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Research Article

The Physicochemical Properties of Deposited Sediments at the Maruba Dam Reservoir Inlet, Machakos County, Kenya

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Energy and water are the two most important natural resources in the globe. In this regard, dams and reservoirs are the critical hydraulic structures that store water and, above all, provide energy required by humanity. However, water storage and the provision of energy by reservoirs and dams have been disrupted by significant environmental changes taking place in the catchment areas and the reservoir environment. These disruptions are brought about by climatic parameters and sediment transport by different eroding agents. One such environmental problem is soil erosion, whose effect is reservoir sedimentation. Consequently, a part of the transported sediment is deposited at the catchment outlet, which serves as the reservoir inlet. This study was carried out to establish the physicochemical characteristics of the deposited sediment at the reservoir inlet. The following parameters were analyzed: particle size distribution, organic matter content, bulk density, porosity, electrical conductivity, penetration resistance, hydraulic conductivity, pH, and nutrients (nitrogen, phosphorous, and potassium) using standard laboratory procedures. The study established that the deposited sediments were predominantly sand particles with mean values of 50.60% and 58.60% for the surface (0–10 cm) or sub-surface horizons (10–20 cm), respectively. The average values for sediment pH, organic matter, porosity, bulk density, electrical conductivity, penetration resistance, hydraulic conductivity, and nutrients were 6.30 and 6.61; 1.91 and 1.80%; 54.10 and 57.10%; 1.22 and 1.14 $g\cdot cm^{-3}$ for the surface and sub-surface horizons, respectively. The most variable parameters were silt content (sub-surface horizon), hydraulic conductivity, penetration resistance, electrical conductivity, nitrogen content (surface horizon), and phosphorous (surface horizon) content with CV >0.35. Based on the present study results, the deposited sediments at the reservoir inlet were found to have low concentrations of nutrients and high sand proportions. Therefore, the deposited sediments appear to have great potential to reclaim the immediate barren dam environment upon enrichment and to promote sand harvesting programs for economic benefits.

1. Introduction

The availability of water in the right quantity and quality is a serious challenge that engulfs many water resources, especially in developing countries [1, 2]. The scarcity of water triggers the actions of related problems, for instance, degradation and abstraction [3]. The available freshwater resources in developing countries are unable to meet the huge demand for water in domestic, agricultural, and industrial operations [4]. As a consequence, retention of river/stream runoffs in reservoirs has been identified as a feasible option for fighting global water challenges [5–7]. Reservoirs, therefore, play an important economic role, which sorely depends on the water storage capacity [8–10]. However, reservoir operations are often subjected to recurring stresses associated with huge water demands from the rising human population and agricultural activities [3, 11, 12]. The problems are further compounded by climate change uncertainties [4, 13]. Despite the important functions of reservoirs, their lifespans are increasingly under threat [14,15]. Accelerated sedimentation rates have been pointed out as the major threat to the storage capacity of reservoirs [14, 16]. Sediment accumulation in reservoirs is a gradual process that occurs with time and eventually leads to the loss of storage capacity [4, 17]. It is a naturally occurring process that strongly depends on both the flow rate and flow regime

[11]. Sedimentation results from the deposition of both the bed load and suspended sediment after the detachment and transport processes [4,18]. Therefore, the process of sedimentation depends on the catchment's surface and topography, land use, soil type, intensity and duration of precipitation, the location and type of reservoir, and river or stream hydrology [4, 6, 12, 19]. The phenomenon is much more noticeable in reservoirs than in other bodies of water [1,20]. This is because the reservoirs impound a larger volume compared to their catchment area [18]. Hence, sedimentation depends on the sediment yield [18], and as such, the rate of sediment buildup in reservoirs has varying intensities [21].

