Predicting Wetland Occurrence in the Arid to Semi—Arid 1 Interior of the Western Cape, South Africa, for Improved 2 Mapping and Management

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Predicting wetland occurrence in the arid to semi—arid interior of the Western Cape, South Africa, for improved mapping and management

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Abstract

As for drylands globally, there has been limited effort to map and characterize such wetlands in the Western Cape interior of South Africa. Thus, the study assessed how wetland occurrence and type in the arid to semi-arid interior of the Western Cape relate to key biophysical drivers, and, through predictive modelling, to contribute towards improved accuracy of the wetland map layer. Field-verified test areas were selected to represent the aridity gradient, rainfall seasonality, hydrogeomorphic (HGM) types and physiographic zones encompassed in the study area. The arid areas of the Karoo physiographic zones had: (1) a low (<1%) proportional area of wetland; (2) an almost complete absence of seepage slope wetlands; (3) ephemeral depressions, all non-vegetated; and (4) much of the wetland associated with valley bottoms confined within a channel. The less arid mountain zones had: (1) a much higher (>3%) proportional area of wetland; and (2) wetlands being predominantly hillslope seepages, but also including valley bottom wetlands.

A spatial probability surface of wetland occurrence was generated based on the statistical relationship of verified wetland presence and absence data points with a range of catchment-scale predictor variables, including topographic metrics and hydrological/climatic variables. This layer was combined with raster images of most likely HGM type within the landscape to provide a final

product of wetland occurrence, attributed by HGM type. Vulnerabilities of the wetlands were identified based on key attributes of the different wetland types, and recommendations were provided for refining the wetland map for the Western Cape.

Keywords: drylands; hydrogeomorphic type; logistic regression; probability; vulnerability

Declarations

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Introduction

Globally, much of the effort to map and characterize wetlands at a landscape scale has been in humid temperate areas, where wetlands tend to be more extensive than in drylands (Hu et al. 2017). In sub-Saharan Africa, the wetlands in drylands literature has largely focused on either the large fluvial systems (Tooth and McCarthy 2007; Ellery et al. 2009) or endorheic depressions (pans) (Goudie and Thomas 1985; Allan et al. 1995). Landscape-level examinations of the occurrence of the full range of different wetland types represented in drylands appear to have been limited to a few studies, notably that of Melly et al. (2016; 2017). This also holds true in the Western Cape, South Africa, where much of the mapping effort and field verification has focused on the relatively high precipitation areas near the coast, with the result that the extensive arid to semi-arid interior of the province, especially to the east, has the lowest level of confidence in wetland spatial extent

and hydrogeomorphic (HGM) type (Van Deventer et al. 2020). However, wetlands in drylands tend to be hydro-geomorphologically distinct from wetlands in humid areas (Tooth and McCarthy 2007) and have an especially important role to play within the landscape in terms of the supply of provisioning services for cultivators, pastoralists and other natural resource users (Scoones 1991). This, coupled with the relatively poor level of mapping in these areas, identifies a clear research gap. Although the occurrence of wetlands is expected to be generally lower in the interior of the Western Cape compared with the coastal areas, there are areas of the interior where climate and other environmental drivers are locally conducive to a higher wetland occurrence. Describing this heterogeneity and the underpinning landscape-level drivers is valuable for baseline mapping and characterization of wetlands and to assist in predicting how land-use change, climate change and other stressors might affect wetlands.

The practical outcomes of the low accuracy of mapping include either delay in projects because of false positives of wetlands, or wetlands being lost to other land developments because they have not been mapped. Furthermore, it results in the true value of natural capital not being accurately audited. There is thus a pressing need for improving the accuracy of South Africa's national wetland map, particularly for the extensive areas of the country which have lacked field verification, including those in the present study.

Wetland HGM types show variable levels of vulnerability to different forces of degradation (Rivers-Moore and Cowden 2012). Since the supply of ecosystem services can typically be inferred based on HGM types, it is important for a wetland occurrence map to be correctly attributed. Mapping wetland presence on its own typically produces a polygon layer that is unattributed. Such maps only become truly useful as the product of integrated ancillary data layers which provide probability values for occurrence, type, and ecological condition, from which wetland practitioners will be able to make statements such as "at this location, there is an 85% probability of a wetland occurring, which is five times more likely to be a seep than a floodplain" (Rivers-Moore et al. 2020).

This study sought to better understand how the occurrence of wetlands generally (and specific wetland HGM types) in the Western Cape interior relate to key biophysical drivers, and, through

predictive modelling to contribute towards cost-effectively improving the accuracy of the wetland layer for the province. The study further demonstrates how the enhanced understanding of biophysical drivers affecting wetlands generally (and specifically of different wetland types) can be used to improve future mapping effort for the province and for dryland environments across the globe.

Methods

Study area

The study area was defined as the central and western interior of the entire Western Cape Province. This coincides with a mean aridity index of 0.133 ± 0.04 , calculated from the ratio of mean annual precipitation (MAP) to mean annual evapotranspiration, where values < 0.2 are classified as arid conditions (Trabucco and Zomer 2019). The boundary was defined according to hydrologically correct sub-catchments rather than strictly along the administrative boundary (Figure 1), provided by the South African National Biodiversity Institute (SANBI) and based on the sub-quaternary catchments derived from the National Freshwater Ecosystem Priority Areas (NFEPA) (Nel et al. 2011) dataset. This translated into 547 catchment polygons with a median area of $\sim 70 \text{ km}^2$. Field test sites were selected to represent the aridity gradient, main rainfall seasons (i.e. winter rainfall vs. summer rainfall), main hydrogeomorphic (HGM) types and physiographic zones represented in the study area.

