of 1: 60 000 (ENTC, 2018). River channels were not digitised for the entire Swaziland as the country is significantly larger than the Maputaland Coastal Plain.

Due to the localised topographical features (interdune systems) and the regional aquifer of the Maputaland Coastal Plain, Grundling *et al*.,(2014a) did not encounter seep wetlands with a slope value >3%, which were frequently encountered in Swaziland. Therefore due to the greater variety of seep gradients identified in Swaziland, which is the reason why best fit cut-off slope values were determined for the different physiographic zones, the studies are not relatively comparable.

The SRTM DEM (NASA, 2000) used to create the Terrain unit map (van den Berg *et al*., 2009), was the same as that used in Swaziland. The accuracy levels of the HGM map of Grundling *et al*., 2014a) was 88% for channelled valley bottoms, 100% for unchannelled valley bottoms, and 33% for seeps. However, the assessment for these three HGM types was only based on 15 reference points and the accuracy does not differentiate between omission and commission errors. Grundling *et al*. (2014a) do also not comment on how well the boundaries of the different wetlands were mapped, and if the slope values of 1-2% was able to distinguish seeps from valley bottom wetlands accurately, considering that only 1 seep was included in the accuracy assessment Grundling *et al*. (2014a).

The accuracy of identifying seep wetlands with the classified wetland probability map was 100% for the producers accuracy, and 88% for the users accuracy. These are higher than the accuracy results of Grundling *et al*. (2014a), however these results were only based on the "probably wetland" map layer which only includes 52% of the wetlands in Swaziland, which is one of the limitations of the wetland probability maps produced for Swaziland. Future research is therefore needed to compare the results of the various wetland probability maps, to wetlands mapped through other techniques such as multi-temporal active remote sensing, or logistic regression models, to determine potential advantages and limitations when compares to these techniques. The imitations of the wetland probability maps identified in this study will be discussed in the following section.

6.4 Limitations to the wetland probability map

Although the wetland probability maps achieved relatively high levels of accuracy, various limitations were identified. This section discusses these limitations and includes general limitations to the mapping technique as well as the limitations in the methods and attribute data used to improve it.

6.4.1 General limitations of the wetland probability map

Due to the map being applied in ArcGIS (ESRI, 2018) which views the study area in two dimensions, it is not always easy to associate a change in vegetation to a wetland from other changes in vegetation. A method to partially overcome this is to use Google Earth (Google Earth Pro Inc, 2019) to verify when a change in vegetation is associated with a wetland or not. This is because Google Earth allows the user to view the area of interest in three dimensions and over multiple years. Although this makes determining whether an area is a wetland or not relatively easier, it is time consuming which relates to the argument of the purpose of the wetland probability map.

Another limitation of the mapping technique is assigning mapping parameters to areas that have been relatively disturbed. Although the mapping regions should include areas that have not been disturbed, which can be used to assign mapping parameters for that respective mapping region, it is not always the case that there are enough pristine areas to derive accurate mapping parameters for an entire mapping region. In Swaziland this was encountered in the forestry plantations of the Highveld, the urbanized regions of the Middleveld, and the Sugar cane plantations of the Lowveld. However, a major advantage of the probability map that counters the above is that it can predict areas that used to be wetlands, but have been transformed to other land uses, particularly forestry, agriculture (e.g. sugar cane) and urban development. This is due to mapping parameters being applied to pristine areas within the same mapping region as the disturbed area. The wetland probability map does not include depressions which are located in the Lowveld and Lebombo regions of Swaziland (Watson, 1986; Hughes and Hughes, 1992), and are a common type of wetland across many regions in South Africa (Nel *et al*., 2011; Grundling *et al*., 2014a; Grundling, 2014b and van Deventer *et al*.,2018a).

6.4.2 Limitations experienced in the attribute data used to improve the initial wetland probability map

The use of attribute data derived fron ancillary data sets to refine the initial wetland probability map proved to be successful. However, limitations in the respective attribute data sets were experienced which would have affected the accuracy of the improved probability maps. The following section discusses the limitations experienced with the Soil map of Murdoch (1970), as well as the SRTM DEM (NASA, 2000).

i.) Limitations experienced with the soil map of Murdoch (1970)

Whilst no accuracy assessment is available for the Soil map of Murdoch (1970), the map was found to be generally well aligned with terrain units, which followed the catena concept. However, some individual soil sets were identified that did not correlate precisely with aerial imagery that could be used to identify the type of soil that should be associated with certain features. For example, the soil sets representing alluvium, sometimes lay next to where a river was located. The alignment issues were however not constant as sometimes the alluvium was to the right of the river, and sometimes to the left. These Alignment issues, although not extensive were also not restricted to the alluvium class, but to the overall map. Given that the digital soil map had been georeferenced from a hardcopy map, and that the map is at a scale of 1: 250 000 produced in 1970, misalignment issues were bound to occur. However, although alignment issues were present, the map was still accurate enough to produce favourable results to improve the initial wetland probability map.

ii.) Limitations experienced with the SRTM Digital Elevation model

The resolution of the DEM was the other limitation experienced with the attribute data used to improve the wetland probably map, as this affected the various morphometric values used to refine the wetland probability map. The SRTM DEM has a spatial accuracy of 30m. This resulted in the 2000 points used to classify and refine the map, each being assigned the average morphometric value of cell within which it was located. The implication of this is that a point could be located 2m from the edge of a cell, but the morphometric value assigned to it would be based on the surrounding 28m towards the other end of the cell. Particularly this included cells located on a break in slope, where the respective points morphometric value would be an average of the mid-slope and toe-slope that the respective cell occupied.

Nevertheless, a cut-off slope value that distinguished the most wetlands from drainage lines, and valley bottom wetlands from seeps, was still extracted that could be used to improve the initial wetland probability map. Further research is required to determine if using a finer scale DEM to assign slope values to points would be able to identify cut-off slope values that exclude less wetlands and valley bottom wetlands from the cut-off slope value, which should increase the accuracy of the improved wetland probability maps. It is also important to note that the wetland probability map was produced at a national scale, and is not intended to be a 100% spatially accurate map.

6.4.3 Limitations experienced with the methods used to refine and classify the initial wetland probability map

Attribute data of soils and morphometrics that were available for Swaziland were able to distinguish wetlands from other watercourses, as well classify wetlands into hydrogeomorphic units, they were not able to do so distinctively. The reasons for this are discussed separately for the respective attribute data types, as well as how these limitations were overcome.

i.) Limitations experienced when using soils to refine and classify the initial wetland probability map

When using soil data to refine the initial wetland probability map, assigning soil classes to either wetlands or other watercourse were not clear cut, as there were soil classes that were attributed to both wetlands and other watercourses. There are two possible explanations for this. The first is the limitations in the misalignment of the map and that the map was produced at a scale of 1: 250 000. However the results of the statistics still showed trends in the distribution of wetlands and other watercourses in relation to certain soil classes, establishing a reasonable degree in confidence in the soil map. The second possible reason is that certain soil classes can occur under both wetlands as well as other watercourse types. This can be explained using two types of soil classifications applied to the soil sets of Murdoch (1970).

