Masters in Environmental Science

School of Animal, Plant and Environmental Sciences

Research Report

The ecological baseline of select endorheic ephemeral pans in an arid African savanna

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DECLARATION

I, Caroline Ann Wallington, am a student registered part time for the degree of Master of Science in Environmental Science, by course work and research report, through the University of the Witwatersrand, Johannesburg, South Africa. This report serves as partial fulfilment for the completion of this degree.

I am fully aware of the plagiarism policies of the University and declare that all the work presented herein is my own unaided work except where I have explicitly indicated otherwise and I have referenced accordingly.

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ABSTRACT

The mosaic of nutrient-rich hot spots in nutrient-poor savannas is of importance to the functioning of these ecosystems. In the Lephalale plains there are the many ephemeral pan wetlands that have received limited scientific attention and are now under threat from mining in the area. The aim of this study was to gain some insight into the ecological baseline of these systems to possibly inform future studies and management approaches. Pans near the small town of Steenbokpan, Limpopo Province, South Africa were sampled in the summer rainfall season along a transect including three 'hydro-ecological' zones being the wetland centre (A), the pan 'riparian-like' area (B) and the surrounding representative terrestrial savanna habitat (C). The data gathered included vegetation species composition, tree density, physiochemical characteristics of the top (0-30cm) and subsoils (30-60 cm) and pan water quality.

The non-wetland areas were characterised mostly by forbs such as *Limeum* and *Indigofera* species and some hardy grasses including *Tragus* and *Aristida* species where more palatable grasses such as *Panicum* and *Digitaria* were present only under trees and shrubs. The pans (Zone A) were characterised by wetland grasses, *Leptochloa fusca* and *Echinochloa colona,* and had no woody species. Tree density around the pans (Zone B) was greater than the surrounding savanna vegetation (Zone C) and this habitat was characterised by a dominance in fine-leafed *Acacia* species. This was in contrast to the terrestrial areas that were largely dominated by broad leafed tree and shrub species (*Combretum and Grewia sp.*). The change from a broad-leaf to fine-leaf dominated habitat is generally associated with a change from nutrient-poor to nutrient-rich soils, which was confirmed in this study. All soil nutrients including key elements and base cations increased significantly from the broad-leafed, through fine-leafed savanna and into the wetland soils. The nutrients showed a positive relationship with clay content, increasing from an average of 13% in the dry soils to 34% in the wetland soils. The water holding capacity too was significantly correlated with clay content, thus supporting the hydrological study gradient along which sampling was carried out. Water chemistry results showed the pans to be largely fresh with some high metal concentrations.

Overall, the results show that these pans are much higher in soil nutrients and differ in species composition and structure from the surrounding nutrient-poor savanna. This highlights the very important functional role that these pans play in this arid environment with respect to biodiversity and nutrient dynamics. The nutritious *Acacia*-dominated (nutrient-rich) patches around the pans, as well as the palatable wetland grasses in the pan, will likely result in these habitats being favourable forage sites for game, especially given that these pans will likely be critical water sources for all fauna in the area. These pans are therefore critical habitats to take into account for management interventions as they will be the first to show sign of degradation. Furthermore, these wetlands and enriched savanna patches likely increase heterogeneity and biodiversity and should be priority monitoring sites for managers and targeted for conservation protection as they play a disproportionately large role in the ecological functioning of this landscape. This research has therefore shown that these pans should be highlighted as important in this ecosystem and further research would be able to enhance the understanding of their importance and sensitivity.

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1. Introduction

Savannas are summer rainfall systems with a varying density of woody trees that coexist with a continuous layer of highly competitive herbaceous grasses (Sankaran, et al., 2008; February & Higgins, 2010; van der Waal, et al., 2011). Abiotic factors, including soil properties and water dynamics, are major determinants of the vegetation patterns of savannas at various scales that, together with the species composition, influence the nutrient cycling of important elements (Scholes & Archer, 1997; Scholes, et al., 2003; Levick & Rogers, 2011). The differences in soil fertility are possibly of greater influence than water availability in savannas, where nutrient-rich savanna soils are characterised by fine-leafed, palatable tree species and grasses whereas nutrient-poor ones are dominated by broad-leafed, less palatable species (Blackmore *et al*., 1990; Scholes and Walker, 1993; Levick *et al*., 2010). These patterns are often observed along a landscape due to the associated clay content of the soil but can also occur in localised enriched patches within a savanna (Blackmore *et al*., 1990; Scholes and Walker, 1993). Wetlands and rivers similarly represent significant pedological and ecological contrasts in savannas (Khomo & Rogers, 2009; Levick *et al*., 2010), which are paradoxically prevalent in the semi-arid to arid regions of Southern Africa. Particularly, non-perennial pans are ubiquitous in these regions, which are inward draining, circular and shallow wetland systems (Goudie & Thomas, 1985; Dini *et al*., 1998). Pans are extremely variable wetland systems in their size, shape and duration of inundation, but also withtheir soil physiochemical characteristics and biodiversity (Allan *et al*. 1995, Kotze *et al*., 2009; Ferreira, 2010). Temporary wetlands including pans, despite being in abundance and having a high ecological importance, have been poorly studied ecosystems and require greater scientific attention and conservation action (Tooth & McCarthy, 2007; Day *et al*., 2010).

The Limpopo plains in the north-western part of the Waterberg District, Limpopo, South Africa are characterised by semi-arid to arid savanna bushveld. This area is topographically flat, with generally sandy soils and dominated by the Limpopo Sweet Bushveld vegetation type (Mucina and Rutherford, 2012). The Limpopo River is the major perennial drainage for this area, however, due to the dry climate and low relief, this area is largely characterised by many scattered depressional wetlands (called pans), which are dry for most of the year but flood intermittently and become thriving wetlands after rainfall. It is expected that these pans represent an important ecological change in the savanna landscape and it was thus the aim of this project to investigate the baseline ecological status of these endorheic, ephemeral wetland systems. Much of this area is targeted for industrial development around the Waterberg Coalfield, which threatens the ecosystems occurring in this largely natural area. Given the lack of scientific knowledge on these wetlands and the threat now posed to them, this project aims to contribute to the baseline information from which to motivate the ecological importance and sensitivity of these pans as nutrient hotspots in this landscape and thus to hopefully assist in the future planning, management and conservation of the area.

1.1. The Research Question

The key research question is:

How do the pans differ from the surrounding terrestrial savanna landscape with respect to the vegetation composition and soil and water properties; including soil texture, soil chemistry, water chemistry, woody plant density and vegetation species composition?

There are two hypotheses that accompany this research:

- Soil nutrient concentrations and clay content are expected to increase from terrestrial to wetland;
- Species composition of the woody and herbaceous vegetation and woody density is expected to differ from terrestrial to wetland.

2. Literature Review

2.1. Savanna dynamics

Savannas are summer rainfall systems varying in the density of woody trees, which coexist with a continuous layer of highly competitive herbaceous grasses (Sankaran, *et al*., 2008; February & Higgins, 2010; van der Waal, *et al*., 2011). They are extremely diverse and occur under a range of climatic conditions with water availability being the primary determinant of the potential maximum proportion of trees (Scholes & Archer, 1997; Staver, *et al*., 2011; Bond & Midgley, 2012); however, disturbance dynamics, such as herbivory, fire and drought, restricts trees to levels below this (Sankaran, *et al*., 2008; Staver, *et al*., 2011). Tree seedlings and "gullivers", a small tree stuck in the browser and grass fire trap (Bond & Van Wilgen, 1996), must establish and grow through an exceptionally strong demographic bottleneck enforced by these disturbances as well as competition (Cramer *et al*., 2007, 2010). Edaphic processes play a major role as there is significant overlap in the rooting zones of trees and grasses that leads to intense competition for resources such as soil water, nutrients and space (February *et al*., 2012). This tree:grass ratio in savannas is critical as it affects many aspects of the system's functionality including carbon sequestration capacities, rates of transpiration, hydrology, faunal activity, nutrient cycling, and ultimately the biogeochemical feedback loops to the regional and global climate (Ludwig, *et al*., 1999; Scholes, *et al*., 2003; Sankaran, *et al*., 2008; Wang, *et al*., 2009; Bond & Midgley, 2012).

Soil properties and water dynamics are major abiotic determinants of vegetation patterns at various scales, which, together with the species composition, influence the nutrient cycling of carbon, nitrogen, phosphorus, sulphur and other important elements (Scholes & Archer, 1997; Scholes, *et al*., 2003; Levick & Rogers, 2011). Savannas that are water-limited are particularly susceptible to nitrogen limitation, where nitrogen is often co-limited with phosphorus (Craine *et al*., 2008; Kambatuku *et al*., 2012). A key edaphic distinction in savannas is that of nutrient-rich versus nutrient-poor soils. The underlying geology largely dictates the inherent nutrient quality and the physical properties that affect soil processes, where, for example, sandstone derived soils are generally of low nutrient quality and basaltic and sometimes granitic soils are nutrient-rich (Scholes, 1990).

These patterns can also be seen along a landscape where catenal processes lead to lower lying areas having a greater nutrient content, which is often related to a higher clay content (Scholes, 1990). Furthermore, biological processes can lead to localised soil enrichment including nutrient upcycling in termite mounds and historical human settlements keeping cattle and bringing in surrounding mud (Blackmore *et al.*, 1990). The differences in soil fertility, arguably of a possibly greater influence than water availability, are strongly linked to vegetation changes where nutrient-rich savanna soils are characterised by fine-leafed tree species (e.g. *Acacia*[1] spp) whereas nutrient-poor ones are dominated by broad-leafed species (e.g. *Combretum spp*, *Terminalia* spp) (Blackmore *et al.*, 1990; Scholes and Walker, 1993; Levick *et al.*, 2010). This has important biogeochemical feedbacks as fine-leafed and broad-leafed species have differing carbon:nitrogen and root:shoot ratios, as well as palatability which affects faunal activity such as browsing and defecation (Scholes, 1990; Scholes and Walker, 1993).

Wetlands and rivers also represent important pedological and ecological contrasts in savannas, which have important catchment and landscape scale influences on hydrogeomorphic heterogeneity and floristic composition (Khomo & Rogers, 2009; Levick *et al.*, 2010). Wetlands perform many complex and important functions in Southern African landscapes including the maintenance of water quality, sediment trapping, carbon storage, streamflow regulation, flood attenuation and maintenance of biodiversity (Kotze *et al.*, 2009). There are many different types of wetlands, which function differently from each other with respect to geomorphology and hydrology and are thus classified accordingly such as valley bottom wetlands, hillslope seep wetlands, floodplains and depressions (Ollis *et al.*, 2013). Furthermore, these wetland types can vary in their ecological functionality across biomes and climatic zones. Drylands, for instance, characterise many parts of Southern Africa and paradoxically contain many wetlands that differ significantly from temperate or tropical regions in their origin, development and functionality (Tooth & McCarthy, 2007). Wetlands in arid regions including savannas, despite being in abundance and having high ecological importance, have been poorly studied and are thus in need of further research (Williams, 1985; Allan *et al.*, 1995; Tooth & McCarthy, 2007).

2.2. Endorheic Wetlands

Inward draining (endorheic) wetlands, generally referred to as pans in South Africa, are particularly prevalent in the semi-arid to arid regions; however, some do occur in wetter climates (Figure 1) (Goudie & Thomas, 1985; Goudie & Wells, 1995). Southern African pans were first described by Alison (1899) as local basins formed by animal activity and eventually better defined by Goudie & Thomas (1985) and Dini *et al.* (1998) as closed basin systems that differ from other lacustrine or palustrine wetlands as they have no flow outlet, are generally circular to kidney-like in shape, have a flat basin floor and are shallow even when flooded

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[1] The International Code of Botanical Nomenclature (the official botanical naming authority) made a decision in July 2005 to reserve the name *Acacia* for Australian species only and thus all African *Acacia*'s have been renamed to either *Senegalia* or *Vachellia*. However, for ease of reading, *Acacia* is still used in this report.

(<3m deep). Given their dominance in arid regions, it is expected that these temporary basin wetlands are of particular ecological significance given the lack of permanent water sources (Williams, 1985; Goudie and Thomas 1985). Pans now fit into the hydrogeomorphic wetland type of ‘Depression Wetlands’, which also includes lakes (>3m deep) and dams, that can be endorheic or exorheic, where the latter has a channeled or diffuse outlet and the former does not (Ellery *et al*., 2009; Ollis, *et al*., 2013). Endorheic pans are isolated from the stream network and often occur in areas of low relief, limited drainage and high evaporation rates, and thus play quite different roles in the landscape because of this (Kotze *et al*., 2009).

Figure 1: Mapped distribution of pans in Southern Africa where the number in the circle represents the density of pans per area on 1:500 000 topographical sheets (Goudie and Thomas, 1985)

The origin and continued existence of pans is of scientific intrigue and debate, for which there are many concepts due to the diversity of these systems (Figure 2). Pans in the drier climates (<500m) have characteristically irregular and intermittent inundation, which can be markedly seasonal or ephemeral, even to the point where they can stand dry for many years between rainfall events (Davies & Day, 1986), for example the large salt pans of the Free State and Nama Karoo (Allan *et al*., 1995; Mucina and Rutherford, 2012). Pans that occur in wetter climates have a more regular, seasonal or even permanent inundation such as many of those found in the Mpumalanga Lakes District (Goudie & Wells, 1995; Allan *et al*., 1995). Non-perennial pans cause bare soil to be exposed and vulnerable to wind erosion, which, over eons, can be a major cause in their evolution as swirling winds remove the fine sediments from the basin (Goudie & Thomas, 1985). Due to high evaporation rates, accumulation of salts often occurs in these pans, where salt-weathering of the underlying vulnerable strata may be a key process ensuring their continued development (Allan *et al*., 1995; Goudie & Thomas, 1985). Furthermore, pans, similarly to other wetlands in drylands, can be associated with palaeo drainage lines, rivers or lakes that have now formed a series of depressions in the drier climate of today and/or where geological barriers now exist (Allan *et al*., 1995; Shaw and Thomas, 1997; Tooth and McCarthy, 2007).

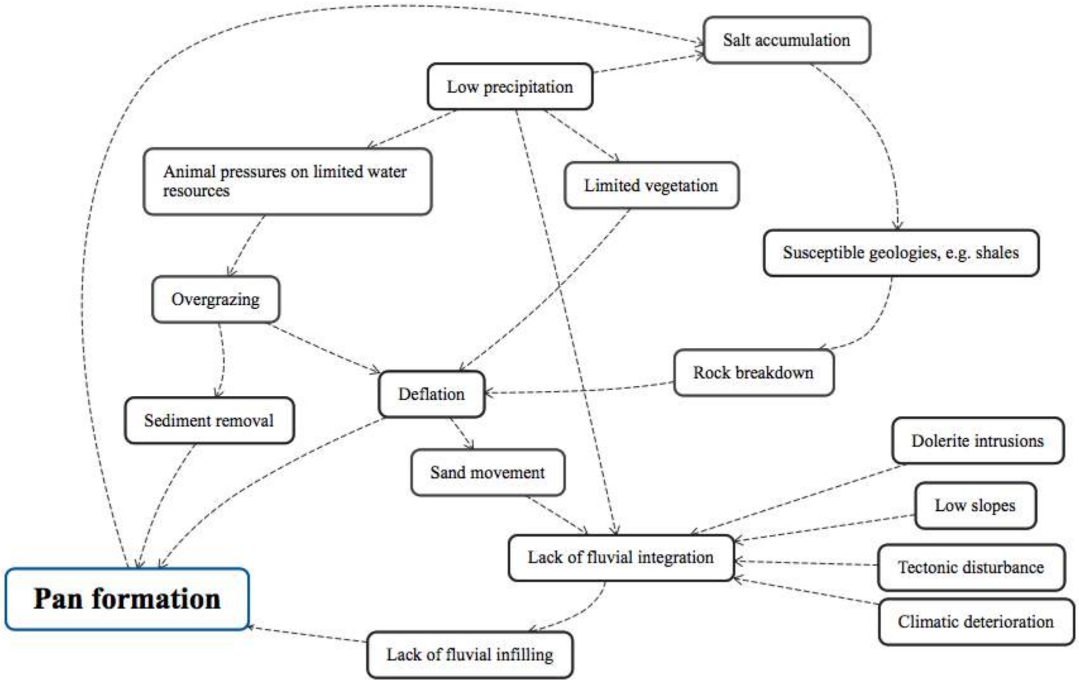

Figure 2: A model for pan development as described by Goudie and Thomas (1985) and Allan et al. (1995)

Non-perennial and ephemeral pans have been documented in abundance in many dry areas of Southern Africa including the Kalahari, the Nama Karoo Bushmanland and the Free State Province as well as the more humid zones such as the Highveld Grasslands (Goudie and Wells, 1995). These pans vary immensely in size ranging from about 1 ha to as large >1000 ha, with some extreme and iconic examples being much larger such as the Etosha Pan in Namibia and the Makagadikgadi Pan complex of Botswana (Sharp and Allan, 1985; Seaman, 1987, Tooth and McCarthy, 2007). In addition, the diversity of underlying geology and climatic conditions determine the water quality in these systems, which can contain fresh water as received from precipitation but in many cases are extremely saline (Allan *et al*., 1995; Tooth and McCarthy, 2007). The sediment of pans can be largely clastic (sand, silt, clay) but also chemical from accumulated evaporites such as calcrete (Shaw and Thomas, 1997). Floristic composition thus varies significantly between and within regions, including the salt adapted *Salsola* species in the Nama Karoo Bushmanland Vloere (salt pans), the reeds and sedges in the Highveld pans, or the mostly open or bare pans of the Free State that contain creeper grass and forb species (Allan *et al*., 1995; Mucina and Rutherford, 2012). Pans are also key birding areas where, for example, these intermittent open water sources are critical stopover feeding spots and breeding grounds for both species of flamingoes along their migratory routes (Simmons *et al*., 1999; McCulloch *et al*. 2003) as well as important habitat for the White-Faced Whistling Duck (Petrie and Rogers, 1997). These temporary systems are also likely providing habitat for specialised and possibly endemic wetland fauna (mainly macro-invertebrates) that are adapted to the ephemeral and erratic conditions (Williams, 1985; Seaman *et al*., 1991; Day *et al*, 2010).

