Assessment of Soil Degradation in a Palustrine Wetland and the Implication on its Water Purification Potential

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Abstract

This study determined the extent of degradation of soils in Khubelu wetland in Lesotho and the impact this may have on its water purification potential. Seventy-two soil samples were collected at different sites and depths around the wetland and characterised for different properties. The values of these properties were then used to determine the chemical degradation index (CDI) of the wetland soils. The soils were non-saline as reflected by the electrical conductivity (EC) values (<0.25 mS/cm), mostly acidic (4.5 < pH < 5.22) with moderate organic matter content (2.06–3.9 %). These soil properties varied with depth and from upstream to downstream of the wetland. Values for soil CDI were 3.42, 3.25 and 3.06 for soils from upstream, midstream and downstream of the wetland, respectively, indicating a decrease in soil degradation from upstream to downstream. The dominance of emergent vegetation in the Khubelu wetland may indicate a potential to get rid of sediments in influents into the wetland but the soil characteristics may present a challenge with regards to the removal of nutrients and organic and inorganic pollutants from these influents. The characteristics of the soils and the extent of soil degradation present some challenges in the performance of the Khubelu wetland as a water purification system especially with regards to nutrients and organic and inorganic pollutants.

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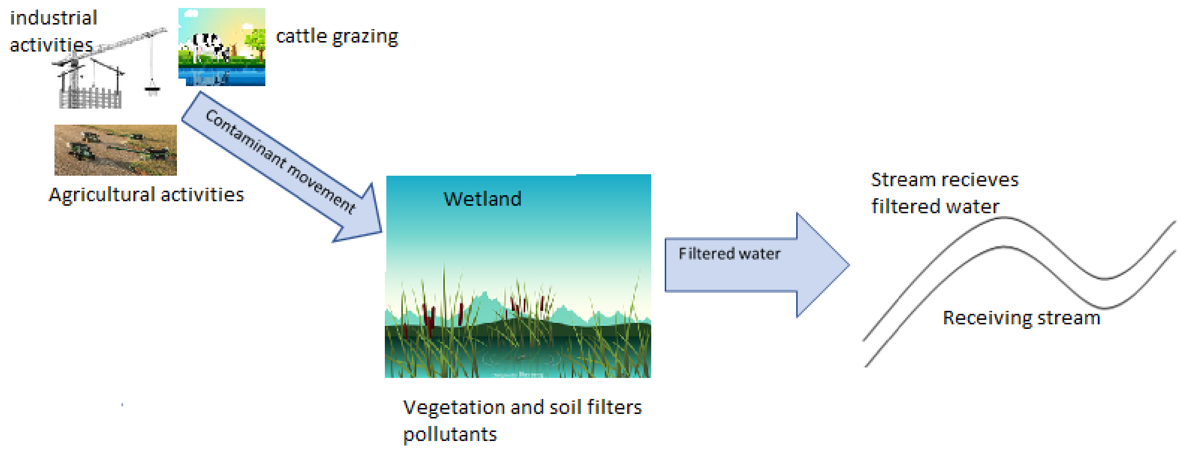

Khubelu wetland soil and vegetation were characterised to determine the wetland's water purification potential. Soils properties varied with depth, and from upstream to downstream of the wetland with emergent vegetation dominating the wetland. Soil degradation was highest upstream and lowest downstream. Khubelu wetland needs to be properly managed to reduce soil degradation and enhance its water purification potential.

Keywords: Chemical degradation index; Contaminant sorption; Emergent vegetation; Sediment trapping; Water Quality, Wetland ecological function

1. INTRODUCTION

Wetlands cover up to 6% of the earth's land surface [1] and perform significant ecological functions where they occur. They retain water during the rainy season, but release it when conditions become drier, hence their description as sponges [2, 3]. Wetland ecosystem functions include water purification, floodwater storage, groundwater recharge, carbon storage, biodiversity support, sediment trapping, and pollution control. Water purification by wetlands remains their most exploited function. According to Huang et al. [4], water purification by wetlands refers to the removal of contaminants such as organic and inorganic compounds, nutrients, and sediments from water entering the wetland. Both natural and constructed wetlands, because of their ability to purify water, are widely used in the treatment of effluents of domestic and industrial origins before their eventual discharge into streams, rivers, and other freshwater reservoirs.

Studies by Díaz et al. [5] show that wetlands can remove up to 99 and 96%, respectively, of nitrate and total suspended solids from influents. The role of nutrients in the development of eutrophic conditions in freshwater bodies and the consequences of eutrophication on water quality and human health have been widely documented [6, 7]. Töre et al. [8] have highlighted the efficiency of wetlands in the removal of endocrine disruptive compounds including personal care products (30–96%), pharmaceuticals (16–99%), bisphenol A (80–100%), and polyaromatic hydrocarbons (60–70%) which compromise water quality and human health should they be exposed to these compounds. Sediments, according to Nasrabadi et al. [9] and Pourabadehei and Mulligan [10], are vectors of potentially bioavailable contaminants in water. In addition, they are stressors of benthos because they negatively impact light penetration in water bodies as a result of increased turbidity, reducing primary productivity of benthic zone autotrophs. Wetlands can remove sediments from influents because of their inherent ability to slow down the velocity of water moving through the wetlands, and the filtration ability of vegetation found therein.

Processes involved in the removal of these contaminants by wetlands from incoming water include sedimentation, chemical precipitation, adsorption, uptake by vegetation, microbial interaction, and filtration, most of which are mediated by wetland soils and vegetation [11, 12]. Wetland soils differ from terrestrial soils because of the anaerobic conditions caused by persistent saturation. They are hydric in nature and are characterized by redoximorphic conditions, low chroma, high clay and organic matter contents, and low pH values. These wetland soil characteristics influence the biogeochemical and water purification processes which take place in these unique ecosystems. The high soil clay and organic matter contents enhance their ability to sorb ionic contaminants from water infiltrating them, thereby acting as filters. Both anaerobic and aerobic conditions occur in wetland soils making them a highly dynamic environment as far as their chemical and biological processes are concerned. The alternation between anaerobic and aerobic biogeochemical processes taking place in the wetland contributes to their ability to retain nutrients that may be contained in water, thus reducing the potential of eutrophic conditions developing downstream [13, 14]. Where wetland soils are degraded, these soil processes are affected with consequences on the progression of processes involved in the purification of water and ultimately the quality of water delivered to rivers and streams served by the wetland. Degradation in wetland soil which could occur naturally or caused by anthropogenic activities such as intensive agricultural activities, climate change, and water deficiencies, include changes in soil nutrient properties, salinity, total nitrogen and carbon contents, as well as organic matter [4]. These changes may influence wetland soil processes and its water purification potential.

The Khubelu wetland in Lesotho is a montane palustrine wetland which sustains the Lesotho Highlands Water Project (LHWP) through the Orange-Senqu River Basin. The LHWP supplies water to the Vaal River in South Africa and any compromise in the health of this wetland may impact water quality in South Africa and neighbouring countries. Anthropogenic activities including overgrazing and overharvesting of wetland resources are threatening this wetland and may result in their degradation. In addition, the undulating nature of surrounding topography of the Khubelu wetland may contribute to high erodibility of the soils in the area which may further compromise the wetland in terms of sediment load. Most studies on wetlands have focused on microbial diversity [15], and wetland plant structure [16]. A few studies [17, 18] have characterized wetland soils but not many studies have focused on wetland soil degradation and how it may affect its water purification function.

This study is aimed at determining the degradation status of the soils in Khubelu wetland and understanding the impact that this may have on the wetland's ability to remove chemical pollutants, sediments, and nutrients from the water it discharges into surrounding rivers. The extent of soil degradation is determined using the chemical degradation index (CDI) of soil developed by Huang et al. [4]. Several soil quality indices have been used to investigate various land and soil conditions. According to Andrews et al. [19], the approach of using soil quality indices for monitoring the effects of various practices on soil functions is a reliable method as it integrates physical, chemical, and biological properties of the soil. Chemical degradation index of soils employs the three main requirements proposed by Andrews et al. [19] for soil indices, which include using a minimum data set, transformation of indicators to scores, and combining the scores into an index. Different soil properties play different roles in the maintenance of soil quality. The CDI of soil uses multivariate statistical techniques to determine the smallest set of these chemical, physical and biological soil properties that account for most of the variability observed in the soil. According to Andrews and Carrol [20], the use of multivariate statistical analyses techniques in the determination of indicator scores minimizes bias and transferability of the index. In the determination of CDI of soils, weights are given to each soil property to reflect their influence on soil quality for the specific purpose under consideration. These weights are then used in the calculation of the CDI instead of the values of the soil properties obtained during analyses. Huang et al. [4] used CDI to determine the degradation status of soil and his studies indicated that CDI scores for degraded wetland soils are usually higher than those for undegraded wetland soils.

