Determining the distribution of wetlands across Eswatini

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Abstract

Eswatini 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 applies a newly developed wetland mapping technique (produced in South Africa) to Eswatini, to provide baseline information on the potential distribution of wetlands across the country. Results of this study show that when applying the mapping technique as it was applied in South Africa, watercourses (rivers, drainage lines, and riparian zones) are more frequently mapped than true wetlands. Given that Eswatini currently uses the broad Ramsar definition of a wetland, the potential wetland map produced in this study is well suited to identify wetlands falling under such definition. However, the technique does not suffice where a more specific definition for wetlands is used. To improve the initial potential wetland map, this study made use of data, obtained from 2 000 points distributed across the initial wetland map, by classifying areas with the highest potential of being wetlands into hydrogeomorphic units. Results indicate that the methods used to improve the initial map areable to distinguish watercourses with a higher potential of being a true wetland and identify certain hydrogeomorphic units. This method can therefore be used to provide baseline data of potential wetland distribution for countries that do not possess the means, or attribute data to produce a comprehensive wetland map.

Keywords: Ramsar Convention; wetlands; Eswatini; mapping; potential wetland distribution

1. Introduction

In southern Africa, the degradation of wetlands is often attributed to a lack of management, which is often a result of governments and landowners not having the resources and information needed to identify wetlands to mitigate against anthropogenic impacts (Mwendera, 2003; Marambanyika & Beckedahl, 2017; Masarirambi et al., 2010). To combat wetland degradation, many governments have established specific laws and policies that aim to protect and govern their use. An overarching convention that steers many of these policies relating to wetlands is the Ramsar Convention. It was established in 1971 and to date has 171 contracting parties (Ramsar Homepage, 2021). The Kingdom of Eswatini (formerly known as the Kingdom of Swaziland) completed the accession to the Ramsar Convention on 15 June 2013 and currently has only three sites designated as Wetlands of International Importance (Ramsar Sites).

Given the generally low household income levels in Eswatini, a large number of its people depend directly on wetlands. They serve as an important water supply for people and provide grazing resources and areas for dry season cropping (Mwendera, 2002). A significant number of women in Eswatini use wetlands as an important economic resource and earn a living off using plants found in wetlands to make various crafts that include sleeping mats, bags, baskets, handcrafts as well as medication (B. Dlamini, 1981;Mwendera, 2003; Zwane et al., 2011). Important cultural ceremonies, including the maiden reed dance, also make use of wetland vegetation (Mwendera, 2003). In southern Africa, it is not always these direct subsidiary uses that result in a loss of wetland area, but rather population expansion and the growing need for land that has been a major driver of wetland loss (Jackson et al., 2016). This highlights the need for adequate management tools to be set in place.

Along with many recommendations concerning the wise use and management of wetlands, the Ramsar Convention specifically recognizes the importance of national inventories as a key tool for informing policies and other actions to achieve the conservation and wise use of wetlands (Ramsar Convention Secretariat, 2010). The Ramsar Convention's handbook (Ramsar Convention Secretariat, 2010) emphasizes that national 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 objectives of an inventory can vary depending on the type of information required as wetland inventories are compiled for various reasons (Finlayson & Spiers, 1999), including the awareness of wetlands on the part of politicians, government officials, land-use planners, students and scientists (Scott & Jones, 1995). Furthermore, in addition to determining the extent and distribution of wetlands, a classification system that distinguishes between different types of wetlands is fundamental to the compilation of a national wetland inventory (Ewart-Smith et al., 2006). Sieben et al. (2018) explain that one of the most important aims of allocating wetlands to a certain type or class is to provide information about the ecosystem services that the wetland provides. Varying forms of evaluation, management and conservation are also needed for different wetland types (Dini & Cowan, 2001).

2. Wetland inventories and mapping in South Africa

Despite attempts to map the wetlands of Eswatini (Franke et al., 2013; Grimwood, 1973; Masarirambi et al., 2010) the country does not yet have a wetland inventory. Given that Eswatini is mostly bordered by South Africa, with the boundaries being political rather than physical, and shares many strategic water sources (Le Maitre et al., 2018), there is a high likelihood that the wetland mapping techniques developed in South Africa are applicable to Eswatini. Van Deventer (2018a); and Van Deventer et al. (2020) recently updated the South African wetland inventory using alternative methods to remote sensing, as users of the previous South African wetland map (Nel et al., 2011) noted several problems with its accuracy (Grundling, 2014; Grundling et al., 2014, 2013; Mbona et al., 2015; Collins, 2018;

Rebelo et al., 2017; Van Deventer et al., 2018b). Van Deventer et al. (2018c); and Van Deventer et al. (2020) combined various sources of on-screen digitized wetlands to map and classify the wetlands of South Africa for the national 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., 2018c). Due to the time and budget constraints of the present study, it was not practical to digitize the wetlands for the entire Eswatini, which led to alternative methods being required.

In addition to the on-screen digitizing of wetlands, South Africa also explored the use of a predictive wetland mapping technique, as an alternative method to remotely sensed wetland mapping (Collins, 2018). The technique is relatively new, and there is a limited understanding of how and where it can be of use (Van Deventer et al., 2018b). On the one hand, while other wetland predictive mapping approaches in the form of probability maps have been conducted in South Africa (Hiesterman & Rivers-Moore, 2015; Melly et al., 2017) along with an increasing international trend in the development of wetland probability maps (Nyandwi et al., 2016; Nyarko et al., 2015; Pantaleoni et al., 2009; Stein et al., 2016) the approaches that yield relatively high accuracies are based on complex statistical models such as Logistic Regression and Bayesian network models that require input variables that are not always available, or not at a fine enough scale for countries such as Eswatini. These forms of statistical models also require an existing inventory of wetland types, which again are not available for countries such as Eswatini. On the other hand, the initial objective of Collins (2018) when developing a wetland prediction map for South Africa, was to rapidly map extensive areas with minimum data, skill, and cost requirements. Although the method of Collins (2018) is referred to as a wetland probability map, it does not create a scaled output that assigns a probability percent or values between 0 and 1, such as a statistical analysis that includes receiver operating characteristic curves (ROC), or areas under the curve (AUC). Rather, the method of Collins (2018) maps low-lying areas that have a potential for wetland occurrence. This paper therefore uses the term potential occurrence, rather than probability of occurrence, although the technique of Collins (2018) has been followed.

The wetland mapping technique of Collins (2018) is based on a Digital Elevation Model (DEM), and focuses on the landscape position criterion for identifying and delineating wetlands in South Africa (DWAF, Department of Water Affairs and Forestry, 2005). The method is based on the assumption that water will accumulate in the lowest positions of the landscape which are likely the areas of highest potential for wetland occurrence (Collins, 2018). 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 be 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. Another disadvantage of this wetland mapping technique is that it does not map depressional wetlands nor seep wetlands not connected to a valley-bottom, as it focuses on wetlands within and adjacent to valley-bottom positions.

Mapping aims to selectively identify wetlands based on the subjective identification from aerial imagery. Data required to produce the map includes remotely sensed imagery (either aerial photographs or satellite imagery) and a Digital Elevation Model (DEM). The mapping technique begins by subdividing the study area into mapping regions which are based on factors pertaining to wetland development and include rainfall, relief and generalized geology. Thereafter, parameters for flow accumulation and a percentile filter analysis are determined for each mapping region based on a trial-and-error approach until the parameters adequately map what the user perceives to be wetland, and are then combined to produce a layer of potential wetlands. The technique is similar to onscreen digitizing, 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. Flow accumulation parameters 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, perceived through expert opinion to be associated with a change in moisture conditions. The 'percentile filter' tool of Whitebox GIS (Lindsay, 2014) is 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 and associated seeps. 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 is specified according to the relief of a particular mapping region. 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 is determined for each mapping region. This allows 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 potential wetlands. For a full description of the methodology, please refer to Collins (2018).

To date, the method of Collins (2018) has been applied to South Africa, but has not been extensively tested; particularly with regard to the extent to which it maps other types of watercourses, such as rivers and drainage lines, which are not always wetlands. This study aimed to apply the methods of Collins (2018) to map potential areas of wetland occurrence in Eswatini and determine the percent of wetlands mapped against other types of watercourses. An attempt was then made to improve the initial potential wetland map to distinguish wetlands from other types of watercourses and to classify the areas with the highest potential of being wetlands into hydrogeomorphic units. Given that the Eswatini is currently in the process of developing a National Wetland Policy (Gumedze, 2019), the wetland map produced in this study has the potential to benefit Eswatini when developing this policy, as well as other African countries, with limited attribute data/input variables, which require a wetland map and do not have the means of digitizing the wetlands in their respective countries.

3. The study area

The Kingdom of Eswatini hosts a wide range of physiographic landscapes (Remmelzwaal, 1993; Dlamini, 2017). The country is bordered by South Africa in the north, west and south, and by Mozambique in the east (Figure 1) and covers 17 364 km^2. Elevation ranges from over 1800 m.a.s.l. in the western plateaux to under 100 m.a.s.l. in the east. It is separated from the Mozambique coastal plains by the Lebombo Mountain range that rises to 600 m.a.s.l. (Remmelzwaal, 1993).

