



The physical, chemical, mineralogical, and hydrological properties of three different wetland types in the Kruger National Park

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Abstract The Kruger National Park is largely in a pristine natural state in terms of development, hydrology, soils, and vegetation. However, little characterisation of its wetlands has been done. This paper therefore set out to characterise the vegetation, hydrology, and soils of three wetlands that developed in three different lithologies. The Malahlapanga, Nshawu, and Tshutshi spruit wetlands selected for this study were underlain by gneiss, basalt, and granite respectively. Four wetness zones were delineated and three replicate transects were identified at each study site. Vegetation was described, while hydrology and redox potential were measured in wells from 19 September 2012 until 28 August 2013 at each wetness zone and replicate. Soils were sampled in 50 mm intervals, analysed and then averaged for the 0–300 mm layer. Malahlapanga and Nshawu had Gleysols, while Tshutshi spruit had Luvisols in the permanent and seasonal zones. Malahlapanga was the only wetland that had high organic carbon contents. The pH measured in water was > 8 for Nshawu and Tshutshi spruit, and between 5 and 8 for Malahlapanga. The wetland zones differed markedly in salinity, with only Tshutshi spruit that could completely be considered non-saline. Calcium dominated as exchangeable cation in

all wetlands, but more so in Nshawu, while elevated sodium concentrations were only observed in Nshawu and Tshutshi spruit. The iron and manganese concentrations increased from the permanent to the upland zone for Malahlapanga and Nshawu, but decreased in the same order for Tshutshi spruit. Data presented here therefore provide a valuable reference for other studies conducted at these sites.

Keywords Hydrology · Hydroperiod · Soil reduction · Vegetation · Wetland soils

Introduction

South Africa is a country very conscious of water particularly due to its climatic disposition, since it receives less than half the global average precipitation (Du Preez et al. 2019). In addition to this, the government is attempting to redress social issues through various strategies, including the provision of potable water and by allocating water equitably amongst people, industry and the environment, as well as creating jobs through mining and agriculture (National Water Act 1998). All of these place pressure on the national water resources and, consequently, the environment as a whole.

In recent years, there has been growing recognition in South Africa and internationally regarding wetland ecosystems and its services (Costanza et al. 2014; Kotze et al. 2020; Parra et al. 2021), including flood

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attenuation, maintenance of river low flow, aquifer recharge, carbon sequestration, immobilisation of pollutants and sediment trapping. Wetlands support a diverse group of organisms and provide a habitat to many flora and fauna, including endangered species, and therefore need protection from exploitation (National Water Act 1998; Ramsar Convention on Wetlands 2018; Williams 2000).

Forestry, mining and agriculture all impact on wetland function. Wetlands are, however, not always protected or prioritised due to the conflicting interests between development and the environment. There is also growing evidence that climate change, with its resultant impact on global temperature and rainfall patterns (Bernstein et al. 2008) might also negatively impact on wetland functionality. All of these factors pose a major threat to wetlands in South African and internationally, and highlight the importance of identifying, delineating and protecting wetlands.

Wetlands in drylands are unique ecosystems that have local positive water balances in an otherwise arid environment (Tooth 2018; Tooth and McCarthy 2007). These ecosystems further lack understanding, primarily due to inadequate research (Williams 1999; Parra et al. 2021). Tooth and McCarthy (2007) propose that wetlands in drylands are characterized by frequent and longer periods of desiccation, greater levels of channelization and sedimentation, more frequent fires, and longer periods of development.

The National Water Act (1998) of South Africa defines wetlands as: “Land which is transitional between terrestrial and aquatic ecosystems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil”, broadly in line with the Ramsar Convention on Wetlands (2018). Wetlands have unique soil chemistry (Ponnamperuma 1972; Vepraskas and Faulkner 2001; Fiedler et al. 2007) that results in unique soil morphology (Vepraskas 2001; Fiedler and Sommer 2004). It is the latter that represents the more permanent environmental properties, and which is preferred as permanent indicator in wetland delineation and interpretation (Vepraskas 2001; DWAF 2005), as opposed to the more temporal vegetation that can easily be removed.

Wetlands in South Africa are identified using the DWAF (2005) wetlands delineation manual that

defines three wetland zones, namely the permanent, seasonal, and temporary saturated zones. All three zones are, however, considered statutory wetlands. The three wetland zones are defined based on four wetland indicators, namely: The terrain unit indicator that identifies those areas in the landscape where wetlands are more likely to occur; The soil form indicator that defines soil forms (Soil Classification Working Group 1991) that are associated with prolonged and frequent water saturation; The soil wetness indicator that defines soil morphological features that have developed due to prolonged and frequent water saturation; and the vegetation indicator that defines hydrophilic vegetation associated with prolonged and frequent water saturated soils.

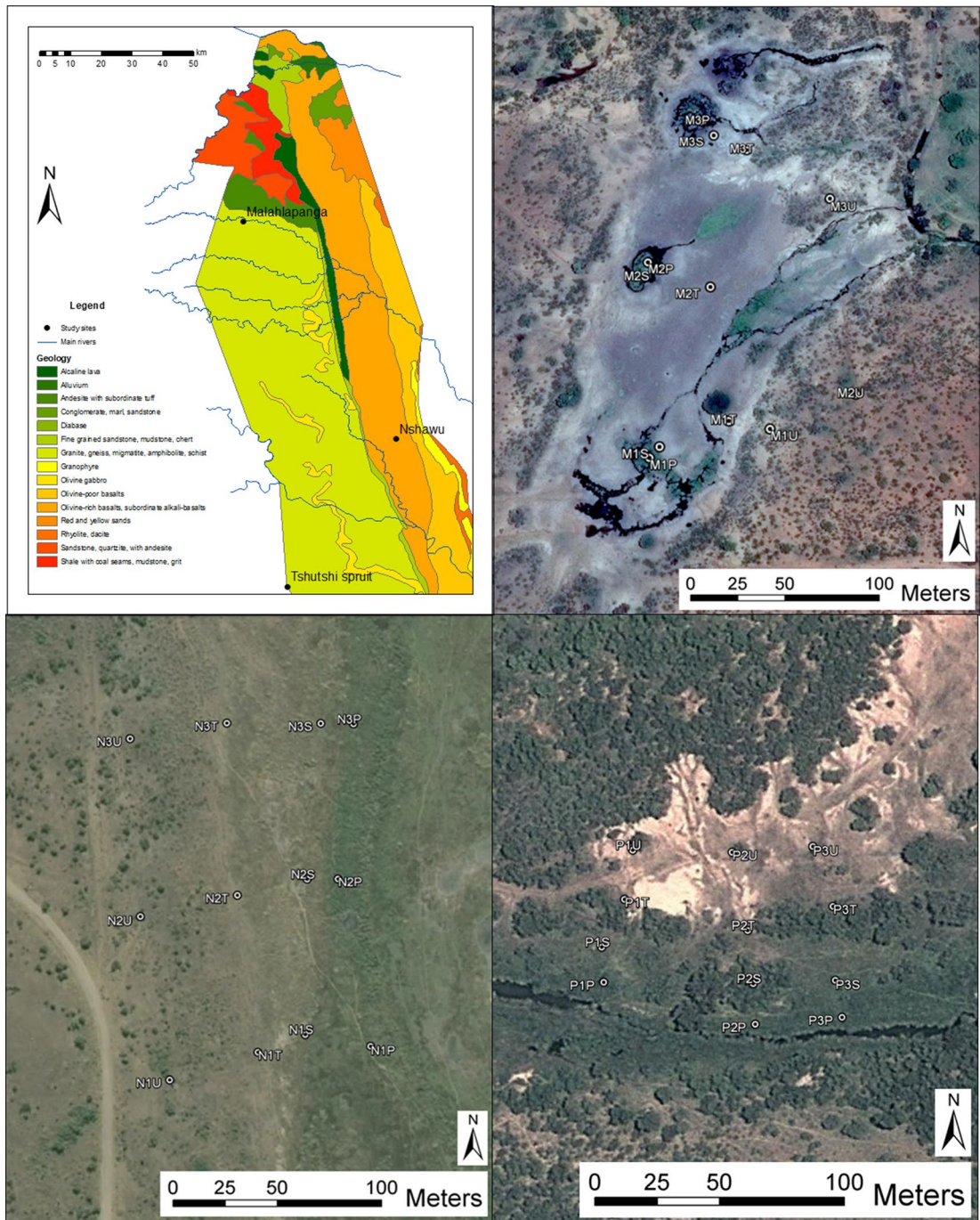
The Kruger National Park, situated in the north-eastern corner of South Africa, was founded in 1898 and now covers more than 19 000 km² (350 km long and 90 km at its widest). As such, the park is the largest in South Africa, has been designated an UNESCO world heritage site, and remains largely unmodified and in a near pristine state in terms of development, hydrology, soils, and vegetation. It also has a large variation in terms of lithology, climate, and hydrology, resulting in a number of different wetland types e.g. channelled and un-channelled valley bottom wetlands and hillslope seeps. There is also a current drive to characterise the wetlands in the Kruger National Park to assist in management and, in a few cases, the rehabilitation thereof.