The study area comprised five primary physiographic zones, which encompass diverse geology and climate (Table 1). The zones represent three mountain ranges, each with relatively high mean annual precipitation (MAP; $> 400 \text{ mm}$), and two areas of flatter terrain in between, the first being part of the Great Karoo and the second the Little Karoo, both with relatively low MAP ($< 200 \text{ mm}$; Table 1).

Data collection

Foundational to the approach of the study was the identification of field-verified test areas within the overall study area. In this study, a test area refers to a geographically-delimited area (preferably $> 20 \text{ km}^2$) within which wetlands have been classified according to hydrogeomorphic (HGM) type and mapped with at least an intermediate level of confidence. This means that at least 20% of the mapped wetlands have been observed in the field close enough to identify whether the dominant

plant species are hydrophytes. In addition, most of the wetlands which have not been observed in the field appear to have the same HGM type and a similar landscape setting and spectral signature to a comparable wetland which has been observed in the field (and from which inferences can be drawn). Given that the resources for collecting primary data were limited, the test areas were derived as far as possible from existing sources. However, where major gaps were found in terms of representing key environmental gradients represented in the study area (in particular, mean annual rainfall and rainfall seasonality) test sites were generated from scratch by collecting primary data.

The criteria used in the selection of test sites were chosen as follows:

- The spread of sites should achieve good representation of the aridity gradient represented in the province, particularly along the drier end of the continuum, which covers much of the interior of the province and has thus far received relatively little attention in terms of wetland mapping effort.
- The spread of sites should achieve good representation of the main rainfall seasons (aseasonal, mainly in the west vs. late summer rainfall, mainly in the east) represented in the study area.
- The spread of sites should achieve good representation of the main hydrogeomorphic types represented in the province.
- Sites with relatively low levels of wetland loss/alteration/creation are preferable to where such levels are high because such impacts “interfere” with the predictive relationship between wetland occurrence and biophysical drivers.
- Sites involving a shorter travel distance and with wetlands which are generally more accessible are preferable to those with longer distances and lower accessibility.
- Sites with existing information on the wetlands are preferable to those without.

All of the datasets outlined above were used, to varying degrees, to inform probability models of wetland occurrence and HGM type. These rely on binary data (e.g. wetland presence or absence) correlated with associated environmental predictor data (for example, elevation). The environmental data included a number of core datasets common across regions and model types,

and use of variables specific to regions or model output. The study included 13 test areas (Table 2) covering a total of 2 520 km².

Predictor variables and spatial datasets

Raster layers for nine predictor variables were used for the wetland models (Table 3). Raster layers comprised a combination of primary data or were DEM-derived. The digital elevation model (DEM) was obtained by first downloading the appropriate 3 arc-second SRTM (~90m resolution) data tiles from the USGS website (USGS 2021), and then merging these together into a single image. Data sinks were filled prior to calculating the DEM-derived surfaces: GRASS r.flow routine for the flow accumulation surface; and SAGA Terrain model roughness for the roughness index. All raster layers were standardised to the spatial extent of the study region.

Model development

Using field-verified datasets of wetland presence and absence across these landscapes, a spatial probability surface of wetland occurrence was generated for the study area. This was based on the statistical relationship of wetland presence and absence data points with a range of catchment-scale predictor variables. These included topographic metrics (elevation, slope, terrain roughness) and hydrological/ climatic variables (mean annual precipitation, flow accumulation, aridity index). This layer was combined with raster images of most likely HGM type within the landscape.

A coverage of random points at a fixed density per sub-catchment was generated using the “random point inside polygons (fixed)” tool in QGIS. Various point densities were evaluated, with the best option being a density of ~0.28 points.km⁻², or approximately 20 points per sub-catchment. Next, a subset of these points coincident with where wetland data were used was selected using the “select by location” tool.

The point sampling tool was used to obtain data values from raster images for all predictor variables, with these exported as a data matrix. A PCA biplot was undertaken to assess relationships between wetland presence/ absence and environmental predictor variables (McCune and Mefford 2011).

The same data matrix was used to define a stepwise logistic regression model for calculating the probability of wetland occurrence (R Development Core Team 2009). Wetland probability of occurrences was spatially represented by multiplying the variable coefficients against their raster images using the Raster calculator in QGIS (QGIS 2018; Figure 1). The probability surface was verified using a receiver operating curve (ROC) to calculate the Area under Curve (AUC) statistic (Medcalc 2021).