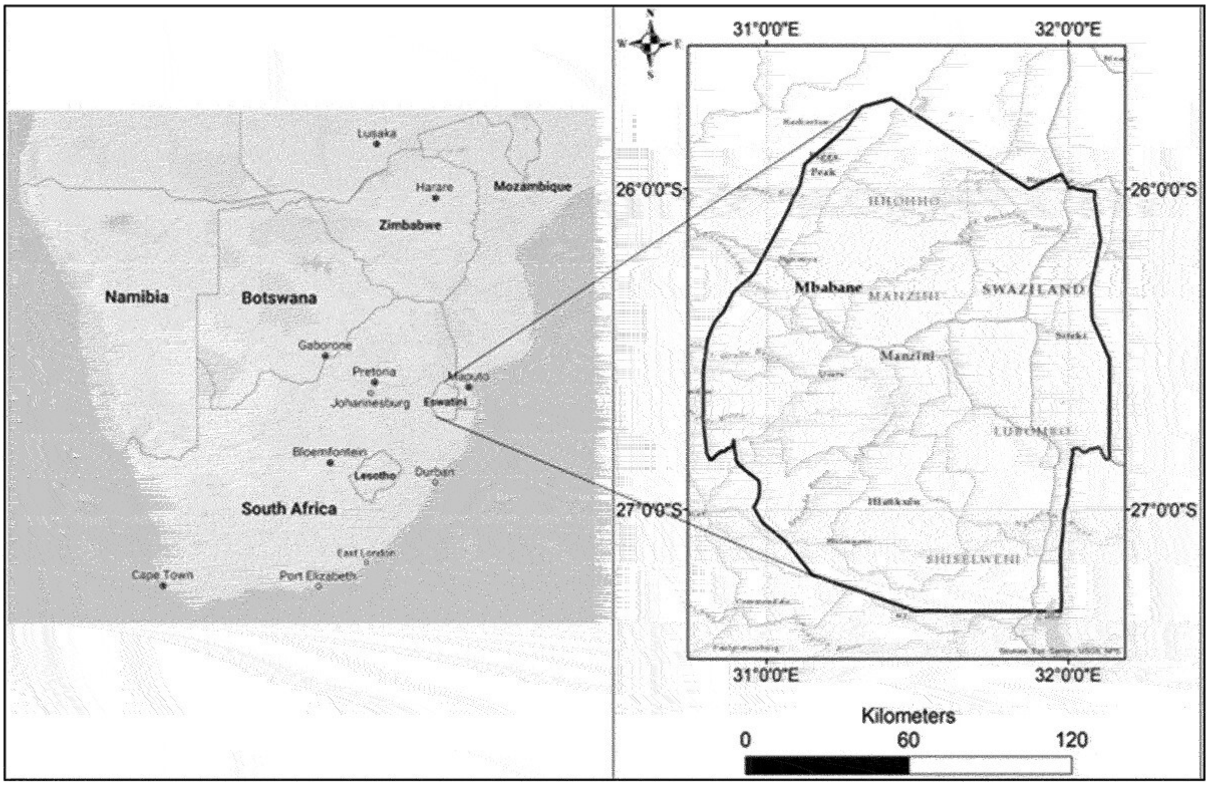


Figure 1. Location map of Eswatini.

Eswatini has a sub-tropical climate, with warm wet summers and cool dry winters. 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 has an average annual rainfall of 1500 mm and mean temperatures of between 16°C and 22°C. Central Eswatini and the Lubombo regions of Eswatini receive between 800 and 1200 mm of rain annually with mean annual temperatures of 20°C and 22°C, respectively. The low-lying eastern plains receive an average 450 mm of rain annually, with temperatures reaching over 30°C in the summer (Matondo et al., 2005).

Eswatini's geology is dominated Precambrian rocks (mostly of Archaean Age) in the west, and sedimentary and volcanic rocks of Karoo age in the east (Schlüter, 2008; Wilson, 1982). The 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). There are six physiographic zones across the country which include the Highveld, Upper Middleveld, Lower Middleveld, Western Lowveld, Eastern Lowveld and the Lebombo (Remmelzwaal, 1993; Figure 2). The geology of each physiographic region as well as other attributes are listed in Table 1, along with descriptions of the topography and landforms of the different regions.

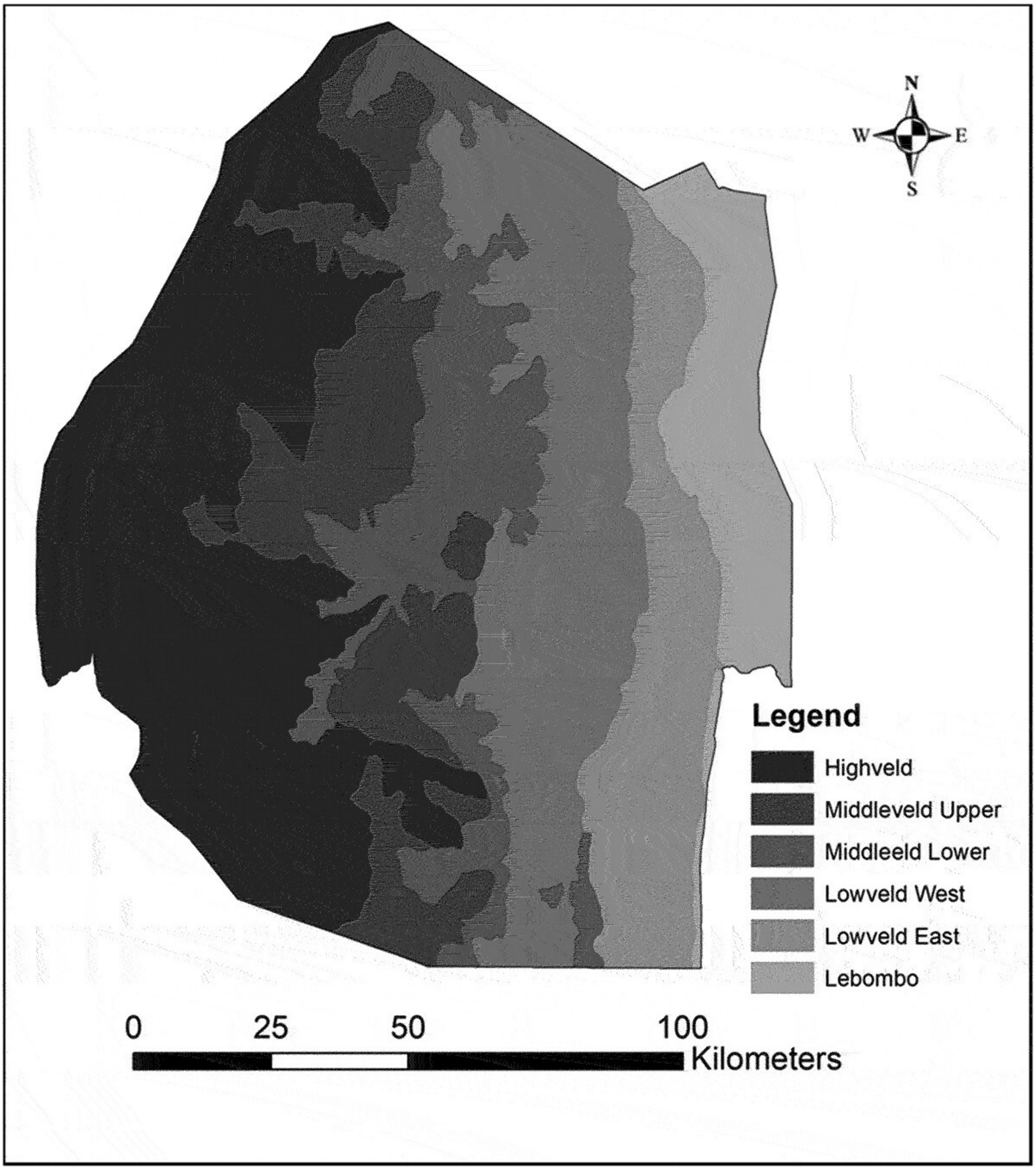
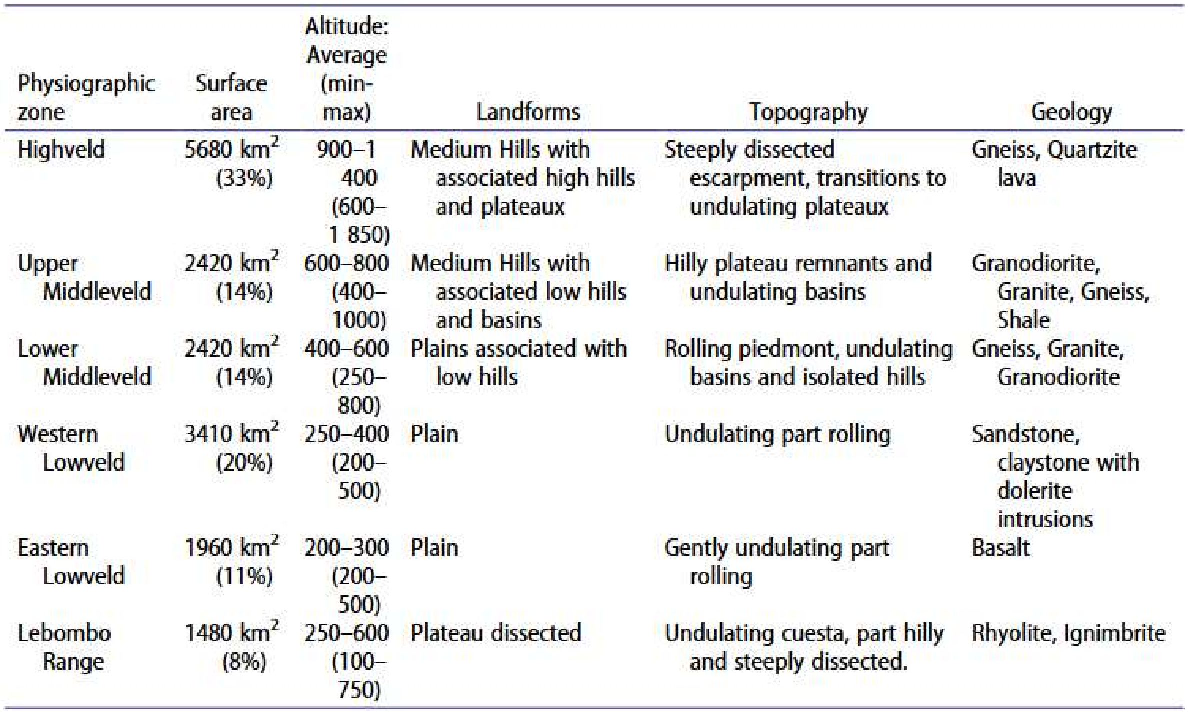


