Determining wetland spatial extent and seasonal variations of the inundated area using multispectral remote sensing

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ABSTRACT

Wetlands can only be well managed if their spatial location and extent are accurately documented, which presents a problem as wetland type and morphology are highly variable. Current efforts to delineate wetland extent are varied, resulting in a host of inconsistent and incomparable inventories. This study, done in the Witbank Dam Catchment in Mpumalanga Province of South Africa, explores a remote-sensing technique to delineate wetland extent and assesses the seasonal variations of the inundated area. The objective was to monitor the spatio-temporal changes of wetlands over time through remote sensing and GIS for effective wetland management. Multispectral satellite images, together with a digital elevation model (DEM), were used to delineate wetland extent. The seasonal variations of the inundated area were assessed through an analysis of monthly water indices derived from the normalised difference water index (NDWI). Landsat images and DEM were used to delineate wetland extent and MODIS images were used to assess seasonal variation of the inundated area. A time-series trend analysis on the delineated wetlands shows a declining tendency from 2000 to 2015, which could worsen in the coming few years if no remedial action is taken. Wetland area declined by 19% in the study area over the period under review. An analysis of NDWI indices on the wetland area showed that wetland inundated area is highly variable, exhibiting an increasing variability over time. An overlay of wetland area on cultivated land showed that 21% of the wetland area is subjected to cultivation which is a major contributing factor to wetland degradation.

Keywords: Wetland extent, remote sensing, ecosystems, change detection, Sustainable Development Goals

INTRODUCTION

Wetlands provide a variety of ecological and economic functions that include water quality improvement, flood regulation and protection, groundwater recharge, shoreline stabilisation, fish and wildlife habitat, agriculture production, aesthetics and biological productivity (Kotze et al., 2009; De Steven and Lowrance, 2011). However, they have been subjected to a host of stress-inducing modifications, such as dredge-and-fill operations, hydrologic modifications, pollutant runoff, eutrophication, impoundment, and fragmentation by roads and ditches; more recently there has been concern about the impact of climate change on wetlands (Levin et al., 2001; Klemas, 2011). These stresses are impacting negatively on the very existence of wetlands and thus on their delivery of services to society; yet society does not have a comprehensive grasp of the magnitude of the problem because knowledge about the importance, spatial extent and seasonal variation of wetlands remains so limited. This calls for a comprehensive method to assess the spatial and temporal changes in wetlands. This has recently become increasingly relevant as the United Nations has identified the importance of protecting and restoring wetlands by including them in Goal 6 of the Sustainable Development Goals (SDGs), which deals with water issues, and specifically in Indicator 6.6.1, which emphasises the change in extent of water-related ecosystems over time.

Wetlands continue to decline globally, both in extent and quality, to severely degraded levels that threaten the very ecosystem services they provide (Gardner et al., 2015). Previous studies have suggested that the world's wetland area has declined by between 64% and 71% since 1900 (Davidson, 2014). Since the beginning of the 20th century more than 66% of Europe's and 50% of the world's wetlands have disappeared (Innis et al., 2000; Zedler and Kercher, 2005; Silva et al., 2007). Wetland loss is mainly due to intensive agriculture, water extraction, urbanisation, infrastructure development and pollution (Russi et al., 2013). However, despite the environmental degradation faced by wetlands, there is increasing demand for the ecosystem services they provide (Suding, 2011). By 2050, global water demand is projected to increase by 55% (Connor, 2015). To meet this growing demand, the services of wetlands must be valued appropriately, or the risks to water security will rapidly increase. This challenge demands an urgent and consistent wetland monitoring mechanism.

According to the Ramsar Convention Secretariat (2013), wetlands are areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by shallow water. Thus the Ramsar Convention defines wetlands (Ramsar, 1971) as areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6 m. They incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than 6 m at low tide lying within the wetlands. The types of wetlands include:

- Marine (coastal wetlands including coastal lagoons, rocky shores, and coral reefs)
- Estuarine (including deltas, tidal marshes, and mangrove swamps)
- Lacustrine (wetlands associated with lakes)
- Riverine (wetlands along rivers and streams)
- Palustrine (meaning 'marshy' – marshes, swamps and bogs)

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There are also man-made wetlands such as fish and shrimp ponds, farm ponds, irrigated agricultural land, salt pans, reservoirs, gravel pits, sewage farms and canals.

Considering these many types of wetlands as defined by the Ramsar Convention, mapping wetlands becomes complex as wetlands differ in landcover; some have open water, others have typical vegetation of different types (hydrophytes) and still others have bare hydric soils. Besides these distinct landcover types, wetlands are also highly variable in spatial extent as the inundated area changes periodically, and often seasonally (Hess et al., 2015; Li et al., 2015). As a result of the landcover differences and spatial dynamics of wetlands, multispectral remote sensing potentially becomes an important time- and cost-effective tool to map and monitor wetlands, especially at fine and medium resolutions (Klemas, 2011; Li et al., 2015). Thus, remote sensing has become an integral tool in wetland intervention, protection and restoration.