Pans are thus especially variable systems with respect to shape, habitat, duration of inundation, physiochemical characteristics and biotic composition that require greater scientific attention and conservation action (Allan *et al*. 1995, Kotze *et al*., 2009; Ferreira, 2010; Day *et al*., 2010).

2.3. The Waterberg Area

The Waterberg is in the north-western part of South Africa, in the Limpopo Province, and borders Botswana along the Limpopo River. The Waterberg mountain range is centrally located within the Waterberg District and is a key landscape feature in the region with the iconic plateau and escarpment zones being major tourist attractions. The other major landscape features, which are in contrast topographically, include the Transvaal Plateau Basin, Pietersberg (Polokwane) Plain and the Limpopo Depression / Valley (LEDET, 2016). The combination of these landscapes has resulted in this region being one of particular significance with respect to biodiversity as the variety of geologies, topographies and soil types along with noteworthy climatic gradients has led to a diversity of floristic habitats and faunal communities (Mucina and Rutherford, 2012; LEDET, 2016). Thus, the Waterberg is home to twenty national vegetation types (Figure 3), of which three are endemic and three near-endemic that contain many plant and animal species of special concern (Desmet *et al*., 2013). Many areas are thus mapped as having critical biodiversity importance and being important ecological support areas at a regional and national level (Desmet *et al*., 2013; LEDET, 2016) (Figure 4). Most of these zones form part of the Waterberg Biosphere Reserve that was declared in 2001 by the United Nations Educational, Scientific and Cultural Organization (UNESCO) due to the conservation significance and to ensure its sustainable development (UNESCO, 2002; Claassen *et al*., 2010).

The Waterberg Mountain Complex is also important with regards to freshwater ecosystems including rivers, wetlands and groundwater reserves (Claassen *et al*., 2010). There are some dolomitic aquifers that are key underground water sources but most of the Waterberg District has limited and sensitive groundwater reserves that must be managed with care. Many rivers originate from the Waterberg mountains that supplies most of the district with freshwater and supports critical aquatic ecosystems; such as the Nyl River and floodplain that lies at the foothills of the Waterberg plateau and is designated as a RAMSAR wetland of international importance since 1998 (Ramsar Secretariat, 2013). Other important Rivers include the Mokolo, Lephalala, Crocodile, Matlabas and Limpopo Rivers and their associated wetlands (Figure 5) (Nel *et al*., 2011; Driver *et al*., 2012; Desmet *et al*., 2013). The wetland features that dominate the Plains and Valleys are depression wetlands or pans, which are ecologically distinctive and important wetland features in these bushveld landscapes. These pans are distributed throughout the landscape; however, some of these form wetland clusters that are critical support areas for ecological process such as increased biodiversity, reproduction and movement of frogs, insects and other fauna, supply of freshwater, and maintenance of wetland functioning in an arid landscape (Nel *et al*., 2011; Driver *et al*., 2012).

The Waterberg, however, is not only rich in biological resources but also minerals including coal, platinum, and iron (Claassen *et al*., 2010). There are five generalised geologies found in the Waterberg District, where the

Karoo Super Group in the north contains significant coal deposits (namely the Waterberg Coalfield) and the Bushveld Igneous Complex in the south has platinum and chromium. The Waterberg Coalfield, located around the towns Lephalale and Steenbokpan (where this research has taken place), constitutes a key remaining coal resource for South Africa as the country is still largely reliant on coal for power generation (WDM, 2017). This area, however, is in a largely natural state, contains the near-endemic Limpopo Sweet Bushveld, and is in between two high priority biodiversity areas, namely the Limpopo River Valley and the Waterberg Biosphere Reserve (Figure 6). Thus, the intensified mining, industrial and urban development for which this area has been earmarked will likely have significant negative environmental impacts including loss of biodiversity, water contamination, air pollution and more (Claassen *et al.*, 2010; DEA, 2014).

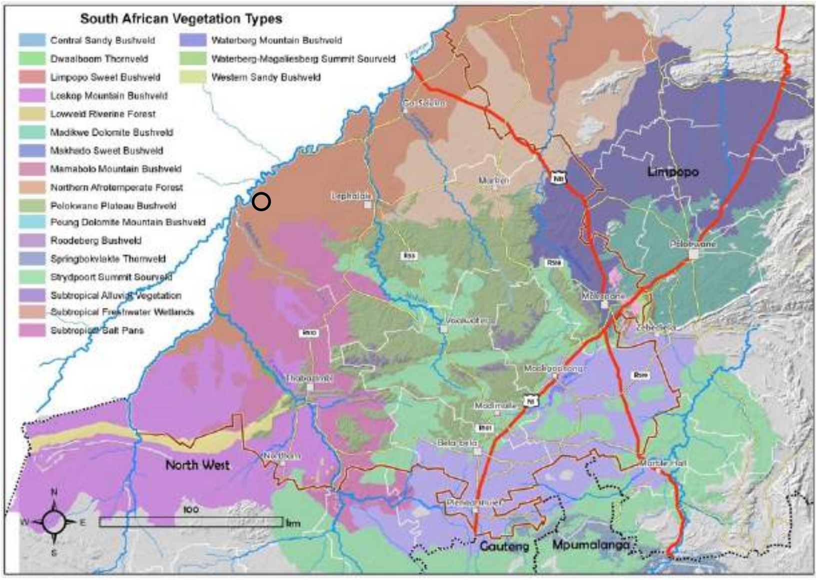

Figure 3 : South African Vegetation Types occurring in the Waterberg District (LEDET, 2016) with the study area circled

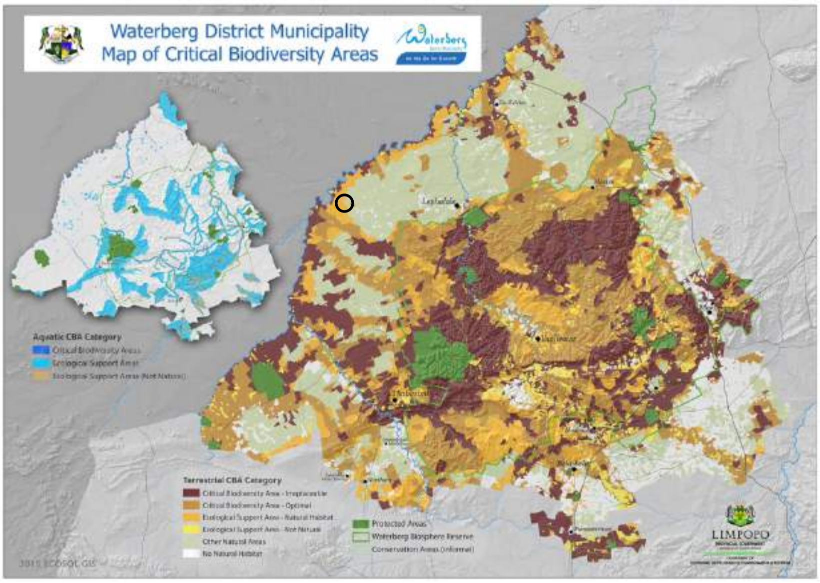

Figure 4: Critical Biodiversity Areas for the Waterberg District (LEDET, 2016) with the study area circled

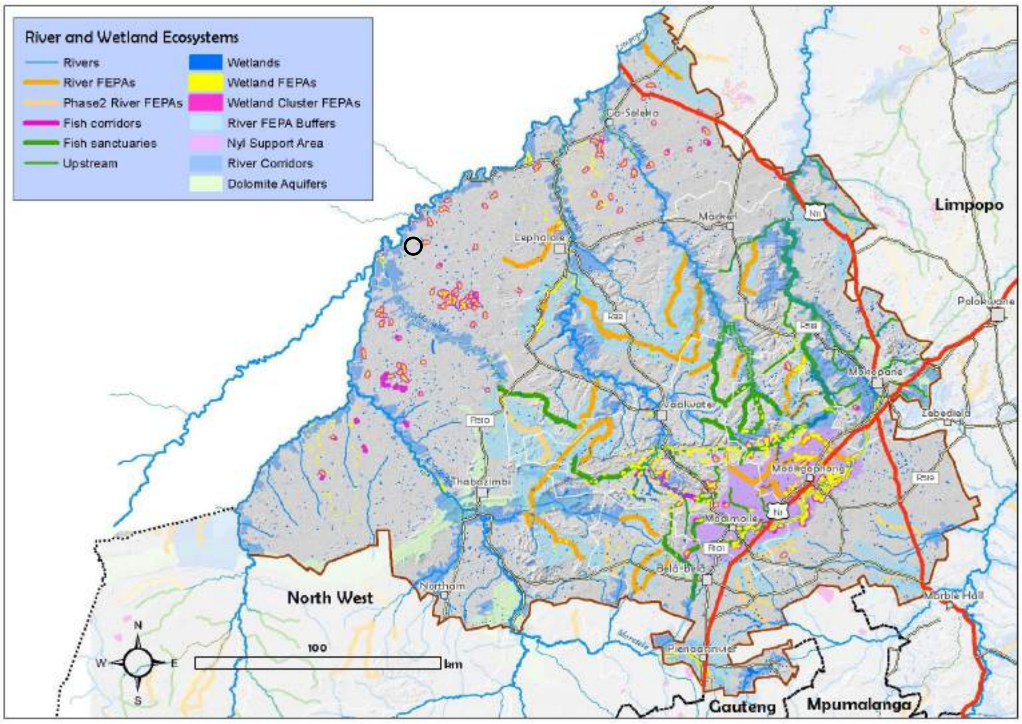

Figure 5: Waterberg District priority wetlands and river ecosystems; map taken from LEDET (2016) with data from Nel et al. (2011) and Desmet et al. (2013), with the study area circled

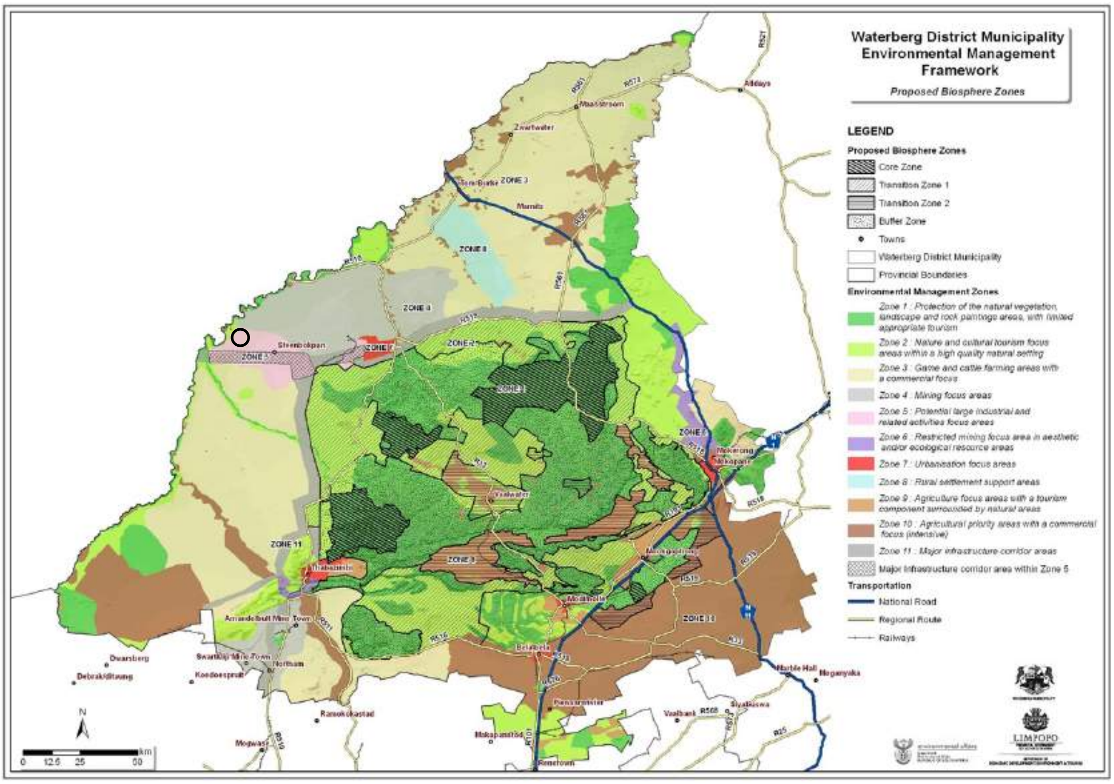

Figure 6: The Waterberg District Municipality Environmental Management Zones and Proposed Biosphere Zones (Claassen et al., 2010) with the study area circled

3. Methodology

3.1. The Study Site

Figure 7: Map of Study Area and Location of Sample Site

The research was done in the western part of the Limpopo Province, South Africa; near the small farming town of Steenbokpan, approximately 50 km west of the town of Lephalale (Figure 7). Topographically this area is largely flat, sometimes referred to the Limpopo plains, from the base of the Waterberg mountain range and into Botswana. The overall area has a semi-arid to arid climate with a unimodal summer rainfall pattern. The mean annual precipitation (MAP) at Lephalale is 405 ± 100 mm (data from 1995 to 2016, South African weather station no. 06743418). However, as the study site is >50km away from this weather station, these data are not fully representative of the exact study site where it is reported to have different rainfall patterns from Lephalale as the storm cells are generally received from the north (Botswana side) and has a lower received rainfall (L. van den Berg-Nicolai, personal communication, January 2017). Thus, the study site is referred to as arid savanna but it may be considered semi-arid. Temperatures vary considerably in this area with very hot summers (max. >35ºC) and cool winters (min. <10ºC) (Mucina and Rutherford, 2012).

The study area is located within the Dwyka group geologies of the Karoo Supergroup that contain multiple major and minor fault lines, giving rise to multiple local geological types in the general area largely derived from sandstone, siltstone or shale (Figure 8). The chosen study sites are within the Wellington local geology form, which is largely characterised by mudrocks with intercalated sandstone and contains coal of the Waterberg Coalfield. The soils of the area, however, are expected to be somewhat disconnected from the underlying geology as they are mostly derived from windblown Kalahari sands. The land type associated with the study area (Ae257 and Ah86) are characterised by red-yellow, sandy, apdeal, free-draining soils with a clay content of <15% (Land Type Survey Staff, 1989). In many areas, calcrete and ferricrete occur at the surface forming locally shallow soils that are often associated with pan wetlands. The Limpopo River is the major river in the study area, which forms the border between South Africa and Botswana, and is more than 6 km north of the study site; no other rivers are within close proximity of the study area. Being an arid climate, the dominant expression of surface water are ephemeral depression wetlands (pans) that are intermittently flooded following rainfall events. The regional vegetation type is the Limpopo Sweet Bushveld, which is a short, uniform and open woodland characterised by the woody species *Acacia nigrescens* Oliv., *A. mellifera* (M. Vahl) Benth., *A.*

erubescens Welw. ex Oliv.*, Combretum apiculatum* Sond.*, Commiphora spp, Boscia spp and Grewia spp. with Dichrotachys cinera* Wright et Arn. having become dominant in overgrazed or disturbed areas (Mucina and Rutherford, 2012).

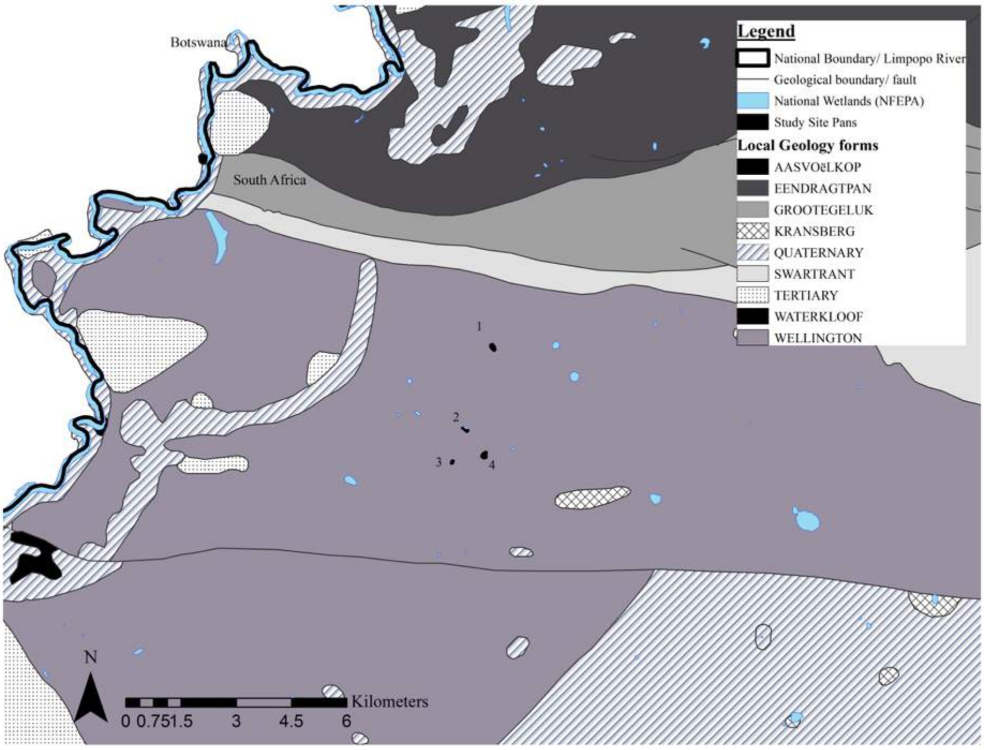

Figure 8: Local geologies of the study area showing the location of the four study sites on the Wellington form

The data for this research were collected at pan sites that were chosen according to multiple criteria including underlying geology, size, intensity of human disturbance, accessibility and presence of water at time of sampling. Out of 20 candidate pan sites identified, four pans were sampled between the 20th and 30th January 2017 (Table 1). All pans in this area are very temporary and hold rain water for a short time, from weeks to months depending in the amount of rainfall, temperature, size of the pan etc. To account for this, fieldwork was carried out in the summer season and was planned around the rainfall patterns to ensure there was water present in the pans. Approximately 80 mm of rain was received on the 24th of January according to a local rain gauge, which resulted in many pans being fully flooded (Figure 9).