Figure 2. The physiographic zones of Eswatini (adapted from Remmelzwaal, 1993)

Table 1. Attributes of the physiographic zones of Eswatini (Swaziland) (modified from Remmelzwaal, 1993)



Physiographic zone	Surface area	Altitude: Average (min-max)	Landforms	Topography	Geology
Highveld	5680 km^2 (33%)	900–1 400 (600–1 850)	Medium Hills with associated high hills and plateaux	Steeply dissected escarpment, transitions to undulating plateaux	Gneiss, Quartzite lava
Upper Middleveld	2420 km^2 (14%)	600–800 (400–1000)	Medium Hills with associated low hills and basins	Hilly plateau remnants and undulating basins	Granodiorite, Granite, Gneiss, Shale
Lower Middleveld	2420 km^2 (14%)	400–600 (250–800)	Plains associated with low hills	Rolling piedmont, undulating basins and isolated hills	Gneiss, Granite, Granodiorite
Western Lowveld	3410 km^2 (20%)	250–400 (200–500)	Plain	Undulating part rolling	Sandstone, claystone with dolerite intrusions
Eastern Lowveld	1960 km^2 (11%)	200–300 (200–500)	Plain	Gently undulating part rolling	Basalt
Lebombo Range	1480 km^2 (8%)	250–600 (100–750)	Plateau dissected	Undulating cuesta, part hilly and steeply dissected.	Rhyolite, Ignimbrite

4. Methods of analysis

4.1 Mapping potential wetlands across Eswatini

There are many definitions for the term ‘wetland’, and for many years this has caused much confusion as to what technically qualifies as a wetland (Mitsch & Gosselink, 2015: Scott & Jones, 1995). Given that Eswatini uses the broad Ramsar definition of a wetland, which includes water that can be static or flowing (Ramsar Convention Secretariat, 2010), other types of watercourses such as rivers and drainage lines would be included under this definition, and implies that the method of Collins (2018) should be well suited. However, countries such as South Africa, who apply a stricter definition of wetlands (Republic of South Africa National Water Act No. 36, 1998), where the water table needs to usually be at or near the surface, or land needs to periodically be covered with shallow water, would not consider all the wetlands that fall under the definition of a Ramsar Convention as constituting a true wetland under their definition. The algorithm developed by Collins (2018) that divides the study area into mapping regions, was initially applied to Eswatini and originally produced 122 mapping regions. Flow accumulation and percentile filter parameters were subsequently determined for each respective mapping region at a 1:50 000 scale. Upon determining these parameters, the initial mapping regions were further split into 160 regions where it was found that thresholds be did not adequately map potential wetland areas within these respective mapping regions. To determine the accuracy of the initial wetland map, two accuracy assessments, which included a field and desktop-based assessment, were undertaken. The accuracy assessments were conducted using both the broad Ramsar definition of a wetland (Secretariat, 2010), as well as the stricter definition used in South Africa (Republic of South

Africa National Water Act No. 36, 1998) to determine the ability of the mapping approach to identify wetlands falling under these respective definitions.

The first accuracy assessment included travelling 510 km through Eswatini on both tarred and dirt roads. Each apparent watercourse that intersected the road, or was situated close enough to the road to be identified, was marked using a Garmin 62 GPS and classified as a 'wetland', 'other type of watercourse', or 'not a watercourse'. Wetlands were further classified into the hydrogeomorphic units of Ollis et al. (2013); and Ollis et al. (2015); other types of watercourses were classified into steep first- and second-order drainage lines, riparian zones based on the definition of DWAF, Department of Water Affairs and Forestry (2005), and rivers. Due to the limited number of 369 observation points, a second, desktop-based accuracy assessment was also undertaken. In order to do this, 2000 random points were distributed across the initial potential wetland map created for Eswatini using the ArcGIS random point's tool (ESRI, 2018). The number of points chosen was found to be the smallest number 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 be 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. The points were then converted to kml format and imported into Google Earth Pro (Google Earth Pro Inc, 2019).

Each point was subsequently classified in the same manner as the field-based accuracy assessment. This was considered to be an acceptable method, considering that visual interpretation of aerial photography by means of manually digitizing wetlands is a well-established method to create and maintain wetland inventories (Melly et al., 2017). Van Deventer et al. (2018c) also used visual interpretation of aerial photography to create South Africa's National Wetland Map 5. Riparian zones were differentiated from steep first- and second-order drainage lines using the elevation profile tool of Google Earth Pro (Google Earth Pro Inc, 2019). 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 classed as 'disturbed' and hence had to be excluded, which left 1735 points that were used to calculate the accuracy of the initial potential wetland 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 & Döll, 2004), that it was not practical to distribute random points outside of the potential wetland map. The wetlands that would have been identified as omission errors would have resulted in a similar sample size to the field-based accuracy assessment, which was already conducted, and added little value to the overall assessment of the map's accuracy.

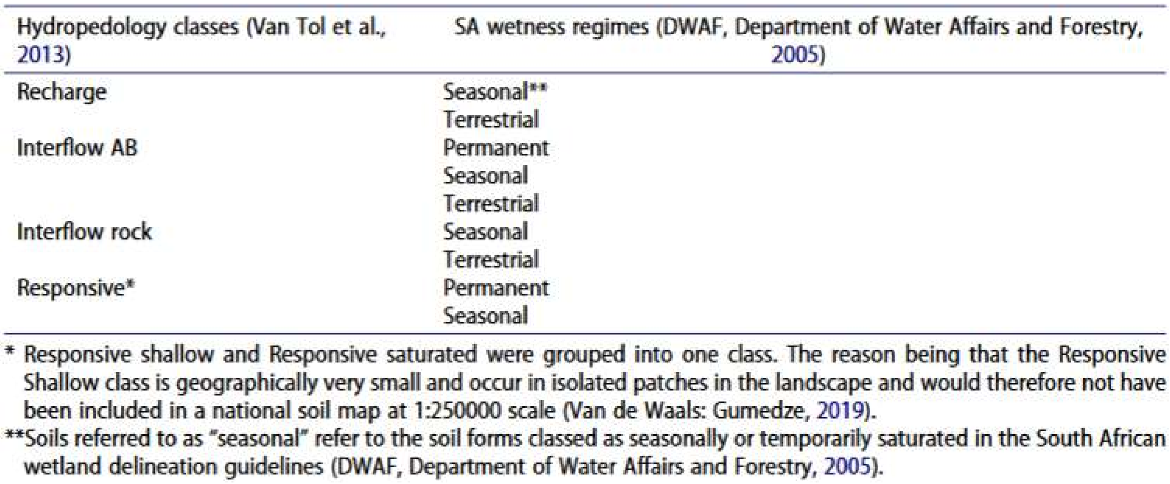
4.2 Improving the initial potential wetland map

4.2.1 Distinguishing between physiographic zones

Before the initial potential wetland map created for Eswatini could be improved to distinguish true wetlands from other types of watercourses, it needed to be determined whether the attributes that would be used to improve the map were the same across the different physiographic zones of Eswatini. If the attributes were the same across the physiographic zones, then the attributes that would be used to improve the map could be applied to the map as a whole, but if the attributes differed across the physiographic zones, then the initial potential wetland map for each physiographic zone would need to be improved separately.

The attribute data used to improve the accuracy of the initial potential wetland map included morphometrics derived from the SRTM DEM (NASA, National Aeronautics and Space Administration, 2000) using the respective tools in ArcGIS (ESRI, 2018), as well as the Soil Map of Eswatini (Murdoch, 1970). Morphometrics included Slope, Curvature, Plane Curvature, Profile Curvature as well as Elevation. The soil map of Eswatini (Murdoch, 1970) contained 32 soil sets that were mapped at a national scale (1:250000). For the purpose of improving the initial potential wetland 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), which was used to group soils with similar hydrological functioning, and the wetness regimes of soil forms listed in the South African wetland delineation guidelines (DWAF, Department of Water Affairs and Forestry, 2005). The two soil classifications were subsequently merged in order for soils to belong to only one of the newly combined soil classes (Table 2).