Wetland HGM type

The Bayesian network model developed by Rivers-Moore et al. (2020) was configured according to which variable states would most effectively predict which wetland areas would be most likely be seeps. For this model, the probability of a wetland being a particular HGM type was conditionally based on four interacting topographic variables classified into state classes. Probability of HGM type was based on case files where each HGM occurrence was associated with the variable state class for elevation, slope, relief ratio and groundwater depth. The raster layers for each variable were reclassified (QGIS: r.reclass) according to the threshold values for variable states; values below this threshold were assigned a NULL value. In the case of seeps, raster images were classified into binary layers: “high” elevation > 500m; “shallow” groundwater < 8m below ground; “steep slopes > 5°. To spatially represent where seeps would be likely to occur, the raster images were multiplied together using the raster calculator. This output image was multiplied with the wetland occurrence probability map to indicate probabilities of wetland seep occurrence.

HGM type vulnerabilities

A rating of the vulnerabilities of wetland types in the study area was undertaken based on: (1) the wetlands’ key biophysical features and likely key water inputs which are sustaining these wetlands; and (2) current impacts on the different wetland types. The level of vulnerability to a specific threat was based on a joint consideration of: (1) the intensity of the anticipated impact if a specific threat was to occur; and (2) the observed current extent of the threat. For example, while the anticipated impact intensity of sewage/ effluent/ pollution on hillslope seeps in the TMG (Table Mountain Group) sandstone mountains is potentially high if it were to occur, the occurrence of

this wetland type subject to sewage/ effluent/ pollution is extremely low, and therefore the overall level of threat for this wetland type and threat type combination is low.

Results

Wetland presence

Based on the field data collected, the arid areas of the Great Karoo and the Little Karoo physiographic zones had the following key results: (1) a similarly very low (0.7%) proportional area of wetland; (2) an almost complete absence of seepage slope wetlands (Figure 1); (3) locally common ephemeral depressions in some areas, with all of these depressions being non-vegetated; and (4) most of the wetland associated with valley bottoms having high stream order, with some being floodplains but many confined entirely to a vegetated channel (Figure 1). The less arid mountain zones of the Great Escarpment, Swartberg/Klein Swartberg and Langeberg had the following key results: (1) a much higher proportional area of wetland (5.2%, 2.6% and 3.6% respectively); and (2) wetlands being predominantly hillslope seepages (Figure 1), with some on very steep (>45%) slopes, but also including valley bottom wetlands.

The relative frequency of occurrence of different HGM types varied markedly across the five physiographic zones (Figure 2). In all three mountain zones, depressions and floodplains were lacking and the hillslope seep (Supplementary Plates 1-4) was the most frequently occurring HGM type, while in the Great Karoo zone, hillslope seep wetlands were entirely absent and in the Little Karoo hillslope seep wetlands had one of the lowest occurrences, with a total of only three seeps recorded, all in close proximity to the Warmwaterbad hot springs, suggesting deep artesian groundwater supply. In the Table Mountain Group (TMG) sandstone mountains, many hillslope seep wetlands were located on steep (>10%) slopes, and some on very steep (>45%) slopes. These seeps varied from permanent to strongly seasonal, suggesting both: (a) relatively “shallow”, rapid recharge-discharge response resulting in seasonal and interflow contribution to seeps; and (b) deeper, higher storage and longer flow paths resulting in a sustained, often constant discharge, as shown by Colvin et al. (2009) and Meyer (2002). In the Great Escarpment, hillslope seep wetlands were most prominent in the Sneeu Berg, with the largest of these occurring on south-facing aspects of the Toorberg mountain, which comprises inclined dolerite sills (Clark et al. 2009). No hillslope seep wetlands were recorded in the Great Escarpment in the Nuweveld mountains between

Beaufort West and Loxton and between Murraysburg and Victoria West, characterized by lower MAP than the Sneeuberge.

In all three mountain zones, the channelled valley bottom (Supplementary Plate 7) was the second most frequently occurring HGM type. This was followed in the Great Escarpment and South Cape fold mountains by the unchannelled valley bottom (Supplementary Plates 5-6), but the latter was absent in the Swartberg Cape fold mountains (Figure 2). In the Great Karoo and Great Escarpment, the unchannelled valley bottom occurred mainly in areas with reasonable (>300 mm) MAP onsite and/or higher MAP in their catchments, and the three largest of these wetlands were all seasonally saturated and located in a broad valley floor with a dolerite dyke across their outflows, from where flow proceeded through a narrow, confined valley, locally referred to as a “poort”. The Langeberg TMG sandstone mountains contained the only known permanently saturated unchanneled valley bottoms, and were the only wetlands in the study area with known peat accumulations.

The most frequently occurring HGM type in both of the Karoo zones was the vegetated channel (i.e. such wetlands were confined to the main river channel, generally with a stream order >2, and did not extend up onto the valley floor, if present) (Supplementary Plates 9-10). In both Karoo zones it was rare to find wetlands extending out of the channel across the valley floor, and where present (Supplementary Plate 8), these were generally located within 10 km of the higher rainfall mountain areas, from which they likely receive surface flows following major rainfall events. In addition, some are supplied by groundwater, for which direct evidence is found for the Prins River (Grenfell et al. 2021). In the Great Karoo, the next most frequently occurring HGM type was the depression, with all depressions being unvegetated, as was the case in the Little Karoo. Most depressions were in some of the lowest rainfall areas of the study area, even occurring where MAP<100 mm.