The wetness regimes of the South African delineation guidelines (DWAF, 2005) list two categories of wetland soils, and by implication a third. The first soil class of permanently saturated soils are soils that are always associated with a wetland because they display redoxmorphic features characteristic of anaerobic conditions. The second class of soils are soils that can be, but are not necessarily, associated with seasonally and temporarily saturated conditions, as this is dependent upon the depth at which redoxmorphic features are encountered within the soil (Richardson and Vepraskas, 2001). If redoxmorphic soils occur within the top 50cm of the soil, the soil can be classed as being wetland (DWAF, 2005). The 50cm is based upon the depth that hydrophyte (plants accustomed to saturated soils) roots can extend into the soil (Richardson and Vepraskas, 2001; Collins, 2005). The third soil class of this classification is those soils of the Soil Classification Working Group (1991, 2018) that are not listed as potential wetlands soils in the South African wetland delineation guidelines (DWAF, 2005), and were classed as terrestrial soils.

The hydrological soil types of Van Tol *et al*. (2013) contain five soil types, of which three can possibly relate to wetlands. This includes the Interflow AB and Interflow soil/bedrock types, where the build-up of water occurs above a textural discontinuity or bedrock can occur within the top 50cm of the soil, resulting in a technical wetland. The other hydrological soil types that can be associated with wetlands is the Responsive saturated type which is also the most likely of the three to be associated with wetlands. The reason for this is because this soil type commonly displays morphological evidence of long periods of saturation, however the morphological evidence is not necessarily in the top 50cm of the soil, which is necessary for it to be classified as a wetland soil (DWAF, 2005). Combining the soil classifications of wetness regimes (DWAF, 2005) and the hydrological soil types of (Van Tol *et al*., 2013) aimed to reduce the above reasons that a soil is not always definitively associated with a wetland or not. Although it was not tested whether the results benefited from this combination, it is expected that they did, give the favourable results of refining the wetland probability map.

Soils could not be used to classify wetlands according to hydrogeomorphic units of Ollis *et al*. (2013). This was expected as channelled and unchannelled valley bottoms, as well as seep wetlands all occur on both permanent and seasonal/temporary wetland soils. The same applies to hydrological soil types. Although it would be expected that riparian zones would occur significantly more on alluvium than wetlands, the results in Appendix 1 showed that both wetlands and riparian zones occurred almost equally on the alluvium soil set which can be either be attributed to the limitations of the Soil Map (Murdoch, 1970), or the fact that Riparian zones can also be wetlands (DWAF, 2005). The results of this study also showed that drainage lines can also frequently occur on soils classed as seasonally/ temporary saturated, as well as both Interflow and Responsive hydrological soil types that occurred in Swaziland.

ii.) Limitations experienced when using slope morphometrics to refine and classify the initial wetland probability map

Slope values were used to distinguish wetlands from first and second order drainage lines. However, slope could not be used to distinguish riparian zones from wetlands, nor was any other morphometric value able to do so. There is also a shortage of literature relating to the above. The reason why morphometrics do not show many statistical differences between wetlands and other watercourses is because of the landscape position of the different types of watercourses. Valley bottom wetlands (both channelled and unchannelled), rivers and riparian zones predominantly all occur in the same valley bottom landscape position, which explains why their morphometrics do not differ significantly. Reasons as to why the Highveld and Upper Middleveld wetlands and other watercourse showed differences in their slope (Table 5.8), is because of the many steep drainage lines (first and second order drainage lines) that occurred in the mountainous terrain of these physiographic zones. These drainage lines provided enough data that could be used to distinguish them from wetlands. Slope is also the only morphometric type mentioned in the South African Wetland classification system (Ollis *et al*., 2013), that is recommended to be used to identify the landscape setting of a wetland.

The cut-off slope value used to distinguish between wetlands and first/second order drainage lines was not distinct. This can be attributed to the limitations of using a 30m DEM, as well as that some wetlands and drainage lines will have similar slope values, although the majority of first/second order drainage lines will have steeper slopes than wetlands. This is why a distinct cut-off slope value could not be determined that completely separates wetlands from drainage lines, but rather a cut-off slope value that included the most wetlands below the value, and also included the least first/second order drainage lines. Similarly, to using slope to refine the wetland probability map, slope was also used to classify wetlands into HGM units by separating seep wetlands from valley bottom wetlands.

6.4.4 Limitations in determining the accuracy of the wetland probability map

Various difficulties were experienced in determining the accuracy of the initial, refined and classified wetland probability maps. Firstly, determining the accuracy of the mapped wetlands of an entire country with verified field samples, require an extensive budget and time which was not available for this study. The accuracy assessment was therefore based on the watercourse verification points collected along 500km travelled by road through Swaziland. Given the mountainous terrain of the country, roads travelled were often restricted to the crests of various mountains and hills, therefore a majority of the sampled watercourses were drainage lies. Another limitation of determining the accuracy of a wetland map is that wetlands often require detailed field work to identify, which is mostly based on redoxmorphic features in the soil. Watercourse/wetland points collected and classified from a car are therefore not completely accurate (it could only determine presence or no presence of wetland).

A reference map for the wetlands of Swaziland did not exist that could be used to compare the results of the probability against. Whilst the Malereo Wetland map (Franke *et al*., 2013) was the best candidate, it only mapped wetlands in the Central and East of Swaziland. The map did also not include Riparian zones as a map class, and provided no definition as to what it included as a wetland. Another candidate was wetland points collected from a helicopter as part of a national alien plan survey (Kotze' *et al*., 2010), but only 63 points were available, and again no definition of a wetland was used.

The nature of the probability map, especially the refined map that was classed into three classes of "probably wetland", "either wetland or other watercourse" and "probably other watercourse", resulted in complications when determining its accuracy. Various forms of an accuracy assessment were therefore applied in Chapter 5 to try and determine how accurate the various maps were. This is probably also the reason why Grundling *et al*. (2014a; 2014b) did not produce an error matrix for their classified wetland map, but rather a table of accuracy levels, and why van Deventer *et al*. (2018b) only provided estimated accuracies of the South African National Wetland Map.

From the various accuracy assessments of the classified wetland probability map produced in chapter 5, it was determined that the "probably wetland layer" includes 52% of the countries wetlands, whilst the "Either wetland or other watercourse" map layer contains 45% of the countries wetlands. However, the "Probably wetland layer" only makes up 15% of the initial wetland probability map, whilst the "Either wetland or other watercourse" map layer makes up 75% of the initial wetland probability map. The "probably wetland" map layer therefore contains a lot more wetlands per surface area mapped. However, these accuracy assessments were only based on 369 confirmed wetland points and further research is recommended to improve the accuracy assessment of the maps produced in this study.