Table 1: Area and location of the four pan sample sites

Pan Number	Area (ha)	Co-ordinates
1	2.51	23°38'8.60"S 27°10'37.13"E
2	0.99	23°39'22.62"S 27°10'14.64"E
3	0.79	23°39'50.66"S 27°10'2.36"E
4	2.57	23°39'46.15"S 27°10'30.27"E

Figure 9: Photos showing sample Pan 1 through different hydrological phases: a) completely dry (July 2016); b) partially wet (22nd January 2017); and c) in flood after a storm event (24th January 2017)

3.2. In-Field Sampling

The different aspects of the fieldwork carried out to achieve the aims of the study are detailed in the sub-sections below.

3.2.1. Drone Aerial Imagery

The use of drones for observation has significantly modified field investigation methodologies in many fields of research. This was a particularly attractive tool for this study as the dense woody vegetation, characteristic of the area, combined with a very flat topographical setting; makes gaining a landscape perspective very difficult. A DJI quadcopter Inspire 1 drone fitted with an HD X3 video camera and gimbal was used. Video was recorded at 4k resolution in MP4 format and images were taken in raw adobe image format (Digital Negative Specification, DNG) and converted to JPEG. This imagery was taken at heights ranging from about 100 m to 300 m above ground, between 11:00 and 14:00, to minimize shadow from vegetation, and at a variety of angles to gain perspective of the pan in its landscape. The camera was angled straight down to take a top-down photo of the pan and its catchment, where the resultant spatial resolution was very high at 5 – 15 cm, which was then georeferenced against Google Earth imagery using at least five identifiable points and imported into the Quantum GIS software program (QGIS version 2.18).

These data were used for interpreting the pan habitat in the context of the landscape as well as determining the dominant trees and change in density as discussed in the next sections. The study sites were divided into three broad 'hydro-ecological' zones based on the preliminary desktop analyses on Google Earth and were ground-truthed with in-field observations of habitat and use of the drone aerial imagery. The zones identified for this study were the pan centre or wetland area (Zone A), the dense tree zone or “riparian” habitat surrounding the pan (Zone B) and the adjacent terrestrial savanna habitat (Zone C). To ensure samples were taken in all areas, a transect was chosen through all of these zones to complete the sampling.

3.2.2. Vegetation and Habitat

The herbaceous component (grass and forb) was sampled according to the dry weight rank method (t’Mannetjie and Haydock, 1963) to determine the species composition. A quadrat size of 0,7 m^2 was used as this has been reported to be best suited in this habitat (Dekker *et al*., 2001). Three random samples were recorded per zone along the chosen transect; totalling nine quadrat samples per pan of which four pans were sampled. Grass and forb species were identified using the Guide to Grasses of Southern Africa (van Oudtshoorn, 2012) and Wild flowers of the Limpopo Valley (van der Walt, 2009), respectively. This was done on site or samples were pressed for identification at a later stage.

A novel approach was taken to assess the composition of the woody species by combining the data from the vegetation sampling and the imagery taken from a drone (Section 3.2.1). In the field, the GPS location and species of each tree and shrub was recorded using an eTrex Venture hand-held Garmin GPS. This was done along a selected transect line through all study zones and within a band of approximately 10 m; additional points were taken as desired to get a more complete data set (Figure 10). All points were imported into the QGIS program and cross-referenced against field-notes and final delineated wetland zone boundaries. Thus, the woody species composition typical of the different zones could be determined. The density of the woody species was not assessed in the field along a narrow transect, but instead analysis of the high resolution drone aerial imagery was used (Section 3.3.1).

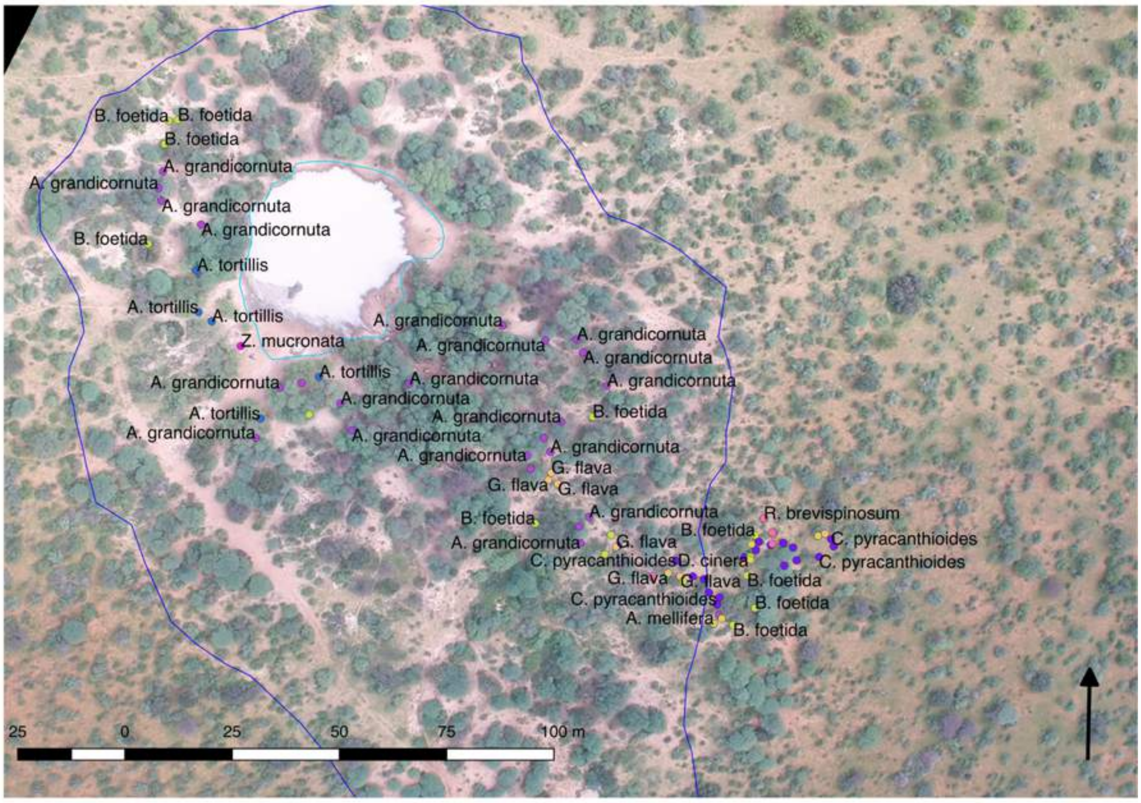

Figure 10: Georeferenced imagery of Pan 1 showing example data set of GPS located woody tree species

3.2.3. Soils

Soil sampling was done with a hand-held auger along the selected transect. Composite soil sampling methodology was carried out, which included three soil samples being taken, then mixed together and thereafter approximately a 2 kg sub-sample of soil was taken and placed into two 50 µm plastic sampling bags. The topsoils (0-30 cm) and subsoils (30-60 cm) were sampled separately in this way and labelled as "a" for upper and "b" for lower horizons. A total of three composite samples were taken in each of the three zones; thus totalling nine soil samples per horizon and per pan, including four pans.

3.2.4. Water Chemistry (CSIR)[2]

Water quality assessments were conducted at the selected sites firstly by measuring the *in situ* water quality parameters (pH and electrical conductivity) using a Hach handheld water quality meter. Secondly, random water samples were collected in pre-cleaned bottles and kept cool and in the dark and analysed at a laboratory accredited by the South African Bureau of Standards for various selected parameters. Water samples of each

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[2] These data were incorporated for completeness but remain the property of the Council for Scientific and Industrial Research (CSIR), who kindly shared the data.

pan were taken during the site visit from 22nd to 24th January 2017. As stated previously, the sampled four pans were chosen as they had water in them upon arrival where most other pans were completely dry. The sampling was completed prior to the large storm event of 24th January and thus the water quality results provide a good representation of the state of the pans prior to an inflow of rain. The pans were not resampled after the rain due to time limitations in the field; however, a rainwater sample was taken for comparison.

3.3. Data Interpretation

3.3.1. Visual Analysis – Woody density

The assessment of tree density was not done in the field but instead using the drone aerial imagery with the aim of gaining a potentially more accurate estimate of woody density over a larger representative area; as well as to showcase the potential ecological application of drones. Due to the high resolution of the georeferenced images (5-15 cm), individual woody plants were visible and thus points were 'mapped' in the estimated centre of each tree and large shrub (±>2m in diameter) in a representative sample area of the riparian and terrestrial savanna habitat (Figure 11). The number of points (i.e. trees) were divided by the total area (m^2) mapped, and multiplied by 10 000 to return the number of woody plants per hectare (ha) to complete the density analysis. This was done for all pans and the values per zone were averaged and the standard deviation calculated.

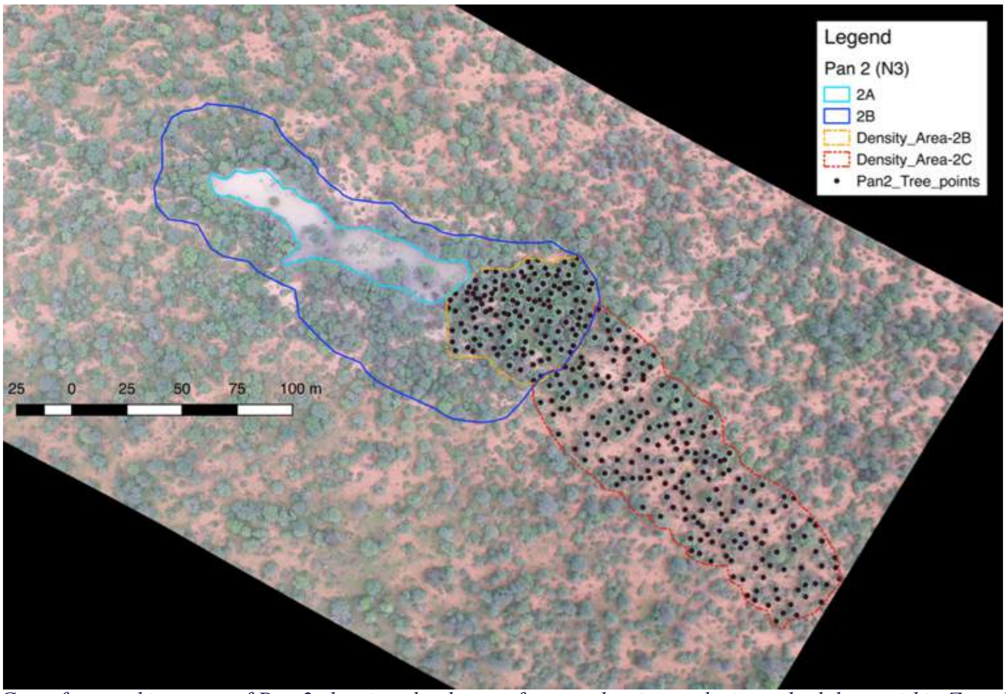

Figure 11: Georeferenced imagery of Pan 2 showing the dataset for tree density analysis methodology within Zone B (riparian) and Zone C (terrestrial)

3.3.2. Laboratory Analysis

3.3.2.1. <u>Soils</u>

The 72 double-bagged soil samples were kept in a sealed bag and sent to the SANAS accredited BemLab in Somerset West for laboratory analysis to determine the following physiochemical properties:

- pH (1.0 M KCl);
- Cation Exchange Capacity (CEC) at pH 7 in mg/kg;
- Water holding capacity through fine fraction texture analysis; and
- Total soil concentrations of:
  - Nitrogen (N) in percent (%);
  - Total Carbon (C) in percent (%);
  - Iron (Fe) in mg/kg;
  - Phosphoros (P) via Bray II analysis in mg/kg;
  - Soluble Sulphur (S) in mg/kg;
  - Calcium (Ca^{2+}) in cmol/kg;
  - Magnesium (Mg^{2+}) in cmol/kg;
  - Sodium (Na^{+}) in cmol/kg;
  - Potassium (K^{+}) in cmol/kg;
  - Copper (Cu) in mg/kg;
  - Zinc (Zn) in mg/kg;
  - Manganese (Mn) in mg/kg; and
  - Boron (B) in mg/kg.

The methodologies utilised by Bemlab for these analyses are summarised as follows: The soil was air dried, sieved through a 2 mm sieve for determination of stone fraction (weight/weight basis) and analysed for pH (1.0 M KCl), P (Bray II) and the total extractable cations including K+, Ca2+, Mg2+and Na+ (extracted at pH = 7 with 0.2 M ammonium acetate) and carbon by means of the Walkley-Black method as well as the LECO Combustion Analysis (The Non-affiliated Soil Analyses Work Committee, 1990). Micro-nutrients (Zn, Mn, Cu & Fe) were extracted with Di-ammonium EDTA (0.02 M) and boron (B) using a 1:2 hot water ratio (The Non-affiliated Soil Analyses Work Committee, 1990). Sulphur (S) was extracted with concentrated phosphoric acid (at pH = 4) according to an adapted method as described in Pansu & Gautheyrou (2006). The extracted solutions was analysed with a Varian ICP-OES optical emission spectrometer. Salinity was determined by measuring the resistance of saturated paste in an electrode cup. Extractable acidity was extracted with 1M KCl and determined through titration with 0.05 M NaOH (The Non-affiliated Soil Analyses Work Committee, 1990). The soil's CEC was determined using 0.2 M ammonium acetate (pH=7 as extractant of exchangeable cations) method, where after the soil is leached with 0.2 M K2SO (The Non-affiliated Soil Analyses Work Committee, 1990). The total $NH4^{+}$ was extracted with 1N KCl and determined colorimetrically as indication of CEC on a SEAL AutoAnalyzer 3 with a 15 mm flow cell and 520 nm filter.

3.3.2.2. <u>Water (CSIR)</u>

Water samples were sent for water chemistry analysis at the CSIR laboratories in Pretoria. These samples were collected in pre-cleaned Polyethylene bottles and frozen until analysis could be performed. The samples, including the four pan samples and one rain water sample, were analysed for the following parameters: EC, pH, Na, Ca, Mg, K, Fe, Cl, Mn, SO_4^{2-}, CO_3^{2-}, HCO_3^{-}.

3.3.3. Data preparation and Statistical analysis

Statistical analyses were carried out to test for significance in relevant datasets using the program Statistica, Version 13 (TIBCO Software Inc.). In addition, graphs were created in Microsoft Excel for Mac, version 15.40 (Microsoft Corporation, 2017) to show the average values of chosen parameters. The data were not continuous variables; however, trend lines were included in the graphs to indicate the potential continuous nature of the constituents along the hydro-ecological gradient of the study sites. Statistica derived Box and Whisker plots were included to present the median and range of the data.

3.3.3.1. Tree Density

The Kruskal-Wallis ANOVA by Ranks test was used to compare the tree density data between the pans to ensure that the study zones were similar enough to allow them to be averaged and assessed, which was confirmed. Thereafter the Kolmorogov-Smirnov (K-S) Test was used to compare the Zone B (Riparian) and Zone C (Terrestrial) tree density data for significance.

3.3.3.2. Soils

The soils data were imported, preliminarily assessed and prepared for statistical analysis in Microsoft Excel for Mac, version 15.40 (Microsoft Corporation, 2017). The soil cation concentration results were converted from cmol(+)/kg to mg/kg by multiplying them by 230, 390, 200 and 120 for Na^{+}, K^{+}, Ca^{2+} and Mg^{2+} respectively. All data were first tested for normality using the Shapiro-Wilks W test and were found to be non-normally distributed – thus non-parametric analyses were required. Given that there were only four sample sites (pans), the pans were first compared against each other to determine if they were statistically similar to allow the parameter values to be averaged per study zone (A, B and C) and soil horizon (a and b). Using the Kruskal-Wallis Rank Sum Test, it was found that within these groupings the pans were similar enough to allow the pans to be assessed as 'replicate' samples and the data interpreted as such. There was an odd exception for some parameters in a select few areas that formed no pattern and was accepted as natural variability.

Thereafter, the Kruskal-Wallis Rank Sum Test was again used with the Kruskal-Wallis Multiple Comparisons Post Hoc Test to determine the significant differences between the three zones for the soil data. The grouping variable was the habitat zone which was further grouped by the two soil horizons, giving results for combined and individual soil horizon. To determine the significant differences between the upper and lower soil horizon data within each zone, the Kolmogorov-Smirnov Test was used to compare the two groups of non-parametric data. The soil horizon was the primary grouping variable and the test was run with the additional grouping of the habitat zone to assess each zone individually. To further assess the relationship between clay content of the soil and water holding capacity, a Regression analysis was carried out where the water holding capacity was the dependant variable.

4. Results

The results are presented and interpreted in the following sub-sections according to the different parameters, being vegetation, soil and water. The integration and discussion of these results are detailed in Section 5.