Correlation of wetlands with spatial datasets

The PCA indicated strong correlation between predictor variables and wetland presence (Figure 2; Table 4). The optimal model for predicting wetland presence was based on four variables (A-pan evaporation, roughness, slope, elevation), with all model parameters being significant ($p < 0.1$; Table 5 and Equation 1). The equation was translated into a spatial product using the raster

calculator (Figure 4). This output indicates distinct regions where wetland occurrence, irrespective of HGM type, is likely to be high (Figure 4). The variable with greatest leverage was slope, succeeded by roughness (Table 5).

$$p(\text{occurrence}) = \frac{\exp^{5.982-0.004(A-Pan)\dots+0.002(elev)}}{1+\exp^{5.982-0.004(A-Pan)\dots+0.002(elev)}} \quad [1]$$

Model performance

Based on the verified wetlands and the authors' knowledge of known wetland rich and wetland poor areas respectively within the study area, indications are that the model is a sound reflection of the situation on the ground. This was supported by the quantitative model assessment of wetland occurrence, based on the ROC, which showed a high level of classification accuracy based on the Area Under Curve (AUC) statistic (Figure 6).

HGM types

The spatial product from the Bayesian network model for predicting wetland HGM type was successful, resulting in a raster image indicating distinct zones within the study area where the prevalent wetlands are most likely to be seeps (Figure 5). Overlaying this image with the probability model indicated that the highest probabilities for seeps were with their being associated with the Cape fold mountain regions (Figure 5).

Discussion

Patterns of wetlands relative to aridity

The following key trends in the study were noted in relation to the gradient of increasing aridity: (1) a decreasing overall extent of wetlands; (2) a general narrowing of the diversity of HGM types towards the most arid extreme, with hillslope seep wetlands confined almost entirely to moderate aridity and unchannelled valley bottoms to moderate and moderately high aridity; (3) an increasing confinement of wetlands in the most arid areas to vegetated channels and unvegetated depressions; and (4) excluding the depressions, an increasing "dependence" on groundwater sources for wetland maintenance, mainly within the channel and at a few hillslopes associated with the artesian discharge of deep groundwater, which were identified at only a single location.

Melly et al. (2016; 2017) also reported a declining overall extent of wetland with increasing aridity and a declining occurrence of hillslope seep wetlands relative to depression wetlands. However, a key difference between this study and that of Melly et al. (2016; 2017) is that while this study included areas with MAP <100 mm, the driest areas included in the study of Melly et al. (2016; 2017) had MAP ~380 mm. This would likely explain why there was not the same “drop-off” of unchannelled valley bottoms and hillslope seep wetlands in the study of Melly et al. (2016; 2017) as that experienced in this study. It may also explain why many of the perched depressions described by Melly et al. (2017) were vegetated, while all the depressions in this study, which were all confined to the arid end of the gradient, were unvegetated. It is likely that the accumulation of solutes, in these largely endorheic sites, acts to suppress vascular plants, as observed in the salt pans of Botswana (Thomas et al. 2014).

Implications for vulnerabilities of the wetlands

Wetlands of all HGM types which occur in the mountain zones, are generally inaccessible and inherently unsuitable for intensive use, e.g. for cultivation (Table 6). In addition, the Cape fold mountains have sandstone-derived soils with generally very low nutrient status, resulting in a low value for livestock grazing and little grazing taking place. In contrast, the Great Escarpment mountains, with their predominantly dolerite-derived soils of a higher nutrient status and their grassy vegetation, are subject to much higher levels of livestock grazing, and are therefore more vulnerable to livestock-related impacts. Furthermore, most of the Great Escarpment areas are privately owned by livestock farmers, whereas extensive areas of the Cape fold mountain zones fall within formally protected nature conservation areas. For these wetlands, the most immediate threat is from invasive alien plants, which are already infesting many of the valley bottom wetlands in this zone and, less so, the hillslope seep wetlands.

Another important threat to the mountain zone wetlands is climate change. It is anticipated that some of the hillslope seep wetlands in particular which are close to a threshold of occurrence in terms of minimum MAP to PET ratio could potentially be lost entirely, even with even a modest increase in the MAP to PET ratio, as predicted with climate change. The coarse resolution of the climate data used in the study did not allow such specific thresholds to be identified. However, it is anticipated that when following the orographic rainfall gradient as one descends from the

relatively high MAP areas at high altitudes to the lower portions then some of the last hillslope wetlands that one encounters before entering the Karoo zone (where hillslope seep wetlands are almost entirely absent) would be amongst those close to this threshold.

In the Great Karoo and Little Karoo, a key factor affecting specific vulnerabilities of a wetland is whether it is groundwater fed. As evident in the most recent drought, groundwater abstraction is widespread and is continuing to increase, exposing groundwater-dependent wetlands to high vulnerabilities. Several of the channel and channelled valley bottom wetlands appear to be groundwater fed, and in the Little Karoo these wetlands, such as the Prins River wetland referred to earlier, appear to be mainly associated with sandstone lithologies. For much of the remaining areas of the little Karoo, lithologies are predominantly shales and siltstones, and aquifers are generally deep and typically of poor quality, and here groundwater abstraction is of a lesser threat to wetlands. As described earlier, in the Great Karoo and Great Escarpment, some of the valley bottom wetlands are associated with dolerite dykes, which are also favoured sites for boreholes (Woodford and Chevallier 2002). Thus, some of these valley bottom wetlands are likely to be vulnerable to groundwater abstraction, but further investigation is required to establish the surface/groundwater connections and degree to which these dolerite dykes (and sills) might act as both geomorphological and hydrological controls.