6.4.5 Observed limitations in the wetland probability maps.

The improved wetland probability maps are very good at identifying probable areas of wetlands, but they have shortcomings in mapping the extent of the wetlands that they map. Whilst these mapping errors are not always visible at a scale above 1: 50 000, they are more evident at scales such as 1:10 000. Figures 6.1 is an example of the classified map at a scale of 1: 50 000, which shows how wetlands are sometimes incorrectly classified. The numbers on the maps and the arrows illustrate where these errors are identified. Descriptions of these errors are presented below.

1. Seeps are sometimes mapped as occurring in a valley floor position between two valley bottom wetlands, where in fact it should be one continuous valley bottom wetland. The reason for this is that when valley bottom wetlands were distinguished from Seep wetlands, a cut-off slope value (ranging from 4^{o}-2^{o} depending on the physiographic zone) was calculated that included the most valley bottom wetlands below the cut-off slope value, whilst including the most Seeps above the value. This method therefore resulted in the steeper valley bottom wetlands (>4^{o}) being incorrectly classified as Seeps.

2. The inverse of the above mapping errors also occurred when Seeps are sometimes classified as valley bottom wetlands, which occurs in gentler sloped seeps (<2^{0}).

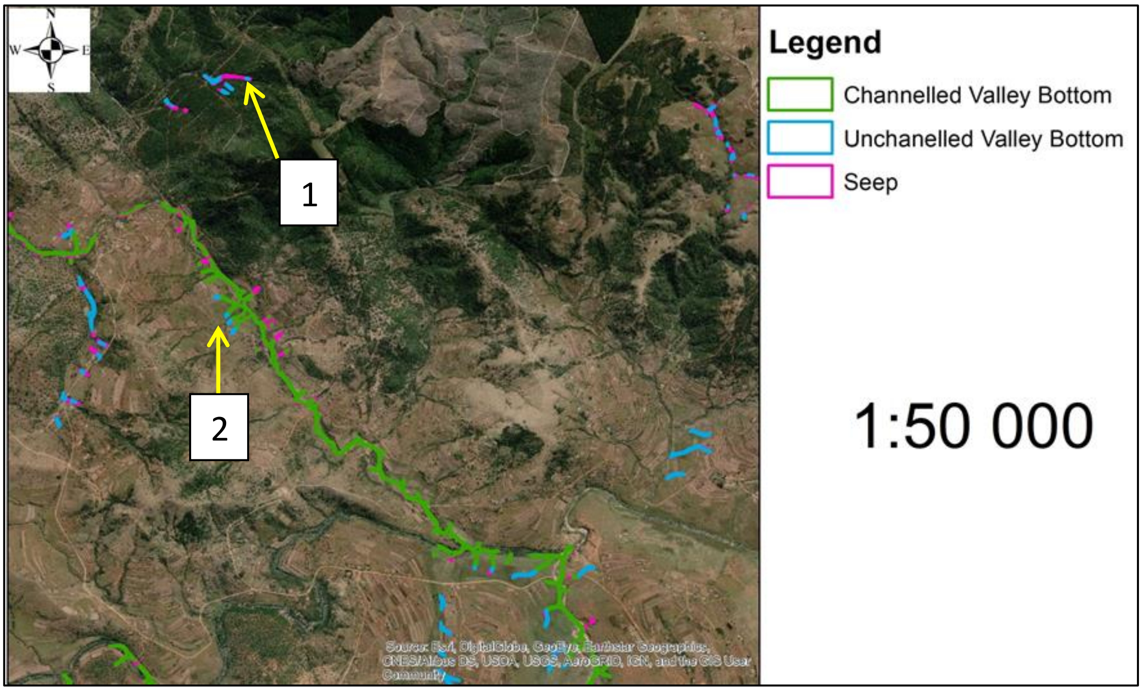


Figure 6.1: Mapping errors that indicate, (1) unchannelled valley bottom wetlands incorrectly classified as Seeps, and (2) Seeps incorrectly classified as valley bottom wetlands.

Figure 6.2 shows an example of the same wetland system shown in Figure 6.1, but at a scale of 1: 10 000. Apart from the mapping error identified in Figure 6.1, Figure 6.2 shows the same mapping error (1) as well as how the wetland probability map does not always accurately map seep wetlands, particularly the wider systems (2). A more accurate representation of the Seep in Figure 6.2 is illustrated in orange.

Despite the above shortcommins of the improved wetland probability maps, the maps are able to serve their purpose which is to identify where wetlands could occur, as well as the possible types of wetland that could be present. The next section of this chapter lists various observations concerning the distribution of wetlands across Swaziland, made from the various wetland probability maps oruduced in this study.

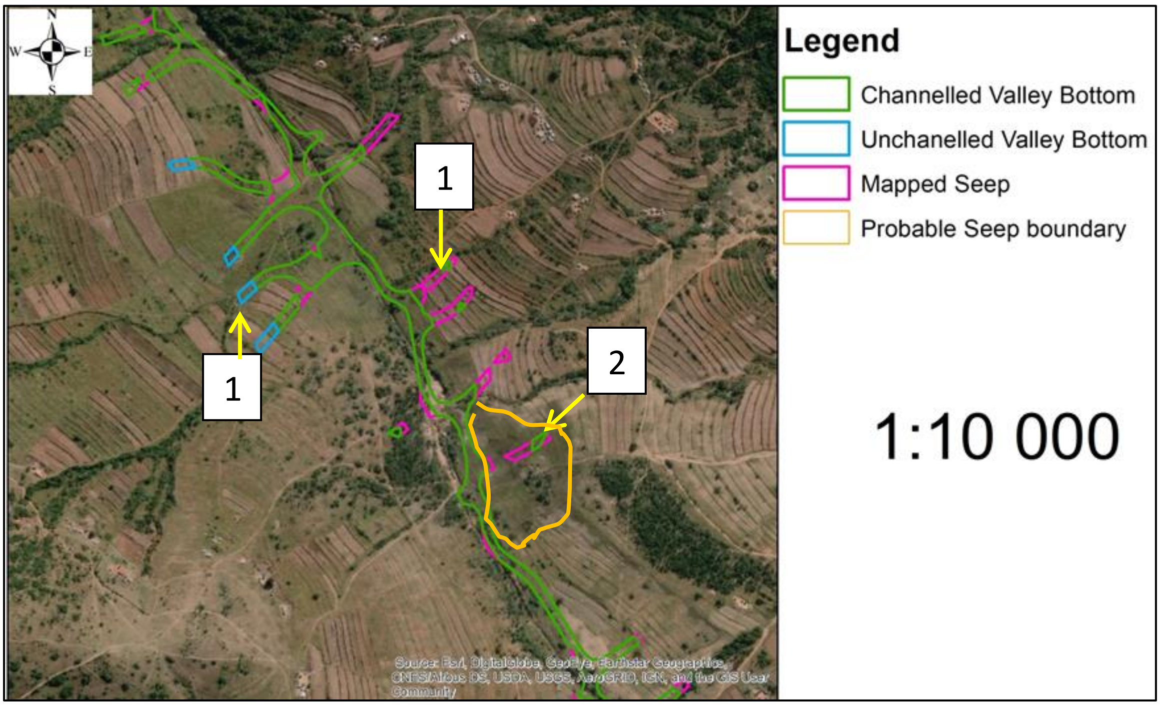


Figure 6.2: A zoomed in image of Figure 6.1 which shows (1) how HGM units can be incorrectly classified, and (2) how the extent of wide Seeps are not always correctly mapped. The probable extent of the Seep in question is demarcated in orange on the map.

