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ORIGINAL PAPER

Spatial patterns in small wetland systems: identifying and prioritising wetlands most at risk from environmental and anthropogenic impacts

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Abstract This study establishes whether analysing the distribution patterns of wetlands could identify key systems that would focus conservation and management decisions, without site-specific data which requires significant logistical and financial resources. In the proposed approach, key wetlands at-risk were identified based on their position in the landscape, through the use of probability modelling and least-cost analyses. The research was based in a semi-arid part of the Eastern Cape, South Africa. The study area has aseasonal rainfall, different land-use zones and an existing spatial dataset, providing an ideal setting to test this method. Wetlands were highly clustered, with higher densities recorded in the south and along larger rivers. Areas that have more-suitable environmental conditions for wetlands were mapped—showing similar patterns to known dense wetland areas. In total, 89 systems were identified as very high-risk, and 414 wetlands were high-risk, to environmental and anthropogenic changes. Seven focal zones were selected by incorporating wetland clusters/hotspots. These zones should be the focus for further research and management that would assess the surrounding environment and the potential effects of land-use or climate changes, and policy adaptation. In summary, this study successfully illustrated the importance of adapting different spatial analytical methods in wetland research, and that desktop studies can be used to focus conservation and management efforts over larger areas.

Keywords Getis-Ord Gi* · Geographical Information Systems (GIS) · Moran's I statistic · Multi-scalar · Structural connectivity · Wetland risk (assessment)

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Introduction

This study uses spatial analyses to provide the link between wetland distribution patterns at a landscape scale and those observed at finer spatial scales, by incorporating various environmental and anthropogenic variables that are known to affect wetlands. These multi-scalar links can be used to provide key information for scale-appropriate conservation and management decisions in the absence of available site-specific studies. This type of research is crucial in areas where there is rapid urban expansion and threats to already limited water resources, such as in the Nelson Mandela Bay Municipality (NMB), South Africa.

Wetland ecosystems are reported to be highly productive ecosystems that lie at the interface between aquatic and terrestrial environments, forming a critical component of the water resources in a landscape as well as critical habitats for many species (Keddy 2010; Semlitsch 2000). Despite their importance, however, many wetland systems are strongly affected by anthropogenic activities such as urban expansion, an increase in agricultural activities and pollution. Recent studies have estimated 64–71% of inland wetlands in the world have been destroyed as a result (Gardner 2015; Machtinger 2007). In several regions in South Africa, it is thought that over 50% of the wetlands have already been lost (DWAF 2005), despite their protection under the South African National Water Act (Act 38 of 1998).

Wetland loss cannot be accurately assessed without sufficient baseline data, which primarily exists in wetland inventories. Globally, there are few adequate wetland inventories describing wetland types and their landscape positioning, particularly for inland and ephemeral systems (Leadley 2014). These inventories have the necessary information to establish the importance of these systems in relation to the surrounding environment, which is vital for instituting sound management and conservation practices.

Wetland research relies on detailed site and/or monitoring data. But this information requires adequate financial and logistical resources. Consequently, decisions involving large areas of concern are reliant on limited data, which is fundamentally lacking for wetlands in South Africa (Malan 2010). Moreover, the ability to predict various environmental and anthropogenic impacts affecting wetlands is limited, especially their responses to such impacts (Malan 2010). In many countries, including South Africa, progress is being made to create more detailed inventory data (e.g. Biodiversity GIS 2011; Schael et al. 2015; van Deventer et al. 2016). However, scientists and managers need to also find different methods and strategies to use data that already exists for monitoring and management purposes.

The surrounding landscape plays a critical role in wetland formation, maintenance and function (Melly et al. 2016). Therefore, it is important to identify which components of the landscape provide these key environmental processes that affect wetland functioning (Krause et al. 2007). For example, the influence of the surrounding landscape has been used in models to predict wetland loss based on wetland habitat and the landscape context (Gutzwiller and Flather 2011), including predicting water quality based on land cover (Amiri and Nakane 2009). A framework can then be developed to assess the risk of significant changes to the surrounding environment, similar to the UK and Ireland used to assess groundwater-dependent wetlands vulnerable to groundwater pressures (Krause et al. 2007).

Landscape ecology breaks down the landscape into two components, the patch (wetland) and the surrounding matrix (catchment) (Wagner and Fortin 2005). The extent of the relationship between patch and matrix is termed "connectivity". A large portion of wetland research focuses on biological connectivity that requires detailed site data, which is not always possible. However, these bio-physical relationships assessed in wetland research are better understood together with the spatial relationships between wetlands—this is referred to as structural isolation and connectivity (Kahara et al. 2009; Morris 2012).

Wetland connectivity occurs on a spectrum of spatial and temporal scales, and knowledge of these multi-scalar interactions contributes towards understanding broader-scaled landscape functions (Leibowitz et al. 2000). Furthermore, the distribution of wetlands should provide insight into the spatial scale at which these systems should be managed. Spatial statistics, using Geographical Information Systems (GIS), are powerful methods that can be used to illustrate and quantify distribution patterns at different spatial scales (Bowen et al. 2010).

This study aims to identify spatial patterns in wetland distribution and how it can be used to identify wetlands most at risk from environmental and anthropogenic changes, without using site-specific data. Systems at risk from such impacts are identified based on their position in the surrounding landscape, using a least-cost analysis and wetland probability map. Such methods provide tools for decision-makers in areas where site-specific data is limited, to prioritise areas for in-depth research that would be needed to facilitate effective conservation and management plans.

Methods

The study area: Nelson Mandela Bay Municipality

This research was based in the NMB, in the Eastern Cape Province, South Africa (Fig. 1). The study area is approximately 1951 km^2, and diverse in its climate, geology, geomorphological features and vegetation. The vast environmental diversity within the Municipality renders it a good test site for links between wetland distribution patterns occurring at a landscape level and at finer spatial scales.

Rainfall is aseasonal (range 423–690 mm), with a mean annual precipitation of 613 mm (Schulze 2007; SAWS 2014). Evapotranspiration rates are three times higher, ranging from 1600 to 2000 mm (Schulze 2007). Consequently, the Municipality is classified as a dryland/semi-arid area with an aridity score < 0.65 (as per UNEP 2009). This has important implications for the occurrence and distribution of wetlands within the study area, as they are predominantly precipitation driven (Melly et al. 2017).