A rough balance between sediment inflow and outflow is considered to exist in natural rivers [15, 17, 22]. Disruption of the natural flow regime affects the geomorphological, hydrological, and even ecological conditions in the upstream and downstream regions of the river [2, 4]. The construction of dams across rivers reduces the flow velocity and consequently enables sediment to settle, thereby causing an increase in sedimentation on the upstream side [2, 4,22]. Since all the reservoirs intercept a percentage of the sediment load carried by stream channels, the active storage capacity of the dam is therefore reduced, and hence, the functionality of the dam is affected [2, 4, 20, 23]. The geomorphological conditions of the reservoir's upstream area are affected by sedimentation [15, 22]. For instance, the narrowing of the stream cross-section area as it approaches the reservoir when the flow reduces [22]. Sedimentation also affects the aquatic ecosystem due to changes that occur in the sediment amount and composition [14]. Sediment carries pollutants such as nutrients and chemicals, most of which hasten eutrophication in reservoirs [24]. Reservoir sedimentation, therefore, can bring about changes touching on the physical, chemical, and biological dimensions of ecosystems [2, 24]. This may lead to the eventual abandonment of the reservoir [2, 4].

Reservoir sedimentation is a chronic problem that affects not only the storage capacity but also sustainable use [10, 12, 15, 20]. In this regard, reservoir sedimentation studies provide a scientific understanding of catchment sediment budgets, depositional processes, reservoir operations, and, above all, the commissioning of dams [25, 26]. Moreover, periodic monitoring is required to assess reservoir capacity and maintenance operations such as dredging [12]. The drenching exercise is a suitable solution to alleviate the problem of sediment accumulation in water bodies such as rivers, reservoirs, and coastal areas [12, 27, 28]. This exercise generates large volumes of sediment that must be disposed of safely or reused beneficially [9, 12, 21]. However, reservoir management strategies are hindered by the complex interactions between physicochemical and biological properties of sediment that experience spatiotemporal variation [6, 16]. For instance, the chemistry of water and that of sediment in reservoirs reflects the catchment geology, anthropogenic inputs, weathering, and erosion processes [6]. Different land use and land cover types bring about variations in sediment supply and sediment chemistry, and as such, there has been a growing concern about sediment discharge and its potential effects on reservoirs [15, 24, 25].

Beneficial reuse of sediments involves placing them or using them for a specific productive purpose [27]. In this regard, the determination of sediment properties helps to make decisions on whether drenched sediments may be used biotically or abiotically [9, 27, 28]. Biotic use of sediments refers to their direct application in areas such as land reclamation, agriculture, horticulture, and forestry, depending on the level of their contamination [8, 27–31]. On the other hand, the abiotic use of sediments includes their use as a construction material and, most importantly, in the construction of dykes, dams, and levees, which are all flood control structures [6, 27]. Therefore, the objective of this study was to examine the physicochemical properties of sediments deposited at the Maruba dam reservoir inlet in order to inform their beneficial use.

2. Materials and Methods

2.1. Description of the Study Area. The study was conducted in the Maruba dam reservoir in Machakos town, Machakos County, Kenya, located at 1.5418°S and 37.2323°E (Figure 1). The dam is built across the Maruba stream and it is the main source of water for Machakos town and its environs. The stream flows from the Iveti hills and traverses land with various land use and land cover types [32]. The dam was constructed in the 1950s at a height of 17 m, with an estimated design yield of 4000 m^3/day [32, 33]. Reservoir operations and management activities are carried out by the Machakos Water and Sewerage Company Limited. Machakos town has a population of nearly 210,000 people, and the estimated daily water demand stands at 8000 $m^3.day^{-1}$ [33]. Agricultural activities, grasslands, bare lands, and forests are the most common land use and land cover types [32]. Agricultural activities and bare lands are major contributors to the Maruba stream's high soil erosion rates and increased sediment yield [32].