Earlier traditional work on wetland extent assessment has used relatively complex methods to compile wetland inventories (literature reviews, map interpretation and digitising, and collation of ancillary data and analysis), often giving incompatible and inconsistent results (Aires et al., 2013; Melton et al., 2013). These traditional methods are generally not as effective as remote sensing when it comes to monitoring wetland dynamics as they are time consuming, date-lagged and often too expensive (Baker et al., 2006). Yet remote sensing can detect and delineate the spatio-temporal changes in wetlands almost effortlessly over defined time periods. The most important advantage of remote sensing over traditional methods is that sensors record images of large areas within defined time frames, facilitating change detection in a timely manner and also allowing the mapping of physically unreachable areas (Klemas, 2013).

Recent advances in sensor design and application have made remote sensing indispensable for wetland monitoring. For example, hyperspectral data are used to distinguish wetland types using spectral bands specifically selected for a given application, and high resolution multispectral sensors are used to map small patchy upstream wetlands (Klemas, 2011). Coastal water temperatures are mapped using thermal infrared scanners, whereas water salinity, soil moisture, and other hydrologic parameters can be measured using microwave radiometers (Klemas, 2010), while forested wetlands are distinguished from upland forests by using synthetic aperture radars (SAR) (Lang et al., 2008). Airborne 'light detection and ranging' (LIDAR) systems are being used to map wetland topography, and produce beach profiles and bathymetric maps (Rosso et al., 2006; Brock and Purkis, 2009). There are other satellite missions that are designed for wetland-related purposes – missions such as the Soil Moisture Active Passive (SMAP), which was launched in January 2015, and the Surface Water and Ocean Topography (SWOT), planned for 2019, which is expected to provide soil moisture and surface water area at unprecedented spatial and temporal resolution (Fluet-Chouinard et al., 2015). These new sensors promise to become valuable in wetland monitoring.

Previous studies successfully explored the use of remotely-sensed data to monitor flood duration, timing and frequency for ephemeral wetlands (Guerschman et al., 2011; Feng et al., 2012; Chen et al., 2013; Huang et al., 2014; Tornos et al., 2015). These studies also used MODIS data to monitor flood extent by differentiating inundated areas from non-inundated areas; yet this research links water-level changes to temporal patterns of spectral indices and thus monitors wetland inundated area seasonal variations. Most studies mapped wetland spatial extent using different methods and sensors, but few studied inundated area seasonal variations. Examples of previous studies on wetland inundated area seasonal variation include Ordoyne and Friedl (2008), Rebelo et al. (2012) and Li et al. (2015). However, these studies focused on single wetlands and did not cover all wetlands within a catchment. The study reported here assesses the seasonal variations of wetland inundated area at catchment level using MODIS and its derived spectral indices. Importantly, the same indices were used to assess wetland degradation over time.

The rapid developments of new remote sensors, data handling capabilities, and image analysis techniques are increasingly making it possible to monitor wetland dynamics in near real-time. Continued and timely assessment of wetlands enables timely intervention for their protection and restoration so that they continue to efficiently provide essential ecosystem services. The advantage of using remote sensing in spatial analysis is that satellite data cover large areas making data collection less costly and less time consuming. This study provides a practical remote-sensing and geographic information system (GIS) technique to delineate wetland spatial extent and monitor seasonal variations of wetland inundated area. The research was done in the Witbank Dam Catchment (WDC), located in the Upper Olifants Basin of the Olifants River in South Africa. The products of this paper are in support of the development of the Indicator method (Dickens et al., 2017) for Target 6.6 of the Sustainable Development Goals (SDGs), which requires countries to monitor the 'change in extent of water-related ecosystems over time'.

MATERIALS AND METHODS

Study area

The Witbank Dam Catchment (WDC)has a surface area of 3 600 km^2. It is part of the Upper Olifants Basin of the Olifants River, a major tributary of the Limpopo River, and occurs upstream of the Witbank Dam in Mpumalanga Province, South Africa. The catchment has a mean annual precipitation of 689 mm and mean annual runoff of 125×10^6 m^3 a^{-1} (Beumer, 2010). Groundwater, which is mainly found in a shallow weathered aquifer, is an important source of water in the sub-catchment. The geology within the catchment consists of igneous and metamorphosed rocks, with occurrences of dolerite intrusions, in the form of dykes and sills, and silicified sedimentary formations (De Lange et al., 2005). Rock formations in the catchment are associated with vast coal deposits. The WDC coalfield is the largest conterminous area of active coal mining in South Africa, producing almost 48% of the country's coal requirements (Hobbs et al., 2008). As a result, coal mining and related industries are the major threats to water quality in the WDC. The threat to water quality and quantity is also worsened by rainfed agriculture, which covers about 38% of the total catchment area. These factors pose a threat to the water resources through nutrient and acid mine drainage contamination.

The dominant soil types are moderately deep sandy to sandy-clay loams (Hobbs et al., 2008). The land use practices of the catchment consist primarily of cultivation (irrigated and rainfed), grassland, coal mining and mineral processing, bushland, urban and scattered rural settlements and power generation. Figure 1 shows the location of the Witbank Dam Catchment in South Africa, and also the main land-use types in the catchment.