Approximately 40% of the NMB has been modified or transformed (Stewart 2010). Urban activities comprise the largest proportion, and are concentrated in the wetter, southeast portion of the Municipality, where a majority of the existing wetlands occur. The northern, drier areas are less developed, with predominantly natural cover (Stewart 2010). Over 14% of the NMB is used for agriculture (e.g. cultivation and livestock farming), and 5% is covered by alien plants (Stewart 2010). The effects of the land-use practices

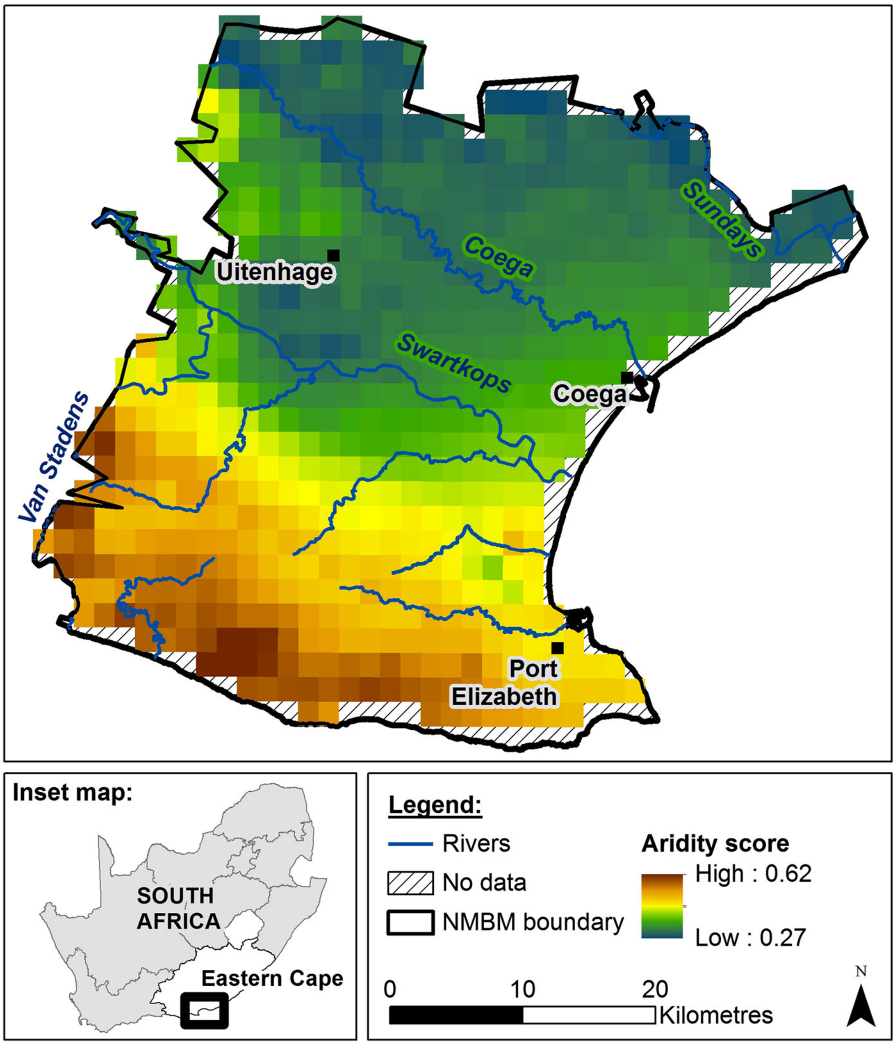


Fig. 1 The Nelson Mandela Bay Municipality (NMB) located in the Eastern Cape, South Africa (inset) showing wetland locations and rivers. The wetland occurrence probability map [modified from Melly et al. (2016)] is also illustrated. Raster has been reclassified from 1 (high probability of wetland occurrence) to 5 (low probability). No data indicates areas that had missing data layers and were therefore excluded from further classification

are compounded by limited water resources, which have been effected in terms of both their water quality and quantity. The extent of the anthropogenic activities has continued without sufficient monitoring, indicating the degree to which wetlands are being modified or destroyed in the Municipality.

NMB wetland spatial database

This study was carried out using an existing digital wetland database of 1712 wetlands, most of which are ephemeral, excluding riverine systems (Schael et al. 2015). The wetlands are comprised of six hydrogeomorphic (HGM) types, including depressions, seeps, wetland flats, unchannelled valley bottom wetlands, channelled valley bottom wetlands and floodplain wetlands (classification of Ollis et al. 2013). Saltpans were included in the statistical analyses except where there were large, artificial salt works that significantly skewed the data.

Quantifying wetland distribution in the landscape

Wetlands can be further understood at a finer scale by the degree of isolation or connectivity of wetland systems. Several landscape-scale environmental variables were useful in wetland distribution in NMB (Melly 2016; Schael et al. 2015). Spatial statistics were run using ArcGIS 10.3 (ESRI® 2014) to further examine wetland distribution patterns in the Municipality, including spatial clustering, spatial autocorrelation and hotspot analyses. Statistical assumptions were checked for each relevant spatial and statistical analysis using standard testing procedures before using the methods outlined below (McKillup 2006; Quinn and Keough 2002; Townend 2013). Spatial clustering of wetlands was calculated using an Average Nearest Neighbour Ratio (ANN), which calculates the observed Euclidean distance of each wetland to the next nearest wetland divided by the expected distance based on a random distribution (Clark and Evans 1954). The ANN was used to measure the extent to which wetlands deviated from a random distribution within the study area at various predetermined spatial scales. A score of < 1 indicates clustering (observed mean distance is less than the expected mean distance) and > 1 indicates dispersion.

A spline interpolation technique was used to create a smoothed wetland cluster surface. A distributional statistic, the z-score, evaluated whether wetlands were clustered (z-score < -1.96) or dispersed (z-score > -1.96) (Quinn and Keough 2002). The distance to the nearest wetland was used as the z-value to highlight areas where wetlands clustered.

Hotspot analyses are often used in the social sciences to, for example, map crime, vehicle accidents or disease risk (Chainey and Ratcliffe 2013). In this study, an Optimised Hotspot Analysis was used to establish which areas have statistically high densities of wetlands. The analysis produces a map of significant hotspots and coldspots using the Getis-Ord Gi* statistic (Getis and Ord 1992; Zhang et al. 2014), and the ANN values as the proxy. Standard settings were used to weight each wetland at the appropriate scale. The Getis-Ord Gi* statistic, like the other spatial statistics, records significance using a z-score and p value. Significant negative z-scores indicate coldspots, areas with uniformly large distances between wetlands, while hotspots are areas where many wetlands are in close proximity to each other.