4.1. Vegetation Composition

4.1.1. Aerial Survey

The use of the drone for aerial analysis was determined to be an exceptionally successful tool to observe the pans within the savanna landscape. Some additional pans were observed whilst the drone was in the air as the aerial vantage point aided in the locating of nearby habitat change which could not be seen from foot. The aerial survey was done prior to the in-field sampling to first gain an understanding of the wetland system in context and ensure the in-field sampling accurately captured all zones along the hydro-ecological gradient; i.e. the wetland areas and dense tree riparian zones were delineated (Figure 12).

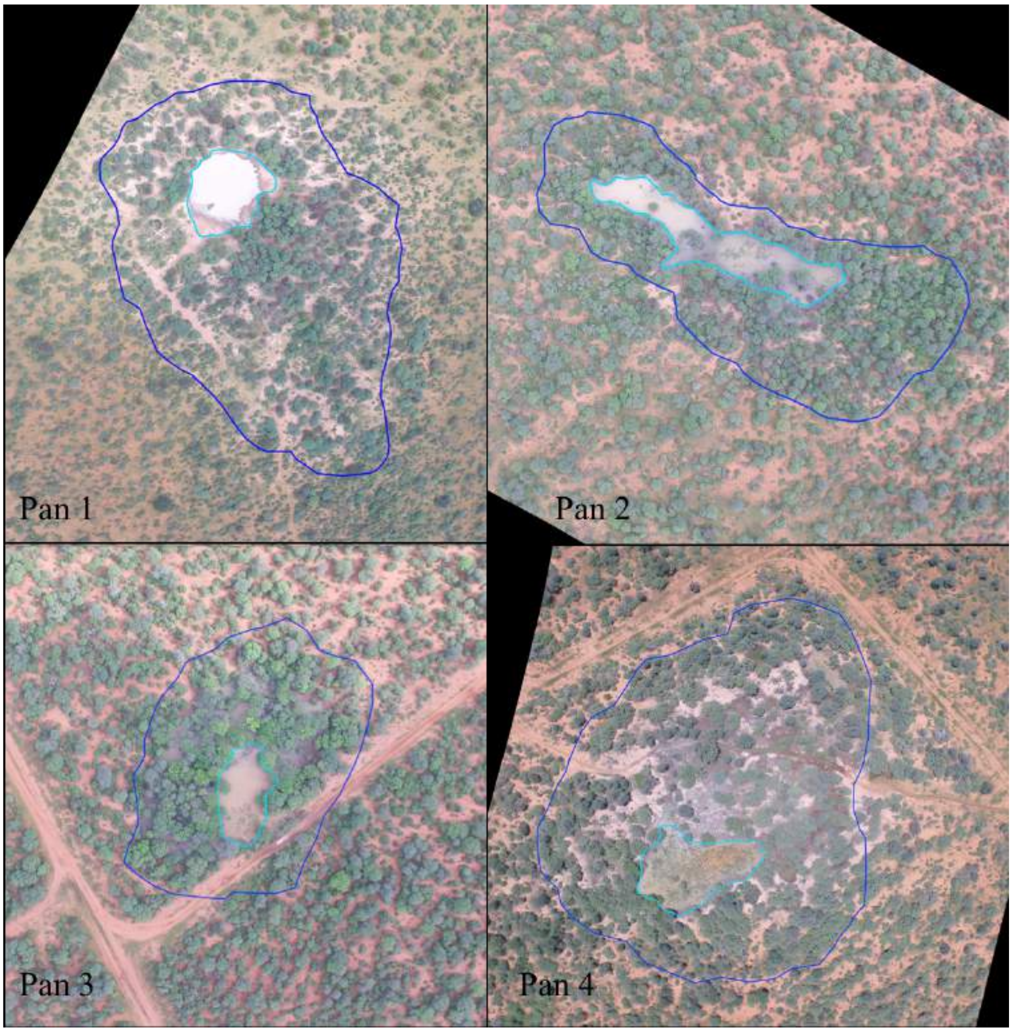

Figure 12: Aerial images of all four pans showing the wetland centre outlined in light blue and the estimated "riparian" zone in dark blue

4.1.2. Herbaceous species

The project area has been under high grazing pressure for the past few years under the management of Boikarabelo Mine and, in addition, there has been lower than average rainfall received (L. van den Berg-Nicolai, personal communication, January 2017). Due to this, the herbaceous vegetation was much lower in abundance than expected. The places where most grasses and forb species were still growing well was underneath bushes and trees, where the dominant grass species were *Panicum maximum* Jacq, *P. coloratum* L., and *Digitaria velutina* (Forssk) P. Beauv. The most common finding was prevalent bare soil with small creeper forb species and hardy grasses, including *Tragus berteronianus* Schult., multiple *Aristida spp*, and *Limeum spp.* (Table 2); the majority being forbs (±70%). No major difference was observed between the riparian and terrestrial zones, except that the riparian zones possibly had more occurrences of grass tufts in the shade of the trees as there were denser trees, increasing the grass component to approximately 60%. The wetland zones contained mostly open water with a small proportion of herbaceous vegetation, which would be exposed soils in the dry season. The pans differed from the surrounding herbaceous vegetation as they were dominated by the water loving grasses typical of seasonal pans being *Leptochloa fusca* (L.) Kunth and *Echinochloa colona* (L.) Link. The aquatic forb *Aponogoton stuhlmannii* Engl was also present in most pans (Figure 13).

Table 2: List of herbaceous species recorded per zone

Form	Zone A: Wetland	Zone B & C: Riparian & Terrestrial	
Grasses	*Leptochloa fusca* *Echinochloa colona* *Panicum coloratum*	*Aristida congesta* Roem. & Schult. subsp. *barbicollis* Trin. & Rupr. *A. sciurus* Stapf. *A. stipitata* Hack. *Chloris virgate* Sw. *Digitaria velutina*	*Panicum maximum* *P. coloratum* *Tragus berteronianus* Schult. *Urochloa mosambicensis* Hack.
Forbs	*Aponogoton stuhlmannii* *Chamaecrista momosoides*	*Limeum dinteri* G.Schellenb *L. fenestratum* (Fenzl) Heimerl *L. sulcatum* (Klotzsch) Hutch. var. *sulcatum* *Commicarpus plumbagineus* (Cav.) Standl. var. *plumbagineus* *Heliotropium nelsonii* CH. Wright *Indigofera hollubii* N.E.Br. *I. trita* L.f. var. *subulata* (Poir.) Ali *I. viciodes* var. *viciodes* Jaub. & Spach.	*Ipomea magnusiana* Schinz. *Pegolettia senegalensis* Schinz. *Pomaria burchelli* (DC.) B.B. Simpson & G.P. Lewis *Ruellia patula* Jacq. *Tribulus terrestris* L. *T. zeyheri* Sond. subsp. *zeyheri*

Figure 13: Water filled pan wetland centre with some herbaceous vegetation including water loving grasses Leptochloa fusca and Echinochloa colona (a & b), as well as the aquatic forb Aponogoton stuhlmannii (c).

4.1.3. Tree Density Analysis

The mean density across the four pans of trees and shrubs (woody species) was found to be greater in the riparian area around the pans with an average of 381 trees/ha, whilst 249 trees/ha characterised the terrestrial Zone C (Figure 14). This however was not found to be of statistical significance using the K-S Test ($N=4$, $p>0.1$). The greater density of trees around the pans was visually observable in the field; which was particularly evident from the drone imagery. The tree density was often used as the first indicator of a potential pan area due to the habitat change. In general, woody plants were absent from the centre of the pans (Zone A), thus this study area was purposefully excluded from the analyses. However, as no pan is identical, there were pans observed in the study area that had few shrubs and trees within the inner most depression zone (Zone A: Wetland) and this included Pan 2.

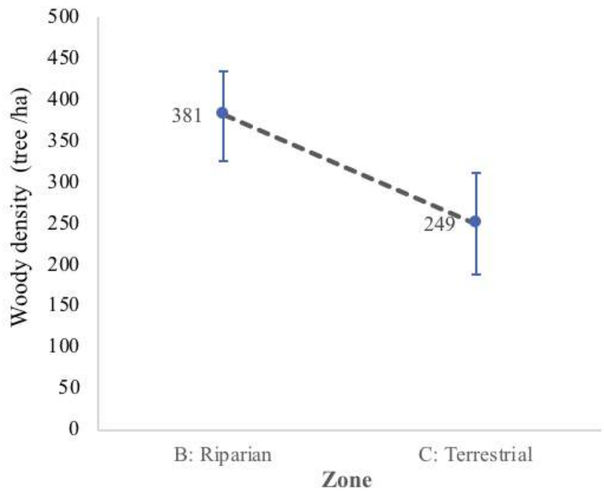

Figure 14: Mean woody plant density per zone; error bars represent standard deviation, including a trend line between zones

4.1.4. Woody Species Composition

A total of twenty one (21) tree and shrub species were recorded across all study sites; however, most species showed some degree of preference for either the terrestrial or pan areas. Of the 21 species, five (5) were recorded only in the terrestrial zone C, six (6) only in the riparian zone B and ten (10) were recorded in both (Table 3) (note that the wetland zone was excluded). Of the ten that were found in both zones, four showed preference to terrestrial zones, four to the riparian zone and the other two did not clearly show a preference in this dataset. The dominant species found in the pan riparian areas (Zone B) were fine-leafed *Acacia* species including *Acacia erubescens* Welw. Ex. Oliv*; A. grandicornuta* Gerstner*, A. mellifera* (M. Vahl) Seigler & Ebinger and *A. tortillis* (Forssk.) Galasso & Banfi, whereas in the outer areas (Zone C) broad leafed species including *Combretum apiculatum* Sond.*, Commiphora pyarcanthioides* Engl. *Boscia foetida* Schinz subsp *rehmaniana* (Pestal.) Toelken, *Grewia flava* DC. and *G. bicolor* Juss were dominant (Table 4). Also, commonly recorded to occur in the broader area of Steenbokpan are *Terminalia sericea* Burch. ex. DC. and *Sclerocarya birrea* (A. Rich.) Aubrév (Mucina and Rutherford, 2012).

Table 3: Count of woody species per zone, also indicating in which pans the species occurred

Species	**Species count per Zone**		**Species present in pan:**			
	B	C	1	2	3	4
Asparagus laricinus Burch.	2			•		
Acacia erubescens	16	25		•	•	•
A. grandicornuta	24		•			
A. mellifera	4	1	•			
A. newbrownii Burtt Davy	2				•	
A. nigrescens (Oliv.) P.J.H. Hurter	10	2		•	•	•
A. senegal (L.) Bitton		3			•	
A. tortillis	9	3	•		•	•
Boscia albitrunca (Burch.) Gilg & Gilg-Ben.		1		•		
B. foetida subsp. *rehmanniana*	14	10	•	•	•	•
Combretum apiculatum		17	•	•		
Commiphora pyracanthioides	5	37	•	•	•	•
Dichrostachys cinera (L.) Wight & Arn.	1	14	•	•	•	
Faidherbia albida (Delile) A. Chev.	2				•	
Grewia bicolor	2	13	•	•	•	
G. flava	16	46	•	•	•	•
G. flavescens Juss.	1			•		
Gymnosporia senegalensis (Lam.) Loes.	1				•	
Rhigozum brevispinosum Kuntze	1	4	•			
Terminalia sericea		4	•			
Ziziphus mucronata Wild. Subsp. *mucronata*	1		•			

Table 4: Woody species separated by zone of preference

Zone mostly recorded in	Species names
Terrestrial only (Zone C)	*Acacia senegal; Boscia albitrunca; Combretum apiculatum; & Terminalia sericea*
Riparian only (Zone B)	*A. grandicornuta; A. newbrownii; Faidherbia albida; G. flavescens; Gymnosporia senegalensis; & Ziziphus mucronata*
Both but preferred Terrestrial	*Commiphora pyracanthioides; Dichrostachys cinera; Grewia bicolor; & G. flava*
Both but preferred Riparian	*Acacia erubescens; A. mellifera; A. nigrescens; & A. tortillis*
Both zones, no clear preference	*B. foetida & Rhigozum brevispinosum*

4.2. Soil Texture and Water Holding Capacity

The soil texture analysis showed a significantly greater clay content in the wetland soils (H(2, n=72)=23.22494, P<0.001), which had an average of 34.5% compared to ±20% to ±16% in the riparian and terrestrial areas respectively (Figure 15). No difference was observed between upper and lower soil horizons in the wetland zone. However, a greater clay content was seen in the sub-soils for the riparian and terrestrial zone soils, although these were not statistically significant. No difference was found in the fine-medium-course sand fraction between zones nor soil horizons. The wetland zone is thus a localised concentration of clay soil in the landscape, which is expected as wetlands (and sub-soils) typically have a greater clay content than surrounding soils. The results support the hypothesis that clay increases into the pan.

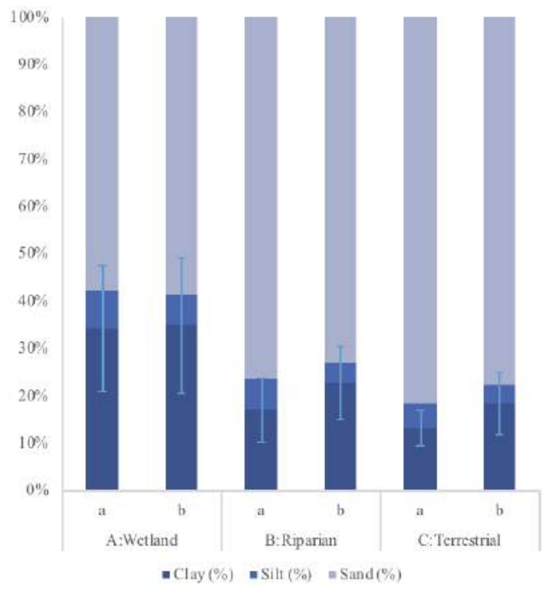

Figure 15: Mean soil percent clay, silt and sand fraction per zone and soil horizon; error bars represents standard deviation of clay content

Soil water holding capacity (WHC) of the soils was analysed as the *percent* capacity at 100 kPa and *total* capacity in mm/m. The soils showed an increasing trend into the wetland from the terrestrial areas for *percent* WHC (Figure 16) and a decreasing trend for *total* WHC (Figure 17). This result firstly confirms that the hydrological gradient along which the study transect was planned (Zone A to C) was present. Percent WHC increased into the wetland, where the wetland soils had significantly greater values in comparison to both the other zones (H(2, n=72)= 21.74570, P<0.01). Furthermore, percent WHC has a significant positive correlation to the clay content of the soils (F(1.70)=375.26, P<0.001) (Figure 16).

Conversely, total water holding capacity (mm/m) was significantly lower in the wetland soils (H(2, n=72)= 37.27294, P<0.001), where these values have a (non-significant) negative relationship with clay percentage (Figure 17). The riparian zone was not significantly different from the terrestrial zone in either analysis. No significant differences were found between the upper and lower soil horizons.

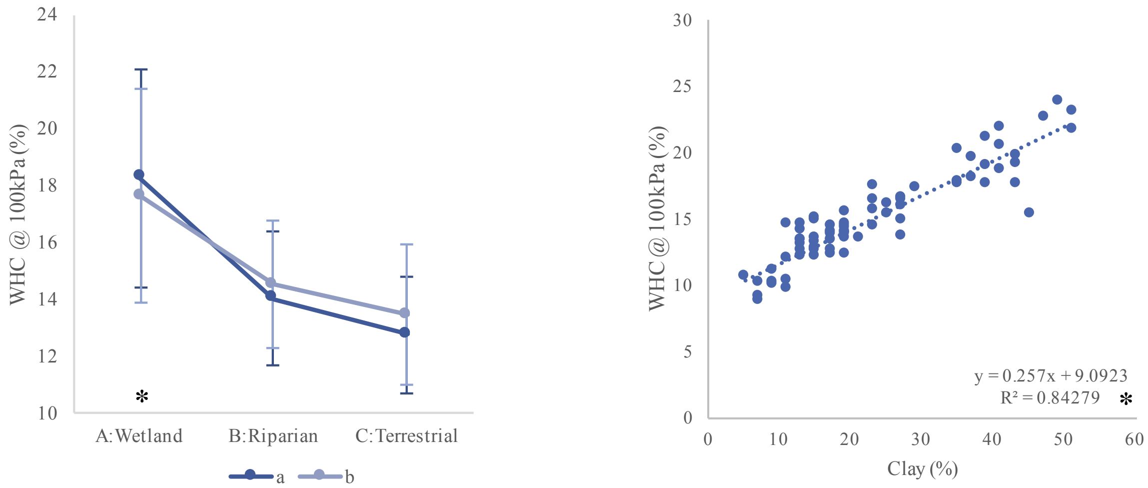

*Figure 16: Percent soil water holding capacity (at 100kPa) per zone and soil horizon (left) and, the overall relationship with soil clay content (right); error bars represent standard deviation, * indicates significance*

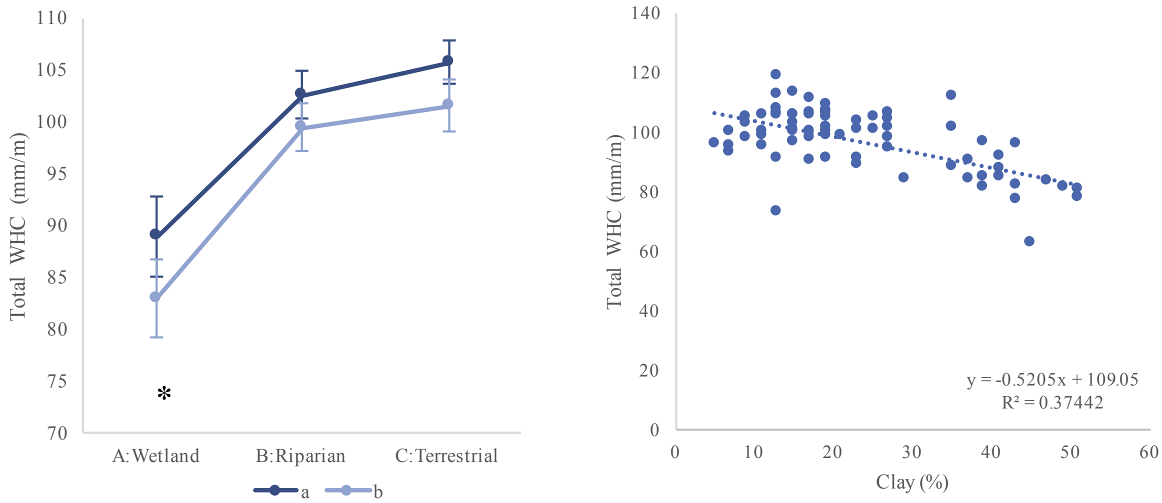

*Figure 17: Total soil water holding capacity per zone and soil horizon (left) and the overall relationship with soil clay content (right); error bars represent standard deviation, * indicates significance, including trend lines between zones*

4.3. Soil Chemistry

4.3.1. Soil pH

The soils had a lower pH than expected, the majority ranging from 3.9 to 5.1, where the terrestrial soils (Zone C) were the most acidic and the riparian soils (Zone B) were the least acidic. The soils in the riparian areas around the pan had a significantly higher pH overall with a median of pH 4.9 compared to the terrestrial soils (pH 4.3) and wetland (pH 4.5) soils ($H(2, N=72)=22.64717$, $p<0.001$) (Figure 18). This result was also found for the topsoils and subsoils separately, where the riparian soils (Zone B) were significantly higher in pH than the terrestrial soils, although non-significantly so against wetland soils (a: $H(2, N=36)=11.76035$, $p<0.01$; b: $H(2, N=36)=10.94043$, $p<0.01$). The topsoils were generally more acidic than the sub-soils in all zones; however this was not determined to be of statistical significance (Figure 19).