Satellite and DEM data download and analysis

The methodology comprises of 2 stages: (i) delineation of wetlands, and (ii) assessing seasonal variations in wetland inundated area. The first stage involved the use of Landsat 8 satellite images and digital elevation models (DEM) to delineate wetland spatial extent. The cloud-free, once-off 2015 Landsat 8 images, with spatial and temporal resolutions of 30 m and 16 days respectively, were used to delineate wetlands using image-analysis tools of remote sensing. The DEM was essential for creating topographic lowlands capable of holding water through the flow-accumulation process in GIS. The flow-accumulation procedure identifies areas capable of holding water using a specified pixel value threshold. This was necessary for the inclusion of all waterbodies as defined in the Ramsar wetland definition (Ramsar, 1971). The procedure thus set out to produce a wetland map for 2015, corresponding to the year of the Landsat data.

The second part of the method involves the use of the moderate-resolution imaging spectroradiometer (MODIS) satellite images to assess seasonal variations in wetland inundated area. The variations were assessed through an analysis of time series 8-day MODIS Bidirectional Reflectance Distribution Function (BRDF)/Albedo product, MCD43 (Strahler et al., 1999), at 500 m spatial resolution. Seasonal variations in wetland inundated area were assessed using a 5-year interval period, i.e., 2000, 2005, 2010 and 2015. The 5-year interval was considered an appropriate period for detecting significant change in wetland area (Kayastha et al., 2012; Coppin and Bauer, 1996). The NDWI are derived from the near-infrared (NIR–MODIS band 2) and shortwave infrared (SWIR–MODIS band 6) reflectances on board NASA's Terra satellite. Of the 36 spectral bands of the MODIS sensor, 7 are specifically designed for land surface studies. These include; blue (459–479 nm), green (545–565 nm), red (620–670 nm), near infrared (841–876 nm), and shortwave infrared (SWIR1: 1 230–1 250 nm, SWIR2: 1 628–1 652 nm, SWIR3: 2 105–2 155 nm). The MODIS MCD43 500-m resolution reflectance datasets, which remove view-angle effects, mask cloud cover and reduce atmospheric contamination (Li et al., 2015), were used for this study.

Two once-off Landsat 8 cloud-free tiles that cover the study area, for the month of September 2015, together with a 30 m resolution ASTER Global digital elevation model (GDEM) and the MCD43 product, were downloaded from the United States Geological Survey (USGS) Earth Data website. The year 2000 was chosen as a reference year for assessing wetland inundated area seasonal variation, as it is the year that the MODIS mission started and thus the first year for which data are available. Table 1 gives the acquisition dates and a description of the satellite images used.

Mapping wetland spatial extent

Once-off Landsat 8 OLI (Operational Land Imager) images acquired in September 2015 were used to delineate wetland spatial extent. The selection of Landsat images was motivated by its free cost, the surface area of the catchment under study (3 600 km^2), and the wetland types dominant in the catchment.