The verified depressions were predominantly in the lowest MAP areas of the study area in the Great Karoo and Little Karoo. All were unvegetated (which appears to be the natural state of these wetlands), are flooded very infrequently and for short duration (from direct precipitation and run-on from their local catchment) and are likely to at least be somewhat saline. These factors provided the primary motivation for assigning a negligible vulnerability of this wetland type to grazing pressure and cultivation, although it is recognized that livestock may potentially impact such systems through physical disturbance of biocrusts, if present (Elliot et al. 2019). In addition, these depressions do not appear to be connected to groundwater and therefore are not vulnerable to groundwater use. Furthermore, they are unlikely to change appreciably in structure as a result of the predicted aridification of climate. However, they could already be close to the minimum flooding duration and frequency required by their current micro fauna and flora, such that even a fairly modest climate-induced reduction in inundation frequency and/or duration would render

these areas no longer suitable for much of this fauna and flora. However, this is not known and would require further investigation. Furthermore, impacts on microbes have potential geomorphological implications given that microbes in the soil surface of drylands form biocrusts which reduce erodibility by wind and water (Elliot et al. 2019). This also requires further investigation.

Model performance and potential

Spatial products of wetland occurrence and type are encouraging. Prediction accuracy was commensurate with other arid-zone studies from non-winter rainfall regions, with Melly et al. (2016) reporting an AUC of 0.66. However, both studies reported lower AUC values than those from Hiestermann and Rivers-Moore (2015), who reported an AUC of 0.84 for a wetter summer rainfall region of South Africa. This suggests that best model accuracy is achieved through regional models, and that dryland regions are likely to have other confounding factors yet to be accounted for.

Wetland presence could be predicted using landscape characteristics (slope, catchment roughness, and elevation), and moisture regime (level of aridity based on A-pan evapotranspiration). This suggests that understanding of wetland presence in the landscape is not only a function of catchment characteristics, but also available water, with higher levels of aridity decreasing the probability of wetland occurrence. The utility value of having climate-related variables in a predictive model is in providing the capability of assessing impacts of climate change on extent of wetland areas. However, the predictor model is only as accurate as the data layers underpinning it. Further refinements include accounting more specifically for topographic heterogeneity linked to rainfall patterns, for example the Cape fold mountains. This could better account for the fact that the aquifer potential varies greatly across TMG areas, with the highest potential areas tending to be associated with faults and strongly folded strata (de Beer 2002) and for which the resolution of the current model did not account but which could potentially be modelled using an approach such as that applied by Blake et al (2010). This refinement could also be extended to exploring in more detail the influence of geology (in particular, the dolerite) on aquifer potential in the Great Escarpment. In addition, aspect may also play a role in improving model accuracy for wetlands in steep slopes, where steep southern aspect slopes may be shaded for much of the day, and

consequently provide areas in the landscape where temperatures and evaporative demand are significantly lower than would otherwise be the case (Clark et al 2009).

Recommendations for mapping

An important limitation of the spatial output of the modelling in this study is that, given its scale, it does not accurately represent individual wetland extent. The current approach has the capacity to be combined with additional spatial layers derived using complementary methods, such as the likelihood of occurrence of different HGM types based exclusively on a flow accumulation surface to indicate regions of probable wetness. By combining both approaches, it is then possible to identify: (1) specific areas of the landscape with a high likelihood of occurrence of hillslope seep wetlands; and (2) specific areas of the landscape where despite having the highest flow accumulation values in the local landscape, the likelihood of the area being a wetland is very low. Both approaches constitute ancillary data that will support the national wetland mapping process (Figure 7). In practical terms, polygons defined as potential wetlands, which have a high probability of occurrence, would be confidently categorized as wetland areas. Conversely, polygons defined as potential wetlands, which have a low probability of occurrence, are unlikely to be wetlands but rather non-wetland drainage lines.

References

- Allan D G, Seaman M T, Kaletja B (1995) The endorheic pans of South Africa. In Cowan G I (ed.) Wetlands of South Africa. Department of Environmental Affairs and Tourism, Pretoria.
- Blake D, Mlisa A, and Hartnady C (2010) Large scale quantification of aquifer storage and volumes from the Peninsula and Skurweberg Formations in the southwestern Cape. Water SA 36: 177-184
- Clark VR, Barker NP, Mucina L (2009) The Sneeuberg: A new centre of floristic endemism on the Great Escarpment, South Africa. South African Journal of Botany 75:196–238.
- Collins, N.B. 2018. Chapter 5: Modelling of probable wetland extent. FS DESTEA internal report, in Van Deventer et al. South African National Biodiversity Assessment 2018: Technical Report. Volume 2a: South African Inventory of Inland Aquatic Ecosystems (SAIIAE). Version 3, final released on 3 October 2019. Council for Scientific and Industrial