6.5 Observations made from the wetland probability map

Hughes and Hughes (1992) originally stated that there are no major wetlands in Swaziland. Results of the wetland probability maps support this statement. However, there are numerous relatively large (> 5ha) wetland systems across the different physiographic zones of Swaziland, that were identified from the wetland probability maps.

In the Highvled, north east of Bulembu, numerous drainage lines originating on the rocks of the Onverwacht Group, that flow in a north west direction make contact with the shales of the Fig Tree Group which act as an impeding barrier to water flow, thereby creating a relatively large wetland system. 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 (4ha) 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. Amongst the many tributaries of the Usuthu River, the Ngwenibisana, Mlambo, Ngwempisi, 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 Mbambane. In the South west of Swaziland, a large channelled valley bottom wetland occurs in a shallow valley that lies near the contact zone between Mozaan sediments and the Insuzi lavas, which is located near Sicunusa.

The only large wetland systems in the upper Middleveld occur to along the White and Black Mbuluzi rivers to the west of Luve and the little Usuth and Umtilane rivers which are tributaries of the Ususthu 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 decrease 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 bottoms and seep wetlands on the Mpuluzi granites which originate in Swaziland 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 that impeded into the Kwetta and Hlatikulu granites cause an impeding effect on water flow that also results in various small (<1ha) 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 of shale and sandstone. The larger of these systems are located along the Komati River in the north of Swaziland, as well as north of Mliba near the Mnjoli Dam. Similar to the Lower Middleveld, dolerite sills in southern Swaziland 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 Pongolo River.

In the North of the Eastern Lowveld where fine grained sandstone of the Clarens formation dissect Karoo sediments, a large wetland system has developed. The Lebombo Rhyolites act as large impeding barrier to many rivers that flow from western Swaziland, where many wetlands have formed in the clays that have weathered from the Sabie River baslats 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 lot less wetlands in the Lebombo Mountains, when compared to the rest of Swaziland. This can possibly be attributed to the more resistant Ryholites 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 Swaziland, which are similar to reasons for wetlands developing in South Africa 9Tooth and McCarthy, 2007; Ellery *et al*., 2008). This includes 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. Contact zones between different types of geologies for example the Mswati Grainites 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 6.3 indicate examples of large wetland systems (>5ha) that occur due to changes in elevation, whilst Figure 6.4 indicated large wetland systems that occur on the contact zones between different geologies.

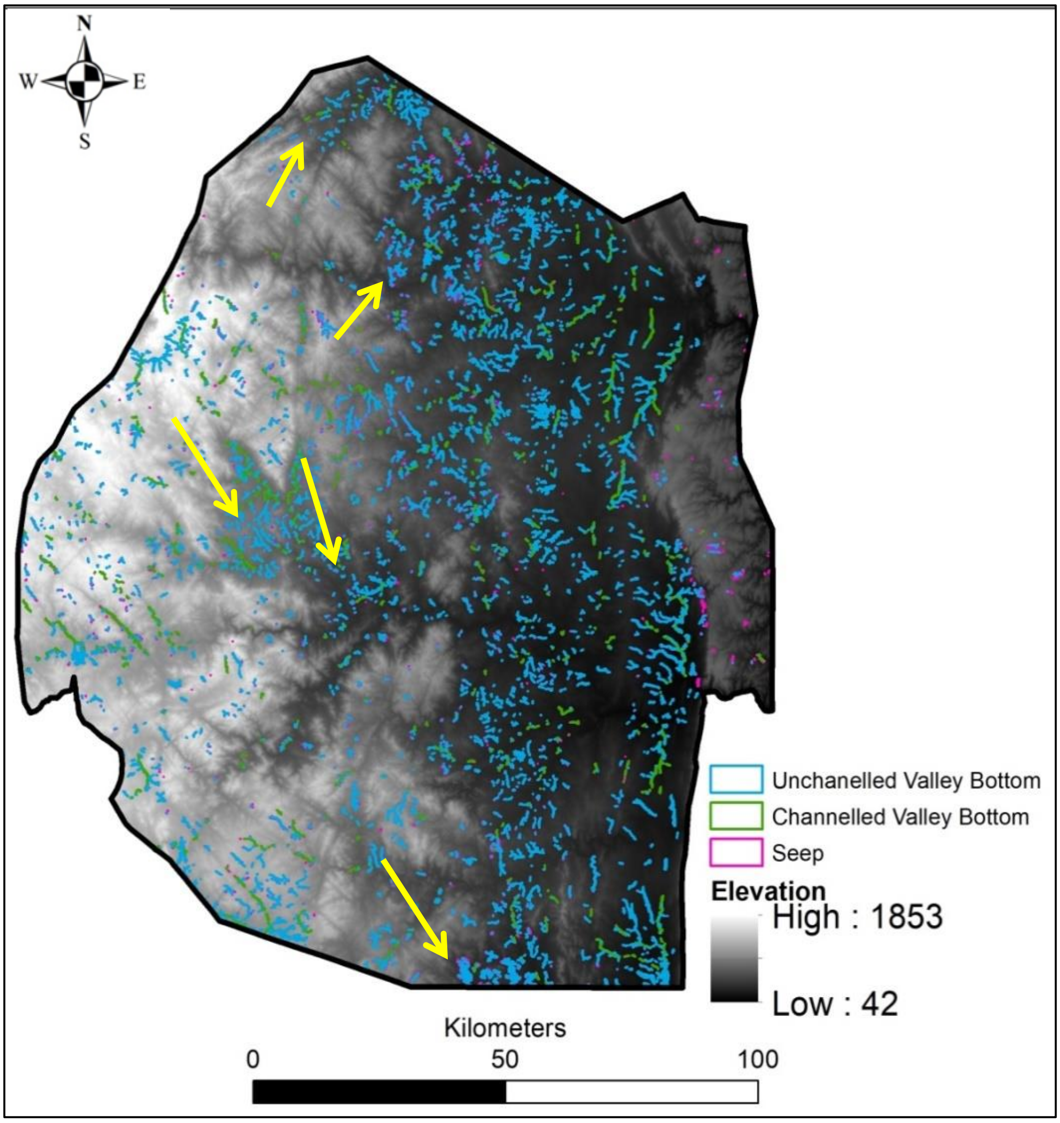


Figure 6.3: Large wetland systems (>5ha) that occur due to a change in elevation, indicated by yellow arrows.