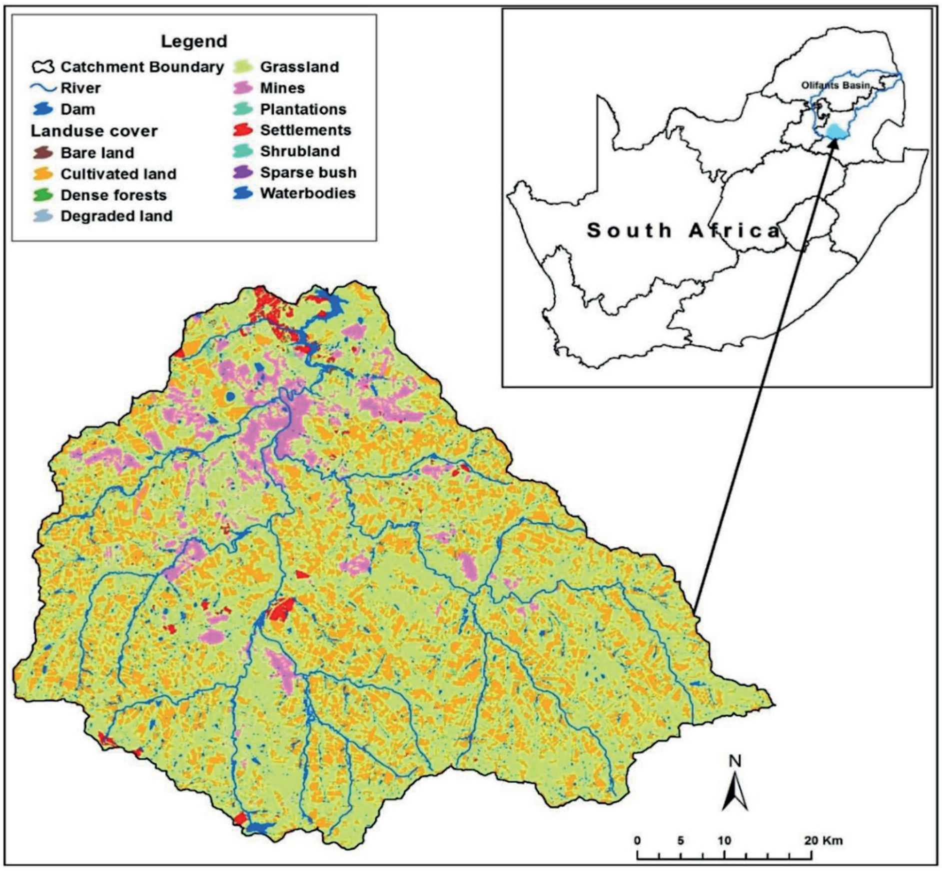

Figure 1
Location of the Witbank Dam Catchment in South Africa, and its landuse/cover categories. Note: Wetlands are NOT indicated on this map

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The analysis included the seasonally flooded parts of the wetland, considering the area covered by hydric soils. Thus, both the core wetland area and the seasonally flooded parts contribute to the overall wetland spatial extent. A supervised classification run on ERDAS Imagine, using a false colour composite image made up of Landsat spectral bands 7, 4 and 2, was used to build wetland training sites which are hydrophytic vegetation, hydric soils, and open water. This was necessary as the major wetland indicator is saturation of land surfaces by water (Lunetta and Balogh, 1999). In the tropics, the three are easily noticeable during the dry season as the vegetation remains green and the seasonally flooded area is visible by its hydric soils. Training sites were developed around these three categories for the supervised classification.

However, due to the complex nature of wetlands, that is, their distinct landcover types, seasonal variations and differing sizes, wetlands mapped from satellite image classification obviously had gaps as some wetlands such as depressions were omitted, and for open water only the area with water was captured leaving out the full wetland spatial extent. This was observed using Google Earth and prior knowledge of the area. However, the remote-sensing classification was important in locating most of the wetlands. The classified wetland map was then improved by merging with a wetland map derived from DEM. The DEM-derived wetlands were developed through the flow-accumulation tool in ArcGIS. The flow accumulation method produces a raster representing the amount of water that flows into each cell (upslope contributing area). The flow accumulation counts the number of pixels that are flowing into downstream pixels. Pixels with high flow accumulation are areas of concentrated flow. The procedure thus identifies all areas of concentrated flow in the catchment where water accumulates, and these include depressions, river channels and seeps. This process has been considered because wetlands are generally found in low areas where water accumulates and along river channels, with the river streams forming the centre of the wetlands (Islam et al., 2008; Lang et al., 2012). Thus wetland mapping should include areas of high water accumulation and river channels with a determined wetland zone on both sides of the channel and around the periphery of the identified wetland areas. Also, as wetlands could be flow accumulation areas, a DEM offers the best opportunity to delineate areas of concentrated flow from upslope contributing areas, thereby distinguishing features capable of holding water (Islam et al., 2008; Lang et al., 2013). The areas on either side of river channels consist of wetlands; for example, valley bottoms form on the sides of river valleys. These types of wetlands were delineated through proximity analysis, taking the river channel as the centre and spreading a distance of 30 m on either side of the drainage system. While the 30 m buffer zone is an approximation for the extent of wetlands on river margins, it has been used as an approximation of the zone alongside rivers in which riverine/wetland ecosystems probably occur (Wenger, 1999, Davies and Nelson, 1994; Macfarlane et al., 2014). The two developed maps were then merged to create the wetland map.

Determining seasonal variations in wetland inundated area

Time-series spectral water indices were used to gauge the seasonal variations of wetland area, through the detection of surface wetness from multi-spectral imagery of the MODIS NDWI data (Li et al., 2015). The NDWI (Gao, 1996; McFeeters, 1996) follow the same logic as the NDVI, that is, a difference between two spectral bands divided by the sum of the two (Tucker, 1979). The NDWI real values range between −1 and +1, where increasing positive values indicate increasing water presence and negative values indicate dry surface. NDWI values above 0 generally represent water presence. The NDWI identifies open-water features and is expressed as (McFeeters, 1996):

$$\text{NDWI} = \frac{NIR\text{-}SWIR}{NIR+SWIR} \qquad (1)$$

Where, NIR is the reflectance spectrum value of the ground target in the near-infrared band (780–890 nm, corresponding to the second band of MODIS), SWIR is the reflectance spectrum value of the ground target in the shorter infrared (1 580–1 750 nm, corresponding to the 7th band of the MODIS). The combined NIR/SWIR indices are sensitive to leaf water and soil moisture and are widely used in vegetation and seasonal inundation studies (Campos et al., 2012; Davranche et al., 2013).

Seasonal and inter-seasonal variations in wetland inundated area for the years 2000, 2005, 2010 and 2015 for the individual identified wetland types were evaluated through the NDWI indices. The NDWI indices, which indicate moisture content, are used as wetland inundated area proxies. Where a wetland is covered by hydric soils or is dry the NDWI values are expected to be low, that is to say lower than −0.3, due to the absence of moisture. But the NDWI values are expected to increase with increasing moisture presence, that is to say, values higher than −0.2 indicate dampness. Therefore, fluctuations in the NDWI values of a wetland area indicate its water occurrence frequency.