The aim of this study was therefore to characterise the physical, chemical, mineralogical, and hydrological properties of three different wetland types in the Kruger National Park. The data presented can thus serve as reference to other studies within the Kruger National Park and also those wetlands in drylands with similar geomorphological setting elsewhere.

Material and methods

Study sites

Three wetland study sites, with Gneiss, Basalt, and Granite lithologies respectively, were selected at Malahlapanga, Nshawu, and Tshutshi spruit in the Kruger National Park (Fig. 1). The wetland zone boundaries were determined by observing changes in topography and vegetation composition (DWAF 2005),



Codes refer first to the wetland (Malahlapanga = M, Nshawu = N, Tshutshi spruit = P), the repetition number (1, 2, 3), and the wetness zone (permanently saturated = P, seasonally saturated = S, temporarily saturated = T, upland zone = U)

Fig. 1 Location of the wetland sites in the Kruger National Park as well as lithology according to Venter (1990; A) and location of the sampling sites within the Malahlapanga (B), Nshawu (C), and Tshutshi spruit (D) wetlands

since these zones have unique vegetation determined by soil hydrology and chemistry. Soil morphology was thus excluded in delineating wetland zone boundaries, since the relation between vegetation and soil morphology was an analogous aim of the larger research project. Three replicate transects were then identified at each wetland site and a monitoring point was established in each wetness zone of each transect, giving 12 monitoring points per wetland site.

Climate

All three study areas were hot, with average annual temperatures that varied between 21 and 22 °C. The rainfall occurred mainly during the summer months and increased from 467 mm a⁻¹ at Malahlapanga in the north to 546 mm a⁻¹ at Tshutshi spruit in the south (Schulze 1997, Table 1). The A-pan evapotranspiration decreased in the same direction from 2156 to 2047 mm a⁻¹, resulting in an increase in the aridity index from 0.22 to 0.27. All three studied wetlands

therefore occurred at the drier end of the UNESCO semi-arid climate class (Cherlet et al. 2018).

January 2013 was an extremely wet month, with 452 mm rain (Fig. 2). The rest of the year was dry except for a few smaller rainfall events (<40 mm) occurring in September, October, and December of 2012 as well as in April 2013. The Shingwedzi region (within which Malahlapanga falls) was also subject to extensive flooding in January of 2013, resulting in several dams breaching and many access roads becoming impassable, leading to data loss for January and February of 2013. Nshawu received very little rain during the course of the study, with the exception of January 2013, while Tshutshi spruit received the least rain during the January 2013 floods.

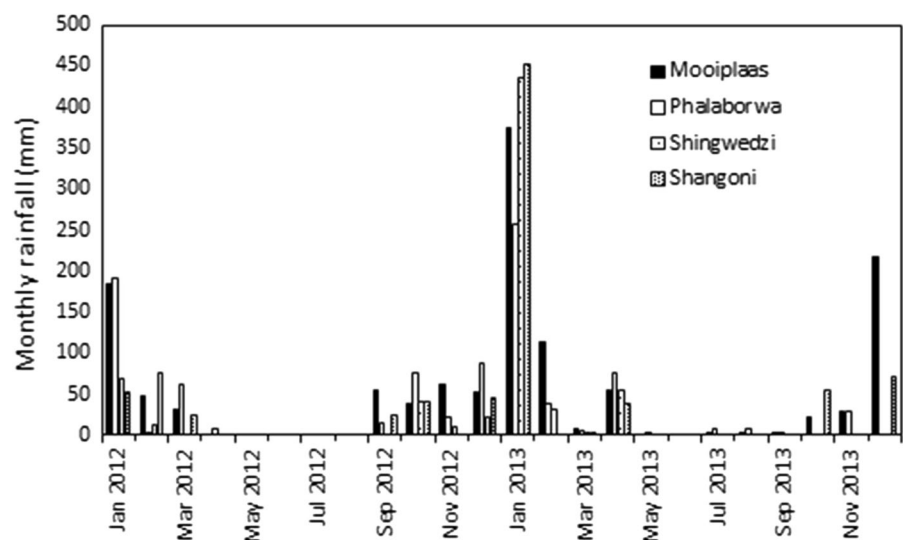
Monitoring wells

The monitoring wells were constructed according to the procedure described by Sprecher (2008) and the Wetlands Research Programme (1993), by drilling

Table 1 Selected average annual long-term modelled climate indicators for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park (adapted from Schulze 1997)

Wetland	Temperature (°C)	Precipitation (mm)	Evapotranspiration (A-pan, mm)	Aridity index (mm mm ⁻¹)
Malahlapanga	22	467	2156	0.22
Nshawu	22	528	2057	0.26
Tshutshi spruit	21	546	2047	0.27

Fig. 2 Monthly rainfall (mm) for selected rainfall stations in the Kruger National Park for 2012 and 2013



holes, approximately 50 mm apart, along the length of a 1.5 m, 50 mm diameter PVC waste pipe. The wells were then installed vertically into the soil and the top sunk 50 mm below the soil surface and finally covered with an end-cap, grass and dung to deter the elephants and to be invisible to tourists. The wells were excavated using a bucket auger, the pipes were placed in position and river sand was poured around it, with a layer of bentonite near the surface to prevent preferential flow of water along the sides of the well. Wells were installed to a shallower depth where restricting layers impeded auguring.

The water table depth was measured in the monitoring wells from the soil surface, every 28 days from 19 September 2012 until 28 August 2013, using a tape measure. When the wells were dry it was noted that the water table was not reached.

A water sample was concurrently taken from the well using a bailer, after the water level measurement had been recorded, and poured into a small clean glass beaker. The pH was then measured in the field with a portable pH/Eh meter (HANNA HI8314 instrument and a HI3230 pH electrode). The pH meter was calibrated with buffers of 4.00 and 7.00 at the beginning of each fieldwork trip. An Eh measurement was taken in a similar manner in the field also using the HANNA HI8314 instrument, but with a Pt electrode (HI3230) attached. The same water sample for the pH measurement was used and the sample was then discarded. The Eh electrode was calibrated at the beginning of each field trip against a 230 mV standard buffer solution.

Negative logarithm of the hydrogen partial pressure (rH) was calculated as:

$$rH = Eh/29 + 2 \times pH \quad (1)$$

when the $rH < 20$ it was interpreted as signifying a reducing environment (Clark 1923).

After the study, the wells at Phalaborwa and Nshawu were removed, while the wells at Malahlapanga were left in situ for continued monitoring.

Vegetation

The vegetation was assessed during the summer growing season. At each of the monitoring points, 25 random sampling points were selected within a 5 m radius from the monitoring well. At each of these 25

random sampling points, the nearest species were identified. Species which were not easily identifiable in the field were given a temporary name and detailed photographs were taken. All species were classified as either being *present* or *dominant* in terms of their abundance at the monitoring point. The species were also classified as being one of the following: upland, opportunistic upland, obligate wetland, facultative wetland, and facultative negative or facultative positive wetland plants. An obligate wetland plant was a plant that occurs for >99% of the time in a wetland or water saturated area. A facultative wetland plant was a plant that occurs 50% of the time in a wetland or water saturated areas, a facultative positive wetland plant occurs between 67 and 99% of the time in a wetland or water saturated area, and a facultative negative wetland plant occurs <25% of the time in a wetland or water saturated area (Van Ginkel et al. 2011).

Soil analyses

A profile pit was dug in each wetness zone at each of the selected wetlands sampled, described (Turner 1991; Schoeneberger et al. 2012), and classified (Soil Classification Working Group 1991; IUSS Working Group WRB 2014).

Composite soil samples were taken from the profile pit walls and by hand-held auger at the other monitoring points. Where auguring was not possible due to coarse fragments, samples were taken from a small pit. Samples were collected at 15 depth intervals: 0–50, 50–100, 100–150, 150–200, 200–250, 250–300 mm. Samples were air dried and lightly crushed using a porcelain mortar and wooden pestle to pass a 2 mm sieve. The peat samples were handled differently: half the sample was dried and sieved while the other half was kept in its moist state for carbon analyses.