2.2. Sediment Sample Collection. The sedimentation process was quite clear and evident at the catchment outlet of the Maruba dam reservoir. The catchment outlet provided a good opportunity for carrying out sampling and studying the properties of the deposited sediments [22]. The dried-up part of the reservoir was designated as the study area, where sediment samples were picked from ten different locations (Figure 2). The sampling points were selected randomly and geo-referenced using a hand-held Garmin GPSMAP 65s global positioning system (GPS) gadget [34]. Undisturbed soil samples were collected using core rings, whereas about two kilograms of disturbed soil was collected in appropriate bags. The samples were collected at the surface (0–10 cm) and sub-surface levels (10–20 cm). The criterion used by [22] for identifying surface and sub-surface depths was adopted in this study. This criterion was based on penetration resistance of soil sediment that showed minimal variation between 0 and 10 cm depth, beyond which it began to drop. The soil samples were collected for the determination of the physicochemical (particle size distribution, penetration resistance, moisture content, pH, organic matter content, and dry bulk density) properties using standard laboratory procedures [35].

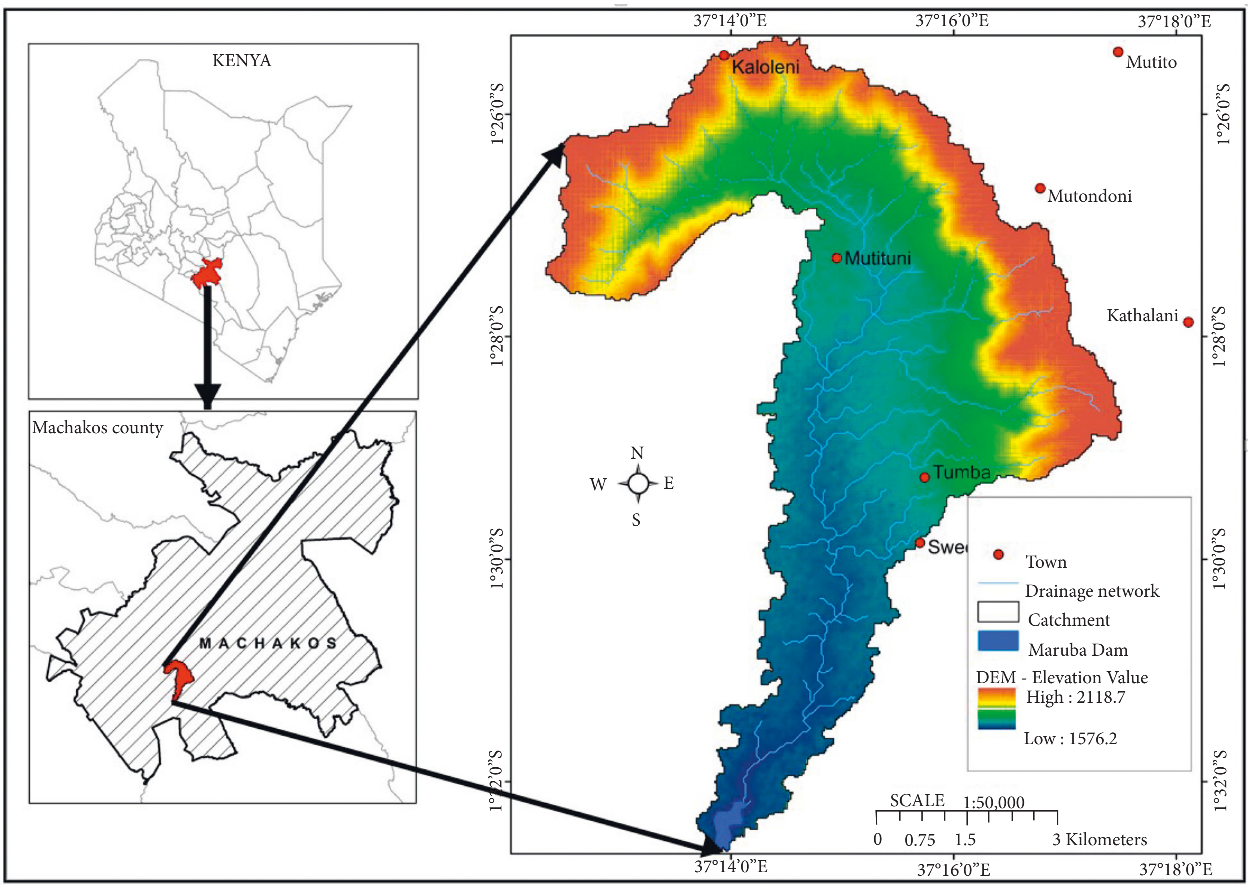

Figure 1: Location map for the study area.