Field verification/work

Field verification of the mapped wetlands was done through field visits, comparison with features on Google Earth and the DEM, and the use of prior knowledge of features present in the study area. The ground-truth points were randomly chosen. Figure 2 is a map showing the distribution of 130 ground-truth points that were used to assess the accuracy of the developed wetland mapping. Ground-truthing of the mapped features was necessary for their verification and accuracy assessment.

RESULTS

Spatial extent of wetlands in the Witbank Dam Catchment

The wetland spatial extent delineated in the Witbank Dam Catchment using the September 2015 Landsat image and

TABLE 1
Satellite images used, acquisition dates and their brief description

Satellite type	Acquisition dates	Description
Landsat 8	September 2015	Two once-off cloud-free tiles, 30 m spatial resolution
MODIS	2000, 2005, 2010, 2015	8-day, 500 m spatial resolution, MCD43 product

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the 30 m DEM is presented in Fig. 3. The map includes all wetlands as defined by the Ramsar definition – lacustrine, riverine, palustrine, opencast mines and other less abundant types. Identified wetland types include depressions, channelled valleys, floodplains, seeps and dams.

The total wetland area in the catchment is 836 km^2, which represents 23% of the total catchment area. The present wetland area is higher than recorded by previous studies that mapped wetlands in the same catchment. The National Freshwater Ecosystem Priority Areas (NFEPA) wetland map (Nel et al., 2011) has an area of 448 km^2, which is almost half of the area calculated in this study and represents only 12% of the total catchment area. The Mpumalanga Highveld (MPHG) wetland study produced a wetland map (Mbona et al., 2015) with a total wetland area of 686 km^2, which represents 19% of the total catchment area. The smaller underestimation of the wetland area reported by the two previous studies could indicate that they did not include the 30 m buffer on either side of the mapped wetlands. Wetland area cannot be considered in isolation from the surrounding landscape. The concept of wetland buffers is well established and forms an integral part of their management (Wenger, 1999, Davies and Nelson, 1994; Macfarlane et al., 2014); thus a 30 m buffer is included here in the extent estimation.

Seasonal variations in wetland inundated area

The graphs in Fig. 4 present seasonal and inter-seasonal variations in wetland inundated area (or moisture content) from 2000 to 2015, as derived from the 8-day MODIS MCD43 NDWI datasets, targeting only the mapped wetland area that includes the buffers. An average NDWI index for each identified wetland in the catchment and for every month of the reference period was calculated to gauge wetland inundated area seasonal variation and wetland degradation over time. The observed changes in wetland inundated area within each year and between the years, as shown by the graphs, indicate the level of wetland area variability and apparent degradation over the featured timeframe. Peaks and lows in the inundated area are observed during the rain and dry seasons, respectively. Generally, the wetlands show moderate moisture content varying between −0.2 and −0.1 NDWI indices. Depressions show both the highest and most severe variability as they are topographical flow accumulation areas (sinks) where water accumulates only for short periods after rains, but during the dry season they become dry as rain is their only source of water. The other types of wetlands, channelled valleys, floodplains, seeps and dams, show an almost uniform trend.

As shown in Fig. 4, maximum wetland area was observed in 2000 but progressively declined over the years; the minimum value was observed in 2015 which coincided with an El Niño–associated drought in the area (Rembold et al., 2016; FAO, 2016). An overlay of the wetland map on the land-use map of the catchment showed that 21% of the wetland area is currently being used either for cultivation, mining or settlements. It becomes evident that there has been a continued decline (shown by the trendline in Fig. 5) of wetlands in the Witbank Dam Catchment over the measured timeframe, which could be due to a combination of associated anthropogenic interference and the onset of a severe El Niño–driven drought.

The graphs given in Fig. 5 show the level of seasonal variability of wetland inundated area by wetland typology over the years during the wettest and driest months, of February and September, respectively. The high variability of the inundated area is due to dry and wet seasons predominant in the catchment. The Mann-Kendall trend test (Kendall and