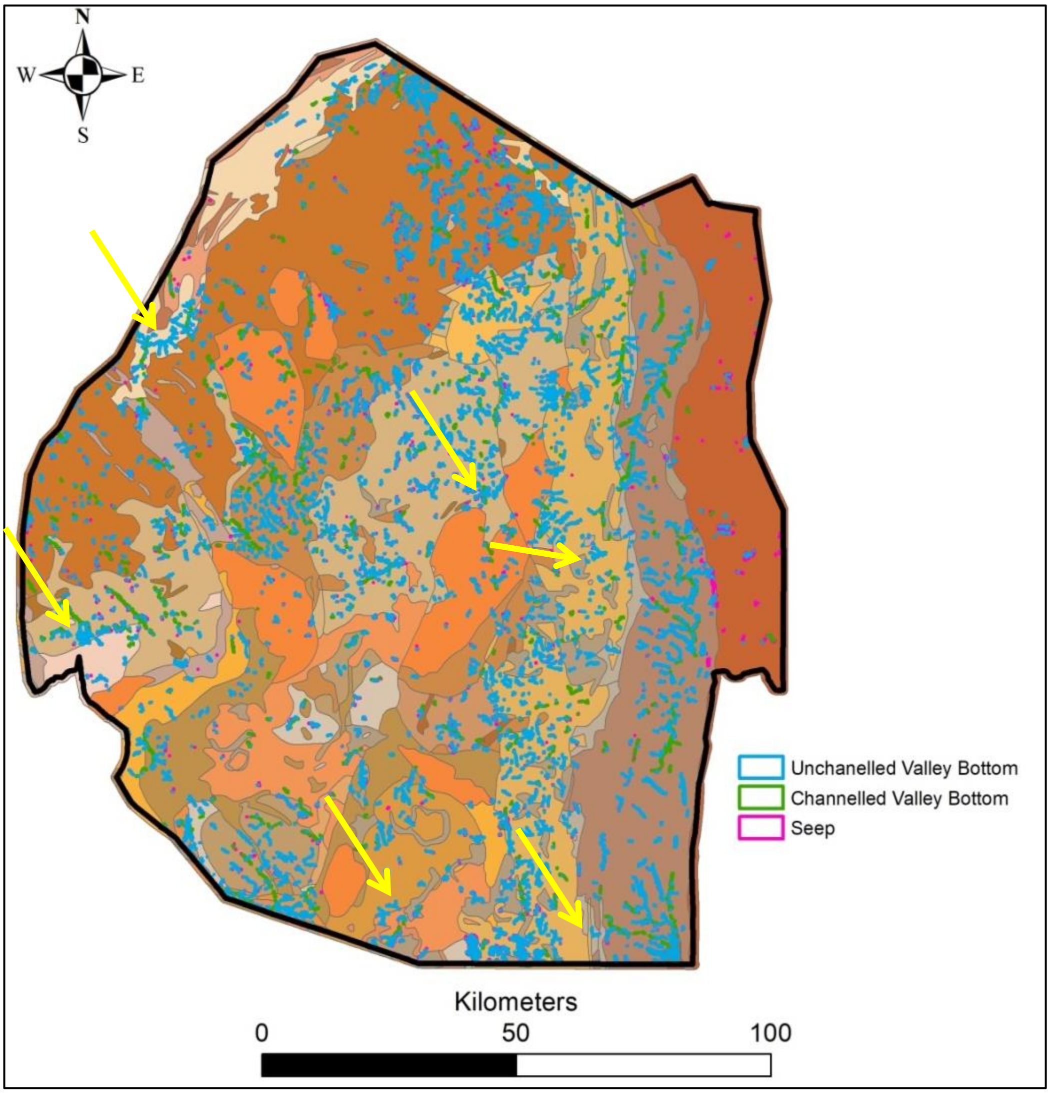


Figure 6.4: Large wetland systems that occur on the contact zones between different geologies, indicated by yellow arrows.

Chapter 7: Conclusion

Along with many recommendations, the Ramsar Convention specifically recognizes the importance of national wetland inventories and classification systems as a key tool for informing policies and other actions to achieve the conservation and wise use of wetlands (Ramsar Convention Secretariat, 2010). Swaziland became a signatory to the Ramsar Convention on the 15th of June, 2013 and to date, does not have a wetland inventory, nor does it use a classification system other than the Ramsar wetland classification (Scott and Jones, 1995) for its three sites of international importance. Given that the wetlands of Swaziland are relatively degraded (Grimwood, 1973; Hughes and Hughes, 1992; IUCN, 1997; Mwendera, 2002; Masarirambi *et al*., 2010), and that the government of Swaziland is currently in the process of drafting a national wetland policy (Gumedze, personal communication, 2019), the country is in need of baseline information concerning its wetlands.

The aim of this study was to apply the newly developed wetland probability mapping technique of Collins (2018) to Swaziland, in order to provide baseline information that will contribute towards the development of a wetland inventory for the country. Furthermore, because there is little understanding of where the mapping technique of Collins (2018) can be of use (van Deventer *et al*., 2018c), this study attempted to determine the capabilities and limitations of the technique.

Three types of wetland probability maps were produced in this study and include 1) the Initial wetland probability map, which was directly based on the methods of Collins (2018); 2) a refined wetland probability map, which partially differentiated true wetlands from other watercourses; and 3) a classified wetland probability map which classified the areas of highest wetlands probability into the hydrogeomorphic units applied in South Africa. Results of the initial wetland probability map indicated that although it obtained a relatively high level of accuracy (82%), these results were based on the Ramsar definition of a wetland which is considerably broader than the South African definition of a true wetland (NWA, 1998). Therefore a majority of the features mapped by the initial wetland probability map would be classified as watercourses in South Africa, and not necessarily wetlands. The reason for this is because the technique maps all low-lying areas with a distinct change in vegetation. In addition to wetlands, this includes Riparian zones, drainage lines, and rivers. In order to improve these results, attribute data, derived from ancillary data sets, was used to partially distinguish wetlands from other watercourses, and to classify the areas with the highest probability of being wetlands into the hydrogeomorphic units of Ollis *et al*. (2013).

These three wetland probability maps each have their own capabilities. The initial wetland probability map can be used to identify watercourses across Swaziland, which includes wetlands, drainage lines, riparian zones and rivers. This will allow the government of Swaziland to identify the continuity between different watercourse systems, thereby allowing the country to move towards a catchment based water resource management approach. The refined wetland probability map, which partially distinguishes wetlands from other types of watercourses, will allow the government of Swaziland to locate watercourses with a high probability of being wetlands, as well as the ability to identify other watercourses across Swaziland that can potentially contain wetlands. In addition to the above advantage of including other types of watercourses, the wetland probability maps acknowledge the dynamic nature of wetlands, where their presence and boundaries are not constant every year and that riparian zones can sometimes display wetland characteristics (DWAF, 2005). Due to the way that the refined wetland probability map was created (ie. Based on soil and slope data), the Government of Swaziland will be able to identify the larger wetland systems across the country, which often provide more ecosystem services than smaller wetlands (see e.g. Kotze *et al*., 2007).

