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Hydraulic properties of different soil types and its implication on koupendri catchment hydrology

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Abstract

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Soil hydraulic properties play vital role for efficient soil and water management, and sustainable growth and productivity of crops. This study was conducted to investigate the hydraulic properties of different soil types found within Koupendri catchment, North-west Benin. Soil samples were randomly collected at 10 sampling points within each soil type using core samplers (7 cm x 8 cm) at 0-20 cm for determination of soil hydraulic properties. Steady state infiltration was also measured at 10 locations or points within each of the soil types identified in the Koupendri catchment using Hood infiltrometer. Data obtained were subjected to analysis of variance using General Statistics software. The results showed that steady state infiltration (SSI), saturated hydraulic conductivity (Ksat), available water capacity (AWC), water content at field capacity (FC) and permanent wilting point (PWP), bulk density (BD) and total porosity (TP) differed significantly ($p<0.05$) across the soil types. The AWC and FC recorded their highest values in Eutric Gleysols and lowest values in Dystric Plinthosols. The highest BD (1.77 g cm^{-3}) and the lowest TP (32.07%) values were all obtained in Eutric Cambisols. However, SSI and Ksat respectively recorded their lowest values (0.98 cm min^{-1}, 8.7 cm hr^{-1}) in Gleyic Luvisols. Generally, our results showed that Dystric Plinthosols have poor water storage and retention capacity whereas Gleyic Luvisols have poor drainage characteristics and therefore prone to flooding due to poor water infiltration and low saturated hydraulic conductivity. The soil hydraulic properties maps of the study area have provided essential and valuable information needed to sustainably manage and conserve the soil and water resources of the catchment.

Keywords: hydraulic properties, soil and water management, conservation, spatial variability, GIS

Introduction

Soil hydraulic properties play crucial role in the transport of water and nutrients in the soils. They are among the most important parameters that determine the soil quality and its capability to serve the ecosystem (Da Silva et al., 2020). These properties include soil saturated and unsaturated hydraulic conductivity, bulk density, available water, permanent wilting point, infiltration rate, field capacity and water holding capacity and water table depth, and are required for various water management activities. Information from these properties is used in hydrology, soil science, agriculture, environmental sciences, and ecology (Durner & Flühler, 2005).

Soil hydraulic properties are highly dynamic and changes as a result of disturbances in land use and management, and diurnal and seasonal changes (Zhou et al., 2008), impact of environmental conditions such as temperature and precipitation changes (Hu et al., 2009; Novak et al., 2009), organic activity and root dynamics (Rasse et al., 2000). Those of special interest and are notable of affecting water transport in soils are soil texture, soil structure, pore volume, pore size distribution, bulk density and organic matter (Strudley et al., 2008; Zhou et al., 2008). For example, Perkins et al. (2007) reported that an increase in soil bulk density led to a decrease in the saturated hydraulic conductivity. As well, an increase in organic matter, decreases the soil water flow, porosity, and soil water retention (Rawls et al., 2004).

Different studies have shown the variation of soil hydraulic properties according to land use change (Bormann & Klassen, 2008; Li et al., 2019). These changes in land use usually have a long-lasting effect on soil texture, organic matter content, bulk density and porosity (Haghighi et al. 2010) and further increases soil erosion by altering plant species composition and soil management (Christianl et al., 2008). However, little is known about the effect of soil types on soil hydraulic properties.

Understanding the soil hydraulic properties and their changes over time may influence future decision making in both agricultural and environmental sectors (Horel et al., 2015). Therefore, the objective of this study was to assess the effect of soil types identified in Koupendri catchment on soil hydraulic properties and their implication for the catchment hydrology. This will provide essential information needed to sustainably manage and conserve the soil and water resources of the catchment.

Materials and Methods

Brief Description of the Study Areas

The study was conducted on 11.8 km^2 area of Koupendri catchment - a part of Volta basin located north-west of Benin. The catchment is located on latitude 10° 43′48″ to 10°46′36″ N and longitude 1° 8′14″ to 1° 11′37″ E (Figure 1). It has relatively flat physiography, with a few local hillslopes which influence the hydrology of the catchment.