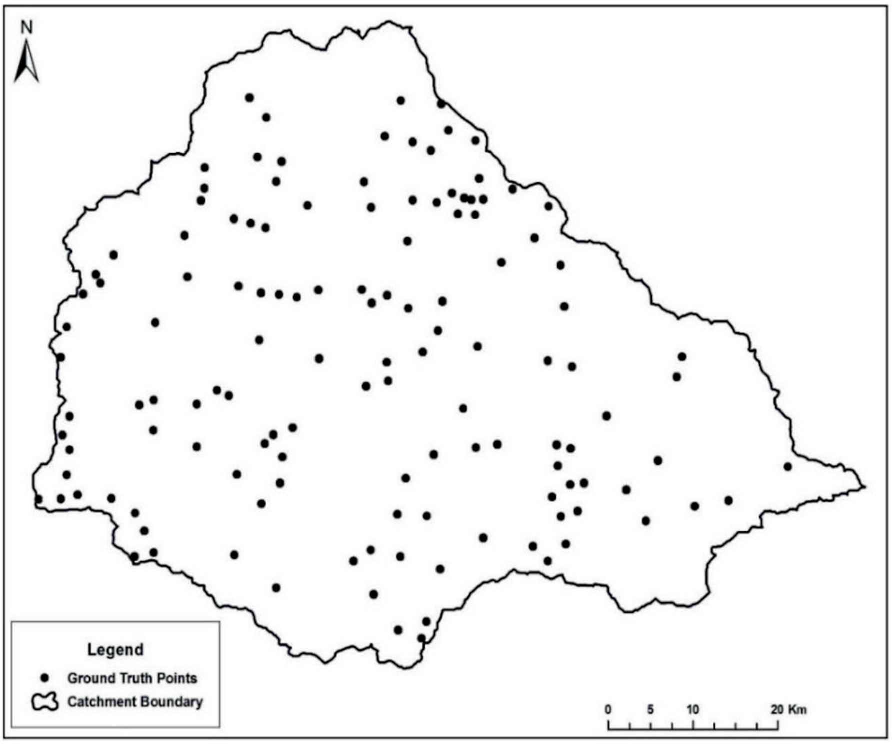

Figure 2
Ground truth points used to validate the mapped wetlands

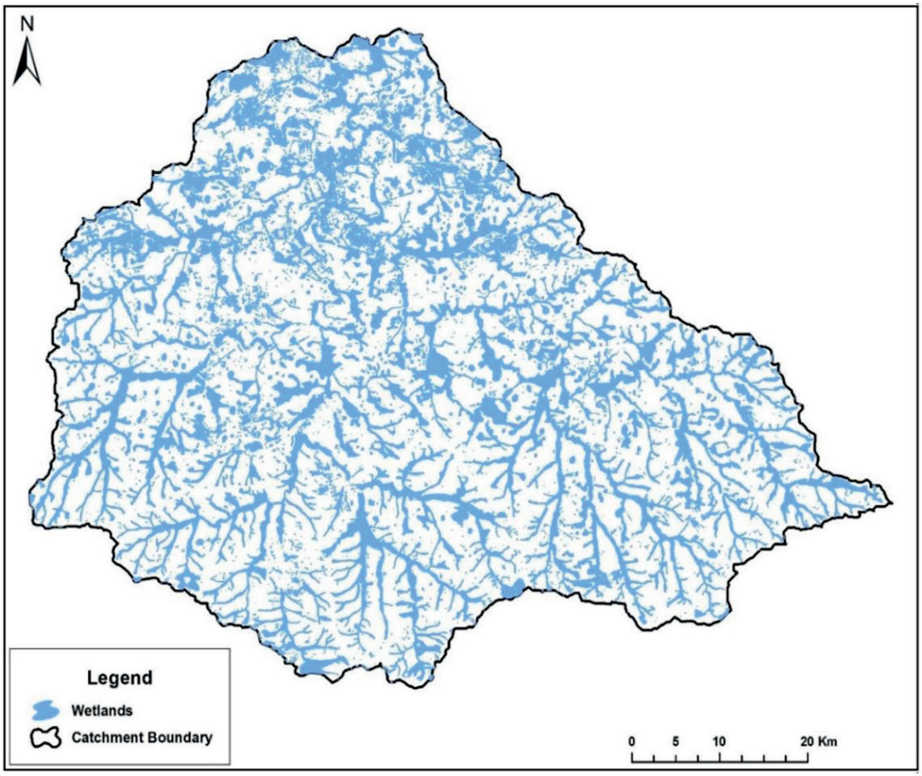

Figure 3
The delineated wetlands using Landsat 8 satellite images and DEM (both at 30 x 30 m resolution)