A Moran's I statistic was run to calculate whether wetlands of similar sizes were more clustered or dispersed, in relation to other size classes within a complex. If systems were of similar sizes (i.e. spatially autocorrelated), this could have an impact on the ecosystem functioning of these systems, such as vegetation zonation patterns. Values around -1 indicated that wetlands of similar sizes were more dispersed, and values closer to 1 indicated that similar sized wetlands clustered together. Further details on the Moran's I statistic is described in Getis and Ord (1992) and Zhang et al. (2014).

The ANN determined if there is spatial clustering. The Getis-Ord Gi* illustrated where these clusters were located (hotspots), or not (coldspots), and the Moran's I statistic was used to determine whether clusters tended to have wetlands of similar sizes within the cluster. Understanding these spatial relationships provides an important step in adequately managing these systems across a landscape as inter-linked ecosystems without relying on detailed site data.

Landscape suitability for wetland presence

A least-cost analysis generally refers to the ability of organisms to move between two patches on a path of least resistance (Rudnick et al. 2012; Weber and Norman 2015). This study applies this method, using the technique to establish whether certain environmental and anthropogenic features would create conditions that would resist or promote wetland occurrence and distribution, thereby describing the structural connectivity of these systems. If wetlands are (partially) a result of the landscape around them, then these systems would be in areas that had suitable conditions (i.e. a lower cost). Consequently, a wetland that is "at-risk" is defined as a system located in a less suitable surrounding environment. High-risk systems can then be used to focus scale-appropriate conservation and management strategies for further, more-in depth analysis.

Several datasets were used for the landscape suitability analysis. These datasets were chosen based on availability and resolution of data, as well as their importance in a wetland occurrence model for the study area (see further detail in Melly et al. 2016). The variables were also tested for collinearity in logistic regression model using an overall condition number before inclusion in further analysis (Quinn and Keough 2002). Datasets were converted from shape files to raster files and resampled to a resolution of 20 m, the resolution of the Digital Elevation Model (DEM) for NMB, where necessary. Different resampling techniques were used for the various data types: nearest neighbour resampling technique for categorical data, cubic convolution for continuous data and bilinear for DEM and DEM-derived data (ESRI® 2017; Keys 1981; Usery et al. 2004).

The variables used for the landscape suitability analysis were: the DEM derived slope and flow accumulation, evapotranspiration, mean annual precipitation (MAP) and annual heat units. Land-use cover was the only anthropogenic variable available that was included in the analysis. These environmental and anthropogenic variables have been shown to be important in wetland occurrence in several studies (Melly et al. 2016; Rudnick et al. 2012; Weber and Norman 2015), as well as covering the basic environmental and anthropogenic features in the landscape.

The six raster layers were reclassified into categories with an associated "Landscape Suitability Score". Higher cost scores were associated with less suitable conditions. Flow accumulation is typically assigned higher cost scores with higher values because it is used to model an increase in flood risk with an increase in flow accumulation. However, in the context of abiotic and biotic connections between wetlands, this variable is a promoter of wetland functioning and connectivity, with higher flow accumulation values increasing connectivity.

Higher cost values were associated with increased anthropogenic impact (Table 1). These higher cost values were used to compensate for the overall weighting of the five other environmental variables when combined. Thus, a high cost scoring anthropogenic activity (e.g. urban activities) would still significantly increase the cell value overall, thereby indicating *less suitable* conditions for wetland persistence.

The six reclassified raster data layers were then summed together using the Raster Calculator in ArcGIS to provide an overall landscape suitability score (high scores pertain to poor conditions for wetland persistence). Non-wetland (absence) points were created in the Geospatial Modelling Environment (GME) program (Beyer 2010), which generates a set of random points. A total of 1700 absence points were created in the study area. Points did not overlap with known wetland locations and were a minimum of 150 m apart. Raster values were extracted for the non-wetland points and known wetland points. If the wetland fell outside the raster range (i.e. values were missing), the nearest cell value was used. A standard t-test was then used to ascertain whether wetlands were located on areas with a lower score than non-wetlands.

An example of a suitable position for a wetland is: natural vegetation (cost score of 10), on a gentle gradient slope (score 100), in an area with a flow accumulation of 600,000 (score 100), low evaporation rate of 1600 mm per annum (score 10), a high rainfall of 650 mm per annum (score 100) and an overall annual heat unit of 2600°days (score 100), with a total cost score of 420. In contrast, a similar region can have the same climate, but if it were located on a steep slope (score 1000) with alien vegetation (score 1000), the location would have a higher cost score of 2310. Therefore, the latter area would be less suitable for wetland development and persistence, and possibly more susceptible to environmental or anthropogenic changes. The output cost-grid was reclassified, with bilinear interpolation in Spatial Analyst Tools (ArcMap 10.3), into five categories, 1 (high landscape suitability, low cost) to 5 (low landscape suitability, high cost score).

Table 1 Cost Score for each of the six data layers (land-use, slope, etc.) used in the least-cost analysis

Cost score	Slope (%)	Flow accumulation per 1000 cells	Evaporation (mm per annum)	MAP (mm)	Heat units (days)	Land-use cover
1	N/A	N/A	N/A	N/A	N/A	Dams
10	0–3	100–1240	1593–1700	700–803	2108–2500	Natural
100	3–9	30–100	1700–1800	600–700	2500–2700	Airfields, recreational open spaces
500	9–15	15–30	N/A	N/A	2700–2800	N/A
1000	15–30	10–15	1800–1900	500–600	2800–2900	Plantations, high density alien plants
5000	30–60	5–10	1900–2000	400–500	2900–3000	N/A
10,000	60+	0–5	2000–2036	378–400	3000–3140	Dumps, mines
100,000	N/A	N/A	N/A	N/A	N/A	Roads, urban areas

A low cost score indicates a suitable environment. Classes were grouped using standard intervals except for flow accumulation, which was defined using quartiles

MAP mean annual precipitation, *N/A* not applicable

Potential areas where wetlands are at increased risk (from environmental and anthropogenic changes) were calculated by combining the cost scores and the values from a wetland occurrence probability map that exists for the study area (Fig. 1) (see Melly et al. 2016).[1] The wetland occurrence probability raster map was also reclassified into five categories from 1 (high probability of wetland occurrence) to 5 (low probability). Wetlands were classed as "at risk": if they were located in areas that were not highly suited to wetland occurrence due to environmental and/or anthropogenic variables. The implication is that a wetland that is situated on a low probability cell (5) (a low value in the logistic regression model) and a low suitability cell (5) (a high overall cost score), is more susceptible to environmental and anthropogenic changes (totalling 10). Thus, the two reclassified grids were added together such that a low overall number indicated a wetland that was less at risk.