The Ramsar Convention also proposes that countries include wetland losses and wetlands with restoration potential in their national wetland inventories (Ramsar Convention Secretariat, 2010). Given that many wetlands in Swaziland are degraded (Hughes and Hughes, 1992; Mwendera, 2002; Frenken and Mharapara, 2002; Masarirambi *et al*., 2010) the wetland probability maps produced in this study are well suited for this purpose due to the methods used to create and improve them. This includes providing the government of Swaziland with the ability to estimate the probability that pieces of degraded land were originally wetlands, identify sites that can be rehabilitated, and provide an estimate of how many wetlands and other watercourses have been lost in the different areas across the country, due to different land use changes. This will contribute towards future water resource management in Swaziland where the government will be able to identify the types of land uses that cause the most damage to wetlands and be able to implement strategies to mitigate against these impacts. Using methods similar to those employed in Uganda, a vulnerability score can be assigned to wetlands using land use maps, population data, and transport routes (Government of Uganda, 2009). The maps can also be used to increase the awareness and interest of wetlands for politicians, government officials, land use planners, students and scientists, which is one of the many benefits of a national wetland inventory (Scott and Jones, 1995).

Should Swaziland decide to follow the wetland mapping techniques used in the South African Inventory of Inland Aquatic Ecosystems (SAIIAE) (van Deventer *et al*., 2018a) where wetlands were manually digitized, the wetland probability maps provide useful guidelines to steer wetland digitizing and classification. Because the wetland probability mapping technique of Collins (2018) can be created using only open source data, it can be applied to various other African countries that require baseline information on wetland distribution. Where a soil map is available, the initial wetland probability map can then be refined to partially differentiate wetlands from other watercourses. If South Africa continues to digitize wetlands across the remaining parts of the country (only 31% of the wetlands in South Africa are currently mapped/digitized at a medium and above confidence level), the wetland probability map of Collins (2018) should be used as a guide to locating the rest of the countries wetlands. The fact that the wetland probability maps can also be used to identify degraded wetlands is also of great importance to South Africa. The reason for this is because the country's definition of a wetland includes drained wetlands, of which the water table is no longer at or near the surface, as well as land that is no longer periodically covered with shallow water (Collins, 2005).

This study also classified the areas with the highest probability of being wetlands in the hydrogeomorphic (HGM) units of Ollis *et al*. (2013). There are numerous benefits to classifying wetlands into HGM units that can be used by the Government of Swaziland. This includes understanding the relationship between organisms and the environment (Brinson, 1993), providing information about how the wetland is connected to the drainage network, identifying how water moves through the wetland, and superficially deriving the ecosystem services that a wetland unit provides at a broad-scale (Sieben *et al*., 2018). This study has also identified how the distribution of the larger wetland systems in Swaziland are governed by changes in elevation, soils and geological contact zones, which occur predominantly along the major river systems of the country. This agrees with previous research concerning wetland distribution in Swaziland (Grimwood, 1973; Hughes and Hughes, 1992; IUCN, 1997), as well as in southern Africa (Tooth and McCarthy, 2007; Ellery *et al.,* 2008, Grundling *et al*., 2014a; Tooth, 2017).

In conclusion, the probability maps produced in this study are able to successfully locate watercourses with a high probability of being wetlands across Swaziland. Although they do not result in a 100% accurate wetland map, they serve the purpose of providing baseline information about the country's wetland distribution. Provided that other countries possess a soil map, the methods used to refine and classify the initial wetland probability map can also be applied to other countries that are in need of this baseline information.

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Appendix 1

Soil sets of Murdoch (1970), classified into the wetness regimes of the South African wetland delineation guidelines (DWAF, 2005), as well as the hydrological soil types of Van Tol *et al*. (2013).

Soil Set (Murdoch, 1970)	**Descriptions and characteristics**	**SA wetland regime (DWAF, 2005)**	**Hydrological soil type (Van Tol *et al*., 2013)**
A	Dark humic top, yellow or yellow brown laomy, deep, acidic, medium texture, imperfectly drained. May have soft iron pan below 100cm	Seasonal	Interflow rock
B	Stratified alluvium, juvenile ,deep, brownish, light textured, occur on lower river terraces, well to somewhat excessively drained.	Seasonal	Recharge
CH	Very deep humic clay, moderately well drained.	Terrestrial	Recharge
CL	Deep, dark reddish brown structured clay, vertic, occur in mid to lower slope positions, imperfectly drained.	Terrestrial	Interflow rock
DH	Highly organic	Permanent	Responsive
DL	Very deep, yellowish, imperfectly drained, may have dark humic top, fine sandy loam to clay loams, layer of mottling and sot iron concretions at depth. Occur in mid-slope positions as discontinuous patches.	Seasonal	Interflow rock
E	Deep coarse greyish bleached sand (E horizon) over clay or iron pan at 60cm or deeper. Gently sloping areas in mid to lower slope positions.	Seasonal	Interflow AB
F	Deep red or yellowish red sandy clay loam, can also be orange sandy clay with lighter top, iron concretions and soft iron pan at depth.	Seasonal	Interflow rock
G	Grey sandy topsoil, light or medium texture over concretions and/or cemented iron pan at very shallow to moderate depth, occurs on gently sloping land, usually above present water tables, imperfectly drained.	Seasonal	Interflow rock
H	Greyish sand over gleyed and mottled sandy clay subsoil with massive blocky structure, poorly (or imperfectly) drained.	Permanent	Interflow AB
I	Hydromorphic soils with gleying and mottling at the surface, mostly stratified alluvium, may have dark humic topsoil, poorly to very poorly drained. Occur in water holes and small depressions where drainage is extremely poor.	Permanent	Responsive
JH	Dark compact topsoil overlying a thick stoneline at about 30-60cm depth, moderately well drained.	Terrestrial	Recharge

JL	Brownish or reddish grey coarse loamy sand, very deep (at least 60cm), light texture, well to somewhat excessively drained. Depth to weathering rock is > 60cm. Occur in upper to mid-slope positions often along major river valleys.	Recharge	Interflow AB
K	Moderately deep blocky black or very dark grey cracking clay, on basic rock (lithomorphic), imperfectly drained (described as poorly). Occur in lower slope positions and bottomlands, or areas of impeded drainage.	Seasonal	Responsive
L	Very deep red sandy clay loam, strong blocky or nutty structure, gradual horizon boundaries, well drained. Occur on gently sloping valley sides or on ancient river terraces.	Terrestrial	Recharge
M	Strongly weathered very deep red to orange sandy clay to clay, generally weak structure and gradual horizon boundaries, relatively acid and low CEC clay, well drained. Occur on upper and midslopes.	Terrestrial	Recharge
N	Brown medium textured sandy loam over red clay, well drained. Occur on gentle lower slopes adjacent to river terraces.	Terrestrial	Recharge
O	Shallow sandy soils (often less than 40cm), light and medium texture, well to somewhat excessively drained. Found on upper to midslopes and the margins of rocky areas.	Terrestrial	Interflow rock
P	Grey weak structure sandy loam (35-60cm deep) over weathering rock, imperfectly drained. Found in upper to midslope positions on and steeper ground	Seasonal	Interflow Rock
QH	deep to very deep, medium texture, grey topsoil, gravelly red to yellow subsoil, merging horizons, on rotten rock, somewhat excessively drained.	Terrestrial	Recharge
QL	Sandy topsoil, abruptly overlying olive yellow sodic, calcareous sandy clay subsoil.	Seasonal	Interflow AB
R	Moderately deep to very deep dark reddish, well-structured clay loam to clay, relatively high base saturation and CEC clay, moderate organic matter, well to imperfectly drained.	Terrestrial	Recharge
SH	Dark humic top, moderately deep to deep , medium texture, well structured, on basic rock, well to moderately well drained.	Terrestrial	Recharge
SL	Very shallow to shallow, medium to heavy texture dark loam clay to clay on basic rock, well to moderately well drained. Depth to hard rock can be considerable. Occurs in upper or mid-slope positions.	Terrestrial	Responsive shallow