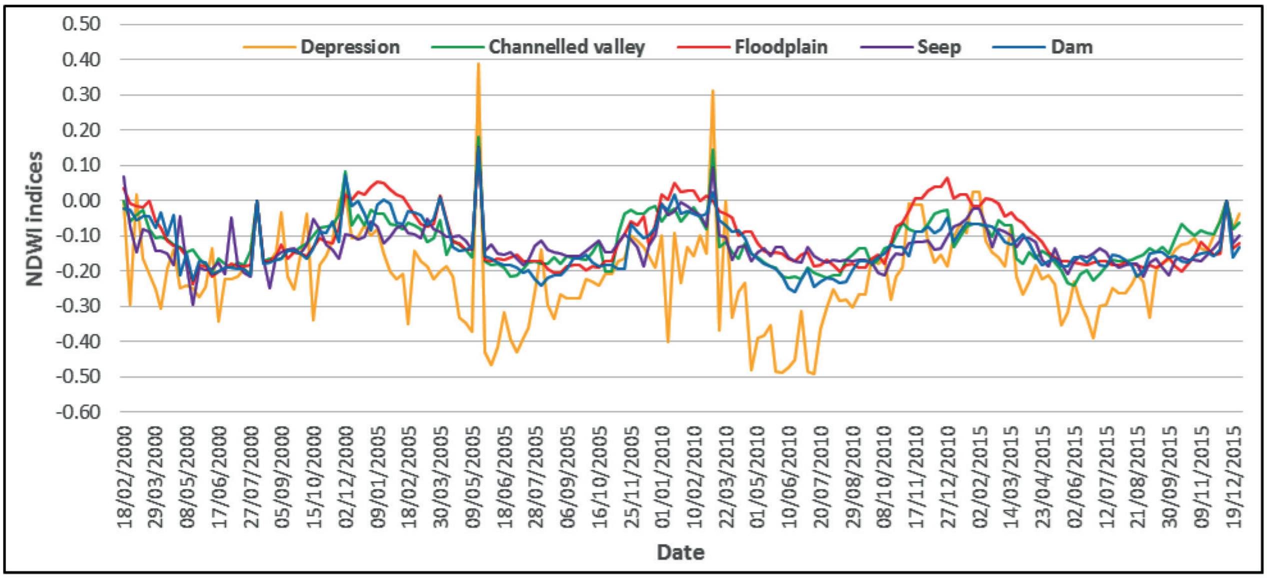

Figure 4
Wetlands seasonal and inter-seasonal variations in inundated area between 2000, 2005, 2010 and 2015

Stuart, 1976; Hamed, 2008) done for the mapped wetlands (Fig. 5 and Table 2) shows significant decline in wetland extent between 2000 and 2015, except in the case of depressions, for which change is insignificant as they are sinks where water only accumulates during the wet season but become dry during the dry season. Thus, the graph for depressions is left out as the decline is insignificant. The decline in wetland spatial extent for seeps, floodplains, dams and channelled valleys is due to water abstraction, cultivation, pollution and excessive groundwater use (Hobbs et al., 2008; Beumer, 2010). From 2000 to 2015 wetland area in the catchment declined by 19%.

The bar graphs in Fig. 6 show changes in wetland inundated area by wetland typology in the catchment between 2000 and 2015, the estimated change by 2025 (estimated through trend analysis), and the overall (averaged) wetland change. Generally, wetland inundated area has been declining over the years and the worst affected types are seeps and dams. The accelerated decline in dam water spatial extent in 2015 could be due to the drought that year and the increased demand for water for irrigation and domestic uses. Also contributing to wetland degradation in the study area are other factors, which include increased evapotranspiration due to rising temperatures (Akpalu et al., 2009), pollution from acid mine drainage from coal mining (Hobbs et al., 2008), and a declining water table due to increased groundwater abstraction (Beumer, 2010).

TABLE 2
Results of the Mann-Kendall trend test for each wetland type in the catchment

Wetland type	Mann-Kendall trend test
Channelled valley	Significant decline at $\alpha < 0.1$
Floodplain	Significant decline at $\alpha < 0.05$
Seep	Significant decline at $\alpha < 0.01$
Dams	Significant decline at $\alpha < 0.01$
Depressions	Insignificant trend at i = 0.10

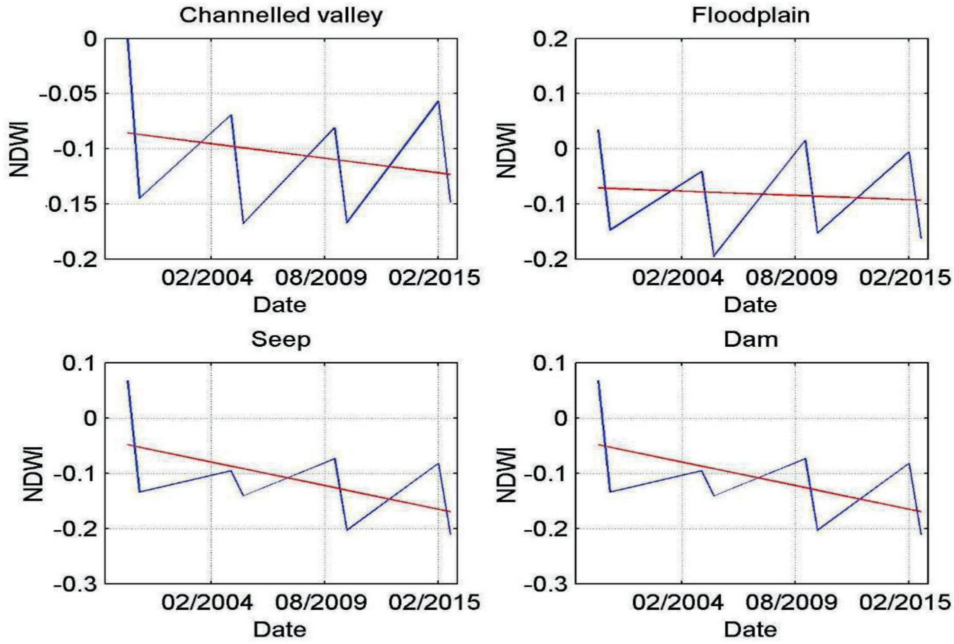

Figure 5
Mann-Kendall trend test for the 4 wetland types whose decline is significant between the wettest and driest months from 2000 to 2015