[1] Significant environmental variables in a Generalised Linear Model were used to create a parsimonious Logistic Regression Model. A probability map was then created in ArcGIS using the selected variables (raster files) and their respective coefficients. A total of 7 out of 19 possible environmental variables were used in the final model. These were: elevation, flow accumulation, flow direction, MAP, temperature, groundwater occurrence and rainfall.

Identifying focus areas for conservation and management

Values were extracted for each known wetland in the NMB, to ascertain how many wetlands were in high-risk areas. Rankings were as follows: very low-risk (1–2), low-risk, (3–4), medium-risk (5–6), high-risk (7–8), and very high-risk (9–10). Key wetlands were identified to automate the process of selecting important wetland complexes. A key wetland had to fulfil two criteria, a risk score of 8–10 and is situated on a hotspot according to the Getis-Ord Gi* statistic. The z-scores obtained from the Getis-Ord Gi* statistic were divided into two categories with a relatively equal number of wetlands within each and were subsequently defined as either hotspots or coldspots. If a wetland only fulfilled one of the two criteria, this wetland would still be considered at risk and was used when selecting an area. Two "at risk" areas that were defined in this way are highlighted in this paper to illustrate how this method can be applied.

Results

Wetland distribution in the NMB landscape

A total of 86% of the systems were less than 1 ha. Only 38 wetlands were larger than 5 ha, and four of these systems were greater than 50 ha (Fig. 2).

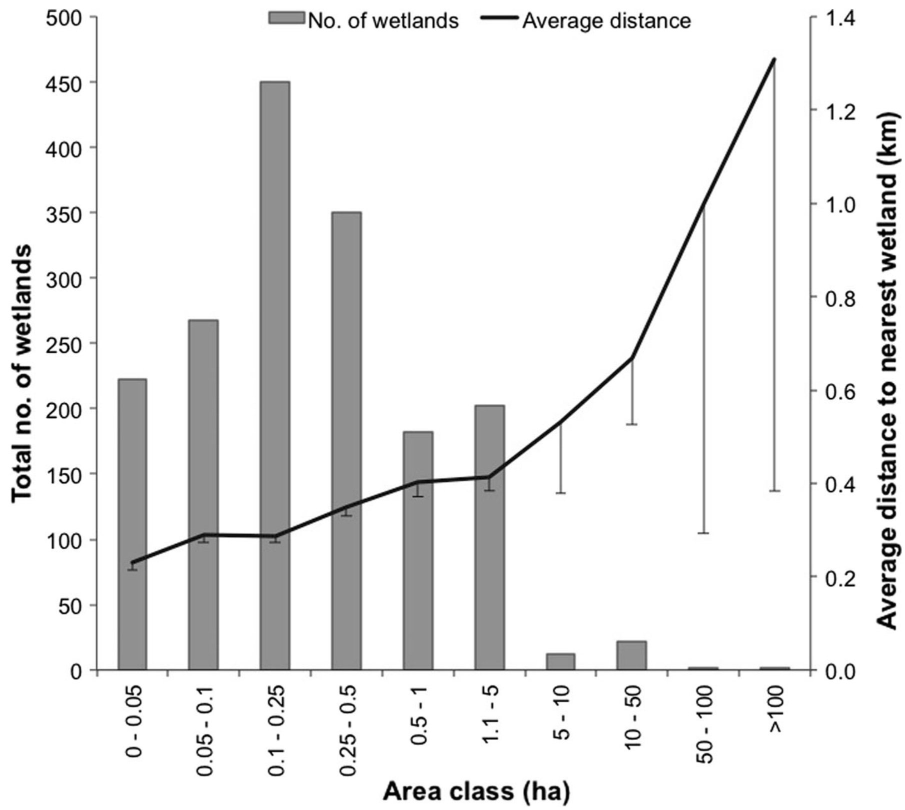


Fig. 2 Number of wetlands (left axis) and the mean nearest neighbour distances between wetlands (right axis) observed in each area class (with − 1 standard error bar shown for display purposes). *Note* x-axis classes are not to scale. Numbers given on the graph denote sample size for the respective area class

Wetlands were found, on average, approximately 329 m (± 8.44 SE) from the nearest neighbouring wetland. The large standard error is mostly due to the variability in distances among larger systems (Fig. 2). The ANN indicated that the systems were significantly clustered (z-score = − 36.93: p-value < 0.0001) (Fig. 2). The log of wetland size and the distance to the nearest wetland was loosely positively correlated (Pearson's statistic (r) = 0.294, t = 12.643, df = 1687: p-value < 0.0001). Figure 2 illustrates this general positive trend in each area class (non-transformed data). Wetlands also did not appear to cluster with other wetlands in the same size class, but rather, formed complexes with different wetland sizes (Moran's I Index, z-Score = 1.71: p-value = 0.088).