- Research (CSIR) and South African National Biodiversity Institute (SANBI): Pretoria, South Africa. Report Number: CSIR report number CSIR/NRE/ECOS/IR/2018/0001/A; SANBI report number <http://hdl.handle.net/20.500.12143/5847>.
- Colvin C, le Maitre D, Saayman I, and Hughes S (2007) An Introduction to Aquifer Dependent Ecosystems in South Africa. WRC Report No. TT301/07 Water Research Commission, Pretoria.
- Colvin C, Riemann K, Brown C, Le Maitre D, Mlisa A, Blake D, Aston T, Maherry A, Engelbrecht J, Pemberton C, Magoba R, Soltau A, Prinsloo E (2009) Ecological and environmental impacts of large-scale groundwater development in the Table Mountain Group (TMG) aquifer system. WRC Report No. 1327/1/08. Water Research Commission, Pretoria, South Africa.
- De Beer (2002) The stratigraphy, lithology and structure of the Table Mountain Group. In: Peterson K and Parson R (eds.) A synthesis of the hydrogeology of the Table Mountain Group – formation of a research strategy. WRC Report No. TT 158/1. Water Research Commission, Pretoria.
- Department of Water and Sanitation (DWS) (2015) Reserve Determination Studies for Surface Water, Groundwater, Estuaries and Wetlands in the Gouritz Water Management Area: Wetland Report. Prepared by Rountree, M (Fluvius Consultants) for Scherman Colloty & Associates cc. Report no. RDM/WMA16/03/CON/0513.
- Ellery W, Grenfell M, Grenfell S, Kotze D, McCarthy TS, Tooth S, Grundling PL, Beckedahl H, Le Maitre D, Ramsay L (2009) WET-origins: controls on the distribution and dynamics of wetlands in South Africa. Water Research Commission Report TT334/09, Pretoria.
- Elliott DR, Thomas AD, Strong CL, Bullard J (2019) Surface stability in drylands is influenced by dispersal strategy of soil bacteria. *Journal of Geophysical Research: Biogeosciences*, 124(11), pp.3403-3418.
- Goudie AS, Thomas DSG (1985) Pans in southern Africa with particular reference to South Africa and Zimbabwe. *Zeitschrift fur Geomorphologie NF* 29: 1-19.
- Grenfell MC, Grenfell SE, Mazvimavi D (2021) Morphodynamic modelling of dryland non-perennial riverscapes, with implications for environmental water allocation. *Prog. Phys. Geog. Earth. Enviro.* March 2021. <https://doi.org/10.1177/0309133321996639>.

461 Hiestermann J, Rivers-Moore N A (2015) Predictive modelling of wetland occurrence of
 462 KwaZulu-Natal, South Africa. *S. Afr. J. Sci.* 111:10. doi: 10.17159/sajs.2015/20140179
 463 Hu S, Niu Z, Chen Y, Li L, Zhang H (2017) Global wetlands: potential distribution, wetland loss,
 464 and status. *Science of The Total Environment* 586:319-327.
 465 McCune B, Mefford MJ (2011) PC-ORD. Multivariate Analysis of Ecological Data. Version 6.16
 466 MjM Software, Gleneden Beach, OR.
 467 MedCalc® (2021) Statistical Software version 20 (MedCalc Software Ltd, Ostend, Belgium;
 468 <https://www.medcalc.org>).
 469 Melly BL, Schael DM, and Gama PT (2017) Perched wetlands: An explanation to wetland
 470 formation in semi-arid areas. *Journal of Arid Environments* 141:34-39
 471 Melly BL, Schael DM, Rivers-Moore NA, and Gama PT (2016) Mapping ephemeral wetlands:
 472 manual digitisation and logistic regression modelling in Nelson Mandela Bay
 473 Municipality, South Africa. *J. Environ. Manage.* 25, 313–330. doi: 10.1007/s11273-
 474 016-9518-7
 475 Meyer PS (2002) Springs in the Table Mountain Group, with Special Reference to Fault Controlled
 476 Springs, In Pietersen K and Parsons R (eds.) *A Synthesis of the hydrogeology of the*
 477 *TMG Formation of a research strategy*, WRC Report No. TT 158/01. Water Research
 478 Commission, Pretoria.
 479 Mucina L, Rutherford MC (eds.) (2006) *The Vegetation of South Africa, Lesotho and Swaziland.*
 480 *Strelitzia*, vol. 19. South African National Biodiversity Institute, Pretoria
 481 QGIS (2018). QGIS Geographic Information System. Open Source Geospatial Foundation Project.
 482 <http://qgis.osgeo.org>.
 483 R Development Core Team (2009) *R: A Language and Environment for Statistical Computing.*
 484 Vienna: R Foundation for Statistical Computing. Available online at: [http://www.R-](http://www.R-project.org)
 485 [project.org](http://www.R-project.org)
 486 Rivers-Moore NA, Cowden C (2012) Regional prediction of wetland degradation in South Africa.
 487 *Wetlands Ecology and Management* 20:491-502.
 488 Rivers-Moore NA, Kotze DC, Job N, Mohanlal S (2020) Prediction of wetland hydrogeomorphic
 489 type using morphometrics and landscape characteristics. *Frontiers in Environmental*
 490 *Science* 8:58. DOI: 10.3389/fenvs.2020.00058.