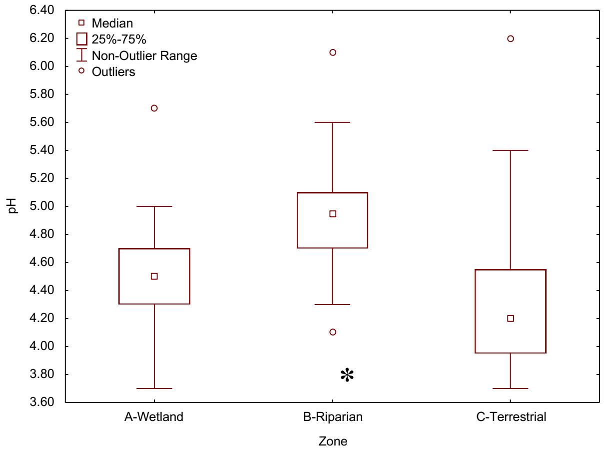

Figure 18: Soil pH per zone, through both soil horizons; * indicates significance,

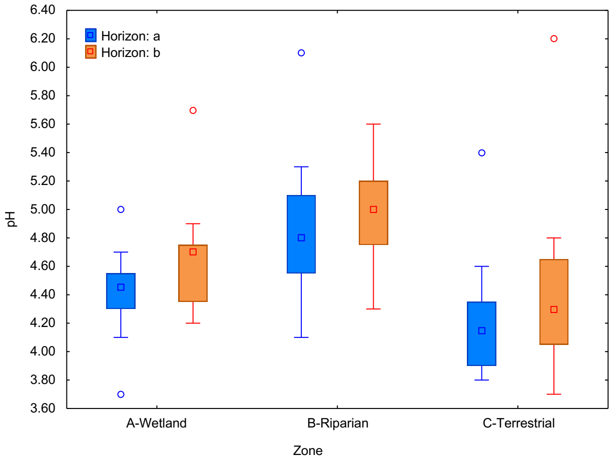

Figure 19: Soil pH per zone, showing upper (a) and lower (b) soil horizons

4.3.2. Key Elements: C, N, P, S & Fe

The soils of Zone C (terrestrial) in the study area had an overall low concentration of the key elements carbon, nitrogen, phosphorus, sulphur and iron. On average across the soil horizons, these elements showed an increasing trend into the wetland soils from the terrestrial zone (Figure 20 to Figure 22). These parameters are highly variable, particularly in the wetland zone. In most cases, significant differences do occur between the hydrological zones, where the terrestrial (dry end) or the wetland soils (wet end) are different from the other two zones. There are also differences for some parameters between the upper and lower soil horizons within a study zone. These results support the hypothesis that soil nutrients increased into the pan. Each element is discussed in detail in the sub-sections below to better understand these patterns.

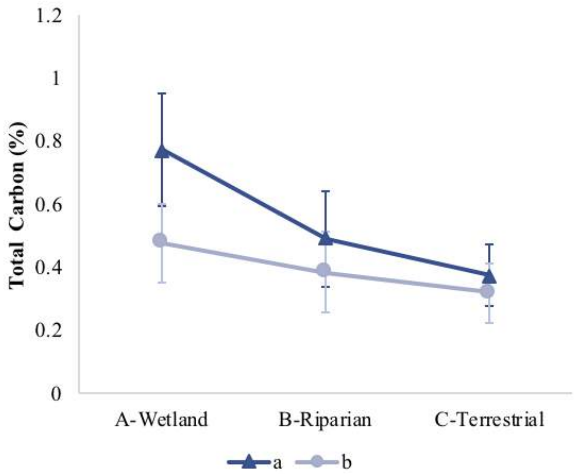

Figure 20: Mean soil Carbon content per zone, showing upper (a) and lower (b) soil horizons; error bars represent standard deviation, including trend lines between zones

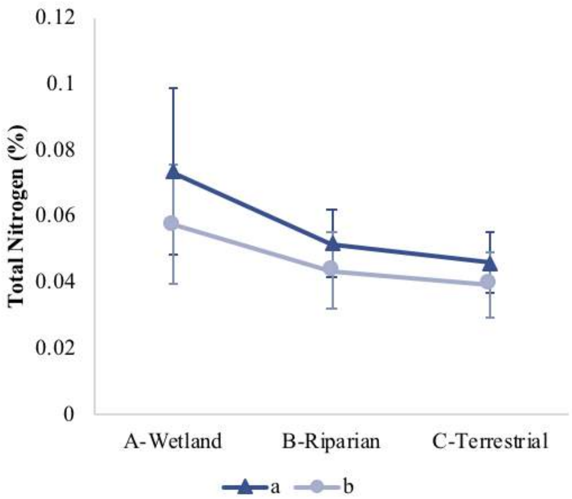

Figure 21: Mean soil Nitrogen content per zone, showing upper (a) and lower (b) soil horizons; error bars represent standard deviation, including trend lines between zones

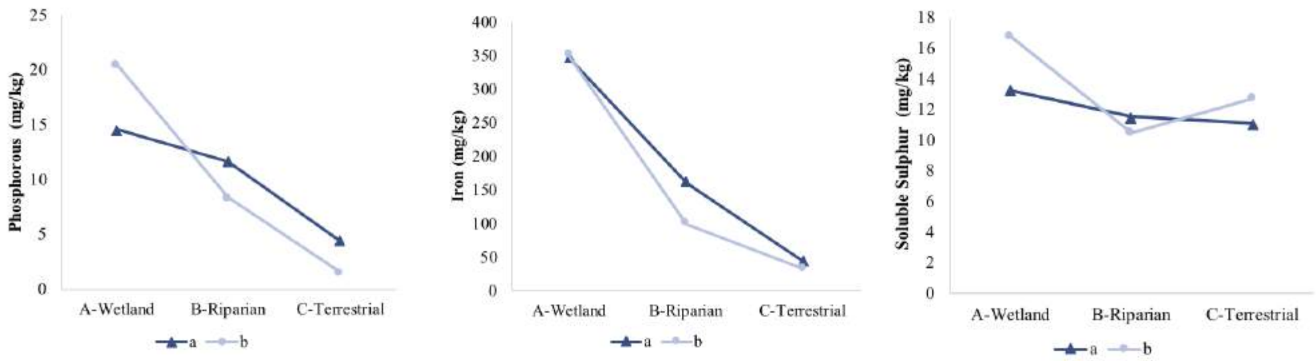

Figure 22: Mean soil content of Phosphorus, Iron and Soluble Sulphur per zone, showing upper (a) and lower (b) soil horizons, including trend lines between zones

4.3.2.1. Total Carbon (C)

The Total Carbon (TC) content of the soil profile was significantly different across the zones ($H(2, N=72)=21.52245$, $p<0.001$). Overall, the wetland soils had significantly greater carbon content compared to the other soils (Figure 25). When looking at the upper and lower soil layers separately, the wetland soils had significantly greater carbon content compared to the terrestrial soils but not from the riparian soils (a: $H(2, N=36)=13.28900$, $p<0.01$; b: $H(2, N=36)=10.47218$, $p<0.01$). The carbon content is greater in the upper soil horizon for all zones, which is likely linked to the litter zone, where this is a significant difference in the wetland soils ($N=12$, $p<0.01$) but not in the riparian nor terrestrial soils ($p>0.1$). In fact, carbon content was the only parameter that differed significantly between the upper and lower soil horizons in the wetlands. The increasing content and range of carbon into the riparian and wetland soils from the dry soils is evident, which is likely due to the animal activity in these zones and an accumulation of vegetation litter.

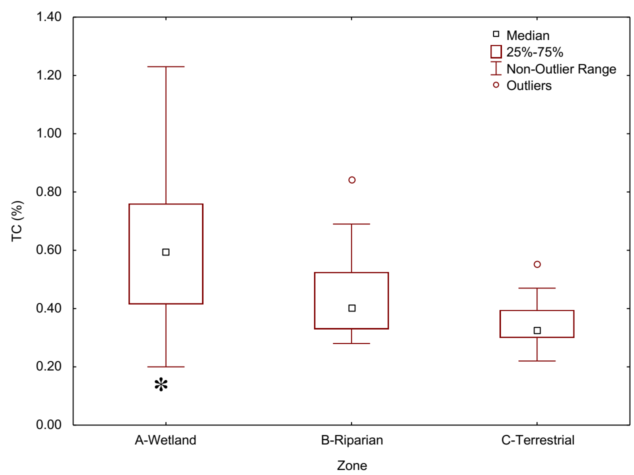

*Figure 23: Soil Total Carbon content per zone, through both soil horizons; * indicates significance*

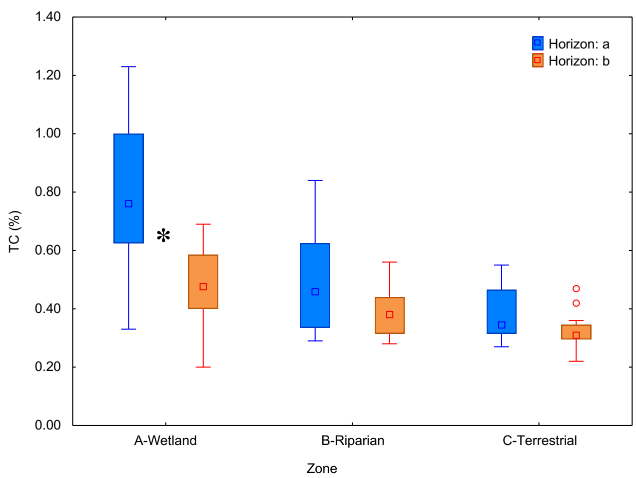

*Figure 24: Soil Total Carbon content per zone, showing upper (a) and lower (b) soil horizons; * indicates significance between soil horizons*

4.3.2.2. Nitrogen (N)

Similarly to carbon, the total nitrogen of the soil profile was significantly different across the zones (H(2, N=72)=18.81102, p<0.01), where the wetland soils differed significantly from the other soils (Figure 25). When looking at the upper and lower soil layers separately, the wetland soils had significantly greater nitrogen content compared to the terrestrial but not the riparian soils (a: H(2, N=36)=11.44321, p<0.001; b: H(2, N=36)=9.399719, p<0.01). Furthermore, the upper soils had on average more nitrogen than lower soils; however, this was not of statistical significance within any of the study zones. The increasing range of nitrogen content in the soils from the terrestrial into the riparian and wetland soils is clearly evident; indicating greater variability in the pans.

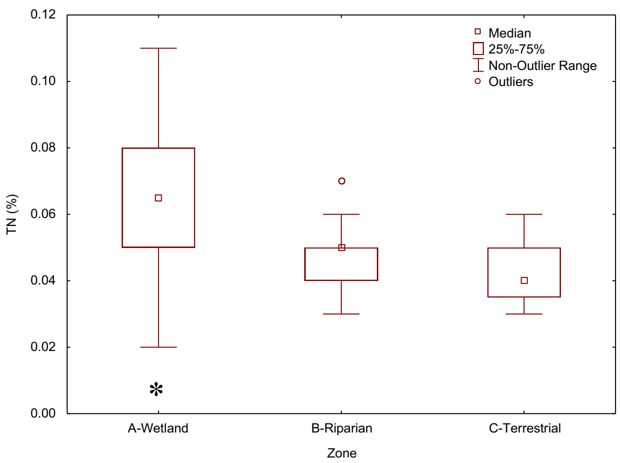

*Figure 25: Total soil Nitrogen content per zone, through both soil horizons; * indicates significance*

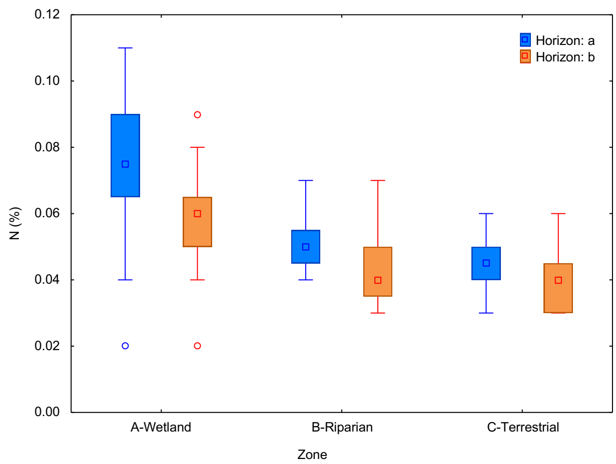

Figure 26: Total soil Nitrogen content per zone, showing upper (a) and lower (b) soil horizons

4.3.2.3. Phosphorus (P)

Soil phosphorus content differed significantly between zones for the soil column as a whole (H(2, N=72)=11.44938, p<0.01), where it was only the wetland soils that had a greater phosphorus content when compared to terrestrial soils but not to riparian soils (Figure 27). Furthermore, when the soil horizons are assessed separately, this was only the case for the lower soil horizon (H(2, N=36)=10.38572, p<0.01). Phosphorus concentration was greater in the upper soil horizon for the two zones except the wetland, where the opposite pattern was observed in the wetland soils (Figure 28). The difference between top and subsoils was statistically significant for the terrestrial soils only (N=12, p<0.001). The wetland and riparian soils had some extreme values as the greatest value in the wetland soil was an order of magnitude larger than that of the terrestrial soils (Figure 27), which is probably often linked to high Iron (Fe) content (Figure 29). Again, the wetland soils showed the greatest variance in concentration.

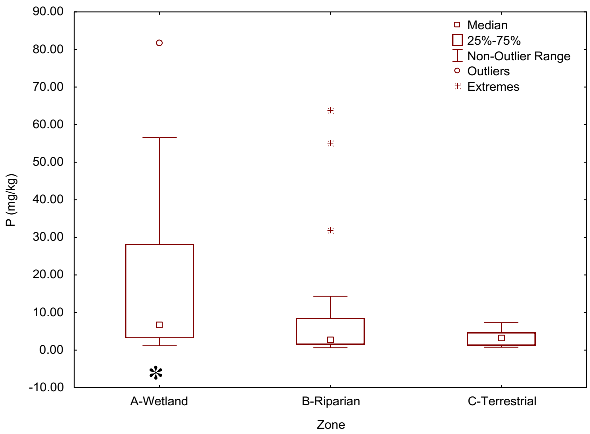

*Figure 27: Phosphorus content per zone & through both soil horizons; * indicates significance*

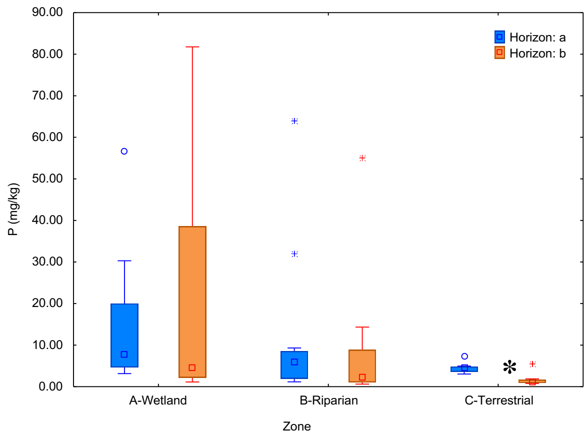

*Figure 28: Soil Phosphorus content per zone, showing upper (a) and lower (b) soil horizons; * indicates significance between soil horizons*

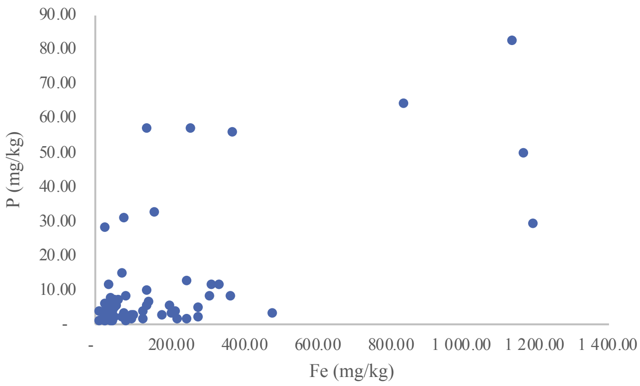

Figure 29: Soil Phosphorus content in relation to soil Fe content in an attempt to explain the extreme values

4.3.2.4. *Iron (Fe)*

Soil iron content increases significantly from terrestrial to wetland soils where each zone is significantly different from each other for both horizons (H(2, N= 72) =47.58695 p <0.001) (Figure 30). When the upper and lower horizons are assessed separately, the terrestrial soils are significantly lower in iron content from the riparian and wetland soils (a: H(2, N=36)=25.74024, p<0.001; b: H(2, N=36)=22.57207, p<0.001). Whilst, the wetland and riparian soils varied from each other, they are not statistically different from each other. The upper soil horizon had generally greater iron than the subsoils for all zones; this was statistically significant only in the terrestrial soils (Figure 31). The wetland and riparian soils had some extreme values that are more than three orders of magnitude greater than the lower values, which were mostly sampled in Pan 1.