2.3. Sample Preparation. Before any laboratory procedure was carried out, the sediment samples were air-dried under room temperature conditions for a number of days [9]. All trapped materials within the sediments were keenly removed, after which uniform mixing was applied [36]. Finally, manual grinding of the sediments was applied and, thereafter, the content was passed through a 2 mm sieve [21].

2.4. Sediment Analysis. The particle size distribution (PSD) was determined using the hydrometer method [37]. Both sediment pH and electrical conductivity were measured using a Hach HQ40D portable multimeter. The procedure for sample preparation for these two measurements is well highlighted in [36]. Before making any measurements, the procedure described by [38] was used to calibrate the portable multimeter. The sediment bulk density and porosity were estimated according to the procedure described by [39]. Sediment penetration resistance was measured in situ using a hand penetrometer (IB, 6000 $kN{\cdot}m^{-2}$, Eijkelkamp). Indoor measurements for saturated hydraulic conductivity can be obtained using constant or variable-head tests [40]. According to [41], the variable-head test is the most suitable for finely grained soils, while the constant-head method is best suited for coarse-grained soils. In this study, the permeability test was conducted using the constant-head test, given the coarse nature of the sediments in the study area. The approach described by [42] was used to estimate the organic matter content in sediments. This method quantifies the organic carbon in sediments, after which the result is converted to organic matter content using a factor of (1.724) [43]. The rapid wet oxidation approach was used to determine organic carbon (OC) in sediments. The protocol developed by [44] and later modified by [45] was followed. Phosphorous and potassium contents were determined using the ICP-OES procedure [46], while nitrogen content was obtained using the Kjeldahl method [8,17].

2.5. Statistical Analysis. Descriptive evaluation of the analytical results was achieved by considering the minimum, maximum, mean, standard deviation, and coefficient of variation (CV) [22]. The classical statistics of the selected physicochemical soil properties observed at the reservoir inlet are summarized in Table 1. The variability in sediment properties was defined using the coefficient of variation, which is usually the most significant parameter in descriptive statistics [47]. According to [48], for $CV \leq 0.10$, $0.10 \leq CV \leq 0.20$, $0.20 \leq CV \leq 0.30$, and $CV > 0.30$ it implies low, average, high, and very-high variability, respectively.

3. Results and Discussions

The most variable parameters were silt content (sub-surface layer), hydraulic conductivity, penetration resistance, electrical conductivity, nitrogen content (surface), and phosphorous

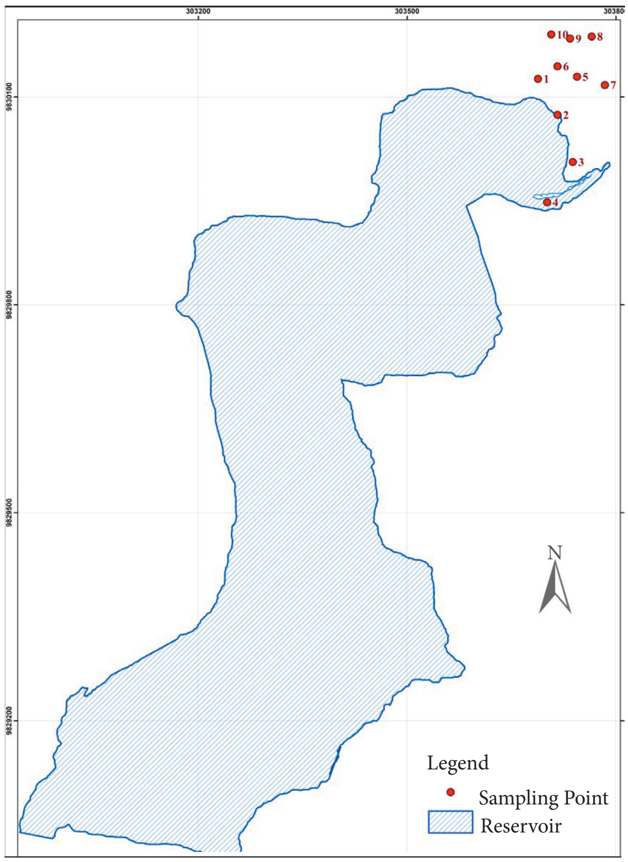

Figure 2: Sampling points at the reservoir inlet.