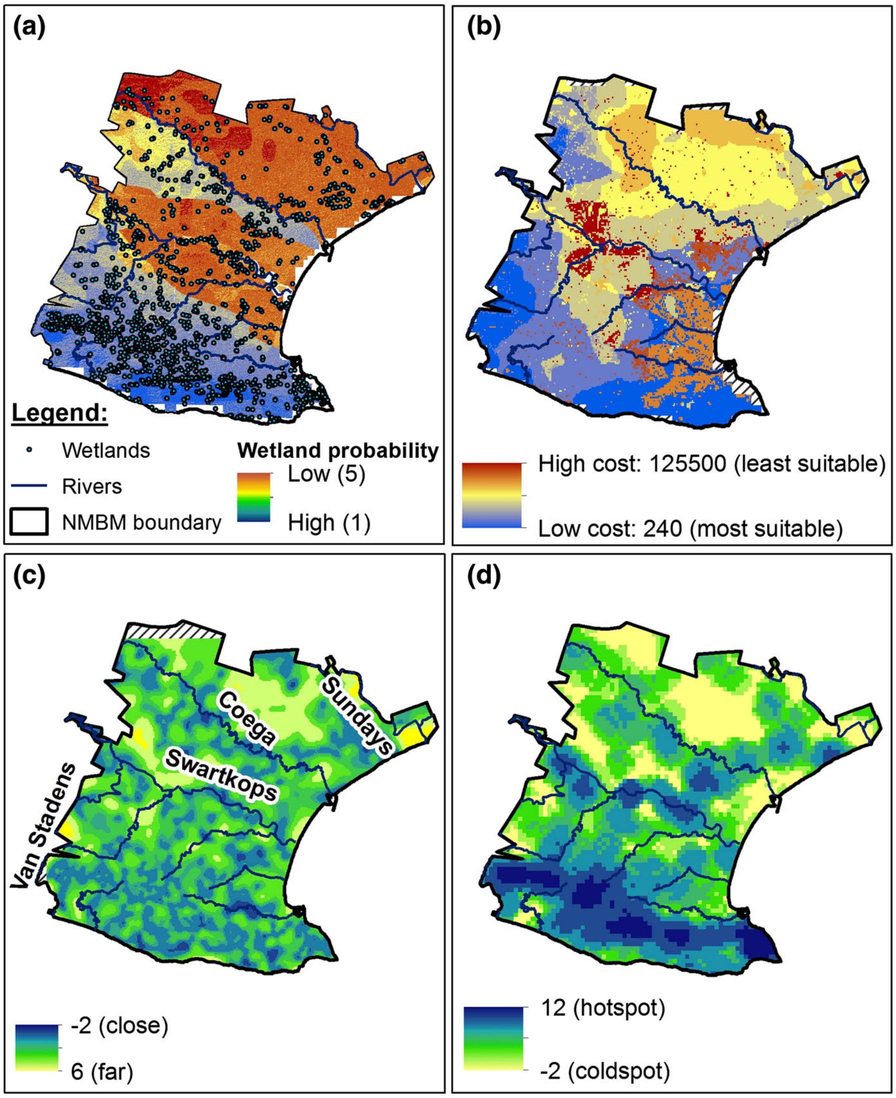
The spatial distribution of these wetlands can be illustrated in various ways. Figure 3a illustrates the location of individual systems as a reference. A spline interpolation illustrates where clustering occurred (in red) (Fig. 3c); these clusters were more prominent in the south, and along the Swartkops and Coega Rivers, than elsewhere (Fig. 3d).

Landscape suitability (cost scores) for wetland presence

Wetlands were located on cells that had a significantly lower average cost score assigned to them (i.e. they were *more suitable* for wetland formation) ($\bar{X} = 17{,}563 \pm 565$ SE) compared to the random non-wetland points ($\bar{X} = 23{,}996 \pm 711$ SE) (t = 7.12, df = 3535: $p < 0.0001$). The landscape suitability map (Fig. 3b) illustrates the higher cost scores attributed to cells associated with the developed areas in the southeast. The northern parts were generally classed as less suitable for wetlands (high cost). The rest of the study area had a mixture of cell values indicating low to medium suitability scores, with sporadic high suitability areas.

The combined outcome of the occurrence model and landscape suitability is illustrated in Fig. 4. This map indicates areas where environmental features and anthropogenic activities create conditions that are least (or most) favourable for wetland formation and resilience. Figures 3 and 4 both show that the areas where wetland conditions are more optimal are in the

Fig. 3 Wetlands depicted by: **a** individual locations on the occurrence probability map (data from Melly et al. (2016)), **b** landscape suitability based on the six layers used in the least-cost analysis (low suitability = high cost and vice versa), **c** average nearest neighbour (ANN) spline interpolation of wetland density, **d** Gi* optimised hotspots



southern areas. Urban activities on the eastern margins of the study area coincide with some of the potential high wetland occurrence probability areas (Figs. 3 and 4).

Identifying wetland systems of concern

The spatial statistics used have illustrated wetland distribution patterns among the mapped systems in the NMB. The combination of mapped data and modelled landscape suitability and probability occurrence data have successfully been used to indicate areas of wetlands that are potentially most at risk to anthropogenic or environmental changes. Mapped wetlands situated on high-risk areas are more susceptible to changes in climate and land-use, compared to systems in low-risk areas. Overall, 45% of the known wetlands in the NMB were found on the very low to low-risk areas (scores of 2–4). A total of 22% of the systems had a medium-risk score. The 89 wetland systems (6%) that occur in very high-risk areas (score 9–10) are priority systems, and the remaining 27% of systems, with a score of 7–8, should also be researched further. Most of these high-risk systems are located in the northern areas, especially along rivers (Figs. 4 and 5). However, these systems were distributed throughout the region and focus areas for management/research could not be easily defined. Focus areas were

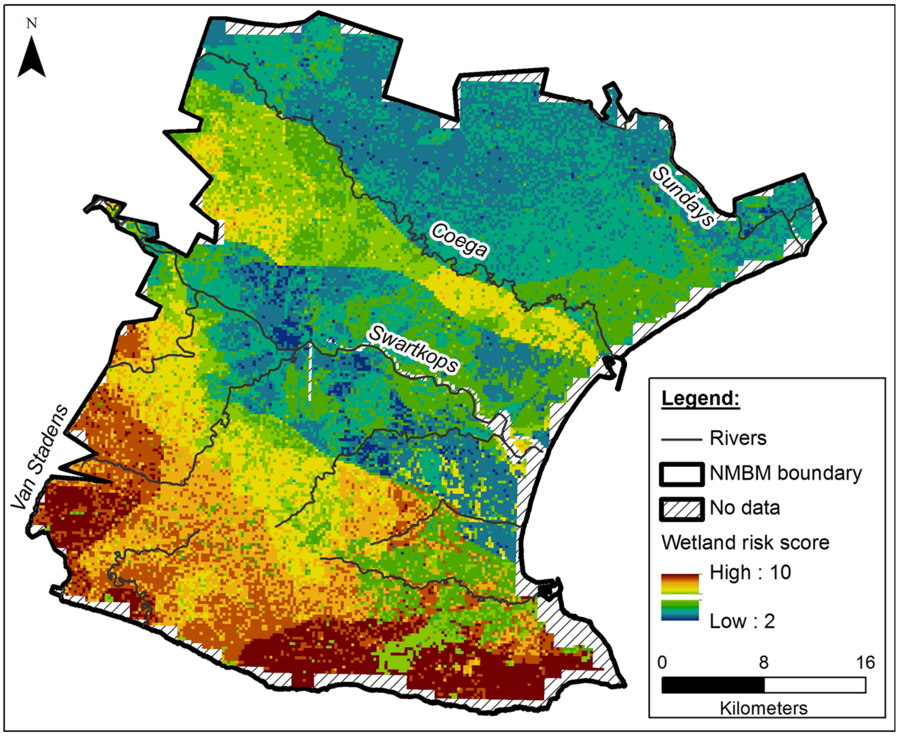


Fig. 4 Areas where wetlands are potentially at risk. Map is a result of the combined logistic regression (Fig. 1) and landscape suitability (Fig. 3b) models

then established through identifying key wetlands, those systems that are classed as at-risk as well as being situated in a hotspot. The additional step in the analysis narrowed down the 89 wetlands at-risk, to 67 key wetlands that were found in seven areas (Fig. 5). These seven areas can then form a realistic starting point to focus further conservation and management decisions.