2. MATERIALS AND METHODS

2.1 Study area

The study was carried out in Khubelu wetland located in North-Eastern Lesotho, with geographic coordinates of 29°1′19.10″S and 28°52′26.01″E (Fig. 1). The wetland covers an area of 0.52 km^2 with minimum and maximum elevations of 2984 and 3019 m, respectively. Lesotho's climate is generally sub-humid to temperate cool, with warm, rainy summers and cool to cold dry winters [21]. The mean annual precipitation in the area ranges from 500 mm in the Senqu Valley to 1200 mm in the north and eastern parts of the country [21]. 85% of rainfall in the area is received between October and April, with frost and snow being common in winter. Basaltic parent material of alluvial origin characterises the Khubelu wetland [22], and due to its formation on steep ridges, the soils in the study area are poorly developed with high erodibility. Khubelu wetland has been utilised by communities in the catchment as a grazing area, putting it under immense pressure. As a result of overgrazing, vegetation cover in the area is declining and signs of erosion are evident. This has threatened sustained water supply to Khubelu River.

2.2 Soil samples collection

Wetland soil samples were collected from eight sampling sites: four of the eight sites (SS2, SS3, SS4 and SS7) were upstream, two sites (SS6 and SS8) were midstream, and the other two sites (SS5 and SS9) were downstream of the wetland (Fig. 2). The downstream region of the wetland is where the wetland empties into Khubelu River. At each of the eight sites, three cores were placed within a 2 m radius. 500 g of soil samples were collected at three depths 0--15, 15--30, and 30--45 cm from each of the cores using an auger. These depths were chosen to characterise the variations in soil properties with depths around the wetland. A total of 72 soil samples were collected from the sampling sites into separate labelled vacuum bags after which they were transported to the laboratory. The soil samples were air-dried, plant roots and stones removed, then crushed using a porcelain mortar and pestle, sieved through a 2 mm mesh sieve, and analysed for various soil properties.

2.3 Soil sample analyses

All soil samples were characterised for their texture, electrical conductivity (EC), cation exchange capacity (CEC), organic matter (OM) content, pH, available phosphorus (P), total carbon (TC) and total nitrogen (TN) using standard methods. For the determination of soil texture, the Bouyoucos hydrometer method was used to determine weight percent of sand, silt and clay in the samples [23], after which soil texture was determined using the textural triangle. A 1 M KCl/soil suspension, 2:1 (v/w), was used for the determination of soil pH as described by Hendershot et al. [24] whereas the water extract of the soil was used to measure soil EC.

Soil available P was extracted using 0.03 M NH_4F and 0.025 M HCl (Bray and Kurtz No. 1 solution) and the content of P was measured using colorimetry. In this procedure, the phosphorus extracted from the soil by the solution reacts with ammonium molybdate, to produce a blue phospho-molybdate complex. The colour enables the colorimetric determination of phosphorus since the intensity of the blueness of the phospho-molybdate complex is proportionate to the amount of phosphorus contained in the soil [25, 26]. The CEC of the soil samples was determined by summation of the exchangeable Ca, Mg, K and Na contained in the soils. These exchangeable bases were extracted using 1 M ammonium acetate [23] after which their concentrations in the extracts were determined using atomic absorption spectrometry. The values of exchangeable Ca, Mg, K, and Na were then summed up to give an estimate of the CEC of the soil samples.

A LECO CN 628 analyser with a furnace temperature setting of 950°C was used to determine total carbon (TC) and total nitrogen (TN) in 100 mg of each soil sample [27]. Results from TN and TC were then used to calculate the C/N ratio of the soils. Loss-on-ignition (LOI) method was used for OM determination. In this method, initial combustion of soil samples takes place for 30 min at 105°C to dehydrate the soil in order to prevent overestimation of soil organic matter (SOM) [28]. The samples are then heated for 3 h at 550 °C in a muffle furnace [29].The percentage of OM in the soil samples is calculated as percentage loss in weight before and after heating the sample in the furnace. All analyses were performed in duplicate with sample and reagent blanks included. The analyses made use of internal laboratory standards for quality control purposes.

2.4 Wetland vegetation characterisation

Vegetation cover across the wetland was determined using 1 m^2 size quadrats [30, 31]. Eight quadrats were randomly placed upstream, seven midstream, and another eight downstream of the wetland to represent the different sections of the wetland. Vegetation species within each quadrat was counted repeatedly and an average of the number of species in each of the counts was used to determine species abundance within each quadrat [32]. The type of vegetation within the quadrats was assessed with the help of the Cowardin vegetation class reference which describes vegetation classes as emergent, scrub/shrub, forest and aquatic bed [30]. These different vegetation types are scored 1.0, 0.8, 0.3 and 0.0 for emergent, scrub/shrub, forest and aquatic bed vegetation, respectively, with regards to their ability to filter out sediments in wetlands [30]. The Cowardin classification gives emergent vegetation a score of 1 in the assessment of a wetland's ability to remove sediments because it is erect, and closer to the ground [31] and is therefore able to trap sediments. This vegetation is also dense enough to reduce water velocity and gives support to microbial population for decomposition of organic contaminants [32, 33].

2.5 Data analysis

The mean of each soil property was determined, and one-way ANOVA with Tukey's Honest significance difference (HSD) post-hoc test was used to determine differences in the mean values of soil properties between depths and from one site to the other after ensuring that the data satisfied the assumptions of ANOVA. Differences in mean values for the various properties between upstream, midstream, and downstream sections of the wetland were also determined using ANOVA, but Tukey Kramer post-hoc test was used since the sample sizes from the upstream, midstream and downstream sections of the wetland were unequal. All analyses were carried at a 95 % confidence limit and an alpha value of 0.05.

The extent of soil degradation in the Khubelu wetland and how this varied from upstream to downstream was determined using the CDI of soil. The CDI was determined using Eq. (1) as described by Andrews et al. [19], Fu et al. [34], Ghaemi et al. [35], and Gvozdić et al. [36].

$$\mathrm{CDI} = \sum W_{\mathrm{i}} Q(X_{\mathrm{i}}) \qquad (1)$$

where W_i is the weight vector for the soil property and $Q(X_i)$ is the membership value for each soil property, determined according to Eqs. (2) and (3).

According to Wang [37], weights for soil indicators could be assigned using experience, mathematical statistics, or models. This study made use of principal component analysis (PCA) with Varimax rotation to determine the weights for each soil indicator as proposed by Fu et al. [34] and to generate factor loadings for the different soil properties [4, 35]. These factor loadings were then substituted in Eq. (1) as weight vectors (W_i) for each of the soil properties [34]. Only factor loadings >0.5 in components with Eigen values > 1.0 were used [19]. The membership value of each soil property was determined according to Eqs. (2) and (3) [4, 34].

$$Q(X_{\mathrm{i}}) = \frac{X_{\mathrm{ij}} - X_{\mathrm{i\,min}}}{X_{\mathrm{i\,max}} - X_{\mathrm{i\,min}}} \qquad (2)$$

$$Q(X_{\mathrm{i}}) = \frac{X_{\mathrm{i\,max}} - X_{\mathrm{ij}}}{X_{\mathrm{i\,max}} - X_{\mathrm{i\,min}}} \qquad (3)$$

where x_{ij} is the mean value for each soil property, and $x_{i\,min}$ and $x_{i\,max}$ are minimum and maximum values for each of the soil properties in the study.