Table 2. Combined soil classes of Van Tol et al. (2013) and DWAF, Department of Water Affairs and Forestry (2005)



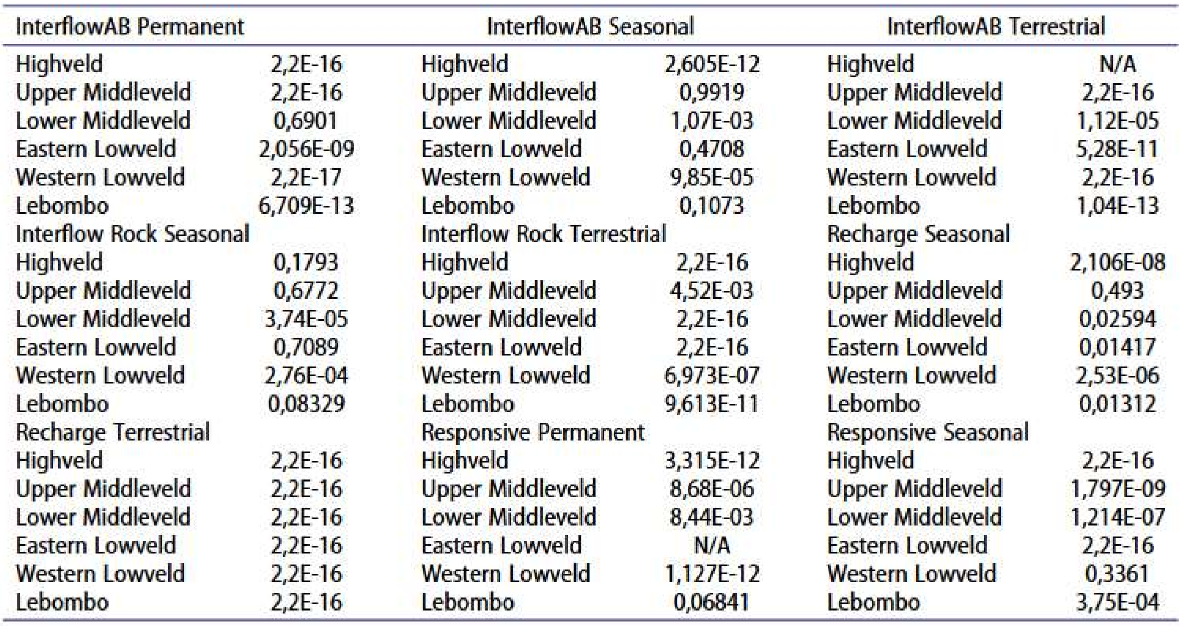
Hydropedology classes (Van Tol et al., 2013)	SA wetness regimes (DWAF, Department of Water Affairs and Forestry, 2005)
Recharge	Seasonal** Terrestrial
Interflow AB	Permanent Seasonal Terrestrial
Interflow rock	Seasonal Terrestrial
Responsive*	Permanent Seasonal

* 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 1:250000 scale (Van de Waals: Gumedze, 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, Department of Water Affairs and Forestry, 2005).

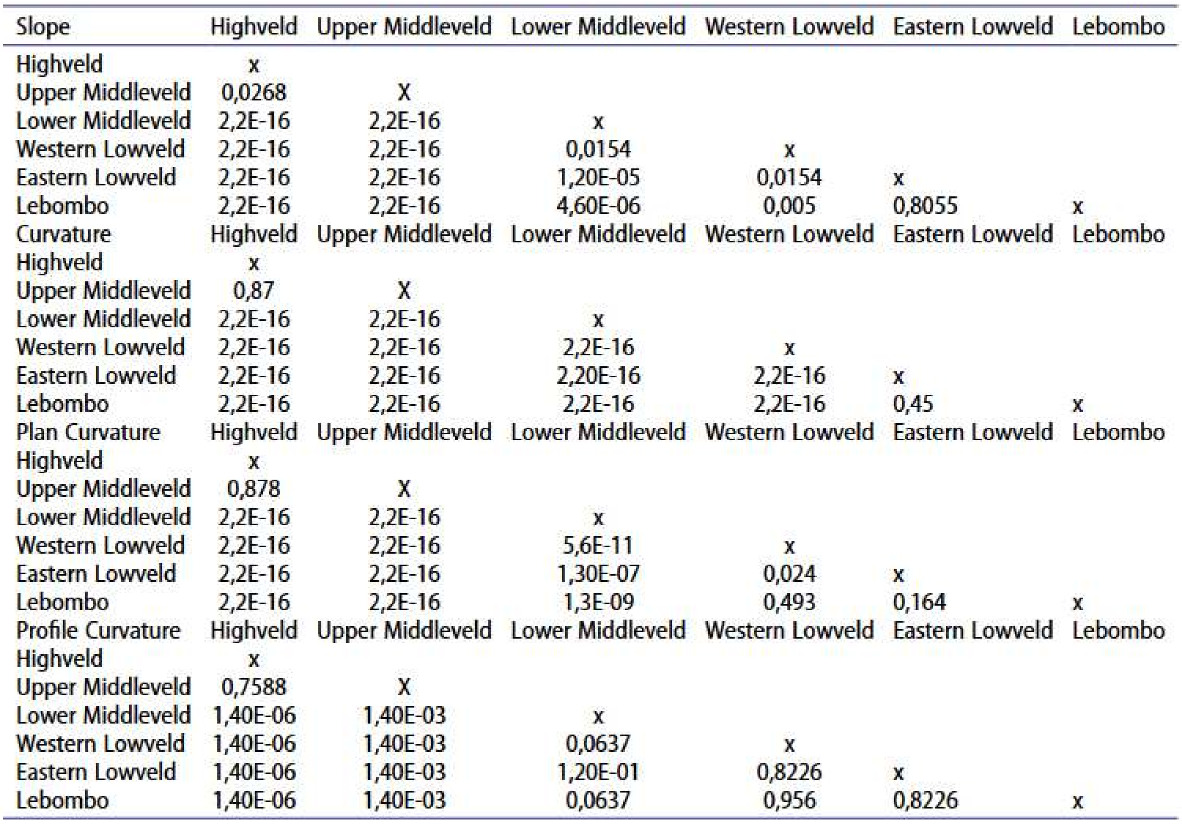
Statistical analysis, in the form of a two-proportion z-test, was performed on the soil classes using the prop.test function in R (R Core Team, 2013), and showed that the null hypothesis that the area of a combined soil class per physiographic region differed to the total area of that soil class across Eswatini can be accepted at the 95% confidence level. The results of this statistical test confirmed that the majority of soil classes per physiographic region exhibited statistically different soils when compared to the soils of Eswatini as the overall population (Table 3). 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 Eswatini and were also tested for a 95% confidence rating (Table 4). Results indicated that the vast majority of physiographic regions have statistically different morphometric values when compared to the morphometrics of other physiographic regions. Therefore, the results of the statistical tests above warrant that the soils and morphometrics should be used separately for each physiographic region to improve the initial potential wetland map.

Table 3. Results of a two-proportions z test, comparing the combined soil classes per physiographic region to Eswatini as a whole, where soils highlighted in grey showed a statistically significant different, whilst those not highlighted did not, when testing for a 95% confidence rate.



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 4. Results of the one-way analysis of variance used to test the equality of the different morphometric values per physiographic region to Eswatini as a whole. Morphometrics highlighted in grey showed a statistically significant different, whilst those not highlighted did not, when testing for a 95% confidence rate.



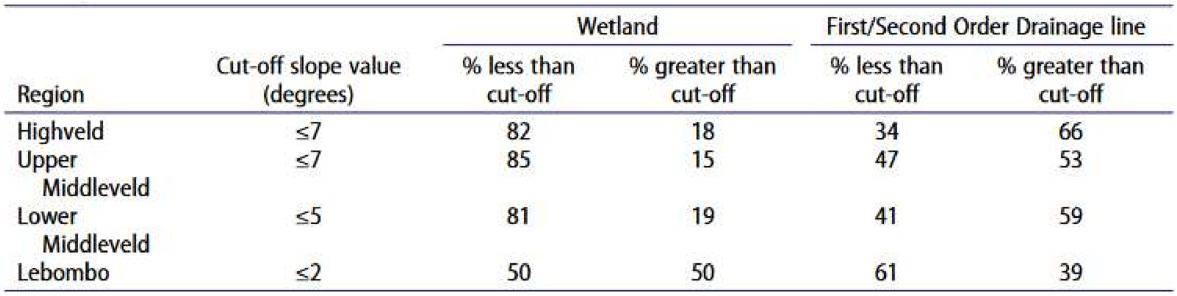
Slope	Highveld	Upper Middleveld	Lower Middleveld	Western Lowveld	Eastern Lowveld	Lebombo
Highveld	x					
Upper Middleveld	0,0268	X				
Lower Middleveld	2,2E-16	2,2E-16	x			
Western Lowveld	2,2E-16	2,2E-16	0,0154	x		
Eastern Lowveld	2,2E-16	2,2E-16	1,20E-05	0,0154	x	
Lebombo	2,2E-16	2,2E-16	4,60E-06	0,005	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