Two examples of these focus areas, where site studies should then be carried out, and/or wetland complexes should be more closely managed and conserved, are indicated in Fig. 5. Available spatial data and aerial photographs indicate that one of these areas is located between the Swartkops and Coega Rivers (Fig. 5, area A). The wetlands in this area are located on a floodplain with a large developed area situated to the east (downslope). The second area is located in a more-arid part of the NMB (Fig. 5, area B). These wetlands are predominantly depressions that are surrounded by natural vegetation, the vulnerable Grass Ridge Bontveld and Sundays Spekboom Thicket, and are underlain by erodible sandstone of the Alexandria Formation.

Discussion

Wetland distribution in the landscape

The majority of wetlands in NMB are small and geographically isolated (Melly 2016; Schael et al. 2015), and wetland complexes are comprised of different wetland types and sizes. This has resulted in dynamic wetland complexes, where the inundation timing and duration differ amongst wetlands within the same complex.

The close proximity between wetlands and the dynamic wetland complexes play an important role in the landscape, by providing more options for the fauna and flora to move between wetlands in a semi-arid area (Bosiacka and Pieńkowski 2012; Wagner and Fortin 2005). Some studies have suggested that movement is limited to less than 1 km, and often, less than 0.5 km for amphibians (Morris 2012; Semlitsch and Bodie 2003).

As demonstrated from the ANN, the average distance between wetlands in the NMB that are less than 5 ha in size is 0.33 km. Therefore, the present wetland distribution is likely sufficient to maintain source-sink dynamics for wetland biota (Semlitsch

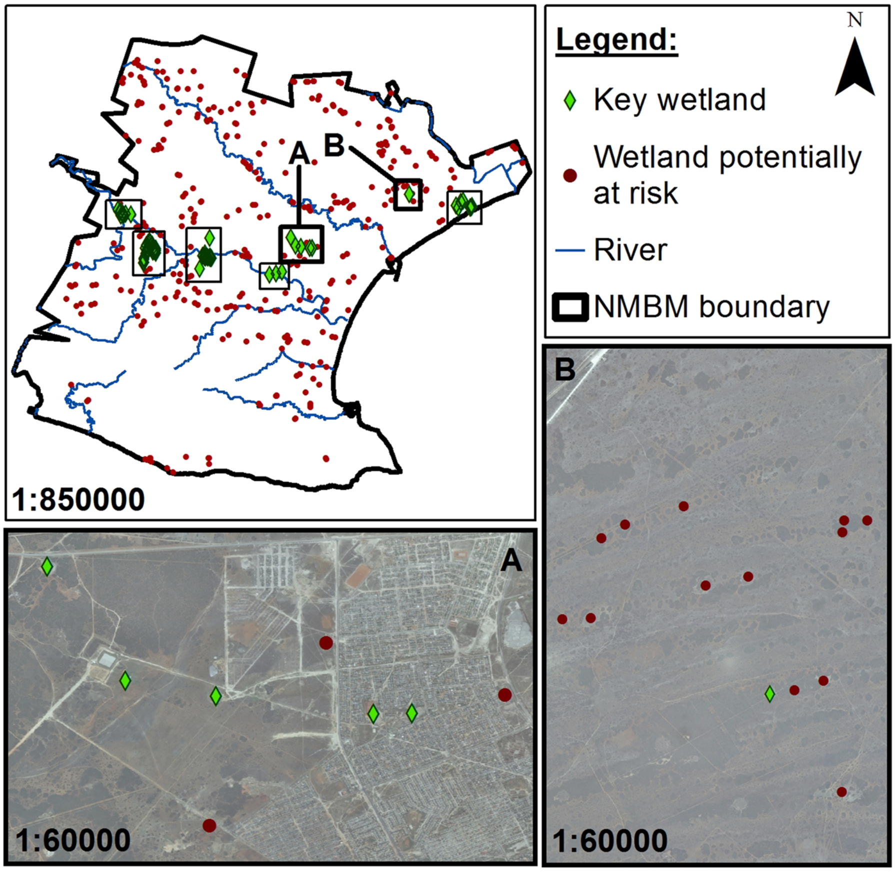


Fig. 5 Key wetlands identified (high-risk wetlands located in a hotspot), grouped into seven management areas. Areas A and B illustrate the key wetlands, as well as the surrounding potentially at-risk wetlands (score of > 8) that should be included in management strategies

2000). What is noteworthy is that this distance is less than a quarter of that measured between wetlands of the same size class on the south eastern Atlantic coastal plain in the USA, which was 1.7 km (Semlitsch and Bodie 1998). If all the wetlands less than 1.2 ha were removed (ca. 89% of the systems), the ANN would still be less than 1 km in the NMB. This suggests that the wetlands in NMB are highly clustered and exist at higher densities than those in other similar environments. However, even though the ANN was still within a normal range for dispersal, removing 89% of the systems in an area would result in a significant loss of habitats for wetland-dependent species, as well as irreversibly affecting ecosystem services (Semlitsch 2000). The authors recognise that single, more isolated wetlands are also important, but due to their small and ephemeral nature, they are often more difficult to manage and conserve. Consequently, these systems should be addressed and included in management plans on a case-by-case basis.

Recent studies in the NMB highlighted the importance of rainfall in wetland formation (Schael et al. 2015). The high wetland densities recorded, ranging from 9 to 20% within the southern catchments, are further evidence (Fig. 3). The semi-arid climate and the increase of wetlands in higher rainfall areas indicate the important role of managing wetlands differently across the various rainfall zones in the NMB.

Landscape suitability for wetland presence

Many authors have made different grids and predetermined categories in an attempt to narrow down the extreme variability of a study area into manageable environmental units. Rains et al. (2013) used a similar method to the one in this study to determine changes in wetland coverage, condition and connection, to prioritise areas for conservation and wetland restoration. In our study, the costs assigned to different variables for the landscape suitability scoring system gave an indication of areas where wetlands are most likely to persist if some environmental or anthropogenic changes occur. Consequently, these systems would be of high value, and possibly easier to manage for conservation and ecosystem service provision.