All analyses were done according to the methods of the Non-Affiliated Soil Analysis Work Committee (1990), unless stated otherwise. The pH was measured in distilled water in a 1: 2.5 soil:liquid ratio. Electrical resistance of saturated paste was measured in a standard electrode cup and resistance bridge. Exchangeable cations and cation exchange capacity were determined using 1 M NH_4OAc , buffered at pH 7 extraction and flame spectroscopy in an Agilent 240Z atomic absorption spectrophotometer. Total nitrogen was measured using the Kjeldahl method,

while organic carbon was measured using the Walkley Black method. The total ‘free’ iron and manganese ‘oxide’ contents were determined using the dithionate-citrate-bicarbonate extraction method (Mehara and Jackson 1960). Soil texture was determined in seven fractions (coarse sand, medium sand, fine sand, very fine sand, coarse silt, fine silt and clay) using the pipette and sieve method.

After analysis, the individual results for the 0 to 300 mm layer were averaged across all three repetitions, to give the topsoil values that are reported here.

Results

Detailed profile descriptions and soil analyses as well as vegetation descriptions are presented by Johnson (2014).

Parent material

Soils of the Malahlapanga wetland derived from Goudplaats Gneiss, a foliated metamorphic rock that has been ferruginised (Fig. 1; Fanning and Fanning 1989; Venter 1990). The parent material was binary, consisting of local alluvium overlying solid rock in the permanent zone, local alluvium in the seasonal zone, local alluvium overlying solid rock in the temporary zone, and local colluvium in the upland zone.

The parent material for the Nshawu wetland derived from basalt, an extrusive basic igneous rock. The permanent, seasonal and temporary zones had alluvium, while the upland zone developed in situ.

The parent material was ferruginised and calcified in all cases (Fanning and Fanning 1989).

At Tshutshi spruit the parent material derived from granite, an intrusive coarse sodic igneous rock, which has undergone advanced physical and chemical weathering and that has been ferruginised in the permanent and seasonal zone and calcified in the temporary and upland zone (Fanning and Fanning 1989).

Topography

A brief summary of selected topographical indicators are presented in Table 2. All wetlands zones fulfilled the DWAF (2005) terrain unit indicator, since this was also used during delineating the zones. The slope shape was generally straight or concave, while the aspect varied from North-facing at Malahlapanga to East-facing at Nshawu and South-facing at Tshutshi spruit.

Vegetation

Malahlapanga

The vegetation at Malahlapanga has been significantly disturbed through animal trampling, to the extent of being barren in the seasonal zone, which allowed for the establishment of numerous small opportunistic dryland species (Table 3). True wetland vegetation indicator species were hence scarce, however, the obligate wetland species *Phragmites mauritianus* was noted in both the permanent and seasonal zones (Table 3). The sharp boundary between the barren area and the *Colophospermum mopane* also served

Table 2 Location and selected topographical indicators for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park

Wetland and coordinates	Wetness zone	Terrain unit	Slope (%)	Shape	Aspect
Malahlapanga 22.8874 S; 31.0404 E	Permanent	Valley bottom	0.0	Straight	North-facing
	Seasonal	Valley bottom	0.5	Straight	North-facing
	Temporary	Valley bottom	0.5	Straight	North-facing
	Upland	Lower footslope	2.0	Straight	Level
Nshawu 23.5221 S; 31.4861 E	Permanent	Valley bottom	1.0	Concave	East-facing
	Seasonal	Valley bottom	1.0	Concave	East-facing
	Temporary	Lower footslope	3.0	Straight	East-facing
	Upland	Upper midslope	3.0	Convex	East-facing
Tshutshi spruit 23.9531 S; 31.1682 E	Permanent	Valley bottom	0.0	Straight	South-facing
	Seasonal	Lower footslope	1.0	Straight	South-facing
	Temporary	Middle footslope	1.0	Straight	South-facing
	Upland	Upper footslope	1–2	Straight	South-facing

Table 3 Plant species composition per wetness zone for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park

Woody species		Malahlapanga				Nshawu				Tshutshi spruit			
		1	2	3	4	1	2	3	4	1	2	3	4
<i>Acacia nigrescens</i>	Dryland					—	—	p-	—				
<i>Acacia robusta subsp clavigera</i>	Dryland	—	—	p-	—								
<i>Albizia forbesii</i>	Dryland					—	—	—	-pp				
<i>Andropogon gayanus</i>	Opportunistic/Dryland					—	-p-	p-	—				
<i>Capparis tomentosa</i>	Opportunistic/Dryland	d-	—	—	—								
<i>Cenchrus ciliaris</i>	Dryland					—	—	p-	dp-				
<i>cf Panicum infestum</i>	Facultative negative					-pp	p-	—	—				
<i>cf Sporobolus ioclados</i>	Facultative negative					—	—	ppd	—				
<i>Chloris gayana</i>	Dryland					-pp	ddd	-p-	—				
<i>Colophospermum mopane</i>	Dryland	—	—	—	ddp	—	—	—	dpp	—	pp-	dd-	ddp
<i>Combretum hereroense</i>	Dryland									p-	—	—	—
<i>Cynodon dactylon</i>	Dryland					—	d-	p-	—	pdd	p-d	-d	—
<i>Dichrostachys cinerea</i>	Dryland					—	—	—	ppp				
<i>Enneapogon cenchroides</i>	Dryland					—	—	p-	ppp				
<i>Eragrostis capensis</i>	Dryland						—	p-	—				
<i>Euclea divinorum</i>	Dryland					—	—	—	p-	-p	-d	-p-	—
<i>Grass species</i>													
<i>Aristida adscensionis</i>	Dryland									—	—	pp-	p-
<i>Aristida congesta</i>	Dryland									—	—	—	-p
<i>cf Dactyloctenium aegyptium</i>	Opportunistic/Dryland	-d	—	—	—								
<i>Chloris virgata</i>	Opportunistic/Dryland	—	—	pp-	—					—	—	pp-	pp-
<i>Cynodon dactylon</i>	Dryland					—	d-	p-	—	pdd	p-d	-d	—
<i>Cynodon nlemfuensis</i>	Opportunistic/Dryland									ddd	-p	—	—
<i>Enneapogon cenchroides</i>	Dryland	—	—	—	-p-								
<i>Eragrostis rigidor</i>	Dryland									—	—	p-	—
<i>Eragrostis sp.</i>	Dryland	—	—	-p	-p								
<i>Gymnosporia senegalensis</i>	Dryland					—	—	—	p-	ppp	-dp	—	—
<i>Lansea schweinfurthii</i>	Dryland	p-	—	—	—								
<i>Leptochloa fusca</i>	Obligate	p-d	—	—	—	p-	—	—	—				
<i>Panicum duestum</i>	Dryland	—	—	—	ppp	—	—	—	-p				
<i>Panicum maximum</i>	Dryland	p-	—	—	—	—	—	p-	p-p	dpd	pdd	ppp	p-
<i>Philenoptera violacea</i>	Dryland					—	—	—	d-	—	-d-	—	—
<i>Phragmites mauritianus</i>	Obligate	ddd	p-	—	—	ppp	p-p	—	—				
<i>Shmidtia pappophoroides</i>	Dryland					—	—	—	pp-				
<i>Sporobolus ioclados</i>	Facultative negative									—	d-	dd-	ddd
<i>Sporobolus pyramidalis</i>	Facultative positive					pp-	-d	ddd	—				
<i>Tragus berteronianus</i>	Dryland	—	—	p-	pdp	—	—	—	p-p	—	—	—	-p
<i>Urochloa mosambicensis</i>	Dryland					—	—	—	ppp	pp-	ppp	-p-	—
<i>Forb species</i>													
<i>Abutilon rehmanni</i>	Opportunistic / Dryland					—	—	—	p-				
<i>Acanthaceae</i>	Dryland					—	—	—	-p				
* <i>Alternanthera pungens</i>	Opportunistic/Dryland	—	—	pp-	—								
<i>Asparagus sp.</i>	Dryland					—	—	—	-p-				
* <i>Bidens bipinnata</i>	Opportunistic/Dryland									—	—	pd-	p-

Table 3 (continued)