Equation (2) was used to determine the membership value for those soil properties which would have high values in undegraded soil, whereas Eq. (3) was used for the determination of membership values for soil properties which would have high values if the soil was degraded. The choice of which soil property is calculated with either equation was based on the roles of these soil properties in various soil processes as they relate to vegetation growth and contaminant sorption. Wetland soil sorption and vegetation characteristics play a major role in water purification. In this study, soil CEC, OM, TN, TC and P were considered to have high values in undegraded soils because of their positive impact on plant growth and contaminant sorption, so their membership values ($Q(X_i)$) were determined using Eq. (2). Soil EC, Na and Ca were considered to have high values in degraded soils because of their negative effect (salinity and crusting) on plant growth, therefore, Eq. (3) was used to determine their membership values ($Q(X_i)$). Chemical degradation index was determined for soils from upstream, midstream and downstream of the wetland to understand how soil degradation varied at different areas of the wetland, and for the whole Khubelu wetland, to determine how degraded the wetland soils generally were. According to Huang et al. [4], CDI values between 2.80 and 4.36 indicate a degraded wetland soil, whereas soils with CDI values between 0.49 and 1.92 indicate an undegraded wetland soil. The effects of the extent of soil degradation on the water purifying ability of the wetland were then inferred.

3. RESULTS AND DISCUSSION

3.1 Physicochemical properties of the wetland soils

Sand and silt contents in the soils were higher than clay contents, with clay content being below 25% in all samples (Table 1). The soils were therefore classified as either sandy clay loam, or loamy, or sandy loam soils as indicated in Table 1. Similar textural properties were obtained in soils from natural wetlands in Pennsylvania by Campbell et al. [38]. The soils showed an increase in the quantities of clay and decrease in sand content with depth around the wetland, which is typical of most soil profiles due to lessivage. The textural properties of Khubelu wetland soils imply good drainage which could allow the seepage of water down to the water table. This may be good for groundwater recharge in the area but if the water is contaminated, it could contribute to the introduction of contaminants into the aquifer.

Soil EC values were all <0.45 mS/cm (Table 1) with significant differences in EC values from one site to the other ($p = 0.03$). The soils in Khubelu wetland could therefore be described as non-saline as soil EC values were all below the EC threshold (400 mS/m) of soils described as saline. Soil EC decreased with depth as indicated in Fig. 3a ($p = 0.001$). A similar pattern of a decrease in wetland soil EC with depth was observed by Raza et al. [39]. Significant differences were observed in the EC of the soils from upstream to downstream ($p = 0.02$) with highest mean values recorded midstream (Fig. 4a).

The pH values of soils around the wetland (Table 1) were all acidic. Differences in soil pH values from one site to the other (Table 1) were insignificant ($p = 0.29$). A similar pH range of 4.37 to 5.88 was recorded by Rasekoele et al. [17] in Khalo-La-Lithunya wetlands, with Olaleye [40] observing a range of 4.69 to 5.44 for wetlands in Butha-buthe and Ha Matela in Lesotho. The acidic pH of the soils is typical of wetland soils because of the prolonged and frequent saturation conditions that these soils are subjected to. Frequent saturation of wetland soils results in lack of oxygen and reduction of NO_3, Mn^{4+}, Fe^{2+} and SO_4^{2--}. It also results in accumulation of CO_2, N_2O, H_2S, CH_4 and humic substances in the soils. According to Bianchini Junior et al. [41] all these have the potential to acidify soils as a result of the release of protons. The acidic conditions of the wetland soils are therefore explained. Insignificant differences were observed in soil pH with increasing soil depth around the wetland (Fig. 3b) (p = 0.015), but significant pH increases were observed from upstream to downstream of the wetland (Fig. 4b).

Soil OM content around the wetland varied as indicated in Table 1 and Fig. 2, with OM content in soils at site SS2 being significantly lower than OM content in soils from sites SS4, SS7, SS8 and SS9 (p = 0.0008). Organic matter content in the surface soils was significantly higher than in lower depths around the wetland ($p < 0.05$) (Fig. 3c). High OM in surface soils has been attributed to high density of plant roots, litter fall and microbial decomposition processes in surface soils. Organic matter content in the downstream soils was also significantly higher than what was observed in soils upstream (p = 0.01) (Fig. 4c). Similar values and patterns for wetland soil OM have been reported by Ren et al. [42]. High OM content in wetland soils is usually associated with high biological productivity.

Values for CEC ranged between 4.04 and 4.42 meq/100 g (Table 1), which are all within the range of CEC of soils dominated by sand particles and primary minerals. Differences in CEC from one site to the other were insignificant (p = 0.42) but slight differences were observed from one depth to the other with soil CEC decreasing with depth (Fig. 3d) ($p < 0.05$). This pattern of soil CEC with depth is similar to what was obtained for OM content in the soils. According to Ngole-Jeme [43], soil CEC is determined by its clay content, clay fraction mineralogy and OM content, with CEC of OM being up to six times higher than the CEC of clay. Despite the high OM content of the soils, the CEC was low, and this could be attributed to the pH of the soils. Soil organic matter has pH-dependent charges which increase with soil alkalinity but decrease as the soil becomes more acidic due to protonation and deprotonation of functional groups contained in organic matter. The acidic nature of the wetland soils would have resulted in lower negative charge density because of deprotonation of the functional groups contained in OM at lower pH values. It could also be an indication that the OM in the soils may not have formed complexes but occur as loose organic material which might not be contributing to the overall charge of the soils. Similar observations have been made by Ngole-Jeme [43]. Results from this study show an increase in CEC values in soils from upstream to downstream, similar to what was observed with soil OM and pH (Fig. 4d). These trends in OM content and CEC of the soils from upstream to downstream may favour increased sorption of nutrients and contaminants as water moves from upstream to downstream of the wetland.

3.2 Nutrient characteristics of the wetland soils

The highest value for P content in the wetland soils was 0.34 mg/kg whereas the lowest was 0.11 mg/kg (Table 2). These values are very low compared to what has been reported in other wetland studies [44, 45]. Available P content in the soils fluctuated with depth (Fig. 5a) and from upstream to downstream of the wetland (Fig. 6a) (p = 0.02). Highest mean values of available P were recorded midstream of the wetland. Significant differences were observed in TC and TN content around the wetland (p = 0.05 for TN and $p < 0.05$ for TC) (Table 2). Values for mean TN and TC decreased with depth (Fig. 5b) but only differences in TC with depth were significant (p = 0.04). Mean TN values increased from upstream to downstream of the wetland whereas TC decreased (Fig. 6b and c). Similar observations have been reported in wetland studies carried out in other countries. Li et al. [46] and Wang et al. [47] reported a decreasing trend in TC across the Zhalong wetland and wetlands running into Qingcaosha Reservoir whereas a decreasing TN was observed in a wetland in Jimma Ethiopia in a study by Sileshi et al. [48]. Soil C and N are expected to show some relationship with soil OM content. In this study, as expected, a strong correlation between wetland soil OM with TC ($r = 0.74$) and TN ($r = 0.85$) further justifies the patterns of TC and TN observed.

The C/N ratios of the soil samples ranged between 6 and 12, which is lower than what was reported by Wang et al. [7]. Carbon/nitrogen ratios also decreased with depth, similar to what was reported by Wang et al. [7] in coastal wetland soils. Soil C/N ratios regulate soil quality and organic matter dynamics through its influence on soil microbial activity and mineralisation of nutrients, especially N. According to Prescott [49], the critical C/N ratio for net nitrogen (N) mineralization is between 25 and 30, or 1.7–2.5%. The low rates of C/N ratios obtained in the wetland soils could indicate a rapid rate of microbial N mineralisation in the wetland, which may affect the amount of N delivered by the wetland to receiving rivers. There were no differences in C/N values with depth as C/N values were 9.6 ± 0.4 at depths of 0–15 cm, 8.0 ± 0.8 at depths between 15 and 30 cm, and 8.2 ± 0.8 at depths between 30 and 45 cm. The C/N ratio of the soils were 10.4 for upstream soils, 8.9 for midstream soils and 6.6 for downstream soils, indicating a decrease in C/N ratio from upstream to downstream.