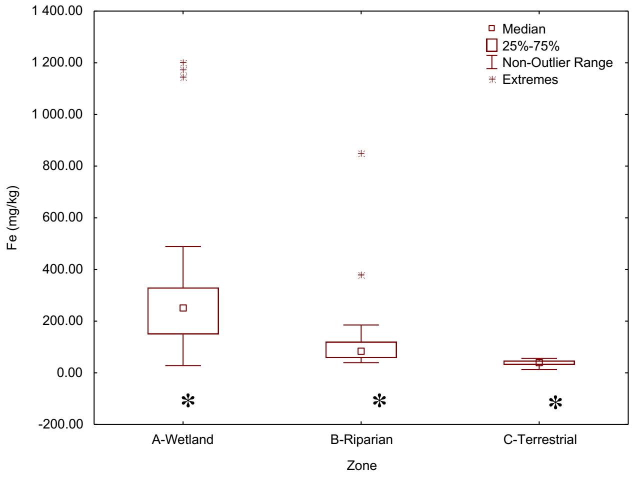

*Figure 30: Iron content per zone & through both soil horizons; * indicates significance*

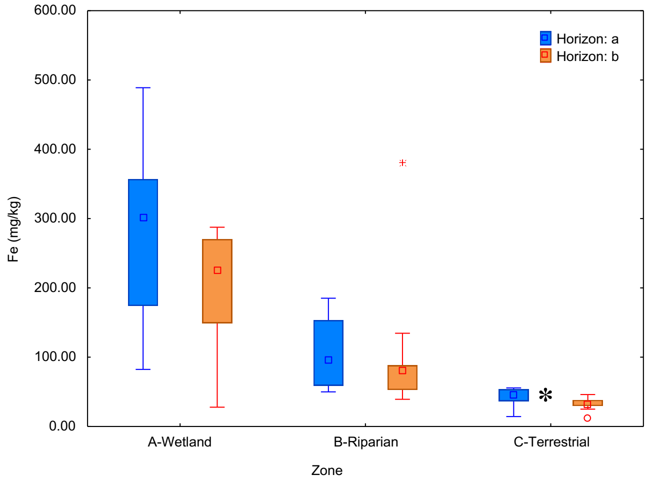

*Figure 31: Iron soil concentration (mg/kg) showing upper (a) and lower (b) soil horizons per zone; * indicates significance between soil horizons – excluding extreme values*

4.3.2.5. Soluble Sulphur (S)

For all soil horizons, the soluble sulphur content of the soils were not significantly different in the three zones. However, there was a greater range of values in the wetland soils compared to that of the terrestrial soils (Figure 32). No significant difference exists between the upper and lower soils in any zone (Figure 33).

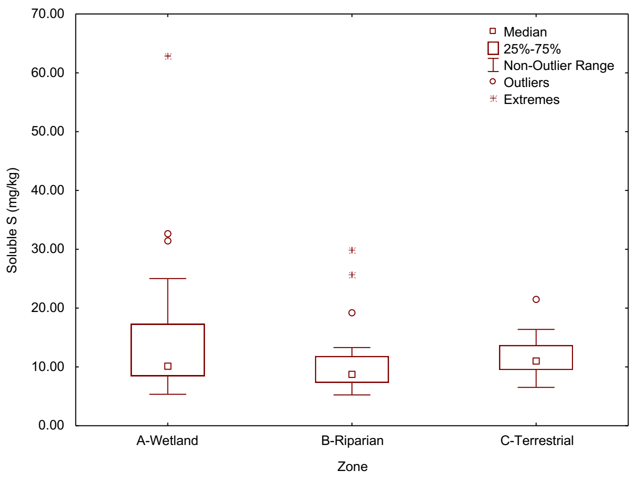

*Figure 32: Soluble Sulphur soil content per zone & through both soil horizons; * indicates significance*

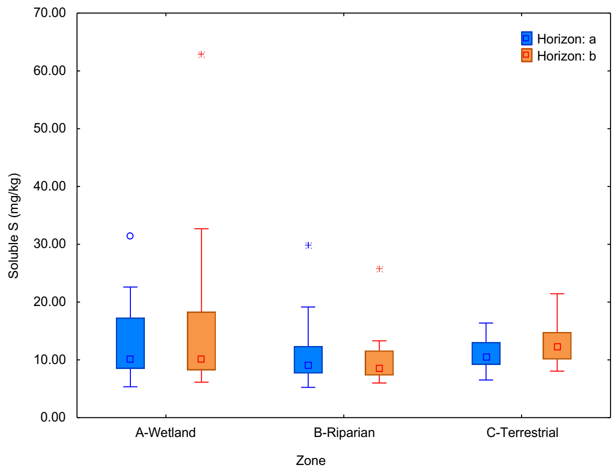

Figure 33: Soluble Sulphur soil concentration (mg/kg) showing upper (a) and lower (b) soil horizons per zone

4.3.3. Base Cations: Na^+, K^+, Mg^{2+} & Ca^{2+}

The terrestrial soils (Zone C) had low concentrations of all cations for arid savanna sandy soils, particularly sodium. All cations showed an increasing trend into the wetland from terrestrial soils for the soil column as a whole (Figure 34). For sodium (Na^+), the wetland soils were significantly different from the riparian and terrestrial zones. For the other cations, it was the terrestrial soils that were significantly different from the wetland and riparian soils. As a generalised observation, the subsoils had greater concentrations of all cations compared to the topsoils, which varied in degree according to the zone. These results also support the hypothesis that soil nutrients increased into the pan. If the soil clay content is used to represent the hydrological study gradient (as clay content has a significant relationship with water holding capacity of the soils; Section 4.2), the cations increase linearly along this gradient (Figure 35); except for Sodium, which increases with a very low R^2 value mostly due to the outlier values. Each cation is discussed in greater detail in the following sub-sections.

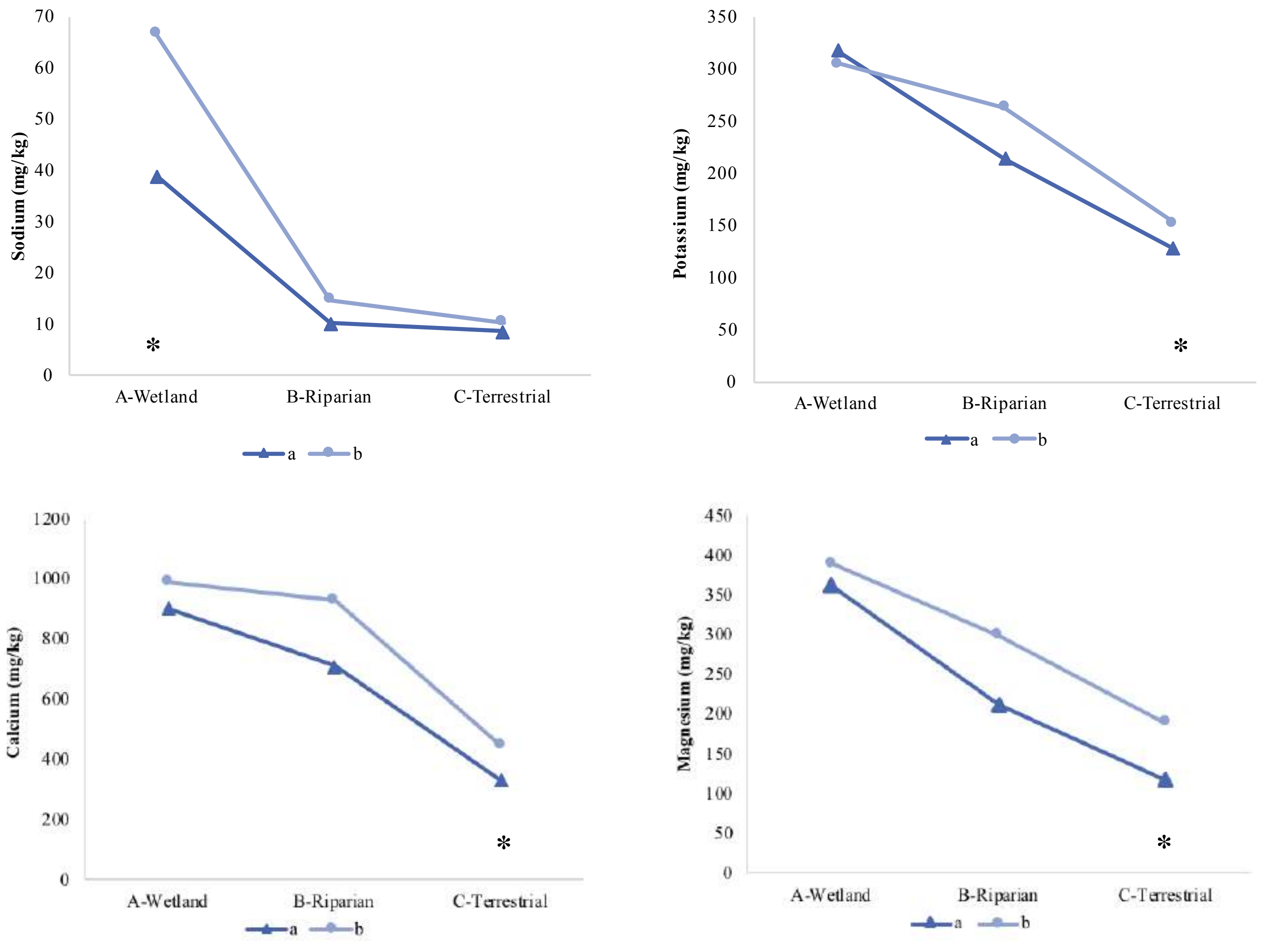

*Figure 34: Mean soil content of Na^+, K^+, Mg^{2+} & Ca^{2+} base cations per zone, showing upper (a) and lower (b) soil horizons; * indicates significance, including trend lines between zones*

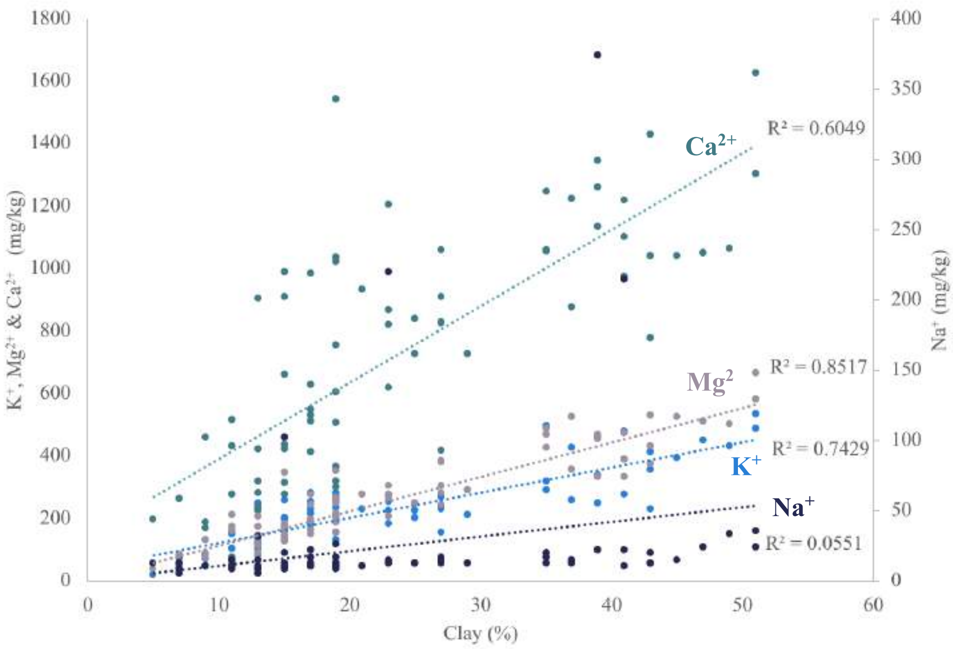

Figure 35: The cation concentrations as a function of clay content along the hydrological study gradient, trend lines indicating linear relationships with R^2 values

4.3.3.1. Sodium (Na^+)

Sodium content of the soil was significantly different between the zones ($H(2,N=72)=28.47004$, $p<0.001$), where the wetland soils were significantly greater than the riparian and terrestrial soils. The wetland soils of Pan 1 had some extreme values that are more than two orders of magnitude greater than the lower values (Figure 36), which correlated with the high Iron content in Pan 1. When the upper and lower horizons are assessed separately, this finding is largely continued (a: $H(2, N=36)=16.54104$, $p<0.001$; b: $H(2, N=36)=14.79329$, $p<0.001$). In the topsoils, the wetland soils differ significantly from the other two zones and in the sub-soils the wetland sodium content differs only from that of the terrestrial soils. When comparing horizons within zones, the subsoils generally had greater sodium content; however, this was only of significance in the terrestrial soils ($N=12$, $p<0.05$) (Figure 37).

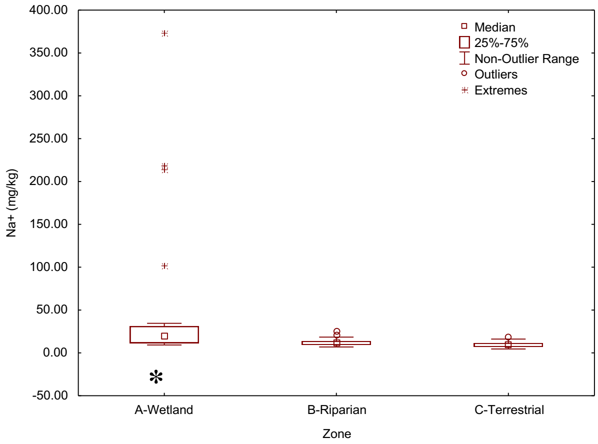

Figure 36: Soil Sodium content per zone through both soil horizons; * indicates significance

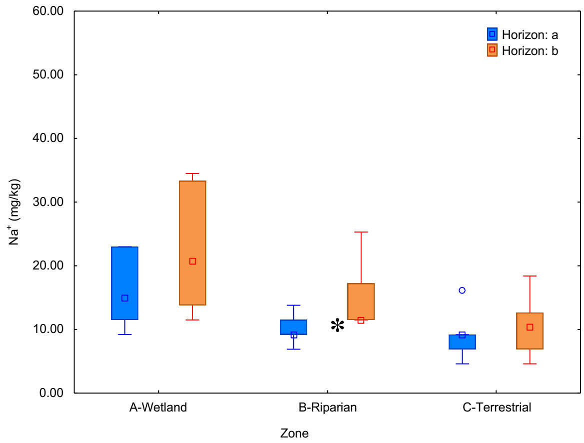

Figure 37: Soil Sodium content showing upper (a) and lower (b) soil horizons per zone; * indicates significance between horizons – excluding extreme values

4.3.3.2. Potassium (K^+)

The potassium content of the soil was significantly different between the zones (H(2,N= 72)=28.10978, p <0.001), where the terrestrial soils were lower compared to that of the wetland and riparian soils, and the wetland soils were not statistically different from the riparian soils (Figure 38). The wetland soils had a greater range of values that spanned that of the other zones' soils. When the upper and lower horizons are assessed separately, this finding remains the same (a: H(2, N=36)=16.53792, p<0.001; b: H(2, N=36)=13.13289, p<0.01). Overall, the lower soil horizons had greater concentrations of potassium except in the wetland and this was only of statistical significance for the riparian zone (Figure 39).