Woody species		Malahlapanga				Nshawu				Tshutshi spruit			
		1	2	3	4	1	2	3	4	1	2	3	4
<i>cf Boscia foetida</i>	Dryland					—	—	—	p-				
<i>cf Campanulacea</i>	Facultative negative	-p-	—	—	—								
<i>cf Neuracanthus africanus</i>	Dryland					—	—	p-	p-				
<i>cf Sesbania sesban</i>	Opportunistic/Dryland					-p-	—	-p	—				
<i>cf Sesuvium hydaspicum</i>	Opportunistic/Dryland	—	—	—	-p								
<i>cf Zaleya pentandra</i>	Opportunistic/Dryland	—	—	p-	p-								
<i>Commelina sp.</i>	Opportunistic/Dryland									—	-p-	-p	-p-
<i>Heliotropium sp.</i>	Dryland					—	—	—	-pp				
<i>Hermbstaedtia odorata</i>	Dryland					—	—	p-	ppp				
<i>Hibiscus cannabinus</i>	Opportunistic/Dryland	-p-	—	—	—					—	—	-p	—
<i>Hybiscus micranthus</i>	Dryland					—	—	—	p-				
<i>Ipomoea sp.</i>	Dryland									—	-p-	-p	—
<i>Justica flava</i>	Dryland									—	p-	—	-d
<i>Pechuel-Loeschea leubnitziae</i>	Dryland					—	—	p-	-pp				
<i>Portulaca oleraceae</i>	Opportunistic/Dryland	—	—	p-	—								
* <i>Sesbania bispinosa</i>	Opportunistic/Dryland	pdp	—	—	—					p-	—	—	—
* <i>Schkuhria pinnata</i>	Opportunistic/Dryland									—	—	p-	—
<i>Sesuvium hydaspicum</i>	Opportunistic/Dryland									—	—	-p-	dp-
<i>Sida cordifolia</i>	Opportunistic/Dryland									p-	—	—	—
<i>Solanum sp.</i>	Opportunistic/Dryland									—	—	-p	—
* <i>Tagetes minuta</i>	Opportunistic/Dryland									p-p	-p-	-d	—
<i>Tragia durbanensis</i>	Dryland					—	—	—	-p-				
<i>Trianthema salsoloides</i>	Opportunistic/Dryland	—	—	ppp	ppp								
<i>Tribulus terrestris</i>	Opportunistic/Dryland	—	—	pp-	p-p								
<i>Sedge and rush species</i>													
<i>Cyperus laevigatus</i>	Obligate					d-	dp-	—	—				
<i>Cyperus obtusiflorus</i>	Opportunistic/Dryland					—	—	p-	—				
<i>Cyperus sexangularis</i>	Facultative positive					ddp	dpp	-pp	—	pp-	—	—	—
<i>Cyperus sexangularis</i>	Facultative positive					ddp	dpp	-pp	—	pp-	—	—	—
<i>Fimbristylis dichotoma</i>	Obligate	-p	—	—	—								
* <i>Juncus effusus</i>	Obligate					—	pp-	—	—				
<i>Pycnopus sp.</i>	Obligate	dpd	—	—	—								
<i>Typha capensis</i>	Obligate									ppp	—	—	—

1 = permanent, 2 = seasonal, 3 = temporary, 4 = upland

*Alien invasive species

cf indicates taxonomy that could not be verified

p = present, d dominant, — = not present in the three replicates per zone for each site

as a boundary between the upland and the temporary wetland zones.

The permanent zone had free water and lush vegetation associated with the peat domes. These peat domes extruded from the surrounding landscape by anything from a couple of centimetres to more than two meters and developed due to lavish vegetative growth on the artesian springs (Grootjans et al. 2010). The obligate grass species *Leptochloa fusca* and *Phragmites mauritianus* were noted as dominant, the facultative negative forb *cf Campanulacea* was present, while the obligate species *Fimbristylis dichotoma* was present and *Pycnopus sp* were dominant. The alien opportunistic species **Sesbania bispinosa* was also recorded in this zone.

The seasonal zone was largely barren, which was attributed to trampling by large herds of buffalo and elephant, attracted by the water emanating from the springs. The only vegetation species recorded in this zone was the obligate wetland species *Phragmites mauritianus*.

The temporary zone was also barren, which hampered the boundary determination between the seasonal and temporary zones. One *Acacia robusta* tree was observed, while opportunistic/dryland grasses *Chloris virgata* and *Tragus berteronias* were present. Several opportunistic/dryland forbs namely alien **Alternanthera pungens*, *cf Zaleya pentandra*, *Portulaca oleraceae*, *Trianthena salsoloides*, and *Tribulus terrestris* were noted.

The upland zone was dominated by the dryland *Colophospermum mopane* and numerous dryland grasses *Eragrostis sp*, *Enneapogon cenchroides*, *Panicum deustum*, and *Tragus berteronias* (dominant). Several opportunistic/dryland forb species namely *cf Sesuvium hydaspicum*, *cf Zaleya pentandra*, *Trianthena salsoloides*, *Tribulus terrestris* were also present.

Nshawu

The vegetation indicators were much clearer for Nshawu than for Malahlapanga and more species were recorded (Table 3). This could be attributed to the size of the wetland, hence the animals were more distributed, resulting in less trampling, as well as the more fertile soil parent material. Species composition changed gradually at the zone boundaries.

The permanent zone had *Leptochloa fusca*, *Phragmites mauritianus*, and *Cyperus laevigatus* as obligate wetland species. The facultative positive wetland species *Sporobolus pyramidalis* and *Cyperus sexangularis* were also present, while *cf Panicum infestum* (facultative negative) was recorded in two repetitions and the opportunistic species *cf Sesbania sesban* was present at one repetition.

In the seasonal zone the obligate wetland species *Phragmites mauritianus*, *Cyperus laevigatus* and alien **Juncus effusus* were noted. The facultative positive wetland species *Sporobolus pyramidalis* and *Cyperus sexangularis* were also recorded, while the opportunistic *Andropogon gayanus* and the facultative wetland negative *cf Panicum infestum* were only present at one repetition each.

Facultative positive wetland species in the temporary zone were *Sporobolus pyramidalis* (dominant) and *Cyperus sexangularis*, while *cf Sporobolus ioclados* (facultative wetland negative) was present at two repetitions and dominant at one. *Andropogon gayanus*, *cf Sesbania sesban*, and *Cyperus obtusiflorus* were noted as opportunistic species.

The upland zone only had dryland species with the exception of the opportunistic *Abutilon rehmanni*.

Tshutshi spruit

Tagetes minuta was the only species that was common between the temporary, seasonal, and permanent zones (Table 3). The species unique to the temporary zone were *Hibiscus cannabinus*, **Schkuhria pinnata* (alien), and *Solanum sp*, while the permanent zone was characterised by *Cyperus sexangularis* and *Typha capensis*. Numerous alien species were also recorded. Compared to the other two wetlands, Tshutshi spruit had the greatest number of alien species, probably because the river originates from and is thus impacted on from outside of the Kruger National Park.

The permanent zone was characterised by the obligate species *Typha capensis*, while the facultative positive wetland *Cyperus sexangularis* was present at two repetitions, with the opportunistic *Cynodon nlemfuensis*, **Sesbania bispinosa* (alien), *Sida cordifolia*, and **Tagetes minuta* (alien) also recorded.

Only one facultative negative wetland species *Sporobolus ioclados* was recorded in the seasonal zone, while three opportunistic species *Cynodon*

nlemfuensis, *Commelina* sp., **Tagetes minuta* (alien) were noted.

The temporary zone had only one facultative negative species *Sporobolus ioclados*, while numerous opportunistic species *Chloris virgate*, **Bidens bipinnata* (alien), *Commelina* sp., *Hibiscus cannabinus*, **Schkuhria pinnata* (alien), *Sesuvium hydaspicum*, *Solanum* sp., **Tagetes minuta* (alien) were recorded.

Sporobolus ioclados (facultative negative) was recorded in the upland zone, while the opportunistic species *Chloris virgate*, **Bidens bipinnata* (alien), *Commelina* sp., and *Sesuvium hydaspicum* were noted.

Hydrology

Malahlapanga

The water table in the permanent zone was within 0.5 m from the soil surface throughout the period of the study (Fig. 3). The missing data for January and February 2013 was attributed to the Shingwedzi Flood when access to Malahlapanga was restricted. It can however, be presumed that there would have been a rise in water table levels over this period due to the magnitude of the flood that occurred. The water table levels fluctuated over the seasons but to a much lesser extent than for the other two wetlands.

It was speculated that because the wetland is fed via groundwater, there was a greater lag period, and that the effect of seasonal rainfall variation was buffered to some extent. This was further substantiated by the decrease in water table level of the seasonal zone. If the permanent zone was significantly reliant on upslope soil water, then the decrease measured in the seasonal zone would also influence the permanent zone. All redox potential measurements occurred in the reduced spectrum, therefore it was concluded that if the soil was saturated with water it would be reduced as well (Fig. 4).