3.3 Wetland vegetation cover

The wetland had emergent vegetation, which according to Hruby et al. [32] has a higher ability to trap sediments. The dominant emergent vegetation around the wetland was *Ranunculus meyeri* covering 50% of the wetland, followed by *Harplocarpha nervosa* covering 30%, while *Scirpus*, *Lobelia* and *Oxalis depressa* species covered the remaining areas. *Ranunculus* is a drought-tolerant species but vulnerable to overgrazing. Most parts of the wetland were therefore bare due to the heavy grazing activities going on in the wetland. The rate of removal of nutrients like nitrates and phosphates by vegetation in the wetland is therefore reduced because of the sparce vegetation cover in the wetland. The low density of emergent vegetation in the wetland also presents a challenge in the ability of the wetland to reduce water velocity, which may contribute to accelerated rates of erosion within the wetland. *Harplocarpha* is a water-loving species, but it covered an insignificant area of the wetland. The ability of the vegetation to trap sediments is therefore also low.

3.4 Extent of degradation of the wetland soils

A total of four components with Eigen values > 1 were obtained from PCA of the soil properties. These four components accounted for 83.9 % of the total variance observed in the soil properties (Table 2). Only component loadings >0.5 in components 1, 2, 3 and 4 were considered for further analyses [50]. The component loadings of the different soil properties which served as weight vectors and the membership values determined using Eqs. (2) and (3) are presented in Table 3. In the determination of membership values, the role of the various soil properties in vegetation growth and soil sorption were taken into consideration. The values for CDI are therefore assumed to be a reflection of soil degradation with regards to vegetation growth and soil sorption, which play significant roles in wetland water purification. The Khubelu wetland soil CDI was 3.29 (Table 3) which is within the range of CDI values of degraded wetland (2.80 and 4.36) according to Huang et al. [4]. Khubelu wetland soil degradation was highest upstream and lowest downstream with CDI values for soils from upstream, midstream and downstream of the wetland being 3.42, 3.25 and 3.06, respectively (Table 3). These soil CDI values indicate a decrease in wetland soil degradation from upstream to downstream. They also mirror the pattern displayed by the soil properties where the soils in the downstream section of the wetland showed a higher sorption capacity based on its soil properties compared to the soils from upstream.

3.5 Implication of soil CDI on wetland water purification function of Khubelu wetland

Water purification by wetlands is determined by the wetland's ability to remove sediments, nutrients, organic, and inorganic contaminants from interstitial water, reducing these to the threshold values allowed for discharge into streams and rivers. The CDI values of the wetland soils indicate that the soils are degraded. According to Benitez et al. [51], a degraded wetland does not have fertile soil for vegetation growth, and nutrient and pollutant regulation. Wetlands trap sediments when the velocity of the water passing through the wetland is reduced, and if filtration of sediments takes place. Sediment trapping and filtration are facilitated by wetland vegetation. Though wetland soils have no direct role to play in the removal of sediments, they do so indirectly through their role in vegetation growth. Poor wetland vegetation structure may present a threat to its ability to trap sediments and absorb nutrients. It could also promote erosion of sediments, increasing the sediment load of the receiving streams. Results from the analyses of the vegetation cover of the Khubelu wetland indicate that the wetland had no shrub and forest vegetation but was dominated by emergent vegetation which covered 100% of the vegetated parts of the wetland. Emergent vegetation according to Faithful [31, 51] is erect, close to the ground, and dense enough to reduce water velocity and contributes significantly towards sediment trapping and filtration.

Nutrient removal in wetlands is also influenced by the abundance of emergent species in the wetlands as this vegetation absorbs nutrients like N and P, reducing their amount in the wetland waters. Organic matter also binds nutrients because the organic forms of most plant nutrients, including N and P, are immobile and unavailable for uptake. Emergent vegetation according to Hruby et al. [32] and Wantzen et al. [33] is always in contact with the soil giving this vegetation type the opportunity to sequester nutrients and pollutants from the wetland water. Adsorption, desorption and precipitation reactions in wetland soils are influenced by soil pH, redox conditions, clay, OM content, organo-clay mineral complexes formed and CEC [52, 53]. The results in this study show that the soils have high OM content but a characteristic low CEC. The low CEC and the prevailing acidic conditions of the wetland soils may contribute towards an increase in contaminant mobility within the soil environment and their eventual release into interstitial water. Low clay content of the Khubelu wetland soil implies reduced sorption capacity which may result in minimal removal of toxic organics through adsorption, with subsequent leaching into the stream.

4. CONCLUSIONS

Wetland soil properties play significant roles in the purification of water in wetlands. This study has revealed that the soils in Khubelu wetland vary from one area to the other, and also from one depth to the other within the wetland. The existing vegetation is dominated by emergent species but most of the wetland is bare due to grazing activities. The bare soils together with poor vegetation upstream of the wetland may be contributing towards high velocity of water, increasing the erosivity of storm water. This may consequently decrease the ability of the wetland to purify water running through it, threatening water quality of the receiving streams. Values for CDI indicate that these soils are degraded, and the extent of degradation decreased from upstream to downstream of the wetland. Sound management practices, which would curb wetland soil degradation, need to be put in place to reduce the discharge of nutrient and contaminant-rich water into nearby streams from the wetland.

Conflicts of Interest:

The authors have declared no conflict of interest.

REFERENCES

[1] W.J. Junk, S. An, C.M. Finlayson, B. Gopal, J. Květ, S.A. Mitchell, W.J. Mitsch, R.D. Robarts, *Aquat. Sci.* **2013**, 75, 151.

[2] B. Seelig, S. DeKeyser, Water Quality and Wetland Function in the Northern Prairie Pothole Region, North Dakota State University, North Dakota **2006**.

[3] J.W. Mitsch and J.G. Gosselink, Wetlands, John Wiley & Sons, New York **2007**.

[4] C. Huang, J. Bai, H. Shao, H. Gao, R. Xiao, L. Huang and P. Liu, *CLEAN – Soil Air Water* **2012**, 40, 1125.

[5] F.J. Díaz, A.T. O′Geen and R.A. Dahlgren, *Agric. Water Manage.* **2012**, 104,171.

[6] C. van Ginkel, *Water SA* **2011**, 37, 693.

[7] J. Wang, J. Bai, Q. Zhao, Q. Lu, Z. Xia, *Sci. Rep.* **2016**, 6, 21137.

[8] G.Y. Töre, S. Meric, G. Lofrano, G. De Feo, Removal of Trace Pollutants from Wastewater in Constructed Wetlands, in *Emerging Compounds Removal from Wastewater*: (Eds: G. Lofrano), Springer, Dordrecht **2012**, p. 39.

[9] T. Nasrabadi, H. Ruegner, M. Schwientek, J. Bennett, S. Fazel Valipour, P. Grathwohl, *PLOS ONE* **2018**, 13, e0191314.

[10] M. Pourabadehei, C. Mulligan, *Chemosphere* **2016**,153,58.

[11] P. Wu, H. Zhang, L. Cui, K. Wickings, S. Fu, C. Wang, *Sci. Rep.* **2017**, 7, 837.

[12] C.R. Jackson, J.A. Thompson, R.K. Kolka, Wetland Soils, Hydrology, and Geomorphology, in *Ecology of freshwater and estuarine wetlands, (Eds*: B. D., R. Sharitz), University of California Press, Berkeley, CA **2014,** p. 23

[13] C.A. Johnston, N.E. Detenbeck, G.J. Niemi, *Biogeochemistry* **1990**,10, 105.

[14] C.C. Trettin, R.K. Kolka, A.S. Marsh, S. Bansal, E.A. Lilleskov, P. Megonigal, M.J. Stelk, G. Lockaby, D.V. D'Amore, R.A. MacKenzie, B. Tangen, R. Chimner, J. Gries, Wetland and Hydric Soils, in *Forest and Rangeland Soils of the United States Under Changing Conditions: A Comprehensive Science Synthesis*, (Eds: R.V. Pouyat, D.S. Page-Dumroese, T. Patel-Weynand, L.H. Geiser), Springer International Publishing, Cham **2020**, p. 99.

[15] L. Lamers, J. Van Diggelen, H. Op Den Camp, E. Visser, E. Lucassen, M. Vile, M. Jetten, A. Smolders, J. Roelofs, *Front. Microbiol.* **2012,** 3,156.