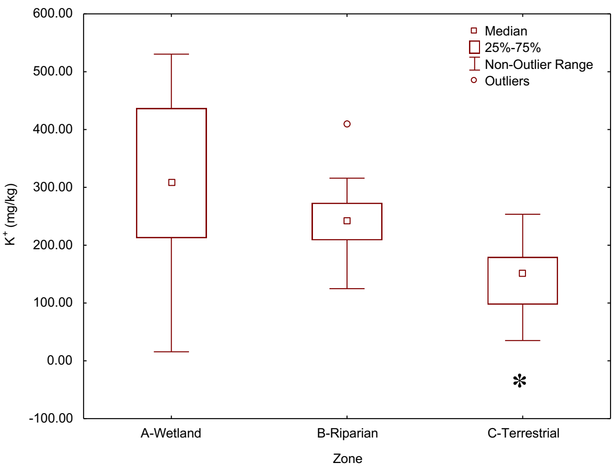

Figure 38: Soil Potassium content per zone through both soil horizons; * indicates significance

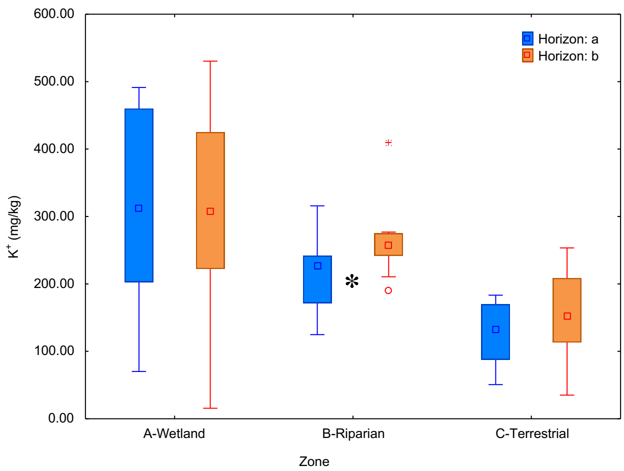

Figure 39: Soil Potassium content showing upper (a) and lower (b) soil horizons per zone; * indicates significance between horizons

4.3.3.3. Calcium (Ca^{2+})

The calcium content of the soil (similar to Potassium) was significantly less in the terrestrial soils compared to that of the wetland and riparian soils (H(2,N= 72)=28.11123, p <0.001) (Figure 40). When the upper and lower horizons are assessed separately, this finding remains the same (a: H(2, N=36)=15.46096, p<0.01; b: H(2, N=36)=13.36643, p<0.01). When comparing the top and subsoils in each zone, on average the sub-soils (lower horizon b) had greater calcium content than the top soils (Figure 41). This was not of statistical significance however in any zone.

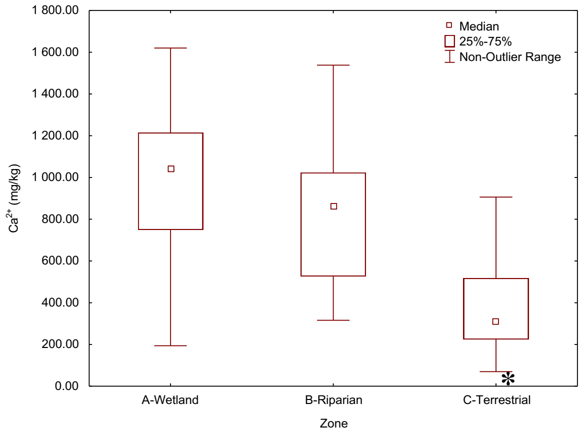

*Figure 40: Calcium soil content per zone through both soil horizons; * indicates significance*

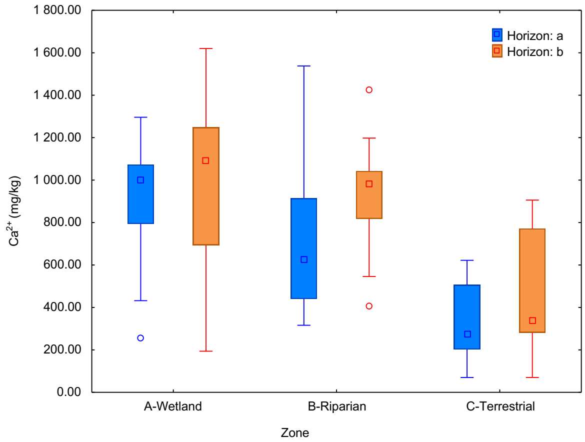

*Figure 41: Soil Calcium content showing upper (a) and lower (b) soil horizons per zone; * indicates significance between horizons*

4.3.3.4. Magnesium (Mg^{2+})

The magnesium content of the soil (similar to potassium and calcium) was significantly less in the terrestrial soils compared to that of the wetland and riparian soils (H(2,N=72)=26.57962, p<0.01). The wetland soils had a greater range of values which encompassed the values for all zones (Figure 42). When the upper and lower horizons are assessed separately this finding is largely continued; however, the wetland soil magnesium content differs significantly only from that of the terrestrial soils (a: H(2, N=36)=17.79396, p<0.001; b: H(2, N=36)=10.71760, p<0.01). When comparing the top and subsoils in each zone, on average the sub-soils had greater magnesium content than the top soils (Figure 41); however, this was not found to be of statistical significance (N=12, p>0.1).

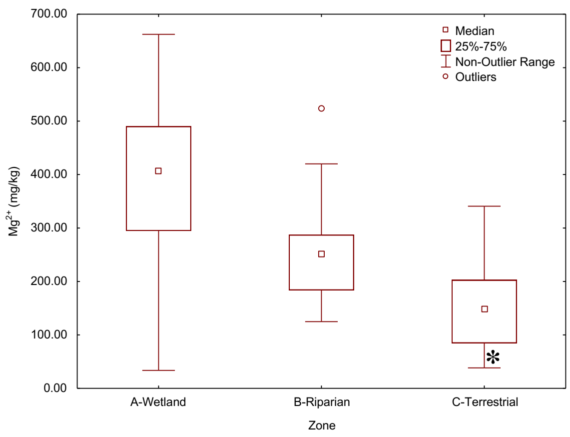

*Figure 42: Soil Magnesium content per zone through both soil horizons; * indicates significance*

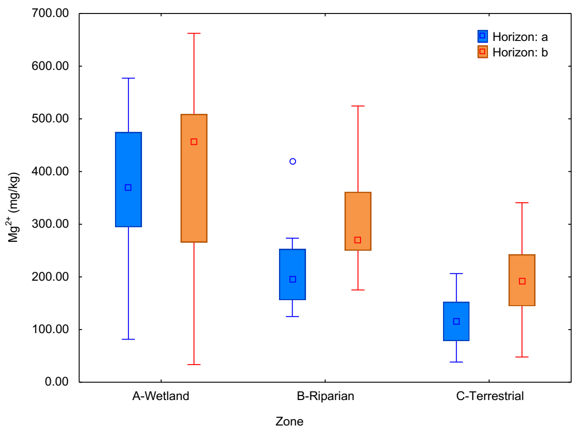

Figure 43: Soil Magnesium content showing upper (a) and lower (b) soil horizons per zone

4.3.3.5. Cation Exchange Capacity (CEC)

In general and similarly to the cations themselves, the cation exchange capacity (CEC) significantly increased into the wetland from the terrestrial soils for the full soil column (H(2,N= 72)=24.21515, p<0.001) (Figure 44). In the upper soils, the wetland soil CEC values were significantly greater than the other two zones but the riparian and terrestrial soils were not statistically different (H(2,N= 36)=2415.81322, p<0.001). The wetland subsoils had a significantly greater CEC than the terrestrial soils only (H(2,N= 36)=11.04196, p<0.01). The sub-soils compared to the topsoils in each zone had a higher CEC in the riparian and terrestrial zones (with only the latter of significance: N=12, p<0.05) (Figure 45). This difference did not apply in the wetland soils where top and subsoils were largely similar (Figure 46). There were two topsoil wetland samples that had extreme CEC values (Figure 45), where the interpretation is unclear as these do not correlate to extreme values of any cation nor soil clay content (Figure 47).

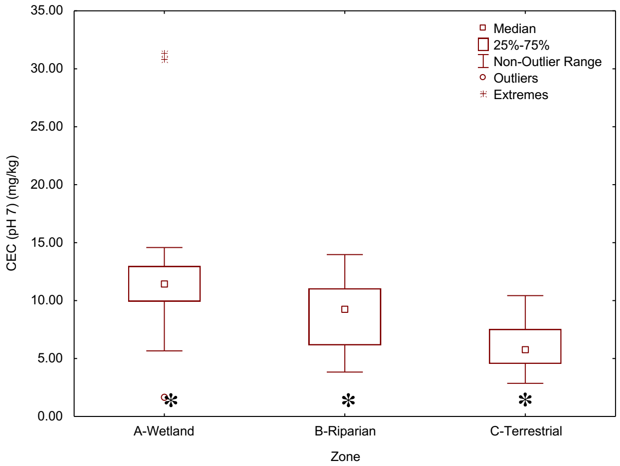

*Figure 44: Cation Exchange Capacity values per zone through both soil horizons; * indicates significance*

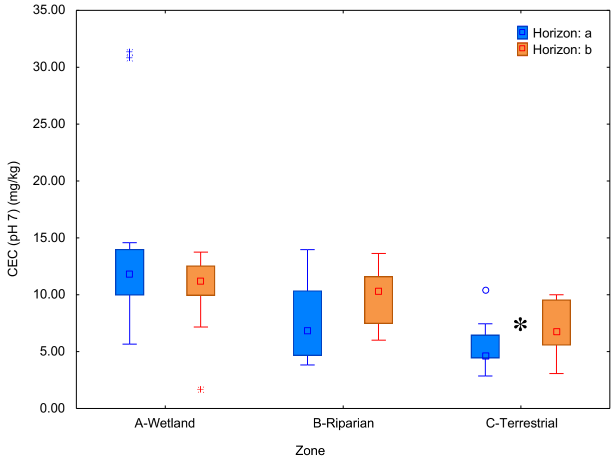

*Figure 45: Cation Exchange Capacity values showing upper (a) and lower (b) soil horizons per zone; * indicates significance between horizons*

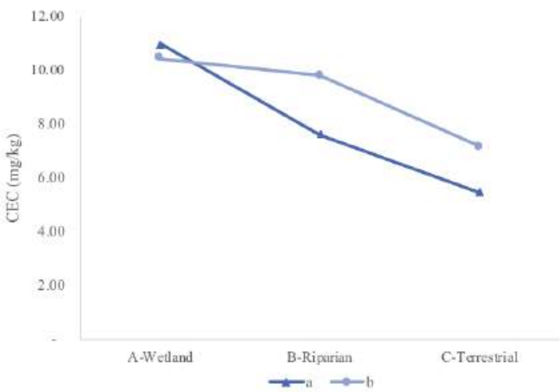

Figure 46: Mean soil Cation Exchange Capacity values per zone, showing upper (a) and lower (b) soil horizons excluding the two extreme values

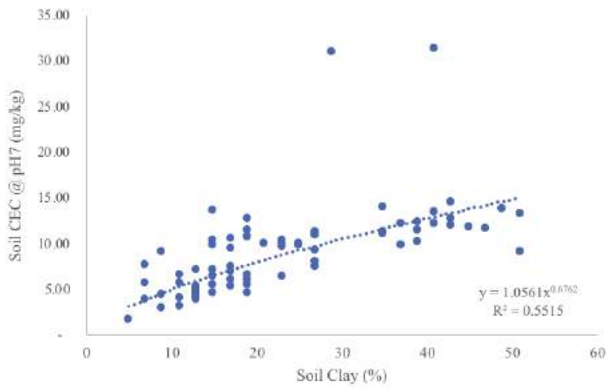

Figure 47: Soil CEC as a function of soil clay content including the two extreme values

4.3.4. Metals: Cu, Zn, Mn and B

The metal content of the soils was not the focus of this research but has been included for completeness. On average, the metal elements copper, zinc and boron significantly increased in concentration into the wetland from the terrestrial soils (Figure 48). Copper and zinc concentrations were significantly different across each zone when assessing the soil profile as a whole; Cu ($H(2,N=72)=43.34210$, $p<0.001$) and Zn ($H(2,N=72)=53.13065$, $p<0.01$). Boron differed significantly as well ($H(2,N=72)=9.152929$, $p<0.01$), where the terrestrial soils were significantly different from the wetland and riparian soils. The range of values also increased along the hydrological gradient and outlier or extreme values were more likely in the wetland soils. A significant pattern was not very discernible for manganese; where the only significant difference was found between the riparian and terrestrial soils ($H(2,N=72)=6.817542$, $p<0.05$).

No significant difference was found between the upper and lower soil profiles within the zones for any of the metals. However, some variance in values was evident where the topsoils had a larger variance (range of values) than the lower soils.

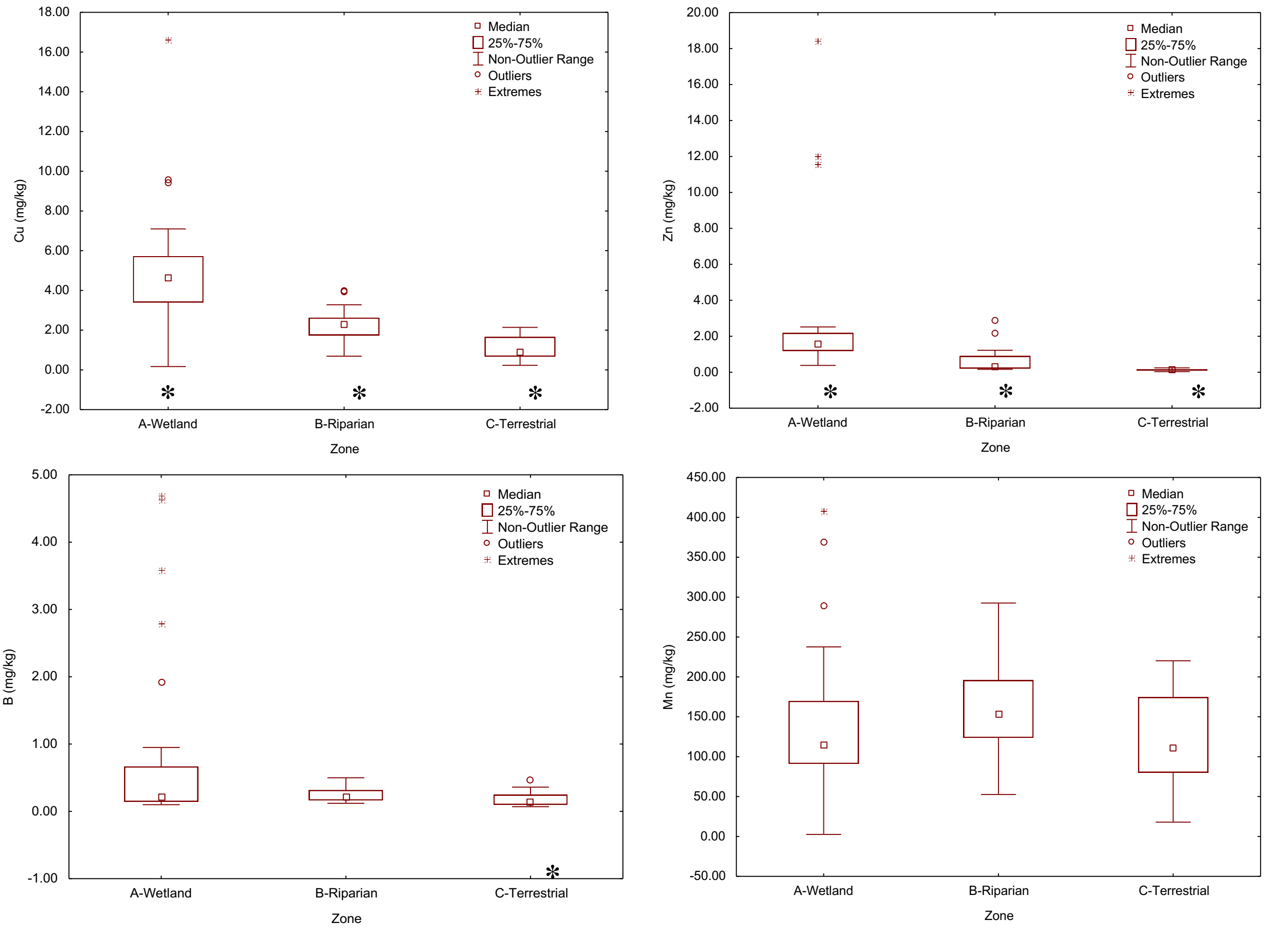

*Figure 48: Concentration of select metals in all soil horizons per zone, * represents significance*

4.4. Water Chemistry (CSIR)

The results of the measured parameters are summarised below (Table 5 - Table 7) for water quality. Interestingly, the pans were found to have low electrical conductivity (± 9mS/m) and salt content (Table 6), which is somewhat in contrast to other ephemeral pans where salt accumulation occurs and leads to high salinity (Allan *et al*., 1995). The pans varied from each other in water chemistry characteristics depending on the parameter. Pan 1 was particularly different from the other pans as some parameters were orders of magnitude greater than the other pans, particularly iron and metals. The rain water in general had much lower values for the water chemistry parameters; however, there were a few exceptions with some pans for select parameters, including iron, sodium, chlorine, total suspended solids (TSS), zinc and aluminium that were high. The high values of iron and aluminium are particularly interesting and are likely representing wet deposition of dust that are possibly being buffered in all pans except Pan 1. These water data represent a snapshot of the pans as their water chemistry is likely to fluctuate throughout the seasons and during the wetting and drying between storm events in the rainy season as seen in other pan systems (Meintjes *et al.,* 1994; de Klerk *et al.*, 2012).