Nshawu

The permanently saturated zone had a water table that rose to within 0.5 m from the soil surface during the length of the study period (Fig. 3). The seasonally saturated zone had a water table to within 0.5 m from the soil surface only after the January 2013 floods. The missing data for the month of January was attributed to the floods. The water table in the temporary zone rose to within 0.5 m from the soil surface a month after the flooding occurred. Conversely to Malahlapanga, an increase in water table level in the seasonal zone was correlated to an increase in the permanent zone. This seemed to imply that water moved through the upland and seasonal zones to the permanent zone.

Fig. 3 Depth to water table, measured in wells, if water was present, for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park [Codes refer to the wetland (Malahlapanga = M, Nshawu = N, Tshutshi spruit, Phalaborwa wetland = P), and the wetness zone (permanently saturated = P, seasonally saturated = S, temporarily saturated = T); Wetland zones with no data indicate that no water was encountered during the measurements]

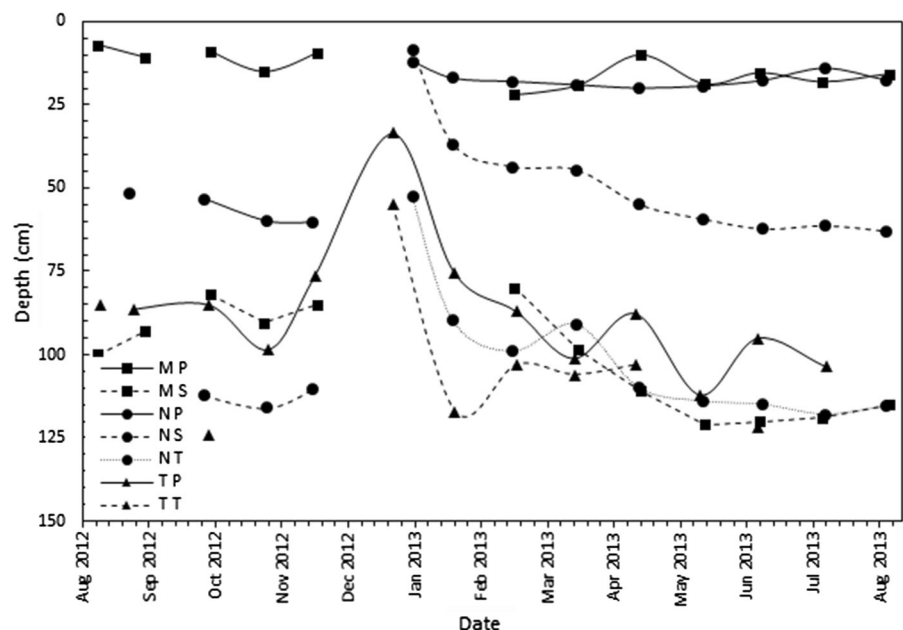
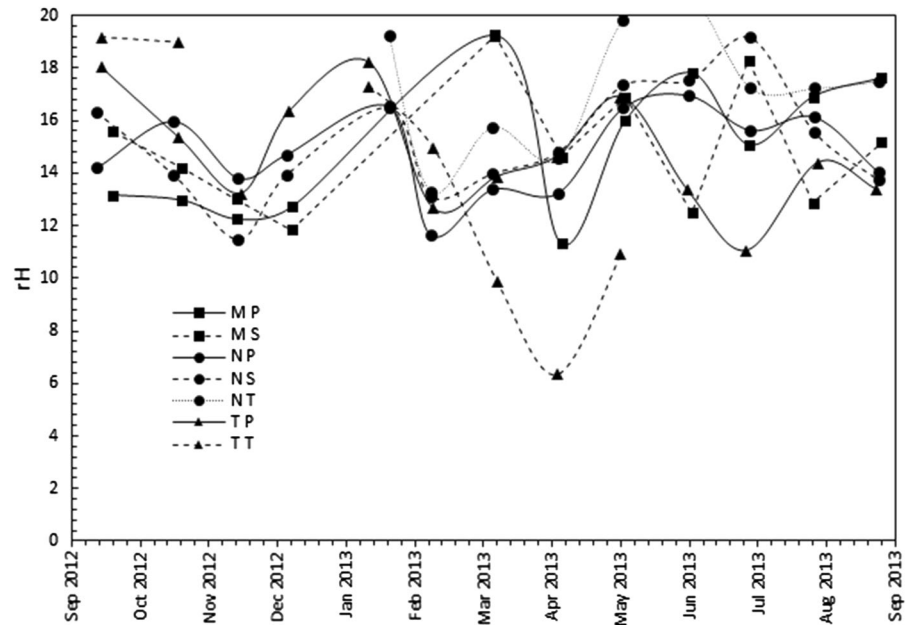


Fig. 4 Negative logarithm of the hydrogen partial pressure (rH) values, measured in wells if water was present, for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park [Codes refer to the wetland (Malahlapanga = M, Nshawu = N, Tshutshi spruit, Phalaborwa wetland = P), and the wetness zone (permanently saturated = P, seasonally saturated = S, temporarily saturated = T)]



While the zone boundaries were determined based on vegetation, there was a strong agreement in terms of the duration of water saturation that was recorded over the study period and the vegetation indicators observed. The water saturated soils were also reduced (Fig. 4).

Tshutshi spruit

For all the wetness zones, the water table did not rise to within 0.5 m from the soil surface, except for the month of January 2013 when the water table in the permanent, seasonal and temporary zones rose substantially due to the floods (Fig. 3). This was attributed to the Tshutshi spruit system being a channelled valley bottom wetland. The water table typically occurred at a depth of 800 mm for the permanent and seasonal zones for all three repetitions and it fluctuated only slightly from month to month. It was speculated that because these zones were comprised of sandy stratified alluvial sediment that the response to a hydrological event would be rapid while the drop in water table after the event would also be relatively quick due to the large pore size distribution expected for these sandy soils. Additionally, the strongly structured upslope soils of the permanent zone would most likely have induced overland flow onto the wetland, exacerbating the event response. The water saturated soils were also reduced (Fig. 4).

Soils

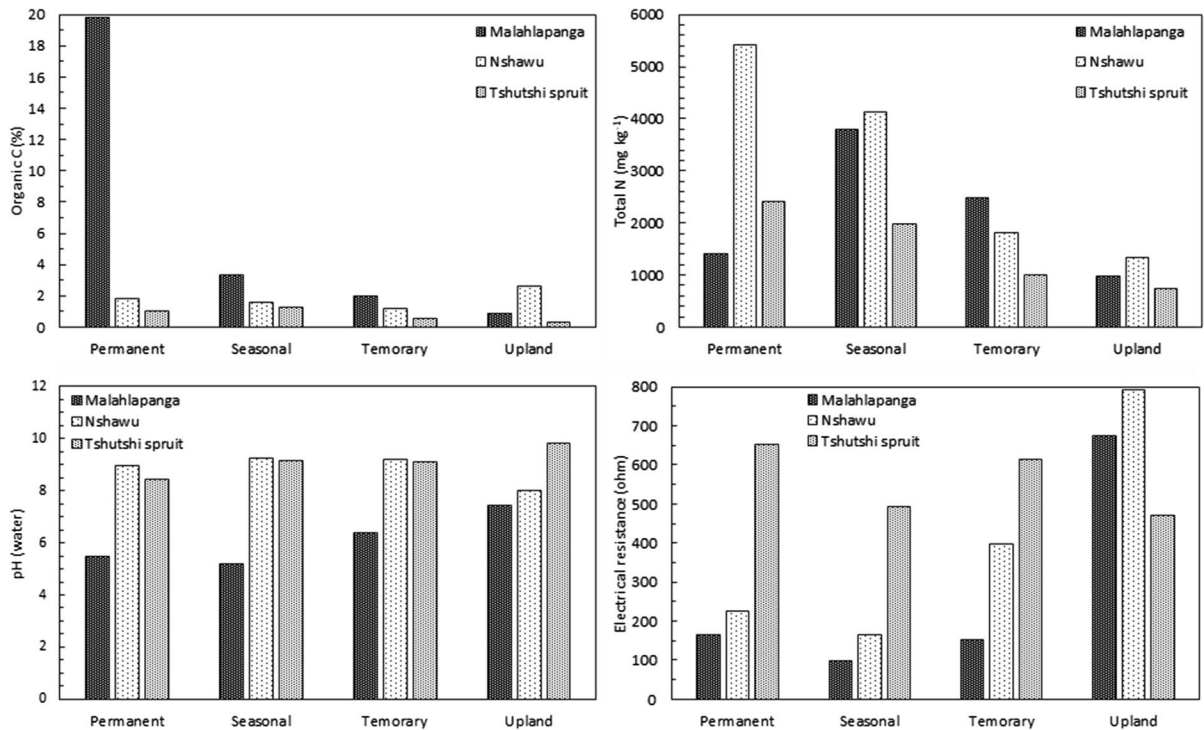
Malahlapanga

For Malahlapanga, the DWAF (2005) soil form indicator distinguished well between the different wetness zones, however, the guidelines implied greater wetness for the temporary zone than was observed during this study (Table 4). This could mean that the Katspruit soil form is not restricted to the permanently saturated zones as the DWAF (2005) guidelines imply, or that the soil morphology may be relict that could reflect a much wetter past. Alternatively, since the wetland is groundwater fed that has a different energy balance to contemporary water and has elevated carbon and nitrogen, it might lead to Katspruit soil formation in drier zones.