[16] G. Agegnehu, P.N. Nelson, M.I. Bird, *Soil Tillage Res.* **2016,** 160,1.

[17] M. G. Rasekoele, B. Mapeshoane, M. Masopha, M.B. Khoeli, T. Nkheloane, M. Mokhatla, T.P. Mots'oane, M. Mots'ets'e, *Afr. J. Rural Dev.* **2017**, 2, 293.

[18] A.W. Cheesman, B.L. Turner, K.R. Reddy, *Biogeoscience* **2014,** 11,6697.

[19] S.S. Andrews, D.L. Karlen, J.P. Mitchell, *Agric. Ecosyst. Environ.* **2002**, 90, 25.

[20] S.S. Andrews, C.R. Carroll, *Ecol. Appl.* **2021,**11,1573.

[21] LMS, Climate of Lesotho, Kingdom of Lesotho **2013**.

[22] DWA, Lesotho National Wetlands Management Programme. Ministry of Water, Government of Lesotho **2005**.

[23] L.P. Van Reeuwijk, Procedures for soil analysis, Technical paper, 9, International Soil Reference and Information Centre (ISRIC), Wageningen, The Netherlands **2002**, 92.

[24] W. Hendershot, H. Lalande, M. Duquette, Soil reaction and exchangeable acidity, in *Soil Sampling and Methods of Analysis*, (Eds: M. Carter), Lewis Publishers, Boca Raton, Florida, USA **1993**.

[25] R.H. Bray, L.T. Kurtz, *Soil Sci.* **1945**, 59, 39.

[26] J. Kovar, G. Pierzynski, Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters, Southern Extension/Research Activity - Information Exchange Group (SERA-IEG 17), Virginia Tech University, Blacksburg, Virginia, USA **2009**.

[27] T. Purakayastha, D.R. Huggins, J.L. Smith, *Soil Sci. Soc. Am. J.* **2008**, 72, 534.

[28] A. Chatterjee, R. Lal, L. Wielopolski, M.Z. Martin, M.H. Ebinger, Evaluation of Different Soil Carbon Determination Methods, *Crit. Rev. Plant Sci.* **2009**, 28, 164.

[29] M.J.J. Hoogsteen, E.A. Lantinga, E.J. Bakker, J.C.J. Groot, P.A. Tittonell, *Eur. J. Soil Sci.* **2015**, 66, 320.

[30] J. Brummer, J. Nichols, R. Engel, K. Eskridge, *J. Range Manage.* **1994**, *41,* 84.

[31] P. Vittoz & A. Guisan, J. Veg. Sci. **2007**, 18, 413

[32] M. Mahajan, & S. Fatima, *Int. J. Multidiscip. Res.* **2017**, *3,* 21.

[33] L.M. Cowardin, V. Carter, F.C. Golet and E.T. LaRoe, Classification of Wetlands and Deepwater Habitats of the United States, U.S. Fish and Widlife Service, Washington DC **1979,** 131.

[31] J.W. Faithful, The fate of phosphorus in wetlands: a review, Queensland. Department of Natural, Research, Queensland, Australia **2015**, p. 53.

[32] T. Hruby, T. Granger, K. Brunner, S. Cooke, K. Dublanica, R. Gersib, L. Reinelt, K. Richter, D. Sheldon, E. Teachout, A. Wald, F. Weinmann, Methods for Assessing Wetland Functions Riverine and Depressional Wetlands in the Lowlands of Western Washington, WA State Department Ecology, Washington, USA, Volume I, **1999**.

[33] K.M. Wantzen, C.M. Yule, J.M. Mathooko, C.M. Pringle, Organic Matter Processing in Tropical Streams, in *Tropical Stream Ecology,* (Eds: D. Dudgeon)*,* Academic Press, London **2008**, p. 43.

[34] B.-J. Fu, S.-L. Liu, L.-D. Chen, Y.-H. LÜ, J. Qiu, *Ecol. Res.* **2004**, 19, 111.

[35] M. Ghaemi, A. Astaraei, H. Emami, M. Nassiri-Mahallati, S.H. Sanaeinejad, *J. Soil Sci. Plant Nutr.* **2013**, 14, 987.

[36] V. Gvozdić, N. Malatesti, D. Roland, *J. Hydroinf.* **2012**, 14,1051.

[37] X. Wang, Application of soil taxonomic classification in the evaluation of soil resources, Science Press, Beijing **1994**.

[38] D.A. Campbell, C.A. Cole, R.P. Brooks, *Wetlands Ecol. Manage.* **2002**, 10, 41.

[39] S. Raza, Z. Ali, I. Zainab, S. Safdar, A. Nimra, Z. Zaidi, K. Aziz, *J. Anim. Plant Sci.* **2015**, 25, 1168.

[40] A.O. Olaleye, Isotopic Signatures (δ13C and δ15N) and Characteristics of Two Wetland Soils in Lesotho, Southern Africa, in: D. Gokce (ed.), *Wetlands Management - Assessing Risk and Sustainable Solutions*, IntechOpen, London, UK **2019,** 13.

[41] I. Bianchini Junior, M. Cunha-Santino, J. Ribeiro, D. Penteado, *Braz. J. Biol.* **2014**, 74,100.

[42] J. Ren, Li, B. Mao, Z. Wang, H. Jia, G. Chen, *Sustainability* **2020**,12,932.

[43] V.M. Ngole-Jeme, *Ambio* **2016**, 45, 374.

[44] Y. Liu, M. Jiang, X. Lu, Y. Lou, B. Liu, *Wetlands* **2017**, 37, 153.

[45] E.J. Dunne, M. Clark, J. Mitchell, J. Jawitz, K. Reddy, *Ecol. Eng.* **2010**, 36,1392.

[46] H. Li, G. Zhang, G. Sun, *Sci. China Technol. Sci.* **2012**, 55, 1973.

[47] Q. Wang, F.-Y. Wan,g L.-H. Xiong, *J. Sustainable Urbanization Plann. Prog.* **2017,** 2, 16.

[48] A. Sileshi, A. Awoke, A. Beyene, I. Stiers, L. Triest, *Front. Environ. Sci.* **2020,** 8, 1.

[49] C.E. Prescott, H.N. Chappell, L. Vesterdal, *Ecology* **2000**, 81, 1878.

[50] S. Fathy, F. Abdel Hamid, M. Shreadah, L. Mohamed, M. El-Gazar, *Res. Environ.* **2012**, 2, 297.

[51] E. Benitez, R. Nogales, M. Campos, F. Ruano, *Appl. Soil Ecol.* **2006**, 32, 221.

[52] P. Biswas, T. Bhattacharya, A. Chanda, S. Das, S. Hazr, *Int. J. Recent Sci. Res.* **2018**, 9, 2(F), 24158.

[53] D. Zhu, H. Zhong, *J. Environ. Sci.* **2015**, 36, 48.

Table 1: Mean values of soil physico-chemical properties around the Khubelu wetland

Sampling site		Wt %			Texture	pH	EC (mS/cm)	CEC (meq/100 g)	OM (%)
		Sand	Silt	Clay					
Upstream	**SS2**	72.2	18.9	9.3	Sandy loam	5.13 ± 0.02	0.10 ± 0.06	4.04 ± 0.12	2.06 ± 0.21
	SS3	52.7	31.07	16.7	Sandy loam	4.96 ± 0.09	0.13 ± 0.02	4.16 ± 0.23	2.11 ± 0.28
	SS4	68.0	16.0	16.0	Sandy loam	5.02 ± 0.09	0.13 ± 0.06	4.09 ± 0.07	2.83 ± 0.59
	SS7	50.7	26.6	22.7	Sandy clay loam	5.03 ± 0.13	0.24 ± 0.04	4.07 ± 0.07	3.90 ± 0.49
Midstream	**SS6**	66.0	16.0	18.0	Sandy loam	5.02 ± 0.05	0.13 ± 0.07	4.37 ± 0.19	2.20 ± 0.4
	SS8	50.8	35.9	13.3	Loam	5.11 ± 0.14	0.25 ± 0.07	4.40 ± 0.08	3.34 ± 0.34
Downstream	**SS5**	67.7	16.3	16.0	Sandy loam	5.16 ± 0.15	0.10 ± 0.05	4.15 ± 0.05	2.16 ± 0.58
	SS9	57.3	26.2	20.0	Sandy loam	5.22 ± 0.01	0.20 ± 0.08	4.42 ± 0.11	2.77 ± 0.56