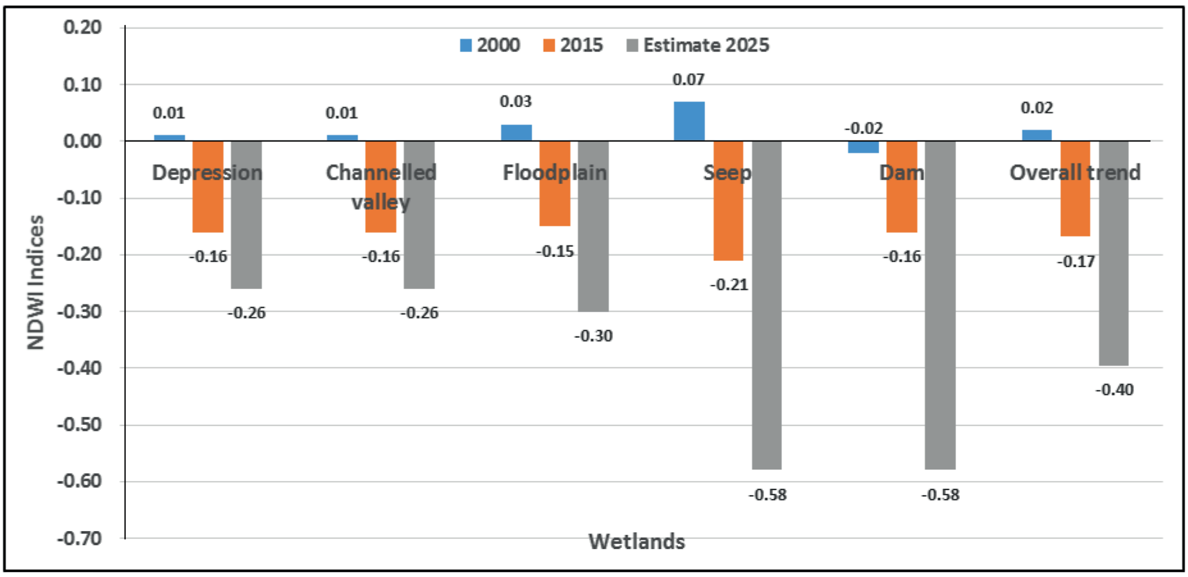

Figure 6
Wetland seasonal variability and decline by wetland typology and trend by 2025

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However, the overall decline in wetland inundated area cannot be attributed to drought alone as drought conditions have not occurred in every year. Other factors like cultivation, which affects 21% of wetland area, are also contributing to wetland degradation in the catchment. Besides the recurrence of drought and increased anthropogenic activities which are aiding wetland degradation in the study area, there are also other contributing factors, which include: increased evapotranspiration due to increasing temperatures (Akpalu et al., 2009), pollution from acid mine drainage from coal mining (Hobbs et al., 2008), and declining water table due to increased groundwater abstraction (Beumer, 2010). The methodology used in this study not only detects changes in wetland inundated area, but also quantifies the changes that have been taking place over the years.

Accuracy assessment of the delineated wetland spatial extent

An accuracy assessment of the classified wetlands was done to determine the quality of information derived from the satellite data, using 130 ground-truthing points (Fig. 2) and visual interpretation from Google Earth. The accuracy of wetland mapping was 73% based on the comparisons between the ground points and their corresponding classes.

DISCUSSION AND CONCLUSIONS

The importance of wetlands to humankind and the environment requires immediate intervention to stop their continued decline both in area and quality. This study tentatively confirms what previous studies have already revealed globally: that wetlands are declining in area and quality (McCarthy et al., 2007; Junk et al., 2013; Davidson, 2014; Gardner et al., 2015; Li et al., 2015). Although not conclusive, as the decline may be due to climatic variability and indeed in 2015 the region was severely affected by the El Niño–associated drought event (Rembold et al., 2016; FAO, 2016), the methodology managed to detect both seasonal variation (Figs 4 and 5) and also a trend showing deterioration. Besides the impact of climate change and shorter-term variability on wetlands, anthropogenic activities such as cultivation, settlement and mining are contributing immensely to wetland degradation in the study area. An overlay of the land-use map on the wetland area map shows that 21% of wetland area is currently subjected to various anthropogenic activities. These activities on wetlands are expected to increase due to demand for more land for settlement, the need for more cultivated land to feed a growing population, and urbanisation. However, where wetland loss is due to anthropogenic influences, if the region is to sustainably uphold the essential ecosystem services provided by the wetlands, then intervention is required to prevent further loss and degradation. Priorities in wetland management should focus on strengthening the assessment, monitoring and restoration of wetlands. Better monitoring of wetland extent, in particular as influenced by seasonal variability, will also enhance monitoring of the Sustainable Development Goal (SDG) 6.6.1 Indicator on change in the extent of water-related ecosystems over time.

Remote sensing and GIS provide good options to map and monitor wetlands as they have the capability to provide information over wide areas at equal time intervals. Besides, remote sensing allows the possibility of mapping physically unreachable areas. Frequent wetland monitoring is important for timely intervention in the case of an identified negative change. Remote sensing has shown its strength in wetland mapping and for monitoring wetland dynamics over time and is thus an important tool for wetland management.

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