4.2.2 Differentiating wetlands from other types of watercourses

The same 2000 random points (reduced to 1735) used in the desktop accuracy assessment, which were classed as 'wetland', 'other type of watercourse', and 'not a watercourse' were used to differentiate wetlands from other types of watercourses, thereby forming the training data set to improve the initial potential wetland map. The soil class (combined wetness regime (DWAF, Department of Water Affairs and Forestry, 2005) and hydrological soil type (Van Tol et al., 2013)) as well as the slope value for each point was subsequently extracted and attributed to each random point. Slope was chosen as the morphometric used to improve the wetland map as it is the morphometric most commonly associated with potential wetland occurrence (Ellery et al., 2008; Grundling et al., 2014; Ollis et al., 2015, 2013). The first step to improving the initial potential wetland map was determining the percentage that the different types of watercourses, identified from the 2000 points, occurred on each soil class per physiographic region. If 75% or more of the random points that landed on a respective soil class per physiographic region were classified as wetland, the sections of the initial potential wetland map that intersected these soil classes were classified as having a high potential to be a wetland. On the other hand, if 75% or more of the random points that landed on a respective soil class per physiographic region were classified as another type of watercourse, the sections of the initial potential wetland map that intersected these soil classes were classified as having a low potential to be a wetland. The sections of the initial potential wetland map that intersected soil classes where less than 75% of the points that landed on them were classified as wetlands, or another type of watercourse, were classified as having a medium potential to be a wetland. No soil classes were found to not be associated with a type of watercourse. A cut-off value of 75% was based on the intended accuracy of the improved potential wetland map.

Since wetlands and other types of watercourses (e.g. riparian zones and rivers) can occur in the same landscape positions, slope values could not be used to differentiate wetlands from all other types of watercourses. However, it could be used to improve the map by differentiating steep first- and second-order drainage lines from wetlands where the slope is most likely too steep for wetlands to occur. Cumulative frequencies were determined for wetlands and first- and second-order drainage lines along slope degree intervals for every physiographic region. Due to wetlands having a lesser slope value than steep 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. This was done through plotting the cumulative frequencies of wetland slope values against the inverse cumulative frequency slope values of steep first- and second-order drainage lines for each respective physiographic region. The cut-off slope value was identified as the intersection between the two frequency lines (Table 5). The Western and Eastern Lowveld did not contain sufficient first-order drainage lines to calculate a slope value that could be used to distinguish them from wetlands.

Table 5. Slope cut-off values used to partially differentiate wetlands from steep first/second order drainage lines.



		Wetland		First/Second Order Drainage line	
Region	Cut-off slope value (degrees)	% 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

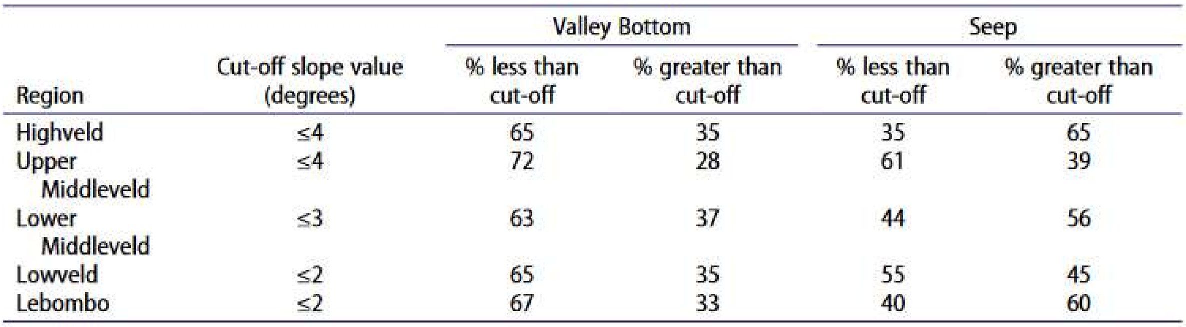
Slope raster layers were reclassed into the respective cut-off values for each region and converted to vectors. Sections of the initial potential wetland map that were included in the high potential to be a wetland category that fell above the respective cut-off slope value, per physiographic region, were then classed as having a medium potential to be a wetland. The improved potential wetland map therefore included three categories, namely: high potential to be a wetland, medium potential to be a wetland and low potential to be a wetland.

The field verification points previously used to test the accuracy of the initial potential wetland map were also used to test the accuracy of the improved potential wetland map. Two approaches to the standard accuracy assessment, based on the methods of Story and Congalton (1986), as well as an informal accuracy test were used to determine the accuracy of the improved potential wetland map. The reason for this is that the improved potential wetland map was categorized into three categories, namely: high potential to be a wetland, medium potential to be a wetland and low potential to be a wetland to create the improved wetland potential map. Due to the reference watercourse data consisting of two classes (wetlands and other types of watercourses), and the error matrix requiring an equal number of vertical and horizontal columns, having three potential wetland classes and two classes for the reference data lead to an uneven number of columns and rows. The full details of the different accuracy tests are provided in Le Roux (2020).

4.3 Classifying areas with the highest potential of wetland occurrence into hydrogeomorphic units

Watercourses that were classified as having a high potential to be a wetland were classified into the hydrogeomorphic units of Ollis et al. (2013), which is the most widely used classification system in South Africa. Wetlands were classified to Level 4A, the focal point of the classification system and the same level used by the South African Wetland Inventory (Van Deventer et al., 2018c). The wetland mapping technique of Collins (2018) has the ability to identify Floodplains, Channelled Valley Bottoms, Unchannelled Valley Bottoms, and to a limited extent Seeps. 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 wetlands from first/second order drainage lines (i.e. determining a cut-off slope value from cumulative frequencies) due to seeps generally having steeper slopes than valley-bottom wetlands (Grundling et al., 2014; Ollis et al., 2013). 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 6)

Table 6. Slope cut-off values used to distinguish valley-bottom wetlands from seeps.



		Valley Bottom		Seep	
Region	Cut-off slope value (degrees)	% 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

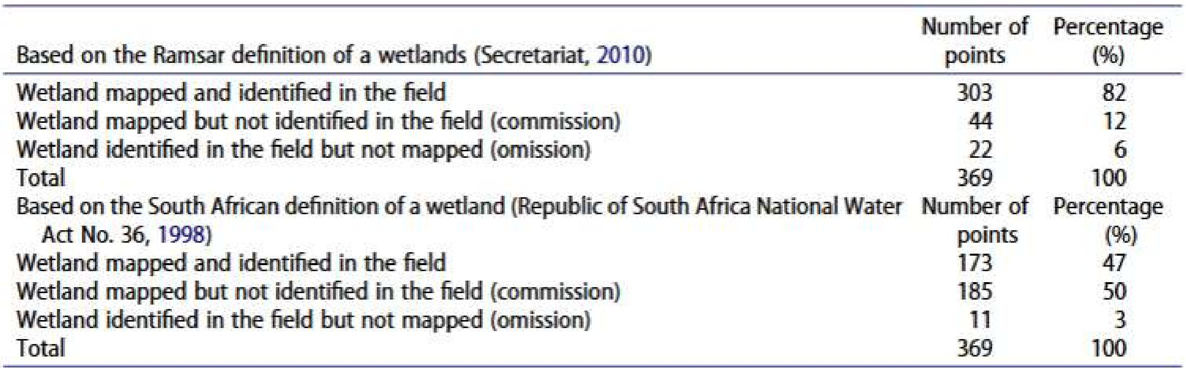
To distinguish channelled from unchannelled valley bottom wetlands, the Rivers layer of ENTC, Eswatini National Trust Commission (formerly known as Swaziland National Trust Commission; 2017) was used, based on the methods of Grundling et al. (2014). The high potential to be a wetland layer was intersected with the Rivers layer (ENTC, Eswatini National Trust Commission (formerly known as Swaziland National Trust Commission), 2017) to extract channelled valley bottom wetlands. Buffers of 100 m were used to account for misalignment of the Rivers layer with imagery that was noticeable below a scale of 1: 50000. Wetlands falling outside of the buffer were classed as unchannelled valley bottoms. Although the Rivers layer is extensive, it was observed from satellite imagery (ArcMap basemaps (ESRI, 2018)) that some first-order streams occur in Eswatini that are not included in this layer. Therefore, wetlands classified as unchannelled valley bottoms may sometimes contain a channel but due to the relatively small size of these streams, they can be described as being driven mainly by lateral inputs. To identify floodplain HGM Units in Eswatini, the major rivers in Eswatini were scanned in Google Earth Pro (Google Earth Pro Inc, 2019) at roughly a scale of 1: 50000, 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 potential wetland map. An example of the classified potential wetland map is displayed in Figure 5. To determine the accuracy of the classified map, omission errors were calculated using field point classed as type of HGM unit, against what HGM unit the classified map predicted it to be. Commission errors were calculated using field points that landed on the high potential wetland map layer but were classed as other types of watercourses.

5. Results

5.1 The initial potential wetland map

The initial potential wetland map created for Eswatini mapped 929,8 km^2 of land which is 5,4% of the country (Figure 3). Results of both the field and the desktop accuracy assessments (Tables 7-8) indicate that the accuracy of the potential wetland map is heavily reliant on the definition that one uses for a wetland. When using the Ramsar definition of a wetland, the field-based accuracy assessment found that the accuracy of the map is 82% with commission and omission errors being 12 and 6%, respectively. However, when using the South African definition of a wetland, the map received an accuracy of 47%. The desktop-based accuracy assessment found that when using the Ramsar definition, the average accuracy of the map was 93%, but only 31% when using the South African definition of a wetland. Wetlands that would fall under the Ramsar definition of a wetland but would not be included under the South African definition, made up 62% of the mapped watercourses.