Table 2 Component loadings of the different soil properties

Variable	Principal component			
	1	2	3	4
$pH_{(in\ KCl)}$	0.284	0.510	0.348	0.642
Avail P	--0.090	--0.417	0.782	--0.183
Ca	0.687	0.371	--0.088	--0.391
Mg	0.384	0.708	--0.385	--0.108
K	0.263	0.701	--0.025	--0.249
Na	0.204	0.178	0.801	--0.337
CEC	0.526	0.792	--0.088	--0.176

EC	0.902	0.179	0.254	0.123
TN	0.897	--0.209	0.022	0.249
TC	0.853	--0.367	--0.010	0.018
OM	0.849	--0.076	0.013	0.338
Eigenvalue	5.245	3.373	2.037	1.096
Total variance %	37.467	24.091	14.547	7.831
Cumulative variance %	37.467	61.558	76.105	83.936

Table 3: Weight vectors and membership values of the different soil properties

Soil property	Weight vector	Membership value			
		Upstream	Midstream	Downstream	Entire wetland
pH	0.51	0.41	0.56	0.40	0.46
EC	0.90	0.71	0.50	0.50	0.79
CEC	0.79	0.70	0.67	0.52	0.72
OM	0.85	0.37	0.50	0.51	0.34
Ca	0.69	0.57	0.45	0.47	0.39
Na	0.80	0.69	0.46	0.44	0.69
TN	0.90	0.38	0.51	0.50	0.37
TC	0.85	0.5	0.50	0.50	0.39
CDI		3.42	3.25	3.06	3.29

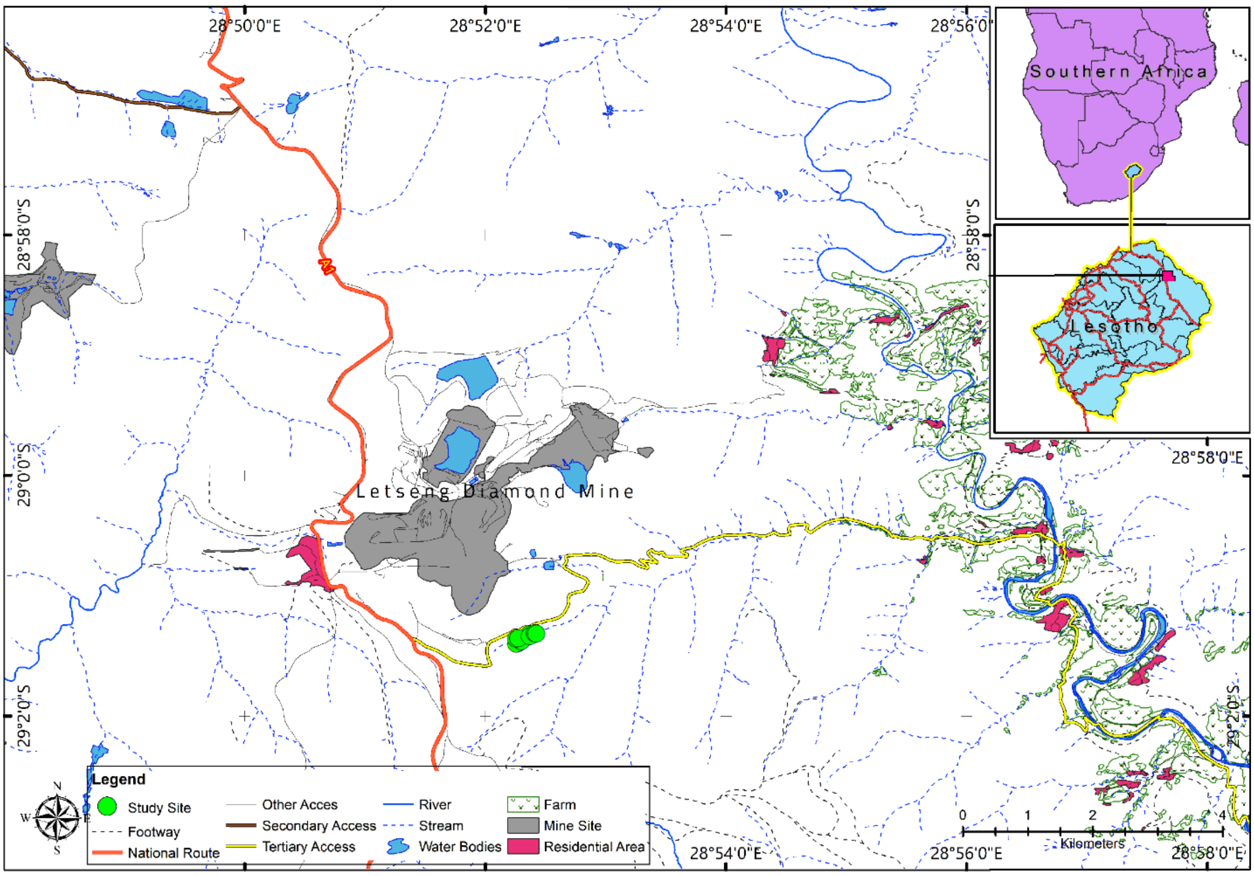

Figure 1: Map showing the location of Khubelu Wetland.