Table 5: Water Chemistry – Key Elements

Parameter		Pan1	Pan2	Pan3	Pan4	Rain sample
Dissolved Organic Carbon	mg/l	61	11	7.4	17	2
Total Nitrogen	mg/l	19	8.6	3.1	1.8	0.9
Total Phosphorus (P)	mg/l	6.2	0.52	0.12	0.19	0.12
Iron (Fe dissolved)	µg/L	152600	1972	67	67	208
Sulphate (SO_4 dissolved)	mg/l	8.4	6.6	6.4	4.1	0.4

Table 6: Water Chemistry – Main quality parameters

Parameter		Pan1	Pan2	Pan3	Pan4	Rain sample
Sodium (Na dissolved)	mg/l	11	2.3	1.6	1.8	2.2
Potassium (K dissolved)	mg/l	44	9.2	6.9	9.4	1.1
Calcium (Ca dissolved)	mg/l	6.9	2.8	4	8.1	0.2
Magnesium (Mg dissolved)	mg/l	17	1.5	2.2	4.3	0.1
Chloride (Cl Dissolved)	mg/l	41	2.2	1.1	1.9	2.9
Electrical Conductivity (EC)	mS/m (25°C)	11	7	7	10	2
Alkalinity as $CaCO_3$	mg/l	38	21	22	41	3.5
Hardness as $CaCO_3$	mg/l	87	13	19	38	<2
Chemical Oxygen Demand	mg/l	76	48	27	48	<5
Total Suspended Solids (TSS)	mg/l	1499	703	378	84	158

Table 7: Water Chemistry – Other metals

Parameter		Pan1	Pan2	Pan3	Pan4	Rain sample
Copper (Cu dissolved)	µg/L	14	6	4	3	<1
Zinc (Zn dissolved)	µg/L	423	6	<2	2	9
Manganese (Mn dissolved)	µg/L	904	8.4	91.9	27.7	17.5
Arsenic (As dissolved)	µg/L	4.3	1	0.8	1.5	<0.5
Cadmium (Cd dissolved)	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5
Lead (Pb dissolved)	µg/l	15.6	0.7	<0.5	<0.5	<0.5
Silicon (Si dissolved)	mg/l	501	9.2	2.8	3.4	1
Aluminium (Al dissolved)	µg/l	232000	4176	224	39	398
Nickel (Ni dissolved)	µg/L	264	15.9	4.6	7.6	2.2
Vanadium (V dissolved)	µg/L	245	2.9	<0.5	<0.5	1

5. Discussion

This research took place in the Limpopo Valley of the Waterberg District, Limpopo Province, South Africa, which is characterised by semi-arid to arid savanna bushveld. Ephemeral endorheic pans are scattered throughout the study area, which are dry for most of the year but flood intermittently and become ‘thriving’ wetlands in this arid landscape. These pans were thus investigated as they represent a change in the local ecology and are expected to be of importance in the savanna landscape. Four carefully selected pans were sampled in the summer rainfall season of 2017 along a transect including three ‘hydro-ecological’ zones, being: the pan centre or wetland area (Zone A), the dense tree zone or “riparian” habitat around the pan (Zone B) and the surrounding representative terrestrial savanna habitat (Zone C). The data gathered includes vegetation species composition and tree density, soil texture and chemistry as well as water chemistry. The results as interpreted and discussed below show that these pans are much higher in soil nutrients and differ in species composition and structure from the surrounding nutrient-poor savanna. This highlights the very important functional role that these pans play in this arid environment with respect to biodiversity and nutrient dynamics.

5.1. Vegetation Structure, Composition and Functioning of the Savanna Habitats

The study area was characterised by less herbaceous biomass than would be expected for the summer rainfall season. Bare soil was prevalent, which differed from neighbouring farms where greater grass biomass was observed, as the overall study area had been very heavily grazed, which limited the use of the herbaceous component for this research. Nevertheless, the herbaceous flora observed in the terrestrial study areas (Zone C) were forbs such as *Limeum*, *Ipomea* and *Tribulis* species with some hardy grass species, including *Aristida* and *Tragus,* which are indicators of stressed veld (van Oudtshoorn, 2012). *Panicum coloratum* and *Urochloa mosambicensis*, which are much more palatable, were also common but only occurred under small trees and shrubs where there was likely more protection from grazing. Whilst the type of species didn’t differ much between the drier terrestrial areas and the ‘riparian’ zone (Zone B), the *Panicum* and *Urochloa* grass species were more common around the pan as there was more shade and protection in the denser Acacia habitat. This may also be in part due to the increased soil nutrient quality found here (discussed in the later section) as these species prefer more fertile soils (van Oudtshoorn, 2012). Grasses that should typically be present in the Limpopo Sweet Bushveld in less overgrazed veld include *Digitatria eriantha* subsp. *eriantha* Steud, *Enneapogon cenchroides* Roem. & Schult, *Eragrostis lehmanniana* Nees and *Schmidtia pappophoroides* Steud. (Mucina and Rutherford, 2012).

The riparian and terrestrial areas differed from each other in woody species composition and structure and the wetland zone was devoid of all trees and shrubs. The terrestrial areas (Zone C) were largely dominated by broad leafed tree and shrub species including *Combretum apiculatum*, *Commiphora pyracanthoides, Boscia foetida* subsp *rehmaniana*, *Grewia flava* and *G. bicolor,* with *Terminalia sericea* and *Sclerocarya birrea* also commonly occurring in the larger area. These species are typically found in well drained, sandy soils and are characteristic of the Limpopo Sweet Bushveld vegetation type of the study area (Mucina and Rutherford, 2012).

However, the vegetation around the pans (Zone B: Riparian) differed in that there were few to no broad-leafed species present but rather a dominance of fine-leafed Acacia species, including *Acacia erubescens, A. grandicornuta, A. mellifera,* and *A. tortillis.* In addition, the Acacia dominated habitat had a higher tree density than the surrounding bushveld, forming closed canopy patches in some areas, which was particularly noticeable from an aerial perspective and was used to identify the location of the pans. Thus, the hypothesis was supported by these results.

The change from a broad-leaf to fine-leaf dominated habitat is important in savanna ecology as it is generally associated with nutrient-poor and nutrient-rich soils respectively, which function quite differently from each other with respect to savanna herbivore behaviour and nutrient dynamics, especially carbon, nitrogen and phosphorus (Scholes and Walker, 1993). The leaves of broad leafed species have a relatively high carbon:nitrogen ratio, which make them less palatable to herbivores but they do however fulfill the "bulk" (carbon) requirement of many herbivores. The fine leaved species, which have a much lower carbon:nitrogen ratio, provide the necessary nitrogen and protein requirements in a herbivores diet and also helps support the herbivores through the nutrient-stressed periods of the year (Scholes, 1990; Scholes and Walker, 1993). Whilst this change in savanna habitat often occurs at geological boundaries or along catenal landscapes (Venter, 1990; Venter *et al*., 2003), it can also occur in small enriched patches (Scholes and Walker, 1993; Grant and Scholes, 2011), such as observed around the pans of the study area. This co-location of broad leafed and fine leafed species thus increases the biodiversity of the vegetation and therefore herbivores, but also most other fauna including invertebrates and bird species (Bell, 1986; Scholes and Walker, 1993).

5.2. Vegetation Structure, Composition and Functioning of the Wetland Habitat

The wetland center of the pans (Zone A) differed from the surrounding zones as it was dominated by wetland grasses, including *Leptochloa fusca* (Swamp Grass) and *Echinochloa colona* (Jungle Rice Grass), which are typical of seasonal pans and are palatable to game and cattle (van Oudtshoorn, 2012). In addition, the water loving forb *Chamaecrista momosoides* was very common and the aquatic floating-leafed herb *Aponogoton stuhlmannii* was present in most pans. Whilst these pans are dry and bare for most of the year, they receive and hold rainwater intermittently during the summer season and provide the wetland habitat that allows these herbaceous species to persist in this semi-arid bushveld. For instance, the large storm event (±80mm) that occurred during the field work resulted in the pans being filled, reaching more than a meter deep in some areas and spilling into the riparian wooded zone. The water of the pans was largely fresh in this study, with low salts, which differs from ephemeral pans of other regions where salt accumulation can occur (Allan *et al*., 1995). It may be of interest to test the water chemistry of these pans between rainfall events to see if this varies as found in other small ephemeral pans in other regions (Meintjes *et al*., 1994; de Klerk *et al*., 2012). These pans will very likely be critical water sources for all fauna in the area; especially given the lack of streams in the relatively flat and dry landscape (Williams, 1985; Goudie and Thomas 1985). Therefore, these pans will attract many game species, likely leading to browsing and grazing being particularly concentrated within and around these pans, which, together with trampling of seedlings, may possibly in part explain the absence of trees and shrubs in the wetland zone. In addition, the seasonal flooding that occurs in these wetlands results in anaerobic conditions (Fey, 2010) and there are very few savanna tree species that can tolerate seasonal anoxia in the rooting zone, thus resulting in the exclusion of woody species (Venter *et al.,* 2003).

5.3. Soil Physiochemical Characteristics along the 'Hydro-Ecological' gradient

The physiochemical properties of the soils differed along the hydro-ecological study gradient from terrestrial to wetland. Whilst some variation was found within the zones, the three broadly defined hydro-ecological zones were found to be valuable in determining the trend from terrestrial to wetland, where in general, the soil fertility, clay content and water holding capacity increased thus supporting the hypothesis. The terrestrial top and sub-soils of the study area (Zone C) were found to be characteristically sandy with an average (±std dev) clay content of 13% (±4%) and 18% (±7%) respectively. This was expected from the Hutton and Clovelly soils that dominated the study area as they largely originate from windblown Kalahari sands (Land type Survey Staff, 1989). On average, the clay content increased to 17% (±7%) and 23% (±8%) in the top and subsoils of the riparian areas around the pan (Zone B) and significantly further into the pans to 34% (±13%) and 35% (±14%) (Zone A) thus becoming clay rich. The increased clay content has a significant positive relationship with percent water holding capacity, which has aided in the surface pooling of rainwater and therefore facilitated the creation of wetland conditions in these pans. Despite having very temporary and unpredictable periods of inundation, these soils were grey in appearance (gleyed), highly structured and sticky when wet, which are characteristics of reduced soils of an anaerobic wetland environment (Fey, 2010). These were in complete contrast to the surrounding red-yellow, apedal, dry, sandy savanna soils of Zone C and that characterise greater savanna area (Land Survey Staff, 1989; Mucina and Rutherford, 2012).

The dry (terrestrial) soils in the study area had an overall low nutrient content of all measured parameters, particularly carbon, nitrogen, phosphorus and sodium when compared to other semi-arid to arid savannas (Scholes and Walker, 1993; Tessema *et al*., 2011; Khomo *et al*., 2011). Low soil fertility is typical of sandy soils as they are highly permeable and do not retain nutrient inputs (Miller and Donahue, 1990) and thus the increase in clay content and soil moisture associated with the pans of the study area has resulted in a significant relative increase in soil fertility. The average carbon content of the terrestrial topsoils (0.37±0.09%) increased linearly into the pan (0.77±0.28%), which was similarly observed for nitrogen in the topsoils (0.043±0.01% to 0.073±0.03%). The topsoils expectedly had greater concentrations for both carbon and nitrogen than the subsoils (30-60cm) as they are receiving the inputs of carbon & nitrogen from aboveground sources and organic processes in the litter layer. Phosphorus is also a key often co-limiting nutrient in arid savannas and grassland systems (Scholes and Walker, 1993; Craine *et al*., 2008), which was on average very low in the terrestrial topsoils (4.4±1.1mg/kg) and subsoils (1.6±1.2mg/kg) of the study area. Phosphorus, however, increases roughly exponentially into the pans as their average and range of concentrations increase almost tenfold. The findings are indicating that these pans are acting as concentrators of phosphorus (and nitrogen), where the pan *subsoils* have the largest range of Phosphorus concentrations overall (2 to 40 mg/kg). The savanna soils, in Zones B and

C of the study area, are thus more strongly water, nitrogen, carbon and phosphorus limited, where the pans (Zone A) are relatively high in all of these.

Similarly, soil iron content was low in the dry topsoils (43.6±12.3 mg/kg) and the sub-soils (32.6±8.8 mg/kg), which also increased roughly exponentially into the pans, reaching an average and range of concentration ten times those of the other zones. Furthermore, there are some very high values of phosphorus in the wetland and riparian soils (±70 mg/kg) and these are predominantly correlated with very high iron concentrations (±900 mg/kg). As these findings were mostly associated with Pan 1, this pan may possibly have an iron rich base such as ferricrete influencing the soil chemistry as ferricrete was observed in the overall study area. Sulphur is also an important element in soils, where soluble sulphur remained more-or-less constant along the hydrological gradient in the topsoils (12±5.8mg/kg) and subsoils (13±8.5mg/kg). Whilst limited comparative data are available for soil sulphur, it is expected that this may become of increasing relevance as anthropogenically enhanced nitrogen and sulphur deposition into the study area will increase due to the burning of coal for power generation, possibly leading to soil acidification. Previous work has indicated that the vegetation of this area is likely to respond variably to sulphur additions, and thus possibly leading to some changes in vegetation composition and structure (Flood, 2015). However, the soils of the study areas were found to be somewhat acidic as the terrestrial soils ranged from a pH of 3.7 - 4.8 and the wetland soils from pH 4.1-4.9. Interestingly, the riparian zone was found to have a significantly elevated pH with a range of 4.1 – 5.6. The pH of soils may require further investigation.

Base cations including sodium, potassium, magnesium and calcium (Na^+, K^+, Mg^{2+} & Ca^{2+}) are important nutrients and chemical constituents in soils. These are generally not seen as major limiting nutrients in dry savannas due to their greater vulnerability to leaching in wetter soils, which can accumulate from high evaporation in precipitates such as calcrete or result in saline or sodic soils (Scholes & Walker, 1993). The dry terrestrial soils of Zone C had low concentrations of these cations typical of similar nutrient-poor sandy savannas (Venter *et al*., 2003; Khomo *et al*., 2011); however, the sodium content was exceptionally low (topsoils:8.6 ±2.9mg/kg and subsoils: 10.3±3.9 mg/kg). Of particular importance in dry savannas, however, is the ratio between the monovalent (mainly sodium) and divalent cations combined with the clay content as this can alter soil structure as with a greater concentration of divalent cations, the clay particles aggregate into sand-sized units instead of repelling each other, thus facilitating vertical movement of water. Whereas, when sodium is high, this can cause clay particles to flocculate and prohibit water movement savanna soils (Venter, 1990; Scholes & Walker, 1993). With such a low sodium content, this may likely result in divalent cations dominating, which will further facilitate the sandy free-draining nature of these soils. Importantly, all the cations increased significantly along the study gradient, where their concentration at least doubled from terrestrial to wetland soils along with clay content. Calcium and magnesium are relatively high in Pan 3 and 4, which can be explained by the calcrete that was observed at the soil surface. Despite this, these pans and the surrounding savanna soils overall are relatively low in these base cations and this is reflected in the low salinity of the water in the pans and may also be playing a role in the unexpectedly low pH of the soils.

5.4. The Pans as Nutrient-Rich Hotspots with Conservation Significance

The ephemeral pans studied in this research are important water sources that are associated with abrupt and small (0.5 to 5 ha) patches of fine-leafed nutrient-rich habitats within the nutrient-poor broad-leaf dominated arid savanna matrix. Therefore, not only are these pans important wetlands, but they are creating changes in the savanna species *composition and structure*, which is thus expected to result in differing *functioning* of these habitats. The nutritious Acacia-dominated (nutrient-rich) patches around the pans, as well as the highly palatable wetland grasses in the pan, will likely result in these habitats being favourable forage sites for game (Grant & Scholes, 2006; Treydte *et al*., 2011). A greater density of game will likely lead to soil enrichment from defecation and urination, thus creating a positive feedback mechanism together with the litter-fall, which can even occur under a single Acacia tree (Dean *et al*., 1999). This has also likely to have played a role in the evolution of these pans in this landscape, where increased densities of game may lead to relative overgrazing on these soils, thus limiting vegetation and exposing the soils to wind erosion in dry seasons and droughts (Goudie & Thomas, 1985). Furthermore, the precipitation of minerals and accumulation of nutrients in these non-perennial pans due to the effects of evaporation can possibly be transported out of the system by wind and be deposited in the surrounding terrestrial landscape (Kotze et al., 2009), leading to the local enrichment of the surrounding zones.

These pans are thus critical habitats to take into account for management interventions as, being preferential forage sites and key water sources, they will be the first to show signs of degradation. This has been observed in similarly enriched hotspots associated with sodic soils and termite mounds (Grant and Scholes, 2011). Moreover, these temporary wetlands will be supporting a greater diversity of avifauna including wetland birds such as flamingoes, which will likely use these pans as stop over points (Simmons *et al*., 1999). These pans are abundant in the Limpopo plains and in some areas form wetland clusters that are identified as having critical biodiversity value in the broader area (Nel *et al*., 2011; Driver *et al*., 2012), which are likely still to be undervalued given the lack of ecological understanding of these pans in the savanna landscape. Therefore, these wetlands and enriched savanna patches are increasing the heterogeneity and biodiversity of the area and thus these pans should be priority monitoring sites for managers and also targeted for conservation protection as they are playing a disproportionately large role in the ecological functioning of this landscape.

6. Conclusion and Future Research

This study has shown the small ephemeral pans of the Limpopo plains in the Waterberg District to be locally enriched habitats within an otherwise nutrient-poor savanna matrix that differ in habitat composition and structure. This highlights the very important functional role that these pans will likely play in this arid environment with respect to biodiversity and nutrient dynamics as well as the provision of water. This research has also added to the knowledge on pans in South Africa, which have been increasingly being recognised as important and diverse wetlands, particularly in arid regions. It is hoped that this research will be used to motivate the importance and sensitivity of these pans in the broader ecosystem, particularly in the context of the planned industrial development in the study area.

The focus of future research that may follow on from this baseline assessment should look to better describe the ecological importance and functionality of these pans in the broader landscape as well as better quantifying their ecosystem services. The research should assess more pans and compare pans across the different geologies in the area. Including more data from the terrestrial savanna matrix between the pans may shed light on the role of these nutrient hotspots in the landscape as well. Sampling at a finer scale along and within the study zones herein may give insight into the hydro-ecological gradient that exists or a more detailed understanding of the nutrient dynamics in the identified zones, which could be done in difference seasons. In addition, future research could include faunal studies, particularly macro-invertebrates, and/or look at other potential nutrient hotspots in the ecosystem, such as termite mounds, to broaden the understanding of the ecological role of these systems in the savanna landscape. Furthermore, the uses of the drone aerial imagery could be further investigated and it is likely that many more applications to ecological research are possible.

7. References

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