Table 7. Results of the field-based accuracy assessment for the initial potential wetland map using both the Ramsar and South African definition of a wetland.



Based on the Ramsar definition of a wetlands (Secretariat, 2010)	Number of points	Percentage (%)
Wetland mapped and identified in the field	303	82
Wetland mapped but not identified in the field (commission)	44	12
Wetland identified in the field but not mapped (omission)	22	6
Total	369	100
Based on the South African definition of a wetland (Republic of South Africa National Water Act No. 36, 1998)	Number of points	Percentage (%)
Wetland mapped and identified in the field	173	47
Wetland mapped but not identified in the field (commission)	185	50
Wetland identified in the field but not mapped (omission)	11	3
Total	369	100

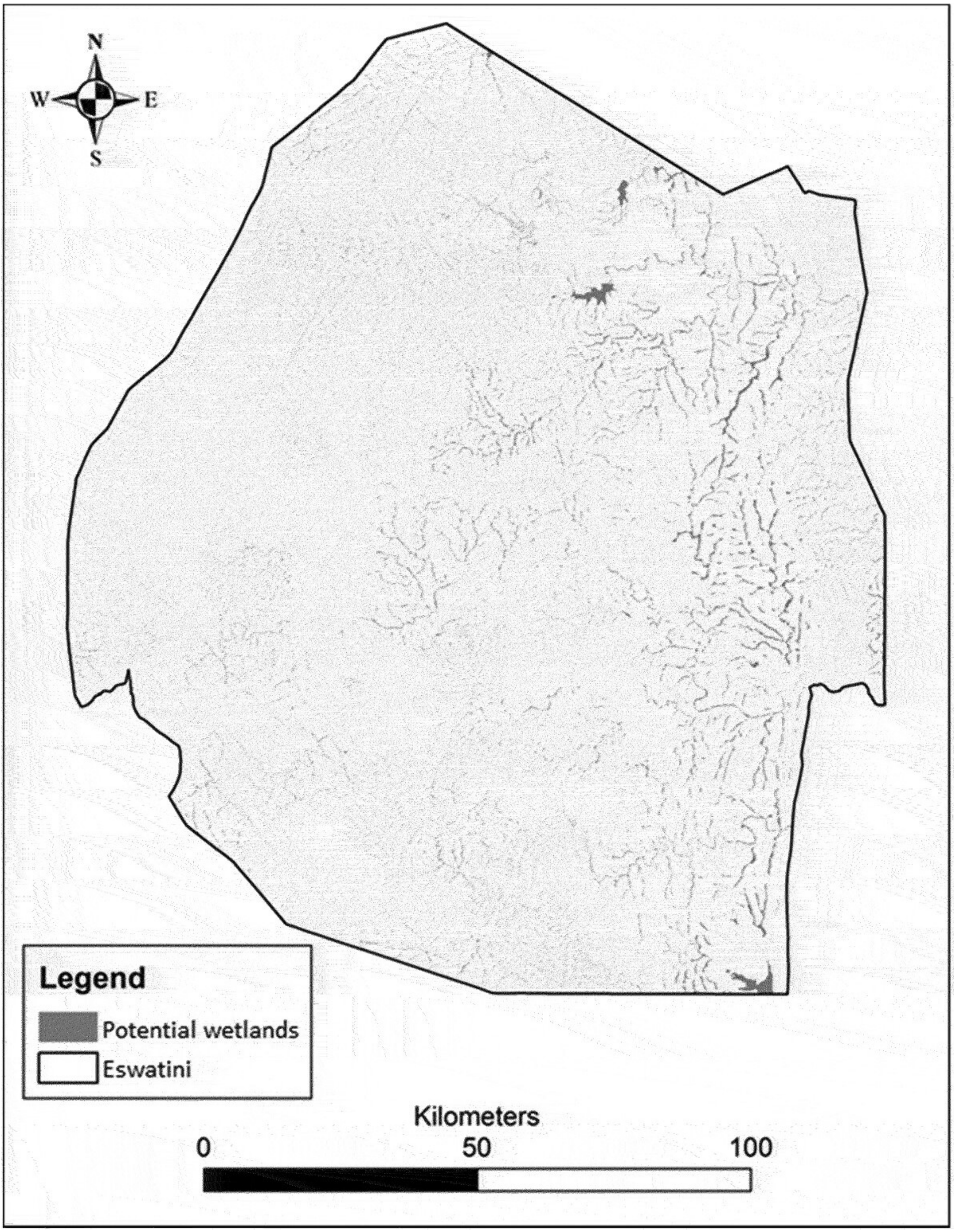
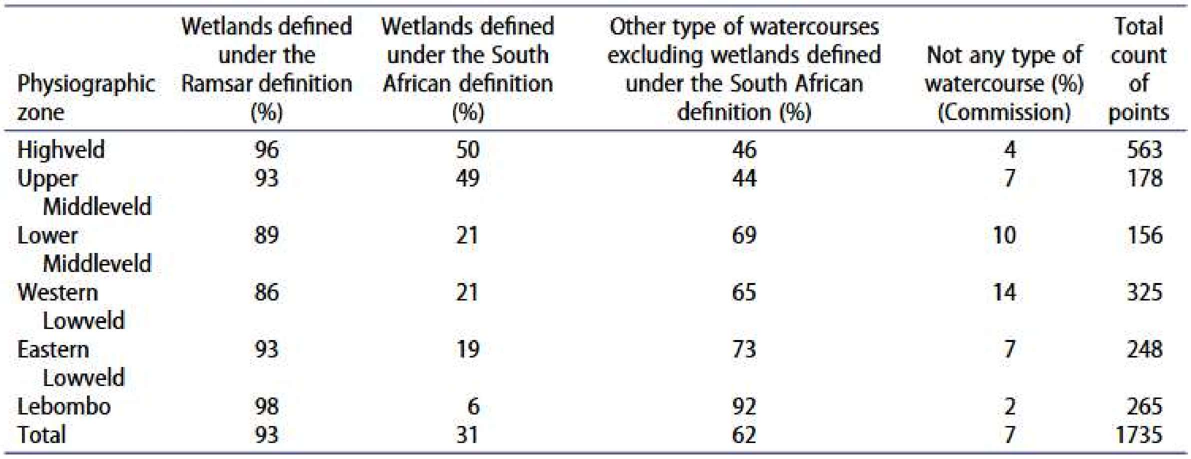


Figure 3. The initial potential wetland map of Eswatini.

Table 8. Results of the desktop-based accuracy assessment for the initial potential wetland map using both the Ramsar and South African definition of a wetland.



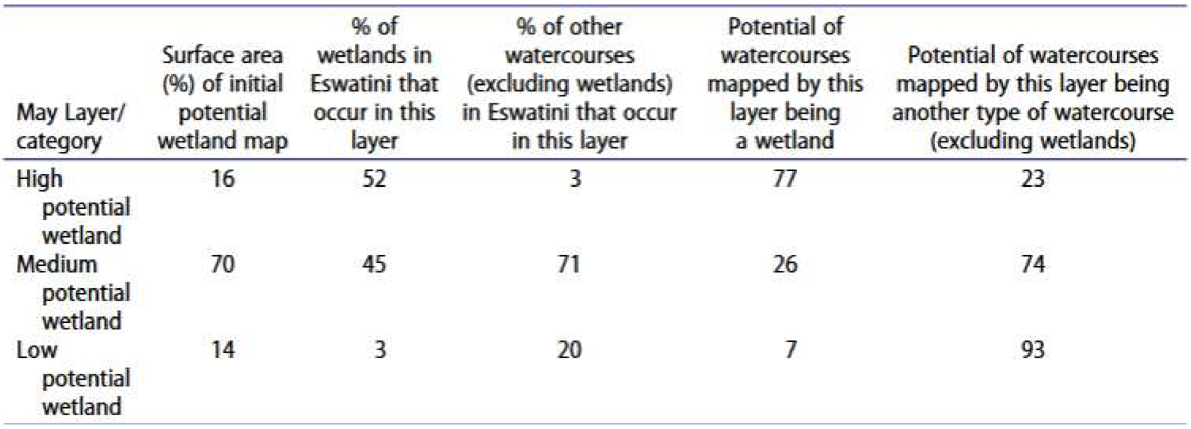
Physiographic zone	Wetlands defined under the Ramsar definition (%)	Wetlands defined under the South African definition (%)	Other type of watercourses excluding wetlands defined under the South African definition (%)	Not any type of watercourse (%) (Commission)	Total count of points
Highveld	96	50	46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

5.2 The improved potential wetland map

An example of the improved potential wetland map is displayed in Figure 4, with its accuracy explained in Table 9 . The total surface area of each layer is as follows:

- High potential to be a wetland = 149 km^2 (16% of the initial potential wetland layer and 0.9% surface areas of Eswatini)
- Medium potential to be a wetland = 650 km^2 (70% of the initial potential wetland layer and 3.7% surface areas of Eswatini)
- Low potential to be a wetland = 131 km^2 (14% of the initial potential wetland layer and 0.8% surface area of Eswatini)

Table 9. Accuracy of the improved potential wetland map of Eswatini.