- Schulze RE (ed) (2007) South African Atlas of climatology and agrohydrology. WRC Report 1489/1/06. Water Research Commission, Pretoria
- Scoones I (1991). Wetlands in drylands: key resources for agricultural and pastoral production in Africa. *Ambio*, 20:366–371.
- Thomas AD, Dougill AJ, Elliott DR, Mairs H (2014) Seasonal differences in soil CO₂ efflux and carbon storage in Ntwetwe Pan, Makgadikgadi Basin, Botswana. *Geoderma*, 219:72-81.
- Tooth S, McCarthy TS (2007). Wetlands in drylands: key geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. *Progress in Physical Geography* 31:3–41.
- Trabucco A, Zomer R (2019) *Global Aridity Index and Potential Evapotranspiration (ET₀) Climate Database*. <https://doi.org/https://doi.org/10.6084/m9.figshare.7504448.v3>
- USGS (2021) SRTM Digital Elevation/SRTM Void Filled 3-Arc. Available online at: <https://earthexplorer.usgs.gov/>
- Van Deventer H, Van Niekerk L, Adams J, Dinala MK, Gangat R, Lamberth SJ, Lotter M, Mbona N, MacKay F, Nel JL, Ramjukadh CL, Skowno A, Weerts SP (2020) National Wetland Map 5: An improved spatial extent and representation of inland aquatic and estuarine ecosystems in South Africa. *Water SA* 46:66-79.
- Woodford A C, and Chevallier L (Eds.) 2002. Hydrogeology of the Main Karoo Basin: Current knowledge and future research needs. WRC Report No. TT 179/02. Water Research Commission, Pretoria.

Table 1 The primary physiographic zones of the Western Cape interior, based on DWS (2015) and Mucina and Rutherford (2012), given in order of occurrence from the north to the south

Physiographic zones	General description	Climate	Main Vegetation Types according to Mucina and Rutherford (2012)
Great escarpment (PZ1)	A semi-continuous mountain system on the edge of South Africa's inland plateau, characterized by dolerite-capped mountains.	MAP predominantly 400-600 mm (very late summer)	Karoo Escarpment Grassland, Eastern Upper Karoo, Upper Karoo Hardeveld
Plains of the Great Karoo (PZ2)	Predominantly low-relief plains, with Karoo Supergroup sedimentary rocks, broken by river valleys and dolerite-capped koppies (hills).	MAP predominantly 100-200 mm (very late summer)	Gamka Karoo, Koedoesberge-Moerdenaars Karoo, Tanqua Karoo, Southern Karoo Reviere
Swartberg Cape fold mountains (including Klein Swartberg) (PZ3)	A continuous mountain system of Table Mountain Group (TMG) sandstone, including the highest mountains in the Western Cape.	MAP from <300 mm in the northern foothills to >900 mm in the mountains (all year)	South Sandstone Fynbos, North Sandstone Fynbos
Little Karoo (PZ4)	A predominantly gently undulating terrain with Bokkeveld shales, broken by river valleys and a few free-standing mountains (e.g. Touwsberg).	MAP is generally low (<300 mm) and in some areas extremely low (<150 mm) (all year)	Western Little Karoo, Western Gwarrieveld, Eastern Little Karoo, Gamka thicket
South Cape fold mountains (PZ5)	A continuous mountain system of TMG sandstone	MAP from <400 mm in the lower foothills to >1000 mm in the southern mountains (all year).	North Langeberg Sandstone Fynbos, South Langeberg Sandstone Fynbos

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Table 2 An overview of the test areas included in the study, with PZ1-6 referring to the numbers designating the different Physiographic zones described in Table 1

Test areas	Brief description
Van Wyksdorp (Groot River and Touws River) 1 948.3 km ²	Predominantly gently sloped lowlands of the Klein Karoo (PZ4 ¹) and including some of its major rivers. Mean annual rainfall is generally low (<300 mm) and in some areas extremely low (<150 mm) (all year).
Ladismith (Klein Swartberg) 103.1 km ²	Hilly lowlands of the Klein Karoo (PZ4) in the south extending into Cape Fold Mountains (PZ5) in the north. A steep rainfall gradient from <200 mm in the lowlands to >700 mm in the mountains (all year).
Kamma River catchment 113.5 km ²	Predominantly Cape Fold Mountains (PZ5). Rainfall from <400 mm in the foothills to >800 mm in the mountains (all year).
Rietvlei to Goliatsberg (Langeberg) ¹ 285.3 km ²	Predominantly Cape Fold Mountains (PZ5) Rainfall from <400 mm in the lower foothills to >900 mm in the mountains (all year).
Swartberg Pass (Groot Swartberg) 29.7 km ²	Predominantly Cape Fold Mountains (PZ5). Rainfall from <300 mm in the northern foothills to >900 mm in the mountains (all year).
Koekoemoers River (Erdvark hiking trail) 113.8 km ²	Great Karoo (PZ2) extending into the Nama Karoo; predominantly hilly with some outlying mountains of the Nuweveld mountain range. Rainfall predominantly 100-200 mm (very late summer) but somewhat higher in the mountains.
Upper Olifants River 214.3 km ²	Little Karoo (PZ); valley of the Olifants River in its upper reaches; rainfall 200-300 mm (all year)
Leeu Gamka 189.0 km ²	Gently undulating plains and hills of the Great Karoo (PZ2), including an extensive area of the Leeu Gamka River valley. Rainfall predominantly 100-200 mm (mainly very late summer)
Sneeuberge 61.5 km ²	Great Karoo (PZ2); lower flat to gently hilly terrain in the west with 300-400 mm of rainfall and the high-lying Toorberg mountain in the east with rainfall 400-600 mm (very late summer) and regular winter snow.
Murraysburg 113.7 km ²	Great Karoo (PZ2); hilly terrain dissected by the Brak River and the upper Buffels River, including broad alluvial washes associated with the Brak River; rainfall 200-300 mm (very late summer)
Nelspoort (Murraysburg to Beaufort West) 116.1 km ²	Great Karoo (PZ2); hilly terrain dissected by the Buffels River and its major tributaries, and including extensive alluvial washes; rainfall 200-300 mm (very late summer)
Beaufort West to Loxton 208.4 km ²	Great Karoo (PZ2); including the southern edge of the Great Escarpment and the lower-lying and gently hilly terrain of Loxton; rainfall >400 in the south decreasing northwards to <200mm in the north
Beaufort West to Meiringspoort 143.3 km ²	Great Karoo (PZ2) plains somewhat dissected by low to medium order drainage lines; rainfall predominantly 100-200 mm (very late summer)