The least-cost analysis was successfully used to establish a landscape suitability grid for wetlands in the NMB. This analysis also highlighted the interaction of various wetland types and sizes across a landscape facilitate or hinder wetland occurrence and persistence at different scales. These interactions, however, do not negate the value of this modelling exercises and the role of modelling in providing stepping-stones to important management decisions, even with limited information. Therefore, certain anthropogenic and environmental features are important in understanding wetland distribution patterns, but there are overarching landscape processes that fundamentally drive wetland occurrence.

The maps produced from this research highlight the need to manage wetlands at both broad-landscape scales and finer scales, the latter of which relates to the distances between wetlands. Wetlands near to one another are well connected structurally; however, they are still influenced by an overall landscape that hinders or facilitates the occurrence and interactions between these systems. The maps produced from this analytical approach can help provide an indication of the spatial and temporal extent of these factors through the analysis of key individual drivers.

Using desktop analyses to target areas for conservation and management

The combination of the wetland probability and landscape suitability grids has provided insight into which areas are likely to be most-threatened due to changes in the surrounding catchment processes, including anthropogenic activities. In terms of wetland management, wetland complexes are easier to manage compared to managing several individual systems, which is why they form the basis of the site selections. Managing complexes would also ensure that at least part of the surrounding habitat has to be managed well to maintain the ecological integrity between wetlands (i.e. allow for sufficient dispersal of fauna and flora) (Semlitsch 2000), providing better structural connectivity, even at a local-scale. Using wetland hotspots helped identify these complexes.

Systems located on high-risk areas need to be closely managed, if possible, as they are most susceptible to changes in climate (flood or drought cycles) and/or anthropogenic activities (e.g. land-use). In addition, extended changes could result in these systems being permanently lost (or decrease in ecosystem functioning), and would no longer form part of the network of connectivity across the broader landscape. However, these decisions will also vary depending on their current state, as a marginal wetland system would be at an increased threat compared to one that is currently highly functioning. Additionally, some sites might not be viable to conserve due to logistical reasons.

This study has demonstrated that approximately 500 wetlands were classified as very high or high-risk, and that many of these systems were grouped within certain areas, some of which were in wetland clusters. Therefore, conservation and management decisions can now be based on focal areas comprised of wetland complexes, in the NMB, and possibly in other geographic areas with similar conditions through using this approach. However, it is important that these outcomes be combined with local knowledge from municipal managers, scientists and conservationists, before further resources are used to initiate plans for conservation and management.

Wetland complexes should be loosely defined to incorporate, or exclude, systems that appear to be linked to surrounding wetlands, for scale-appropriate management decisions. This study has illustrated how wetlands that are at a risk and within wetland complexes, can be identified using the landscape suitability analysis. The method was further refined by incorporating wetlands in hotspot areas, as is an indication of the extent of complexes. Several conservation and management strategies and recommendations can now be applied to the seven areas based on existing spatial data that directly relates to the surrounding land-use. Further research is necessary in this area to ensure that these systems are conserved, if viable.

Wetlands in similar drier regions of the globe (comparable to Area B in NMB, Fig. 5) might be equally as highly vulnerable to human induced impacts, due to fewer rainfall events and infrequent inundation periods. These systems would, therefore, require more conservation protection to prevent degradation and loss during extensive dry periods that would only become evident when inundation occurs.

Even though systems have not been classified as being at risk using this method, it does not mean they should not be conserved, managed or that their importance or value within the landscape is insignificant. Wetlands located in low-risk areas also require protection and possibly should be prioritised, since they also provide valuable ecosystem services, although they are less likely to be adversely affected if environmental or anthropogenic influences were to change.

Conclusions and future directions

This paper has successfully provided a set of spatial and analytical tools that both describes wetland distribution patterns and elucidates wetlands that are particularly vulnerable to land-use and environmental/climate changes. The method introduced can help prioritise areas for further conservation and management efforts, minimising the logistical cost of carrying out extensive field studies in the preliminary stages of a project. However, this type of research cannot replace the in-depth knowledge needed to create effective long-term conservation and management plans.

Although many of the wetland systems in the NMB would commonly be termed "isolated", they appear to be closely connected at a landscape level, a feature that is potentially unique to similar semi-arid settings. This connectivity is also strengthened by the close proximity between wetlands, as well as the mosaics of wetlands with different inundation patterns due to their differing sizes and HGM types. Understanding these spatial patterns of wetland formation is also an important foundation for relating these patterns to wetland functioning. In other study areas, shifts in wetland occurrence and wetlands at-risk could be ascertained by selecting a different set of variables (for logistical or statistical reasons) in the earlier analytical steps, as well as by manipulating the scores of the variables used in the analyses. This may result in different spatial variables becoming significant in the least-cost analyses. This should form a key component of future research using these methods.

Selecting categories for high-risk systems and hotspots must remain flexible, as there are many geographical factors that would influence which systems should be included in a category. However, repeating this method in other study areas would be useful to further refine this method. In addition, key landscape features that hinder/promote structural and functional connectivity between systems should also be identified as well as how the functional connectivity relates to the spatial organisation of these wetlands within a landscape.

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References

Amiri BJ, Nakane K (2009) Modeling the linkage between river water quality and landscape metrics in the Chugoku district of Japan. Water Resour Manag 23:931–956

Beyer HL (2010) Geospatial Modelling Environment. Version 0.3.3 Beta

Biodiversity GIS (2011) National wetlands inventory (version IV) created by the CSIR. Distributed by SANBI

Bosiacka B, Pieńkowski P (2012) Do biogeographic parameters matter? Plant species richness and distribution of macrophytes in relation to area and isolation of ponds in NW Polish agricultural landscape. Hydrobiologia 689:79–90. https://doi.org/10.1007/s10750-011-0850-x

Bowen MW, Johnson WC, Egbert SL, Klopfenstein ST (2010) A GIS-based approach to identify and map playa wetlands on the High Plains, Kansas, USA. Wetlands 30:675–684. https://doi.org/10.1007/s13157-010-0077-z

Chainey S, Ratcliffe J (2013) GIS and crime mapping. Wiley, West Sussex. https://doi.org/10.1002/9781118685181

Clark PJ, Evans FC (1954) Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology 35:445–453. https://doi.org/10.2307/1931034

Department of Water Affairs and Forestry (DWAF) (2005) A practical field procedure for identification and delineation of wetlands and riparian areas. Pretoria