The organic carbon content in the permanent zone was markedly higher than that of the seasonal, temporary and upland zones due to the peat substrate accumulation. Average organic carbon values in the topsoil of the permanent zone was 19.8%, while values in the seasonal, temporary and upland zones were less than 4% (Fig. 5). These are very high organic carbon values for South African conditions (Van Huyssteen et al. 2021). There was a definite decrease in organic carbon with increased distance from the permanently saturated zone. The highest total nitrogen

Table 4 South African (Soil Classification Working Group 1991) and WRB (IUSS Working Group WRB 2014) soil classification per wetness zone for the three study sites in the Kruger National Park

Study site	Wetness zone			
	Permanent	Seasonal	Temporary	Upland
Malahlapanga	Champagne 1200 Eutric Gleysol (Hyper-humic, Salic)	Kroonstad 1000 Epigleyic Fluvisol (Siltic, Eutric)	Katspruit 1000 Mollic Gleyic Fluvisol (Endoruptic)	Glenrosa 1111 Hyposodic Cambisol (Endoskeletal)
Nshawu	Katspruit 2000 Calcic Gleysol (Eutric, Vertic)	Katspruit 2000 Calcic Mollic Gleysol (Eutric, Vertic)	Steendal 2000 Bathypetric Endogleyic Hypercalcic Calcisol (Endoruptic)	Milkwood 2000 Eutric, Skeletic Leptosol (Arenic, Ochric)
Tshutshi spruit	Dundee 1220 Epigleyic Fluvisol (Eutric)	Sterkspruit 2100 Epigleyic Fluvisol (Sodic)	Sterkspruit 2100 Calcic Endogleyic Solo- netz (Novic, Endofluvic)	Brandvlei 2000 Calcic Endogleyic Fluvisol (Sodic, Eutric)

**Fig. 5** Organic carbon (C), total nitrogen (N), pH_{H₂O}, and electrical resistance for the topsoils per wetness zone for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park

content was observed (Fig. 5) in the seasonal zone (3796 mg kg⁻¹) followed by the temporary zone (2483 mg kg⁻¹). The upland zone had the least total nitrogen (980 mg kg⁻¹), in line with the low organic carbon content of this zone. The permanent zone had very low total nitrogen concentration (1417 mg kg⁻¹) that contrasted to the very high organic carbon and

was thus attributed to denitrification in this zone (Verpraskas and Faulkner 2001). The pH values at Malahlapanga ranged from 5.5 in the permanent to 7.4 in the upland zone (Fig. 5). The upland zone had the highest electrical resistance of 673 Ω that decreased to 98 Ω in the seasonal and 166 Ω in the

permanent zone, indicative of the saline artesian water (Fig. 5, Grootjans et al. 2010).

The exchangeable cations could not be measured in the high organic carbon soils of the permanent zone. At between 14 and 23 $\text{cmol}_c \text{kg}^{-1}$, the Malahlapanga soils had the second highest exchangeable calcium content, after Nshawu (Fig. 6). The magnesium content was about ten times higher in the upland than in the temporary or seasonal zones, while the potassium and sodium concentrations did not really vary between the zones. The seasonal, temporary and upland zones had CEC values below 30 $\text{cmol}_c \text{kg}^{-1}$ (Fig. 7). The upland zone had slightly lower CEC values due the fact that there was less organic matter and also possibly less weathering and clay formation.

Malahlapanga had the highest iron concentrations of the wetlands studied. The amount of iron in the topsoils was directly related to the wetness zones, with the permanent zone that had the least amount of iron (4073 mg kg^{-1}), while the upland zone had the most ($14,372 \text{ mg kg}^{-1}$). The iron concentrations increased in almost even increments from the permanent to the upland zone (Fig. 7). Contrary to iron, the manganese

concentrations were lowest in the Malahlapanga topsoils, but it followed a similar trend, ranging from 39 mg kg^{-1} in the permanent zone to 872 mg kg^{-1} in the upland zone (Fig. 7). This suggested that iron and manganese were similarly reduced and leached from the wetter zones.

Texture analysis was not conducted for the permanently saturated zone topsoils due to the high organic carbon content thereof. The clay content was largely similar between the seasonal and temporary zones, at 27% and 29% respectively and decreased to 22% in the upland zone (Fig. 7). This decreased clay content in the upland zone was attributed to the constrained chemical and physical weathering of the upland zone soils.

Nshawu

The DWAF (2005) soil form indicator accurately described the hydrological conditions at Nshawu (Table 4). The soils in the temporary and upland zones had an abundance of calcium carbonate concretions that could also be observed on the soil surface

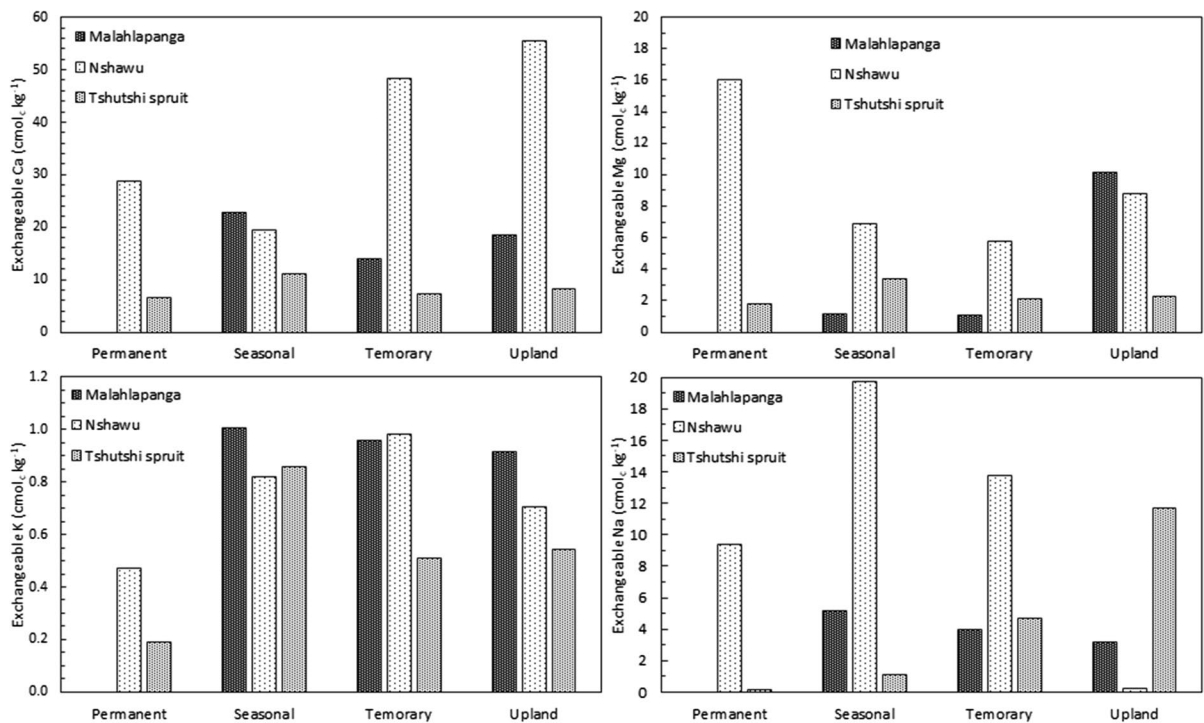


Fig. 6 Exchangeable calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) for the topsoils per wetness zone for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park