(surface) content with CV > 0.35. This variation was attributed to environmental and anthropogenic parameters [22,49]. The variability of the chemical properties was a reflection of the alluvium and colluvium nature of the sediment deposits [50].

3.1. Sediment Texture. Soil textural characteristics have a significant effect on other soil parameters such as permeability, infiltration, structure, runoff, and consistency[51]. Textural characteristics of sediments serve as important tools for the assessment of possible effects that result from sediments' focusing, slumping, and even inhomogeneity that may occur in the composition of sediments. Unevenly distributed particle size has a potential effect on a number of soil physical parameters [52]. In this study, the mean proportions of sand, clay, and silt particles were 50.60, 27, and 22.40% for the surface horizon and 58.60, 23.20, and 18.20% for the sub-surface horizon. The surface horizon had the lowest sand content but the highest clay and silt fractions, while the sub-surface had the opposite trend. In both horizons, the predominant soil particles were sand, with fewer clay and silt fractions. The soil sediments were categorized as light soil because of the high proportion of sand content relative to clay [51].

The predominant textural class is sandy clay loam for surface and sub-surface horizons. The sand content increased with the sediment depth, whereas clay and sand fractions showed the opposite trend. This phenomenon could be indicative of eluviation and illuviation processes. According to Buurman et al. [53], the occurrence of translocated clay in sandy material is in the form of coatings on sand grains and pebbles and also as bridges between grains, where ultimately the intergranular spacing is completely filled. Soil scientists have attributed such clay coatings in sediments to the illuviation process, which basically occurs at the surface and even several meters below [53]. Likewise, geologists have attributed coatings of translocated clay in coarse sediments to the mechanical infiltration process in muddy overland flow [53]. The clay illuviation process is climate dependent, and above all, it is restricted to the vadose zone [53].

Sandy soil is characterized by low cohesion, thereby making it prone to detachment and transport by eroding agents and forming sediment. Furthermore, a higher proportion of sand is associated with higher permeability, thereby inducing landslide effects and more erosion [54]. This is a phenomenon that is quite common with deposited sediments. A large percentage of the finely grained particles, mainly clay and silt, find themselves transported into the reservoir, unlike sand particles, which are deposited at the catchment outlet. The capability of the soil to hold an appreciable amount of water, allow movement of water, be workable, and above all, being fertile is influenced by its texture. Thus, finely grained particles affect the plastic index and permeability characteristics of the soil. Thus, a higher percentage of finely grained soil particles obstruct the movement of water through the soil medium [41].

3.2. Sediment pH and Electrical Conductivity. The mean sediment pH values were 6.30 and 6.61, respectively, for the surface and sub-surface horizons. An association between somewhat acidic conditions and farming would have existed in the watershed area where agricultural activities are the main land use [40]. The pH of the sediment may have been caused by weathering reactions and mineral composition as a result of erosion and deposition processes [55]. Furthermore, oxidative weathering, acid rain, fertilizer use, and excessive rainfall would all have contributed to the somewhat acidic conditions [55]. Water circulation in the deposit area might have had an impact on the pH fluctuations in both horizons [40]. The mean electrical conductivity, on the other hand, was 0.39 $dS \cdot m^{-1}$ for both the surface and sub-surface horizons. This occurrence most likely demonstrated the independence of cation and anion concentrations from sediment particle size. The results show that the sediments' electrical conductivity ($<1\ dS \cdot m^{-1}$) does not point to a highly mineralized environment [56].