ESRI® (2014) ArcMap 10.2.2 for Desktop (Advanced). Redlands, California

ESRI® (2017) Cell size and resampling in analysis for ArcMap 10.6

Gardner RC et al. (2015) Ramsar Briefing Note 7. State of the world's wetlands and their services to people: a compilation of recent analyses. Punta del Este, Uruguay

Getis A, Ord JK (1992) The analysis of spatial association by use of distance statistics. Geogr Anal 24:189–206. https://doi.org/10.1111/j.1538-4632.1992.tb00261.x

Gutzwiller KJ, Flather CH (2011) Wetland features and landscape context predict the risk of wetland habitat loss. Ecol Appl 21:968–982
Kahara SN, Mockler RM, Higgins KF, Chipps SR, Johnson RR (2009) Spatiotemporal patterns of wetland occurrence in the Prairie Pothole Region of eastern South Dakota. Wetlands 29:678–689. https://doi.org/10.1672/07-09.1
Keddy PA (2010) Wetland ecology: principles and conservation, 2nd edn. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511778179
Keys R (1981) Cubic convolution interpolation for digital image processing. IEEE Trans Acoust Speech Signal Process 29: 1153–1160. https://doi.org/10.1109/TASSP.1981.1163711
Krause S, Heathwaite AL, Miller F, Hulme P, Crowe A (2007) Groundwater-dependent wetlands in the UK and Ireland: controls, functioning and assessing the likelihood of damage from human activities. Water Resour Manag 21:2015–2025
Leadley PW et al (2014) Progress towards the Aichi Biodiversity Targets: an assessment of biodiversity trends, policy scenarios and key actions, CBD Technical Series No. 78. Secretariat of the Convention on Biological Diversity, Montreal, Canada
Leibowitz SG, Loehle C, Li B-L, Preston EM (2000) Modeling landscape functions and effects: a network approach. Ecol Model 132:77–94
Machtinger ET (2007) Temporarily flooded wetlands. Natural Resources Conservation Service (NRCS), Washington, DC
Malan H (2010) The status of research on wetland ecology, management and conservation in South Africa. Emperors Palace, Johannesburg
McKillup S (2006) Statistics explained: an introductory guide for life scientists. Cambridge University Press, Cambridge
Melly BL (2016) Factors influencing ephemeral wetland distribution, structure and ecological function within Nelson Mandela Bay Municipality (NMBM), South Africa. Ph.D., Nelson Mandela Metropolitan University
Melly BL, Schael DM, Gama PT (2016) Mapping ephemeral wetlands: manual digitisation and logistic regression modelling in Nelson Mandela Bay Municipality, South Africa. Wetl Ecol Manag. https://doi.org/10.1007/s11273-016-9518-7
Melly BL, Schael DM, Gama PT (2017) Perched wetlands: an explanation to wetland formation in semi-arid areas. J Arid Environ 141:34–39. https://doi.org/10.1016/j.jaridenv.2017.02.004
Morris K (2012) Wetland connectivity: understanding the dispersal of organisms that occur in Victoria's wetlands. Arthur Rylah Institute for Environmental Research, Heidelberg
Ollis DJ, Snaddon CD, Job N, Mbona N (2013) Classification system for wetlands and other aquatic ecosystems in South Africa. User manual: inland systems. vol Biodiversity Series 22. SANBI, Pretoria. https://doi.org/10.13140/2.1.3857.0248
Quinn GP, Keough MJ (2002) Experimental design and data analysis for biologists. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511806384
Rains M, Landry S, Rains K, Seidel V, Crisman T (2013) Using net wetland loss, current wetland condition, and planned future watershed condition for wetland conservation planning and prioritization, Tampa Bay Watershed, Florida. Wetlands 33:949–963. https://doi.org/10.1007/s13157-013-0455-4
Rudnick D et al (2012) The role of landscape connectivity in planning and implementing conservation and restoration priorities. Ecological Society of America, Washington, DC
Schael DM, Gama PT, Melly BL (2015) Ephemeral wetlands of the Nelson Mandela Bay Metropolitan area: classification, biodiversity and management implications. Water Research Commission, Gezina. https://doi.org/10.13140/RG.2.1.2029.9122
Schulze RE (2007) Modelled climate data. Water Research Commission, Gezina
Semlitsch RD (2000) Size does matter: the value of small isolated wetlands. Environmental Law Institute, Washington, DC
Semlitsch RD, Bodie JR (1998) Are small, isolated wetlands expendable? Conserv Biol 12:1129–1133. https://doi.org/10.1046/j.1523-1739.1998.98166.x
Semlitsch RD, Bodie JR (2003) Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles. Conserv Biol 17:1219–1228. https://doi.org/10.1046/j.1523-1739.2003.02177.x
South African Weather Service (SAWS) (2014) Unpublished monthly rainfall data from three meteorological stations in NMBM—Port Elizabeth Airport, Coega Port and Uitenhage. Collected from 1950 to 2013
Stewart W (2010) Final conservation assessment and plan for the Nelson Mandela Bay Municipality. SRK Consulting, Port Elizabeth
Townend J (2013) Practical statistics for environmental and biological scientists. Wiley, Chichester. https://doi.org/10.1002/bmb.2002.494030049996
United Nations Environmental Programme (UNEP) (2009) Global map of aridity. CRU CL 2.0 Global Climate Dataset. Climate Research Unit of the University of East Anglia, UK
Usery EL, Finn MP, Scheidt DJ, Ruhl S, Beard T, Bearden M (2004) Geospatial data resampling and resolution effects on watershed modeling: a case study using the agricultural non-point source pollution model. J Geogr Syst 6:289–306. https://doi.org/10.1007/s10109-004-0138-z
van Deventer H, Nel J, Mbona N, Job N, Ewart-Smith J, Snaddon K, Maherry A (2016) Desktop classification of inland wetlands for systematic conservation planning in data-scarce countries: mapping wetland ecosystem types, disturbance indices and threatened species associations at country-wide scale. Aquat Conserv Mar Freshw Ecosyst 26:57–75. https://doi.org/10.1002/aqc.2605
Wagner HH, Fortin M-J (2005) Spatial analysis of landscapes: concepts and statistics. Ecology 86:1975–1987. https://doi.org/10.1890/04-0914
Weber T, Norman J (2015) Functional connectivity modeling and optimal siting of conservation networks in the Midwest USA. Ecol Inf 30:277–2883. https://doi.org/10.1016/j.ecoinf.2015.07.002
Zhang J, Atkinson P, Goodchild MF (2014) Scale in spatial information and analysis. CRC Press/Taylor & Francis Group, Boca Raton. https://doi.org/10.1201/b16751-15