May Layer/ category	Surface area (%) of initial potential wetland map	% of wetlands in Eswatini that occur in this layer	% of other watercourses (excluding wetlands) in Eswatini that occur in this layer	Potential of watercourses mapped by this layer being a wetland	Potential of watercourses mapped by this layer being another type of watercourse (excluding wetlands)
High potential wetland	16	52	3	77	23
Medium potential wetland	70	45	71	26	74
Low potential wetland	14	3	20	7	93

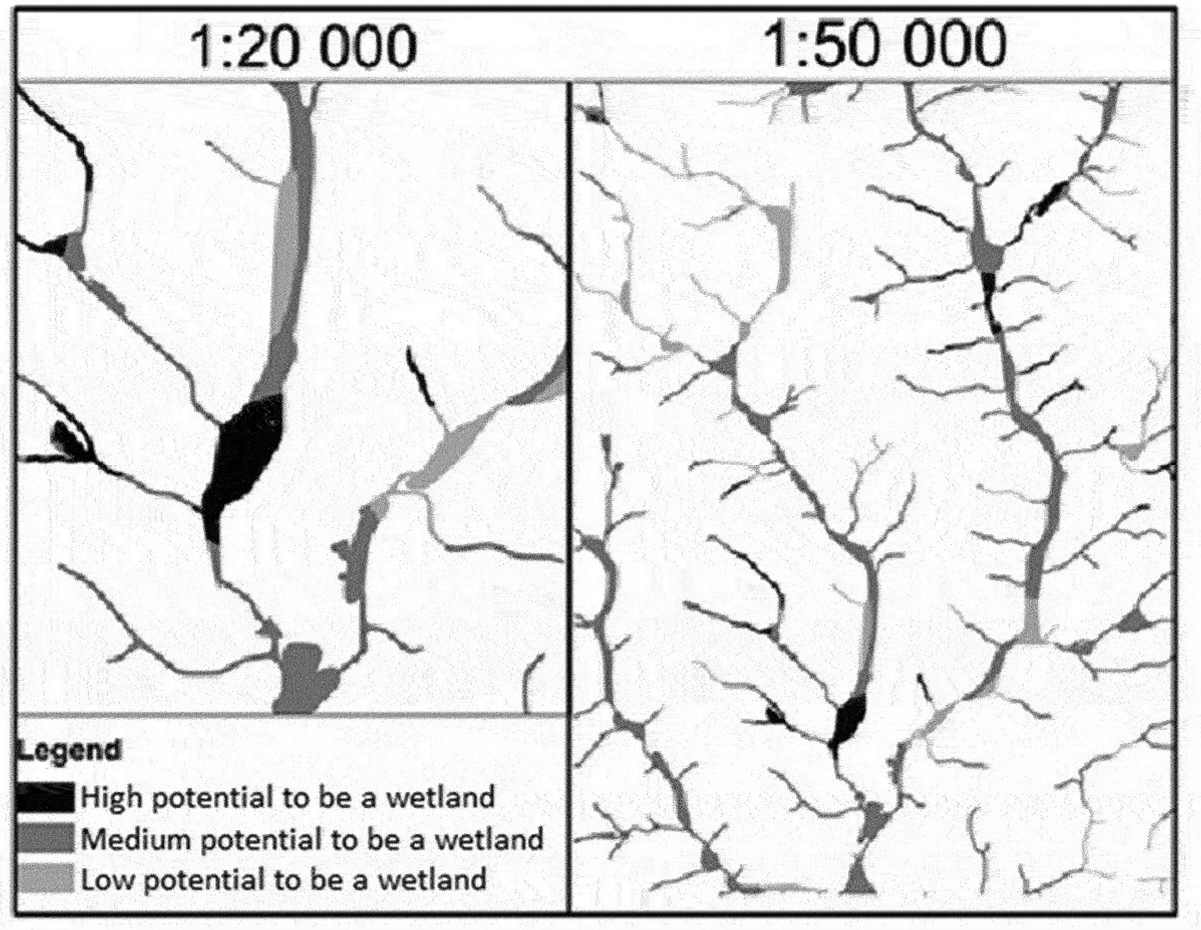


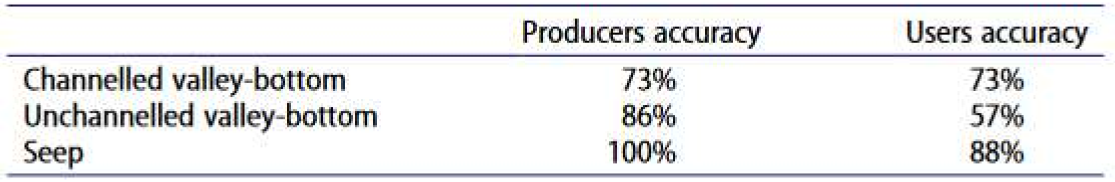
Figure 4. An example of the improved potential wetland map at a 1: 20000, and 1:50000 scale.

Although the 'high potential to be a wetland' map layer only makes up 16% of the surface area of the initial potential wetland map, it includes 52% of the identified wetlands and only 3% of the identified 'other watercourses' from the 2000 random points. Of the watercourses mapped by the 'high potential to be a wetland' layer, 77% are wetlands and 23% are 'other watercourses'. The 'medium potential to be a wetland' map layer makes up 70% of the surface area of the initial potential wetland map, and includes 45% of the wetlands, and 71% of the 'other watercourses'. Of the watercourses mapped by the 'medium potential to be a wetland' map layer, 26% were wetlands and 74% were other watercourses. The 'low potential to be a wetland' map layer makes up 14% of the surface area of the initial potential wetland l map and includes 20% of the 'other watercourses', and 3% wetlands. Of the watercourses mapped by the 'low potential to be a wetland' map layer, 93% were other watercourses and only 7% were wetlands.

5.3 The classified potential wetland map

The summarized results of the accuracy assessment for the classified potential wetland map are displayed in Table 10, with an example of the map illustrated in Figure 5. Although the number of sample points used for the accuracy assessment of the classified wetland map was relatively small (51), the results have shown that the methods used to classify wetlands into HGM units were partially able to distinguish valley bottom wetlands from seep wetlands, as well as channelled valley bottoms from unchannelled valley bottoms. The producer's accuracy of the 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%. Seeps were again the highest at 88%, unchannelled valley bottoms the lowest at 57% and channelled valley bottoms at 73%.

Table 10. Accuracy of the potential classified wetland map**.**



	Producers accuracy	Users accuracy
Channelled valley-bottom	73%	73%
Unchannelled valley-bottom	86%	57%
Seep	100%	88%

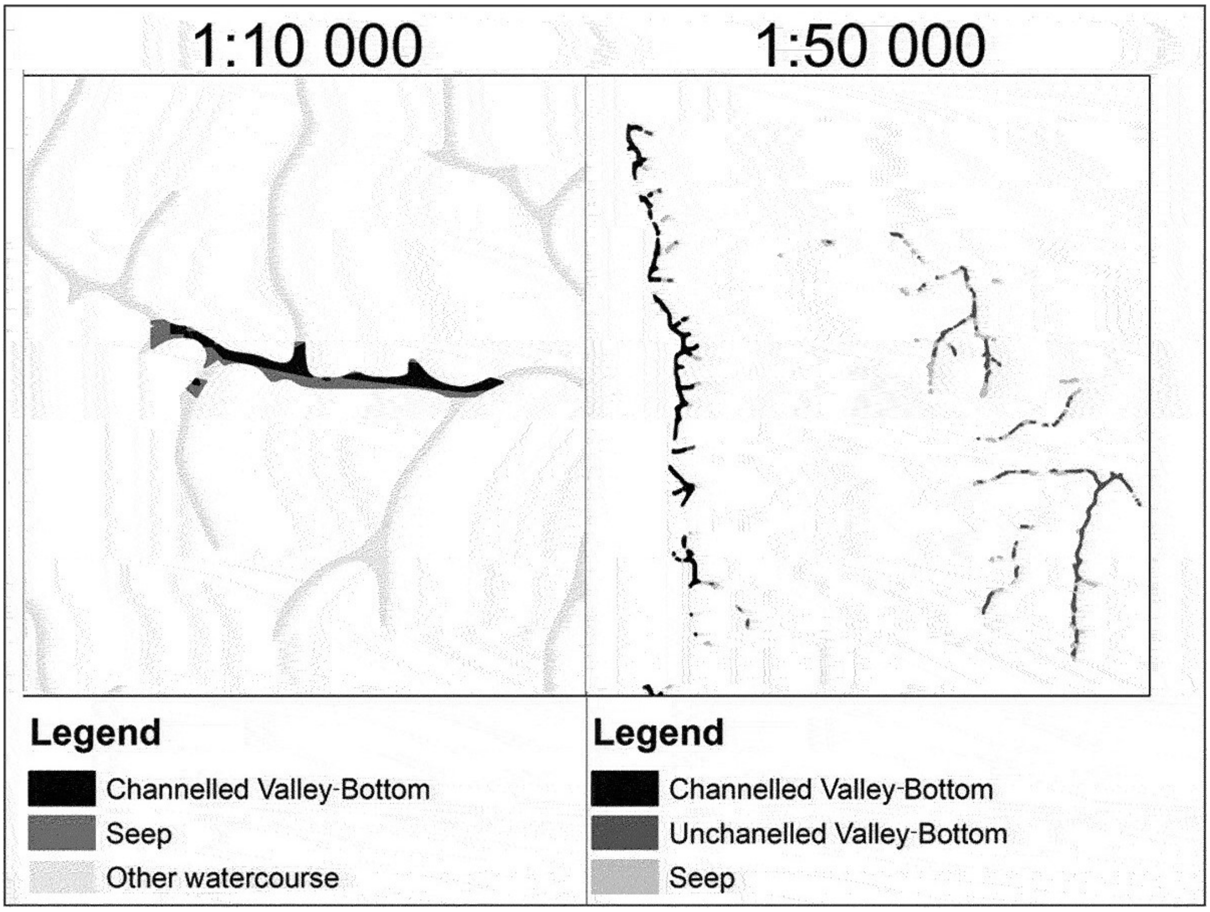


Figure 5. An example of the classified potential wetland map at a 1: 10000, and 1: 50000 scale.