3.3. Sediment Bulk Density and Porosity. The bulk density of soil is one of the most basic physical properties and it relates well with porosity, where both are related in an inverse relationship [57]. Soil porosity has an effect on aeration conditions, permeability, and root growth, and as such, it is an important measure of fertility in soils [57]. Soil bulk density affects water retention by the soil as well as permeability characteristics [57]. The mean bulk densities for

Table 1: Physicochemical properties of the deposited sediments.

Sediment properties	Sediment layers	Min	Max	Mean	SD	CV
Sand content (%)	Surface	40.30	70.30	50.60	11.50	0.23
	Subsurface	42.50	78.30	58.60	11.30	0.19
Clay content (%)	Surface	19.20	33.20	27.00	6.20	0.23
	Subsurface	16.20	30.20	23.20	4.70	0.20
Silt content (%)	Surface	8.70	30.30	22.40	6.40	0.29
	Subsurface	4.70	27.30	18.20	6.90	0.38
Bulk density ($g \cdot cm^{-3}$)	Surface	1.10	1.38	1.22	0.08	0.06
	Subsurface	1.01	1.23	1.14	0.09	0.08
Porosity (%)	Surface	48.10	58.70	54.10	2.85	0.05
	Subsurface	53.40	62.00	57.10	3.23	0.06
Hydraulic conductivity ($cm \cdot hr^{-1}$)	Surface	0.07	0.73	0.35	0.25	0.71
	Subsurface	0.08	0.53	0.29	0.16	0.55
Penetration resistance (kPa)	Surface	98.00	3727.00	1563.20	1284.30	0.82
	Subsurface	75.50	2314.00	916.50	701.60	0.77
pH	Surface	6.17	6.60	6.30	0.20	0.03
	Subsurface	6.40	6.77	6.61	0.18	0.03
Electrical conductivity ($dS \cdot m^{-1}$)	Surface	0.18	0.52	0.39	0.16	0.41
	Subsurface	0.14	0.79	0.39	0.28	0.72
Organic matter (%)	Surface	1.11	2.55	1.91	0.60	0.31
	Subsurface	1.41	2.15	1.80	0.32	0.18
Nitrogen content (%)	Surface	0.03	0.14	0.11	0.05	0.45
	Subsurface	0.07	0.12	0.10	0.02	0.21
Phosphorous (ppm)	Surface	11.36	28.22	17.51	7.40	0.42
	Subsurface	11.36	16.53	13.16	2.40	0.18
Potassium (%)	Surface	0.25	0.46	0.38	0.09	0.24
	Subsurface	0.32	0.60	0.43	0.12	0.28

the surface and sub-surface soil sediment layers were 1.22 and 1.14 $g \cdot cm^{-3}$, respectively. The observed bulk density values were an indication of the binding effect brought about by clay particles, making the sediments less susceptible to erosion [58]. Since the sand proportion of sediments increased with an increase in depth, this therefore explains the decline in the sediment bulk density. In this study, the mean porosity was 54.10 and 57.10% for the surface and subsurface horizons, respectively. An inverse relationship was noted between sediment bulk density and porosity.

3.4. Sediment Permeability. Soil permeability is greatly influenced by both soil texture and its structure. Permeability measures the rate of water percolation through a given soil medium [41]. It depends on the soil's texture, structure, and bulk density [51]. During large storm events, a perched water table is likely to form in the sub-surface zone that has low permeability. As a consequence, infiltration is slowed down, and therefore surface runoff makes a major route for hydrologic flows, resulting in increased erosion of deposited sediments [51]. The mean permeability values for the surface and sub-surface layers were 0.35 and 0.29 $cm \cdot hr^{-1}$, respectively. The hydraulic conductivity of the soil sediments was found to be quite low. This was attributed to the relatively high proportion of finely grained particles in the sediments resulting from eluviation and illuviation processes.