TH	Greyish moderately deep (30-80cm), very acid, loamy sand to sandy loam on deeply weathered whitish soft rock.	Terrestrial	Responsive
TL	Dark grey or dark brown sandy clay loam to clay loam, medium to heavy texture,overlying a mottled and gleyed clay which may contain mottles and concretions, imperfectly to poorly drained, occurs in midslope positions where drainage is impeded.	Permanent	Interflow Rock
U	Rock outcrops, large boulders or bedrock unconsolidated debris of talus slopes, alluvial pebbles, etc. Steep and very steep slopes, somewhat excessively or excessively drained. Includes small pockets of associated very shallow and shallow soil.	Terrestrial	Recharge
V	Very deep brown, grey or black cracking clay, strongly vertic with blocky structure, calcareous but generally no calcic horizon, poorly drained. May be gleyed. Occurs in lower slope positions and bottomlands.	Permanent	Responsive
W	Deep (usually > 150cm) red or yellowish red sandy loam to sandy clay, weak structure, alluvium of river terraces,predominantly well drained.	Terrestrial	Recharge
X	Coarse textured stratified alluvium of present river floodplains, low sand banks and channels, no profile differentiation.	Seasonal	Recharge
Y	Saline or saline-alkaline, dark, deep to very deep,clay calcareous, poorly drained, often caused by irrigation, found on colluvium. Occur in bottomlands.	Permanent	Responsive
ZH	Red to orange sandy clay loam to sandy clay, weathering rock at 90cm depth, well drained.	Terrestrial	Recharge
ZL	Grey coarse sandy loam, abruptly overlying dark grey prismatic sandy clay with vertic properties, found in gentle slopes and lowland areas, poorly drained.	Interflow AB	Interflow AB

Appendix 2

Results of the Anova Test used to determine if hydrogeomoprhic units and other watercourse types showed significant differences in their morphometric values across the different physiographic zones of Swaziland. CVB= channelled valley-bottom, UVB= Unchannelled valley-bottom, Dl= drainage line. Green represents a statistical difference, whilst red does not.

Highveld	Slope							Curve						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x													
First/Second Order dl	2E-16	x												
not	0,0024	0,7217	x											
Riparian	0,0032	5,8E-10	0,0303	x							0,07874			
river	0,2818	0,00003	0,252	0,6176	x									
seep	1,3E-07	1,2E-15	0,0387	0,6176	0,4534	x								
uvb	0,5982	2E-16	0,0021	0,0023	0,1978	0,000005	x							

Lower Middleveld	Slope							Curve						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x							x						
First/Second Order dl	0,08	x						1	x					
not	0,478	0,235	x					0,629934	0,514727	x				
Riparian	0,772	0,019	0,207	x				0,999999	0,999992	0,215964	x			
river	0,772	0,171	0,675	0,531	x			1	1	0,564629	0,99999	x		
seep	0,531	0,171	0,772	0,216	0,772	x		0,998183	0,997226	0,900424	0,975557	0,998023	x	
uvb	0,207	0,207	0,829	1,4E-06	0,478	0,531	x	0,221222	0,194124	0,027102	0,19499	0,197616	0,119702	x

Upper Middleveld	Slope							Curve						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x													
First/Second Order dl	7,3E-08	x												
not	0,00025	0,82646	x											
Riparian	0,05763	0,00397	0,01957	x							0,307			
river	0,85801	3,1E-07	0,00021	0,06102	x									
seep	0,000074	0,00026	0,01293	0,81458	0,0016	x								
uvb	0,5036	2,7E-06	0,00021	0,03073	0,67806	0,00397	x							

Western Lowveld	Slope							Curve						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x													
First/Second Order dl	0,089	x												
not	0,39	0,265	x											
Riparian	0,867	0,028	0,089	x							0,8023			
river	0,544	0,153	0,674	0,207	x									
seep	0,218	0,271	0,562	0,022	0,338	x								
uvb	0,223	0,012	0,028	0,158	0,049	0,012	x							

Eastern Lowveld	Slope							Curve						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb								x						
First/Second Order dl								0,999615	x					
not								0,992343	0,854021	x				
Riparian				0,08749				0,99627	0,714128	0,999985	x			
river								0,206074	0,110203	0,044176	0,012793	x		
seep								0,668111	0,661271	0,291253	0,211744	0,998049	x	
uvb								0,979532	0,993056	0,755738	0,722206	0,803825	0,988298	x

Lebombo	Slope							Curve						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x							x						
First/Second Order dl	0,48221	x							x					
not	1	1	x							x				
Riparian	1	0,00096	1	x							x			
river	0,53922	0,000061	0,53922	0,04395	x							x		
seep	0,53922	0,00726	0,57742	0,4114	1	x							x	
uvb	1	0,57742	1	1	1	1	x							x

Highveld	Curve_plan							Curve_prof						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x							0,08517						
First/Second Order dl	0,018	x												
not	0,852	0,454	x											
Riparian	0,539	0,852	0,622	x										
river	0,959	0,454	0,852	0,622	x									
seep	0,852	0,018	0,852	0,589	0,959	x								
uvb	0,539	0,018	0,852	0,346	0,622	0,454	x							

Lower Middleveld	Curve_plan							Curve_prof						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x							0,05555						
First/Second Order dl	0,788197	x												
not	0,98025	0,198701	x											
Riparian	0,997108	0,860529	0,600472	x										
river	1	0,778323	0,95097	0,998404	x									
seep	0,998668	0,387567	0,999872	0,854621	0,994697	x								
uvb	0,134646	0,420278	0,045069	0,168836	0,135789	0,069491	x							

Upper Middleveld	Curve_plan							Curve_prof						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x							0,528						
First/Second Order dl	0,00096	x												
not	0,46025	0,46843	x											
Riparian	0,45222	0,63097	0,82463	x										
river	0,12635	0,11603	0,87651	0,63387	x									
seep	0,04481	0,12635	0,96032	0,76152	0,82213	x								
uvb	0,15222	0,93056	0,63097	0,76152	0,46843	0,52518	x							