6. Discussion

When using the Ramsar definition of a wetland, the initial potential wetland map received predictive accuracies of 82% and 93%, for the respective field and desktop accuracy assessments, implying that it has the ability to identify most wetlands falling under such definition, in a country with physiographic landscapes such as Eswatini. The commission errors, of not mapping any type of watercourse, for both the field and desktop-based accuracy assessments were relatively similar (6% and 7%). However, the percentage of wetlands that would fall under the Ramsar definition but not the South African definition, differed substantially between the two accuracy assessments (39% and 62%). This could possibly be attributed to the biased sampling of the field-based accuracy assessment, which was restricted to road access and therefore mostly excluded steep slopes, where many first- and second-order drainage lines were mapped. Therefore, the initial potential wetland map does not suffice as a wetland map for countries such as South Africa, who use a more specific definition for the term wetland (Republic of South Africa National Water Act No. 36, 1998) as the map received accuracies of 47% and 31% when using the South African definition of a wetland.

A comprehensive wetland map was, however, not the intended purpose of the wetland mapping technique created by Collins (2018). The intended purpose was to map extensive areas, with limited data and cost (Collins, 2018). For this, it is well suited, especially for countries that are signatories of the Ramsar Convention but do not have the means to produce a highly detailed wetland map. Considering that Eswatini uses the Ramsar definition, the Initial potential wetland map is suited to be used as a baseline source of information with regard to the approximate distribution of wetlands across the country. Riverine wetlands are also the most common wetland type in Eswatini (IUCN, International Union for Conservation of Nature, 1997) which is the type of wetland that the wetland mapping technique is best suited to map (Collins, 2018). Statistically derived wetland mapping techniques such as Hiesterman and Rivers-Moore (2015) and Melly et al. (2017) may have yielded more accurate results but the attribute/input data required for such techniques are frequently not available in developing countries such as Eswatini.

The methods used to improve the potential wetland map were not able to definitively distinguish wetlands from other types of watercourses but were able to identify watercourses with a higher potential of being a ‘true wetland’, as opposed to other types of watercourses. Neither wetlands, nor other types of watercourses were solely attributed to a type of soil class. This could be partially due to the generalized 1: 125000 scale of the soil map, as it is unlikely that soils classed as responsive, and permanently saturated would be attributed to steep first/second order drainage lines. This highlights that a 1: 125000 scale soil map can be of use to partially distinguish wetlands from other types of watercourses but that other input variables, or a soil map at a finer scale, would be needed to more accurately distinguish wetlands from other types of watercourses.

Table 5 shows that, although wetlands and first- or second-order drainage lines can occur on the same slope values, the method of intersecting cumulative frequencies was, however, able to include a relatively large percent of wetlands below certain slope values in respective physiographic zones. In the Highveld, Upper and Lower Middleveld, 82%, 85% and 81% of the respective sample wetlands occurred below these slope values. These cut-off slope values, however, also resulted in 34%, 47% and 41% of the first- and second-order drainage lines in these respective physiographic units being included below the respective cut-off values. Results of using this method in the Lebombo region were less favourable, as only 50% of the sample wetlands, and 61% of the first- or second-order drainage lines were located below the cut-off slope values. The relatively small slope differences between the slopes of wetlands and first- or second-order drainage lines in the Lowveld did not allow this method to partially differentiate between the two. Cut-off slope values also ranged from 2 to 7 degrees across the different physiographic regions, highlighting that wetlands form on different slope positions across Eswatini. This could be due to other variables such as geology and climate that vary amongst physiographic zones. In general, the slope values of wetlands were found to be concentrated around lower slope values, and first- or second-order drainage lines were relatively spread out.

Similar difficulties were observed when attempting to distinguish valley-bottom wetlands from seep wetlands, as was originally shown in Table 6. The cut-off slope values ranged from 4 to 2 degrees and were only able to partially distinguish these types of wetlands from each other. This could be due to the scale of the SRTM DEM (NASA, National Aeronautics and Space Administration, 2000), but it is not uncommon for seep wetlands to also occur on relatively flat areas (Ollis et al., 2013). For example, in the Highveld, a cut-off slope value was identified that included 65% of valley-bottom wetlands below the value, but also 35% of seeps below this value. The methods used to partially distinguish first/second order drainage lines from wetlands, and valley-bottom from seep wetlands are therefore coarse, but do provide some indication of whether the watercourses mapped have a greater, or smaller chance of being a true wetland. Further research is needed to test this method using a DEM that has finer-scale resolution than the 30 m SRTM DEM, as this may have contributed to the large amount of overlapping slope values.

It is also important to note that the potential wetland map produced in this study does not include depressional wetlands, that have previously been identified in the Lowveld (Hughes & Hughes, 1992), and Lebombo physiographic regions of Eswatini, nor hillslope seeps that are not connected to a valley-bottom. However, these can be manually digitized to supplement the potential wetland map. Despite the limitations of the potential wetland maps produced in this study, the results show that they are still able to identify the larger wetland systems across the country.

The coarse HGM classification system (Ollis et al., 2013) applied to Eswatini can still aid in the conservation of wetlands, as they provide indications of the types of wetlands that occur in different parts of the country. Hydrogeomorphic classification systems identify the processes that are fundamental to the sustained existence of different wetland ecosystems (Brinson, 1993) and can also be used to highlight the sensitivity of various wetlands to certain changes, and establish mechanisms to mitigate against certain impacts (Smith et al., 1995). In addition, the classified potential wetland map can be 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).

7. Conclusions

This study has shown that the wetland mapping technique of Collins (2018), which uses freely available open-source data, can be used to provide information of the baseline distribution of watercourses and wetlands across a country. This is especially the case for countries such as Eswatini that do not have the means to produce a comprehensive map, but are urged to generate one by the Ramsar Convention, of which they are a signatory (Ramsar Convention Secretariat, 2010). Given that Eswatini uses the Ramsar definition of a wetland that does not necessarily distinguish wetlands from other types of watercourses, the potential wetland maps created in this study can suffice as a means to identify most wetlands until the country acquires the means to produce a more comprehensive map. Should Eswatini follow the wetland mapping techniques used in the South African Inventory of Inland Aquatic Ecosystems (SAIIAE; Van Deventer et al., 2018c), where wetlands were manually digitized, the potential wetland maps provide a useful guideline to inform wetland digitizing and classification. In addition, if South Africa were to continue digitizing wetlands across the remaining parts of the country that were assigned a low confidence rating, it is recommended that the wetland mapping technique of Collins (2018) be used as a guide to locating the rest of the country's wetlands. Due to the potential wetland maps having the ability to identify degraded wetlands is also of great importance to South Africa (Collins, 2005), as well as countries that are signatories to the Ramsar Convention. In this instance the potential wetland maps can be used to compliment manually digitized wetlands that are no longer visible from aerial imagery. The potential wetland maps can also be used to compliment statistically derived wetland probability maps (e.g. Hiesterman & Rivers-Moore, 2015) as the technique of Collins (2018) includes other types of watercourses such as riparian zones and drainage lines, and also indicates surface water links between different watercourses that are not included in these statistically derived methods.

This study has also shown that large-scale attribute data can be used to partially distinguish wetlands from other types of watercourses, through identifying areas with a higher potential of wetland occurrence, using relatively simple techniques. Should countries possess soil maps of a smaller scale than the 1: 125000 soil map used in this study, the methods developed here should produce better results. The same principle applies regarding the DEM used in this study, as the 30 m resolution of the SRTM DEM (NASA, National Aeronautics and Space Administration, 2000) could be a limiting factor in distinguishing wetlands from other types of watercourses, or valley-bottom wetlands from seeps, as the differences between these features could be less than 30 m. Nevertheless, slope values and associated soils would still be able to identify areas with a higher potential of wetland occurrence given the scale of those datasets.

The limitations of the potential wetland map as well as the improved and HGM-classified maps need to be acknowledged. The maps do not identify depressional wetlands and seeps not connected to the valley-bottom. Also, they are not at present able to definitively distinguish between wetlands and other types of watercourses, nor valley-bottom wetlands from seeps. However, it is argued that the advantages of the maps outweigh their limitations. The maps are still able to locate most areas with a high potential of wetland occurrence and can serve as preliminary guides to locating wetlands across Eswatini. Their most important feature is that they can be produced with a limited investment of budget, time, and skill, making them a feasible option for many countries.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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