3.5. Sediment Organic Matter. Soil organic matter is an important component that results from biological sources, either living or nonliving [59]. It is a primary soil parameter that cements soil aggregates, thereby enhancing their stability [52]. The presence of organic matter in the soil is a good indicator of the soil's health status since its effects are manifested in its different properties and functions [40]. Undecomposed organic material that appears on the soil surface helps in the dissipation of the kinetic energy of the rainfall drops, while the highly decomposed material (humus) binds the soil particles [50, 58]. However, this may not apply to deposited soil sediments since the major eroding agent is flood water [60]. The organic matter content in the soil influences its permeability since it makes the soil quite porous. Thus, reduced organic matter in soils leads to decreased porosity and increased bulk density, where the end result is reduced infiltration. The average values of organic matter content were 1.91 and 1.80% for surface and subsurface sediment horizons, respectively. According to Nsabimana et al. [52], most sandy-textured soils are characterized by low organic matter content, below 2%. The results indicated that the sediment deposits had low proportions of organic matter content. The quite low levels of organic matter are characteristics of deposited soils at reservoir inlets. This situation is associated with disturbances that result from periodic storms where most of the organic matter finds its way into the receiving water body [60]. Furthermore, a higher clay content in the surface horizon could have led to an increased organic matter content since mineralization was inhibited due to poor aeration conditions [22].

3.6. Sediment Penetration Resistance. Penetration resistance is an important parameter that predicts how easily plant roots can penetrate through a soil medium [61]. The mean penetration resistance was 1563.20 and 916.50 kPa for the surface and sub-surface horizons, respectively. These penetration resistance values were lower in both horizons than those that would impede plant root growth (less than 2000 kPa) [62]. The surface horizon had the highest values of penetration resistance. This could have been attributed to the compacted layer in the topsoil, resulting from animal traffic. Penetration resistance is an indication of soil compaction; hence, it is related directly to soil bulk density [61]. This was well confirmed by this particular study, since the bulk density for the surface horizon is higher. However, high values of penetration resistance and soil bulk density may not be indicative of harmful compaction in the soil [62] because the apparent strength of compacted sediment layers depends on the moisture content in the respective layers [61].

3.7. Sediment Nutrient Content. The chemical analysis of deposited sediments showed that mean nitrogen, phosphorous, and potassium contents were 0.11% and 0.10%, 17.51% and 13.16 $mg{\cdot}kg^{-1}$, and 0.38% and 0.43% for the surface and sub-surface horizons, respectively. Both nitrogen and phosphorous contents were higher at the surface horizon, whereas for potassium, the trend was quite the opposite. Ordinarily, sediment deposition is an irregular process that depends on the storm magnitude, and for this reason, nutrient concentrations would also be variable. Finer particles are usually transported more than coarse ones, and this is often an indicator of the density current [9]. Once the density current stops, the deposition of fine-grained particles stops. This explains why the chemical concentration of nutrients is highest in the deposition area [9]. The nitrogen, phosphorous, and potassium contents in commercial fertilizers range between 14% and 30% [63], 1.7% and 22.7%, and 2.5 and 51.5% [64], respectively. Therefore, the nutrient content in the bottom sediments is far too low for them to be applied directly as fertilizers [63]. In this regard, the direct use of bottom sediments as fertilizers should not be discouraged, and at least, enrichment with nitrogen and organic carbon should be encouraged [63].

4. Conclusion

The study investigated some physicochemical properties of deposited soil sediments at a dam reservoir inlet, based on two horizons (surface: 0–10 cm; sub-surface: 10–20 cm). Sand particles were found to be quite predominant, with less clay and silt fractions. The sediments were slightly acidic, with a mean pH ranging between 6.1 and 6.6. Both penetration resistance and sediment bulk density were highest at the surface horizon, indicating a highly compacted surface. The nutrient content in the sediments was low, but there is potential for them to be used in agriculture after enrichment. Moreover, the sediment deposits at the reservoir inlet may be used to reclaim barren land around the dam reservoir by enhancing vegetation and tree growth. On the other hand, particle size distribution suggests that sand harvesting activities may be explored for economic gains and for management of the reservoir.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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