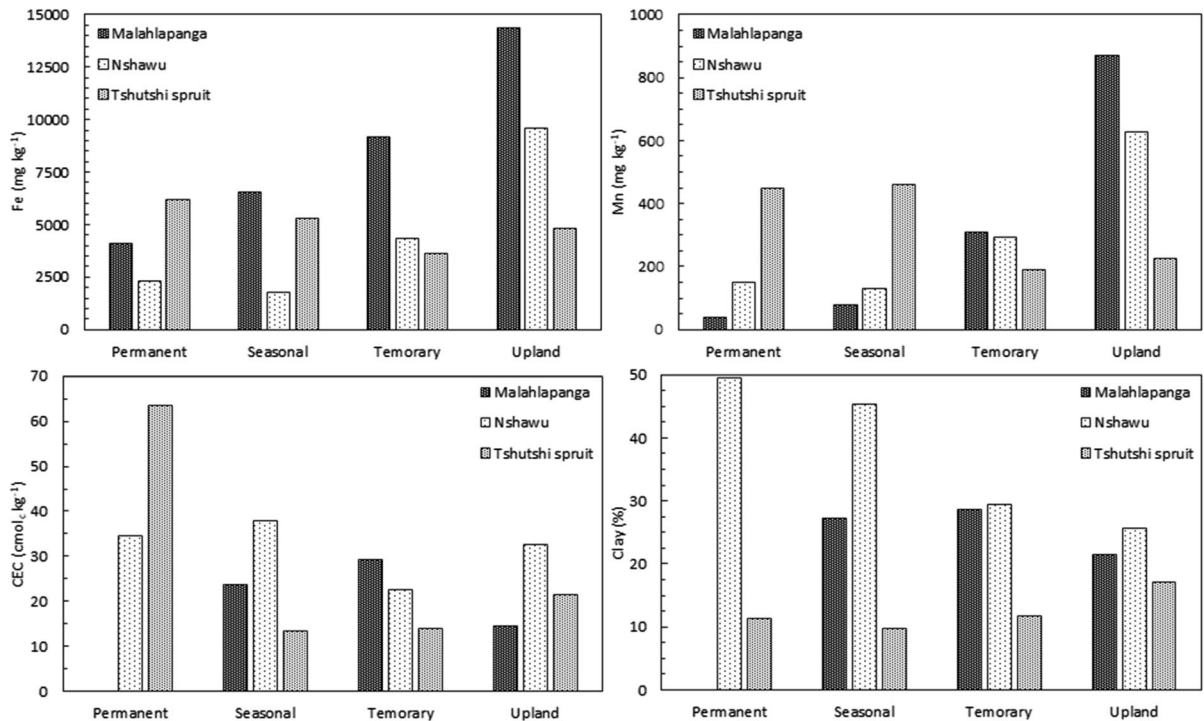


Fig. 7 Iron (Fe), manganese (Mn), cation exchange capacity (CEC), and clay content for the topsoils per wetness zone for the Malahlapanga, Nshawu, and Tshutshi spruit wetlands in the Kruger National Park

and impeded augering. The seasonal and permanent zones lacked these calcium carbonate concretions and instead had well-developed gley characteristics (grey ped faces, with iron and manganese mottles) typical of Katspruit soils (Le Roux et al. 1991; Soil Classification Working Group 1991) or the Gleysols (IUSS Working Group WRB 2014; Van Huyssteen 2020).

The average organic carbon content was $< 3\%$ for all four wetness zones, with the temporary zone that had the lowest organic carbon of 1.2%. The upland zone had the highest organic carbon content (2.6%) of all the zones (Fig. 5), but this value probably should be considered extraneous. The nitrogen values all decreased with wetness and in line with the organic carbon, except for the upland zone where the total nitrogen content was more in line with the expected low values (Fig. 5), in contrast to the high measured organic carbon values. The pH was very high and ranged from 8.0 in the upland to 9.3 in the seasonal zone (Fig. 5). The high pH could be attributed to the basalt parent material that gave rise to sodic and calcareous soils. Electrical resistance increased from the permanent to the upland zone,

indicating that salts were accumulating in the wetter areas (Fig. 5). These salts were also attributed to the basalt parent material that resulted in soils high in salts and carbonates.

Nshawu had very high calcium and magnesium concentrations in the upland and temporary zones, but also in the permanent and seasonal zones (Fig. 6). Calcium seemed to be concentrated in the upland zone and varied between $19.5 \text{ cmol}_c \text{ kg}^{-1}$, while magnesium seemed to be concentrated in the permanent zone and varied between 5.8 and $16.0 \text{ cmol}_c \text{ kg}^{-1}$. Potassium concentrations were much lower than the calcium and magnesium and varied from $0.5 \text{ cmol}_c \text{ kg}^{-1}$ in the permanent to $0.98 \text{ cmol}_c \text{ kg}^{-1}$ in the temporary zone. The upland zone had very low sodium of $0.25 \text{ cmol}_c \text{ kg}^{-1}$, which increased to $13.8 \text{ cmol}_c \text{ kg}^{-1}$ in the temporary and $19.7 \text{ cmol}_c \text{ kg}^{-1}$ in the seasonal zone and then decreased to $9.4 \text{ cmol}_c \text{ kg}^{-1}$ in the permanent zone. In general, the calcium and magnesium concentrations decreased, while the potassium and sodium concentrations increased from the upland to the permanently wet zone. The expectation was that all the exchangeable basic cation concentrations

would increase towards the permanent zone (Le Roux et al. 1991; Vepraskas and Faulkner 2001), but this trend was probably overshadowed by the high concentrations of these elements in the basalt parent material (Venter 1990). The CEC varied between 34.6 $\text{cmol}_c \text{kg}^{-1}$ in the permanent zone and 22.6 $\text{cmol}_c \text{kg}^{-1}$ in the temporary zone (Fig. 7) and was probably related to the variation in clay content (Fig. 7).

The upland zone had distinctly more iron than the other three zones, with the permanent and seasonal zones that had $< 2500 \text{ mg kg}^{-1}$ while the temporary upland zones had $> 4000 \text{ mg kg}^{-1}$ (Fig. 7). This suggested that the iron was reduced and leached from the wetter zones. Manganese largely followed a similar trend, increasing from 151 and 131 mg kg^{-1} in the permanent and seasonal zones respectively to 292 and 629 mg kg^{-1} in the upland and temporary zones respectively (Fig. 7).

Nshawu had the highest clay contents, with the permanent zone that had almost 50% clay that decreased to 45% in the seasonal zone, and 29% in the temporary and 26% in the upland zones respectively (Fig. 7). The extremely high clay content was attributed to the basalt parent material (Venter 1990) that largely weathers to the clay-sized fraction. Clays were also expected to accumulate in the permanent and seasonal zones, with the accumulating water. As such it was expected to further impede water drainage and thus exacerbate frequency and duration of water saturation (Van Huyssteen et al. 2007).

Tshutshi spruit

For Tshutshi spruit, the observed soil forms were not in agreement with the DWAF (2005) soil form indicator criteria for the permanent, seasonal, and temporary zones, while the Brandvlei 2000 that was observed in the upland zone, which was presumed to be the driest, did meet the DWAF (2005) criteria for a seasonal or temporary zone soil at the family level (Table 4). The soils at Tshutshi spruit, especially in the upland, seasonal, and temporary zones were sodic, with strong coarse columnar structure near the soil surface for the seasonal and temporary zone soils. The seasonally saturated and permanently saturated zone soils also had alluvial stratification, probably due to the close proximity to the river.

The organic carbon contents were the lowest across all wetness zones of the three wetland systems

studied. For Tshutshi spruit, the seasonal zone had the highest organic carbon contents of 1.3%, with the upland zone having the lowest content of 0.3% (Fig. 5). The total nitrogen ranged from 2405 mg kg^{-1} in the permanent wet zone to 744 mg/kg in the upland zone, with the C:N ratio that varied between 4 and 6 (Fig. 5). The pH ranged from 8.4 in the permanent to 9.8 in the upland zone (Fig. 5). These very high pH values were attributed to albite in the granite parent material that released sodium into the soil, buffering the soil pH at these high values (Bohn et al. 2002). This was also reflected in the high exchangeable sodium content of these soils. The electrical resistance values showed that these soils were not saline, with no large variation between the various zones. The slightly lower salt content of these soils could possibly be attributed to the granite parent material that resulted in more sandy soils that were better leached (Fig. 5).