Western Lowveld	Curve_plan							Curve_prof						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	0,4443							0,9046						
First/Second Order dl														
not														
Riparian														
river														
seep														
uvb														

Eastern Lowveld	Curve_plan							Curve_prof						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	0,06297							x						
First/Second Order dl								0,984636	x					
not								1	0,978105	x				
Riparian								0,999999	0,970348	0,999988	x			
river								0,023274	0,014846	0,024105	0,005327	x		
seep								0,66792	0,846511	0,648168	0,596931	0,852388	x	
uvb								0,851338	0,970831	0,83355	0,815115	0,593633	0,998431	x

Lebombo	Curve_plan							Curve_prof						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	0,06828							0,307						
First/Second Order dl														
not														
Riparian														
river														
seep														
uvb														

Highveld	Elevation						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x						
First/Second Order dl	0,990157	x					
not	0,885828	0,606736	x				
Riparian	0,968686	0,99901	0,579472	x			
river	0,327623	0,517838	0,113934	0,922599	x		
seep	0,694686	0,046406	0,99971	0,321151	0,014776	x	
uvb	0,382379	0,107658	0,998046	0,158472	0,012039	0,891777	x

Lower Middleveld	Elevation						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x						
First/Second Order dl	0,902929	x					
not	0,818759	0,094916	x				
Riparian	0,450746	0,002141	0,999972	x			
river	0,489554	0,014458	0,99896	0,99983	x		
seep	0,781048	0,07795	1	0,999998	0,999604	x	
uvb	0,966281	0,999603	0,676782	0,561204	0,518973	0,654516	x

Upper Middleveld	Elevation						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x						
First/Second Order dl	0,999998	x					
not	0,999944	0,999236	x				
Riparian	0,999006	0,993632	0,999999	x			
river	0,899704	0,716928	0,993647	0,99871	x		
seep	0,078465	0,026158	0,147127	0,07186	0,00031	x	
uvb	0,996933	0,99851	0,988954	0,974856	0,849285	0,975775	x

Western Lowveld	Elevation						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x						
First/Second Order dl	0,6271	x					
not	0,9983	0,6271	x				
Riparian	0,814	0,4219	0,6336	x			
river	0,1715	0,6271	0,023	0,0021	x		
seep	0,6271	0,9983	0,3036	0,023	0,2688	x	
uvb	0,9983	0,6271	0,9983	0,8966	0,2688	0,6271	x

Eastern Lowveld	Elevation						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x						
First/Second Order dl	0,999941	x					
not	1	0,999482	x				
Riparian	0,013985	6E-07	0,031804	x			
river	0,654382	0,536745	0,607237	8,4E-06	x		
seep	0,867758	0,558913	0,917096	0,780484	0,101759	x	
uvb	0,924058	0,651889	0,958124	0,576272	0,12652	0,999997	x

Lebombo	Elevation						
	cvb	First/Second Order dl	not	Riparian	river	seep	uvb
cvb	x						
First/Second Order dl	0,05817	x					
not	0,06526	0,86467	x				
Riparian	0,00628	0,0214	0,54342	x			
river	0,00628	0,00052	0,05817	0,00628	x		
seep	0,41097	0,46171	0,51469	0,06526	0,00628	x	
uvb	0,73684	0,57023	0,66667	0,32748	0,2382	1	x

Appendix 3

METADATA FOR THE WETLAND PROBABILITY MAP OF SWAZILAND.

PROJECT DETAILS

Project title: The hydrogeomorphic distribution of the wetlands in Swaziland, and their prediction.
Start date: Januray 2017
End date: November 2019
Study Area: The Kingdom of Eswatini (formerly known as Swaziland)

PROJECT DATA AND METADATA DESCRIPTION

Data generated: July 2017

Geographical Coverage
The Kingdom of Eswatini (formerly known as Swaziland)

Description
One final vector layer has been created that contains three classes
1. The initial wetland probability map, based on the methods of Collins (2018)
2. The refined wetland probability map, which distinguishes wetlands from other watercourses
3. The classified wetland probability map, which classifies the areas of the initial map with the highest probability of being wetland into the hydrogeomorphic units of Ollis *et al*. (2013).

Methods:
The source data used to create the wetland probability map was the 90m SRTM data, interpolated to 30m horizontal resolution, and 2008 SPOT Images. The wetland probability map was created through selectively identifying mapping parameters (flow accumulation and percentile filters), that best represent potential wetland sites within a mapping area. Soil (Murdoch, 1970) and slope values derived from the SRTM data were then used to refine the initial wetland probability map into three classes of varying wetland probability. The rivers layer of Swaziland, along with slope values were then used to classify the areas with the highest probability of being wetland into the hydrogeomorphic units of Ollis *et al*. (2013). Details on how soils and slope values were used to improve the initial wetland probability map are provided in the thesis accompanying this metadata set.

Legends
1. The initial wetland probability map
- potential wetlands

2. The refined wetland probability map
-probably wetland
-either wetland or other watercourse

-probably other watercourse
3. The classified wetland probability map
-Channelled valley bottom
-Unchannelled valley bottom
-Seep

Data Usage rights:
The data are intended for use by registered researchers only and the database administrator (DBA). The datasets may be used for non-profit research, non-profit nature conservation / environmental management only. A copy of the data set will be handed over to the Eswatini National Trust Commission once this thesis has been examined.

PEOPLE AND ORGANISATIONS:

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SPECIFICATIONS

Projected Coordinate System:	WGS_1984_Albers
Projection:	Albers
False_Easting:	0,00000000
False_Northing:	0,00000000
Central_Meridian:	25,00000000
Standard_Parallel_1:	20,00000000
Standard_Parallel_2:	-23,00000000
Latitude_Of_Origin:	0,00000000
Linear Unit:	Meter

Geographic Coordinate System:	GCS_WGS_1984
Datum:	D_WGS_1984
Prime Meridian:	Greenwich
Angular Unit:	Degree

Appendix 4

Ethics Approval

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee

E-mail: ethics.nas@up.ac.za

30 October 2019

ETHICS SUBMISSION: LETTER OF APPROVAL

Mr JP le Roux
Department of Geography Geoinformatics and Meteorology
Faculty of Natural and Agricultural Science
University of Pretoria

Reference number: 180000131
Project title: The hydrogeomorphic distribution of the wetlands in Swaziland and their prediction.

Dear Mr JP le Roux,

We are pleased to inform you that your submission conforms to the requirements of the Faculty of Natural and Agricultural Sciences Research Ethics committee.

Please note the following about your ethics approval:

- Please use your reference number (180000131) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.
- Please note that ethical approval is granted for the duration of the research (e.g. Honours studies: 1 year, Masters studies: two years, and PhD studies: three years) and should be extended when the approval period lapses.
- The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

Post approval submissions including application for ethics extension and amendments to the approved application should be submitted online via the Ethics work centre.

We wish you the best with your research.

Yours sincerely,

Chairperson: NAS Ethics Committee