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521	Table 3 List of raster-based predictor variables for modelling probability of wetland occurrence and most likely HGM type	
	Data layer	Source
	Elevation (m)	USGS (2021) 90m Digital Elevation Model
	Slope (degrees)	DEM-derived
	Roughness	DEM-derived
	Relief ratio	DEM-derived
	Flow accumulation/ runoff	DEM-derived
	Groundwater depth (metres below ground)	Colvin et al. (2007)
	Aridity index	Trabucco & Zomer (2019)
	A-pan evaporation (mm)	Schulze (2007)
	Mean annual precipitation (mm)	Schulze (2007)
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524 **Table 4** Eigenvalues for PCA in Figure 3

Variable	1	2
% Cum. Var.	38.496	63.718
Presence/ Absence	0.0176	-0.1274
Aridity Index	0.4857	-0.2061
A-pan evap.	-0.4837	-0.0761
Slope	0.233	0.5621
Runoff	0.0683	0.0246
Elevation	-0.1266	0.4623
MAP	0.497	-0.0576
Roughness	0.2414	0.5597
Groundwater	-0.3867	0.2976

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Table 5 Variables for wetland occurrence model for predicting wetland probability of based on data for the arid interior zone of the Western Cape Province (n = 1292; Presence/ Absence of 231 vs.1061). All coefficients were significant for $p < 0.05$

Variables	Estimate	Std. error	z-value	Pr(> z)
Intercept	5.98213	1.18684	5.040	4.65E-07
A-Pan evap. (mm)	-0.00410	0.00053	-7.756	8.74E-15
Roughness (m)	0.03848	0.00950	4.049	5.14E-05
Slope (°)	-0.12285	0.03905	-3.146	0.00165
Elevation (m)	0.00196	0.00021	9.515	2.00E-16

Table 6 A preliminary rating of the level of vulnerability¹ of the main wetland types in the Western Cape interior to selected major threats

Broad wetland types	Major threat types						
	Climate change	Local groundwater use	Upstream dams/ abstractions/ diversions	IAPs	Sewage/ effluent/ pollution	Grazing	Cultivation
Hillslope seeps – TMG mountains	***	*	*	**		*	
Hillslope seeps – Great Escarpment mountains	***	*	*	*		**	*
Hillslope seeps – Karoo	**	**	**	*		**	
Channelled valley bottom – TMG Mountains	**	*	*	**			
Channelled valley bottom and floodplain – Karoo	**	***	***	***	*	*	**
Unchannelled vb – TMG mountains				***		*	
Unchannelled vb – Great Karoo	***	**	***	**	*	**	*
Depressions - Karoo	**		*				

Vulnerability is scored on the following scale: []=Negligible; [*]=Low; [**]=Intermediate; [***]=High

Figure 1 Study area, showing physiographic regions, with presence/ absence wetland data points indicated. Inset (left) location of the Western Cape Province in South Africa, while inset (right) shows the arid interior study region within the overall aridity gradient of the Western Cape Province.

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Figure 2 Proportional contributions of wetland HGM types to overall wetland area per physiographic region

Figure 3 Principal components analysis of wetland presence/ absence relative to predictor variables (see Table 2 for further details). Convex hulls indicate wetland presence (1) versus absence (0) sites.

Figure 4 Probability of occurrence of wetlands within the arid interior study region of the Western Cape Province, represented as a continuous probability layer reclassified into probability class intervals

Figure 5 Raster image of potential seep regions in the study area, based on corresponding variable states from rivers-Moore et al. (2020) (top), and the associated probability surface for seeps using the probability of wetland occurrence model for the study area (lower)

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Figure 6 Receiver operating curve of false positive versus true positive classification rate for prediction of wetland occurrence model the study region (AUC = 0.78)

Figure 7 Mixed modeling approach within the context of the national wetlands mapping process

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [WetlandWCapeinteriorSupplementaryplates.pdf](#)