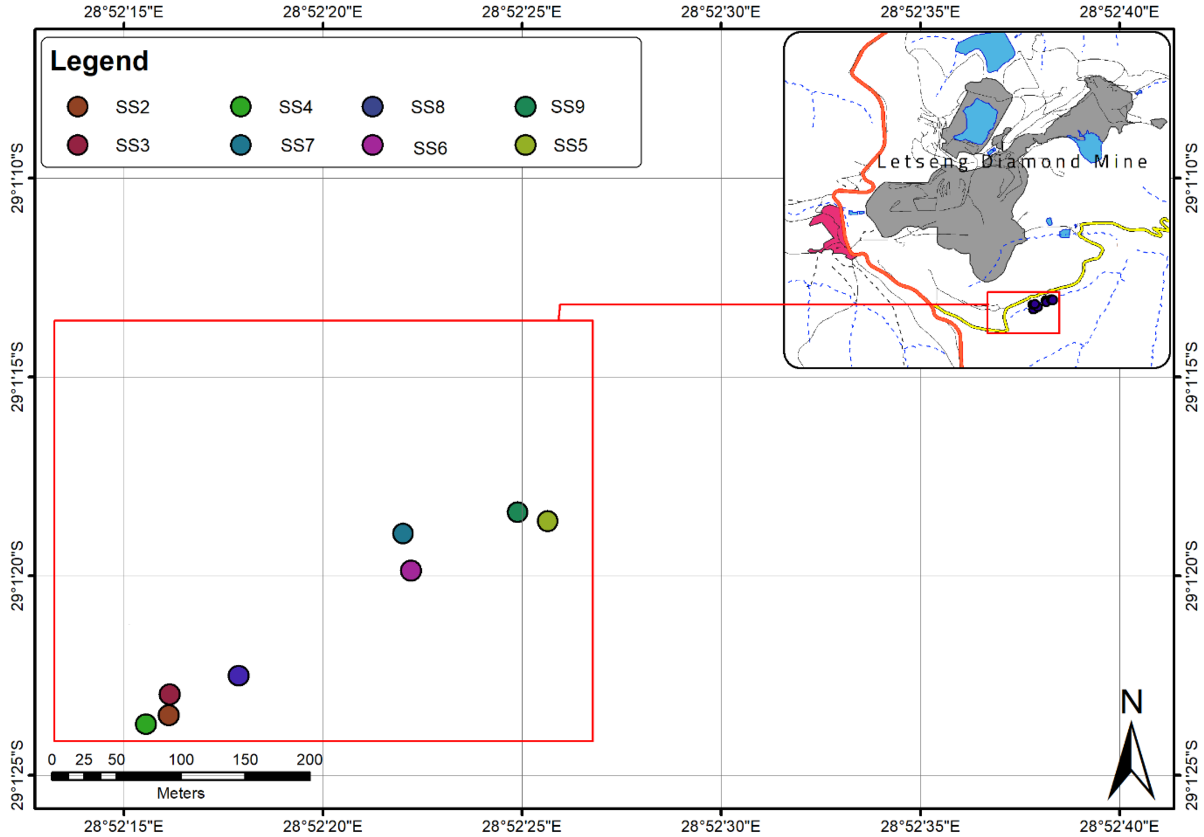

Figure 2: Map of Khubelu wetland showing sampling sites

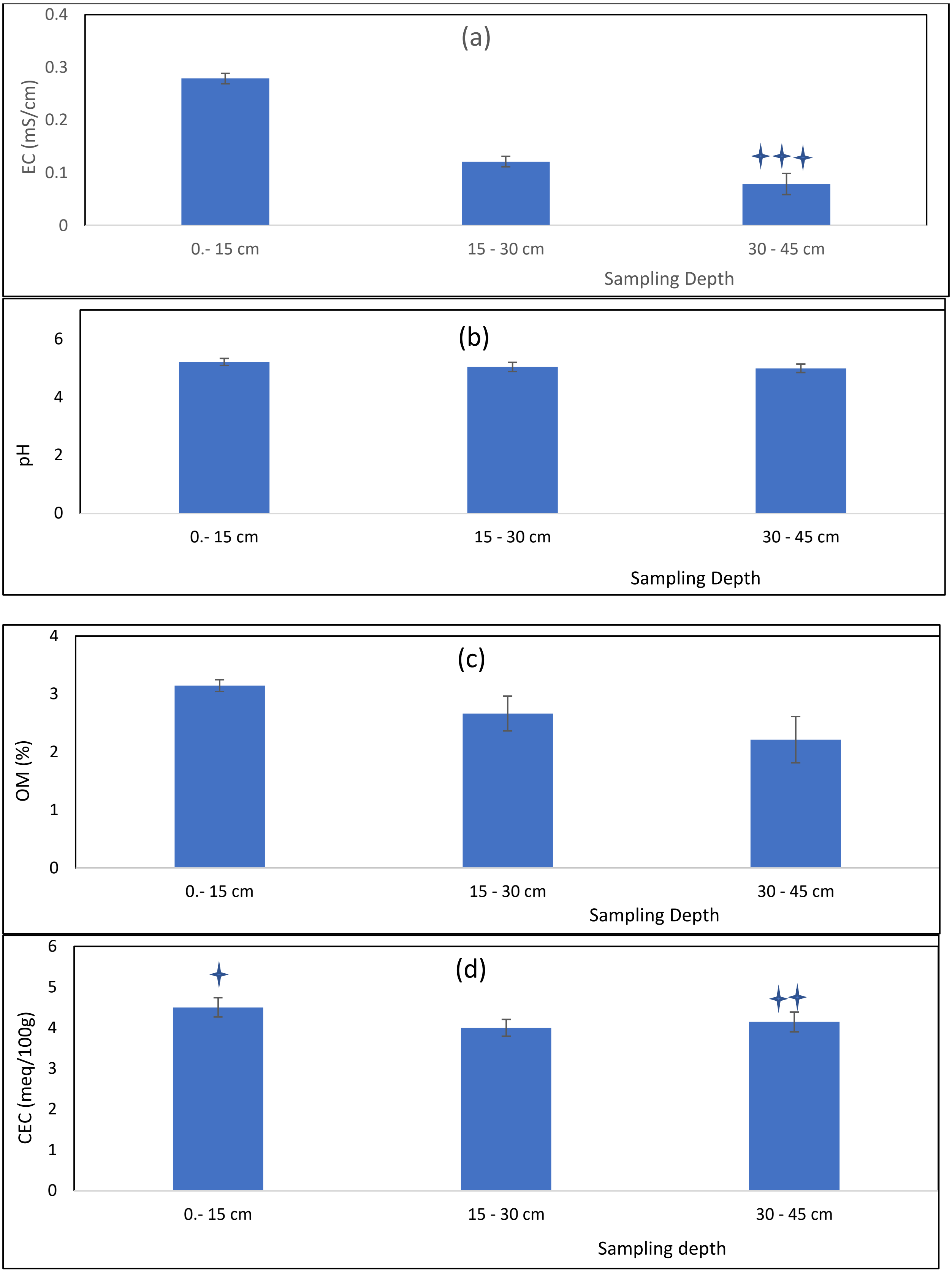

Figure 3: Variation of soil physico-chemical properties with depth around the wetland

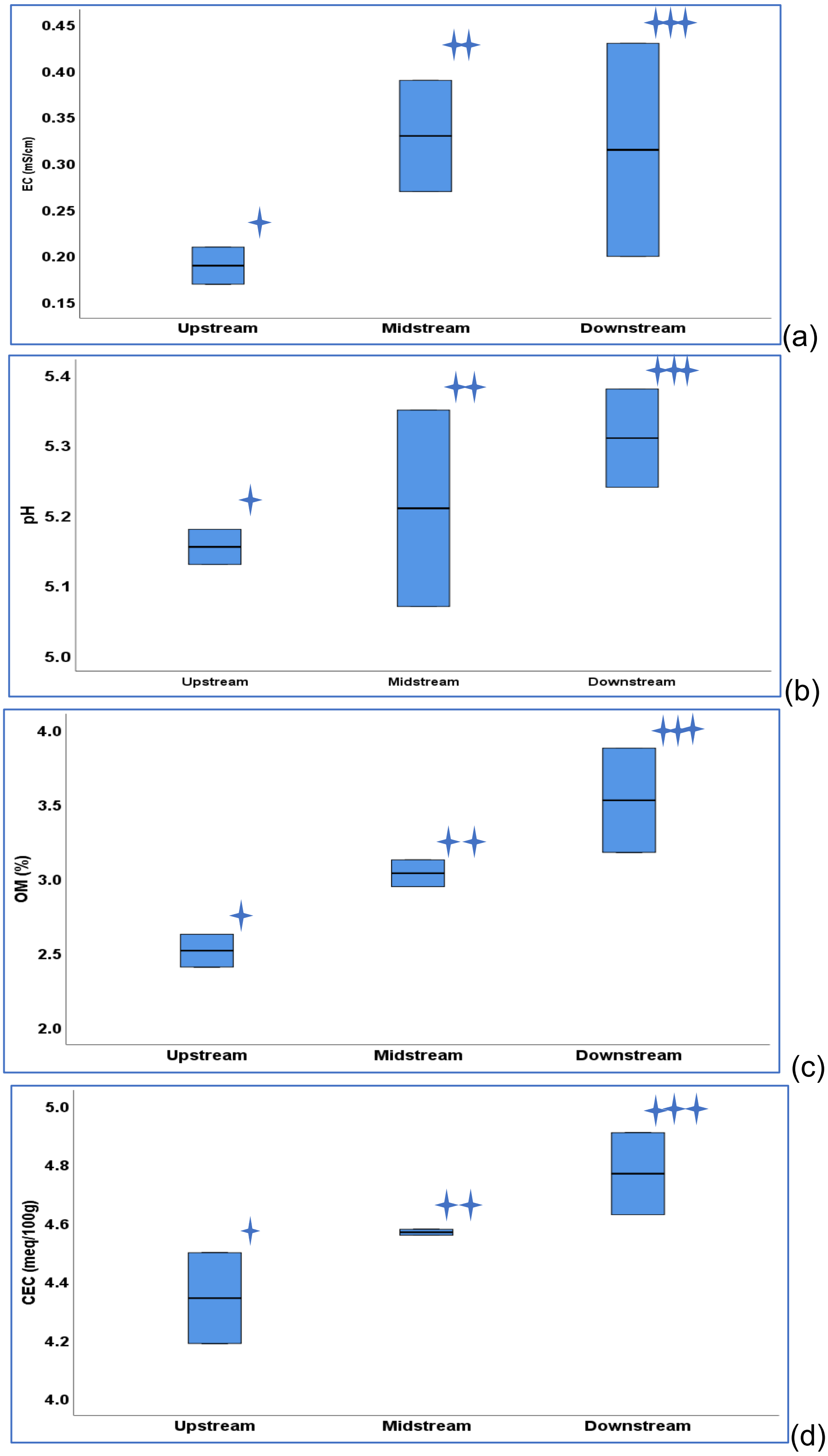

Figure 4: Mean values of wetland soil properties showing their variation from upstream to downstream of the wetland