Tshutshi spruit had the lowest exchangeable basic cation concentrations of all the studied wetlands (Fig. 6), probably related to the granite parent material (Venter 1990). Calcium varied from 6.5 $\text{cmol}_c \text{kg}^{-1}$ in the permanent to 11.2 $\text{cmol}_c \text{kg}^{-1}$ in the seasonal, 7.2 $\text{cmol}_c \text{kg}^{-1}$ in the temporary and 8.2 $\text{cmol}_c \text{kg}^{-1}$ in the upland zones. Magnesium was much lower to between 2.1 $\text{cmol}_c \text{kg}^{-1}$ and 3.4 $\text{cmol}_c \text{kg}^{-1}$ in the seasonal and temporary zones respectively, while the potassium was lowest in the permanent zone (0.2 $\text{cmol}_c \text{kg}^{-1}$) and increased to 0.9 $\text{cmol}_c \text{kg}^{-1}$ in the seasonal and 0.5 $\text{cmol}_c \text{kg}^{-1}$ in the temporary and upland zones. Sodium dominated the exchange complex of the upland zone soils and decreased drastically from 11.7 $\text{cmol}_c \text{kg}^{-1}$ to 0.18 $\text{cmol}_c \text{kg}^{-1}$ the permanent zone. At 63.4 $\text{cmol}_c \text{kg}^{-1}$ the CEC in the permanent zone was very high, probably related to the high organic carbon content (Fig. 5), followed by 21.6 $\text{cmol}_c \text{kg}^{-1}$ in the upland zone, concomitant with a high clay content (Fig. 7). The seasonal and temporary zones had some of the lowest CEC values of all wetland zones studied (Fig. 7).

The iron content at Tshutshi spruit was less than at Malahlapanga, but more so than at Nshawu. Converse to the trend observed for Malahlapanga and Nshawu, the permanent zone had the most iron (6209 mg kg^{-1}), followed by the seasonal (5294 mg kg^{-1}), temporary (3618 mg kg^{-1}), and upland zones (4828 mg kg^{-1}). A possible explanation for this reversing trend was iron enrichment of

the wetland from upstream. The manganese followed a similar trend to iron, with the seasonal and permanent zones that had 447 and 462 mg kg⁻¹ respectively compared to 191 and 224 mg kg⁻¹ in the temporary and upland zones respectively. This suggested that manganese suffered a similar fate to the iron. Accumulation of iron and manganese were expected to occur in the permanent and seasonal wetness zones, since these elements are reduced under water saturated conditions and then accumulate with the water (Vepraskas and Faulkner 2001). The topsoils of Tshutshi spruit had much less clay than the topsoils of the other wetlands studied. The permanent, seasonal, and temporary zones all had < 12% clay, while the upland zone had 17% clay (Fig. 7). The lower clay content was attributed to the granite parent material (Venter 1990).

Discussion

The three wetlands selected for this study varied distinctly from each other in terms of their physical, chemical, mineralogical, and hydrological properties. Malahlapanga was a unique thermal hot spring fed predominantly by groundwater, resulting in the accumulation of organic matter that played a major role in the soil chemistry of the system as was evident from the elevated salinity and organic carbon. Nshawu was unique in terms of its basic parent material and sheer size. The accumulation of calcium carbonate nodules was prominent in the temporary zone and also affected the soil chemistry of the system. The Tshutshi spruit was extremely basic, from especially a high exchangeable sodium percentage, and was probably also influenced by runoff rather than groundwater and base water flow. Salts were also a major factor that influenced the soil chemistry of the system. Only Malahlapanga and Nshawu had water saturation in the permanent zones within 0.5 m from the soil surface, but when the soils were saturated they were also reduced.

Malahlapanga and Nshawu had Gleysols, while Tshutshi spruit had Luvisols in the permanent and seasonal zones. Malahlapanga was the only wetland that had high organic carbon contents, to the extent that it was a borderline Histosol. The other wetlands all had less than 2% organic carbon. At Nshawu and Tshutshi spruit the pH was greater than 8, and

between 5 and 8 for the wetland zones of Malahlapanga. All the wetland zones studied differed markedly in salinity, with Tshutshi spruit the only wetland that could be considered non-saline. Calcium dominated as exchangeable cation in all the wetland zones studied, but more so for Nshawu, due to the basalt parent material. Elevated sodium concentrations were only observed at Nshawu and Tshutshi spruit, but high exchangeable sodium percentages were only detected at Tshutshi spruit. The ‘free’ iron and manganese from ‘oxide minerals’ increased from the permanent to the upland zones at the Malahlapanga and Nshawu wetlands, but decreased from the permanent to the upland zone for the Tshutshi spruit wetland.

The lithological properties of Malahlapanga, namely, the fractured Goudplaats Gneiss of the Soutpansberg Group, were the key drivers in the formation of the system. This geological phenomenon provided the permanent saline artesian water that resulted in the hydrological conditions required for the peat formation and carried with it the salts that influenced the mineralogy of these soils. This study found that the water table only rose to within 0.5 m from the soil surface in the permanently saturated zone. However, it was not possible to determine how high the water levels rose during the January 2013 floods, due to inaccessibility. The soil chemistry of the wetland was mainly influenced by the accumulation of organic material. Due to the wetland being fed by groundwater and not runoff meant that animals concentrated around this water source, which then impacted on the surrounding vegetation. The seasonal zone was largely barren due to animal trampling and lacked the wetland vegetation indicators that were expected.

The basic basalt parent material at Nshawu determined the soil chemistry of the wetland. The basalt parent material was rich in calcium and combined with the seasonal hydrological fluctuations, produced an abundance of calcium carbonate nodules. The wetland zones, which were mapped based on vegetation, were in strong agreement with the soil hydrological data. The permanent and seasonal zones were saturated to within 0.5 m from the soil surface and after the January 2013 floods the water table also rose to within 0.5 m from the soil surface for the temporary zone. There was a lag in the rising of the water table depths after the floods, suggesting that the wetland was fed by groundwater and not just surface runoff. This groundwater could not be

related to a permanent source, as was the case with Malahlapanga. The high pH recorded was attributed to the basic parent material and calcium carbonate minerals. The vegetation at Nshawu was much more diverse than at the other two wetlands. A possible reason for this was the higher soil nutrition and fertility, and that the wetland was under much less pressure from animals due to its size, in comparison to Malahlapanga.

The mineralogical and chemical characteristics of the Tshutshi spruit wetland system were determined by the granite parent material, coupled with the hydrological regime, which acted more like a riparian wetland than a valley bottom wetland. This was evident from the depositional stratification in the soils on the banks of the Tshutshi spruit. Because the Tshutshi drains from Phalaborwa town, it probably also brought chemical pollutants and alien plants that should be of concern. The Tshutshi spruit therefore had the highest number of alien vegetation species compared to the other two wetlands. The water table only rose to within 0.5 m from the soil surface during the January 2013 floods. Albite in the granite parent material probably caused the soils at Tshutshi spruit to be very high in sodium and resulted in an extremely basic pH, while the drier zones were more saline.

The three wetland systems each faced unique conservation and therefore management challenges. Malahlapanga was the only water source in an otherwise parched landscape and was therefore prone to excessive use by especially elephant and buffalo in the dry season. Trampling and digging for fresh water could thus result in the destruction of the peat domes. This unique system was driven by groundwater and any restoration attempts should therefore monitor animal congestion and the outflow of water. Nshawu was the most pristine of the three wetland systems studied and as such do not face any significant threats, probably also due to its size. Water in the Tshutshi spruit originates from outside the conservation area and was therefore prone to chemical, particulate, and biological pollution and should thus be monitored. The sodic nature of the soil at Tshutshi spruit also renders it particularly prone to dispersion and water erosion, especially when the vegetative cover is removed through fire or excessive grazing. This should be monitored and addressed if necessary.

When related to the water tables, the DWAF (2005) soil form indicator distinguished well between wetness zones in some wetlands and poorly in others. This would suggest that the soil form alone could not be relied on as an absolute indicator of wetness zones.

Conclusions

Wetlands are unique ecosystems where the soil chemistry and morphology, and vegetation are determined by the duration and frequency of water saturation. These ecosystems are, however, under threat locally in South Africa and internationally, because the services that they provide are not necessarily recognised and valued. It is especially the water provisioning and filtering services that are critical in a drought-prone country such as South Africa.

The Kruger National Park situated in the north-eastern corner of South Africa is largely unmodified and has unique variation in terms of lithology, climate, and hydrology. It thus offered an exceptional opportunity to study the soil properties of wetland ecosystems in this arid environment. This paper thus aimed to characterise the soil physical, chemical, mineralogical, and hydrological properties of three different wetlands in the Kruger National Park. This data can serve as reference and to identify possible managerial inputs required.

The three wetland systems differed markedly in terms of geology, soils, vegetation and hydrology. Malahlapanga was severely impacted on by animals in search of drinking water, while Tshutshi spruit was impacted on by the upstream town of Phalaborwa. Nshawu was the only system studied that seemed to be in a near pristine state.

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Authors contributions Van Huyssteen conceptualised and supervised the study, obtained funding, finalised the manuscript, and acted as corresponding author, while Johnson collected the data, analysed the samples and wrote the initial draft manuscript.

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Data availability Data is available from the corresponding author.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflicting or competing interest.

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