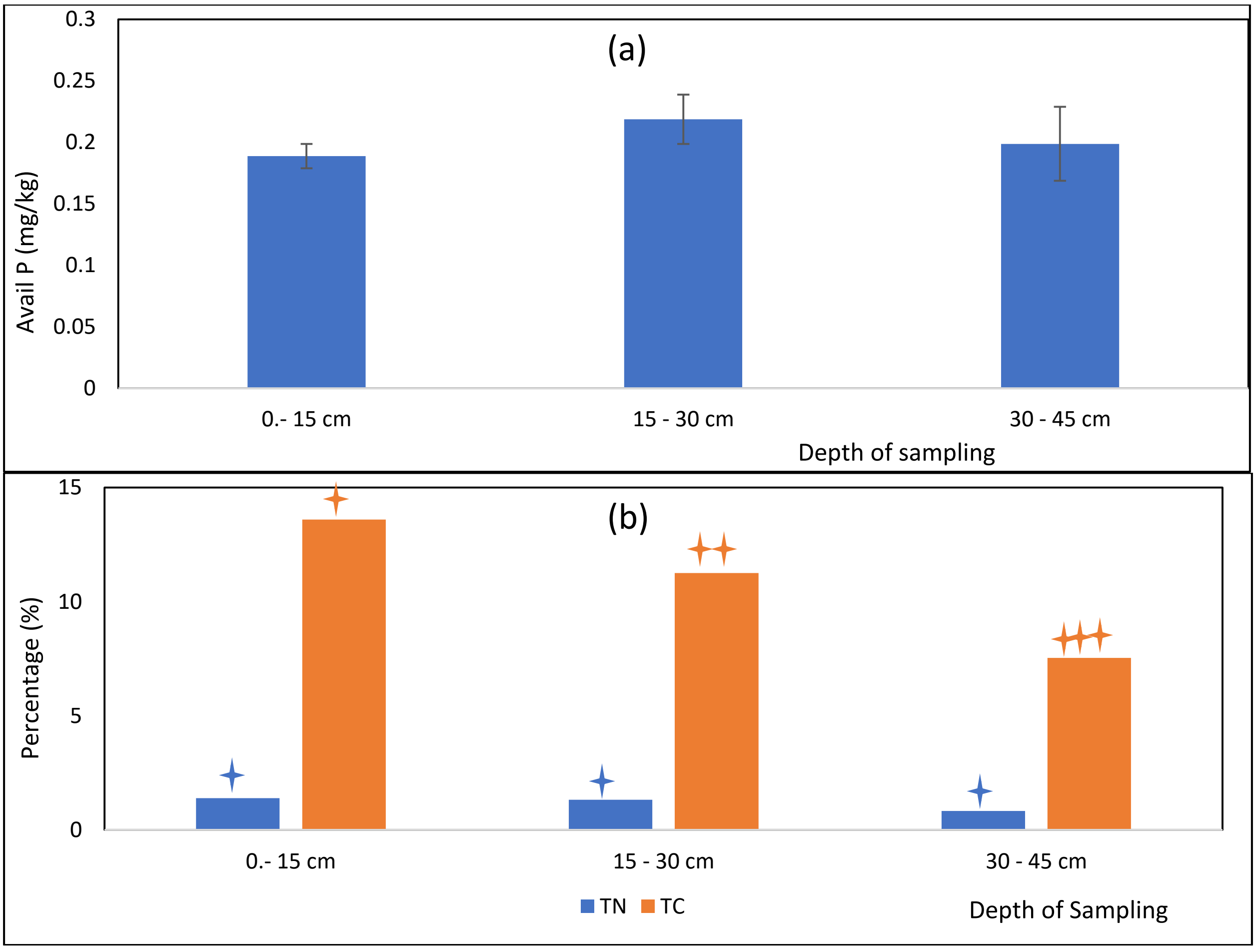

Figure 5: Variation of Mean values of soil Total carbon and nitrogen with depth around the wetland

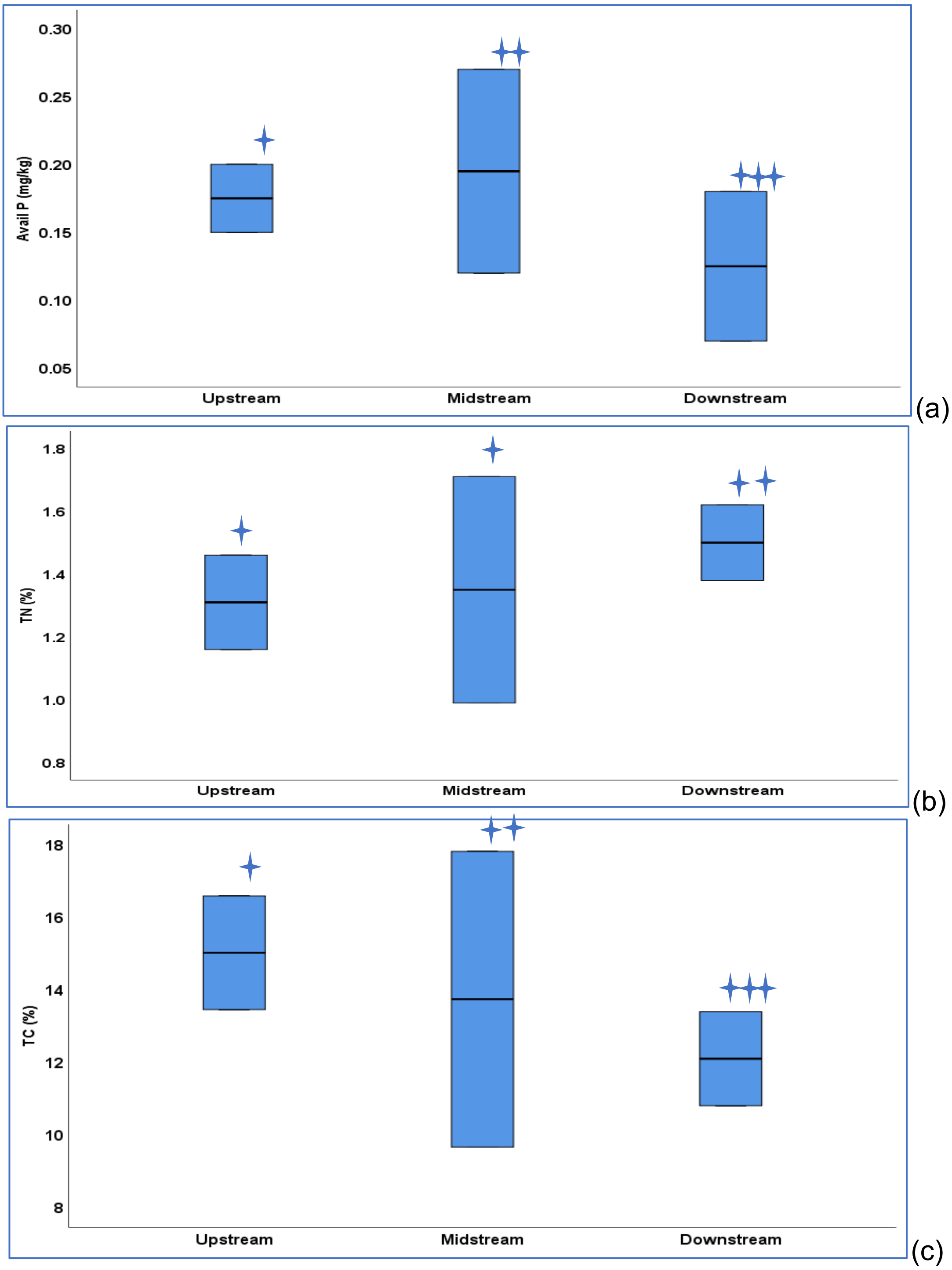

Figure 6: Variation of mean values of soil nutrients from upstream to downstream the wetland