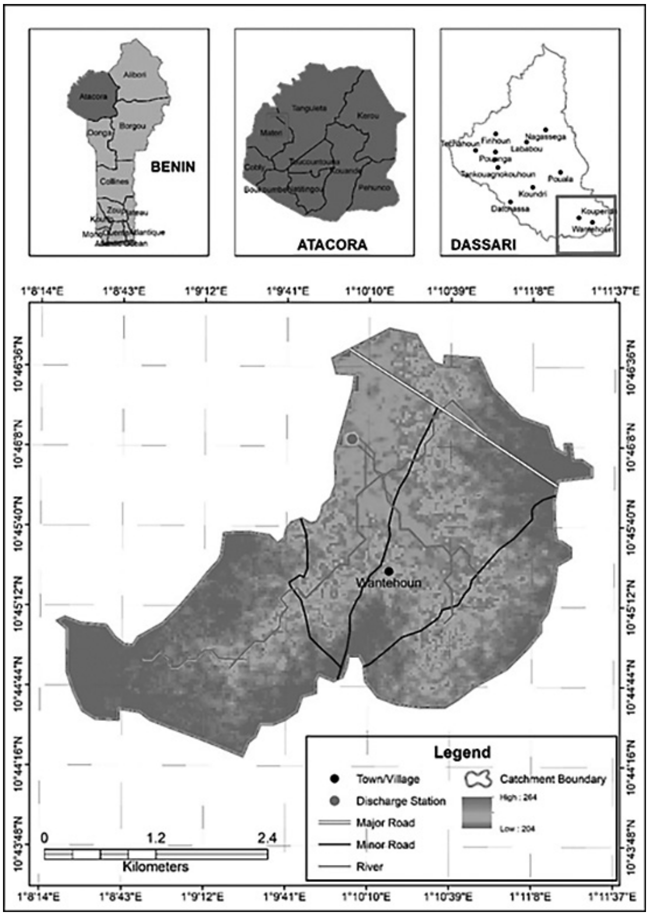

Figure 1.

Climatic Information

The catchment has a unimodal rainfall distribution pattern with distinct wet (rainy) and dry seasons. The rainy season lasts for about five months, from May to September while the dry season lasts for seven months, from October to April. Annual rainfall varies between 900 and 1200 mm, with a yearly mean of 920 mm. During the rainy season, temperature varies between 25 and 30°C, with a relative humidity that can reach up to 97% in August. Between March and April, the temperature reaches a maximum of between 42 and 45°C. The relative humidity throughout the season is between 25 and 55% (Azuka et al., 2015).

Geology and Geomorphology

The geology of northwestern Benin is made up of the Precambrian Voltaian (Faure & Volkoff, 1996). The general relief of the catchment can be characterized as an undulating pediplain relief overlying a Precambrian crystalline basement. Fersialitic and ferralitic soils are dominant often with gravelly or plinthic horizons. A study at the catchment by Azuka et al. (2015) using FAO/UNESCO legends revealed that the catchment is made up of varied soil types: Dystric Plinthosols, Endo-dystric Plinthosols, Eutric Cambisol, Gleyic Luvisol, and Eutric Gleysols (Figure 2) and this finding forms the basis of this study.

Vegetation and Land Use

The catchment is located within the Northern (dry) Sudanian region according to the vegetation zone classification of Benin by Wezel & Böcker (2000). The Sudanian vegetation is dominated by grassland and trees/shrubs of low density composed of *Combretum* spp., *Acacia gourmaensis* and *Crossopteryx febrifuga*.

The major land use is agriculture which focuses on grain crops such as maize (*Zea mays*), sorghum (*Sorghum bicolor*), rice (*Oryza sativa*) etc., tuber crops such as yam (*Dio-

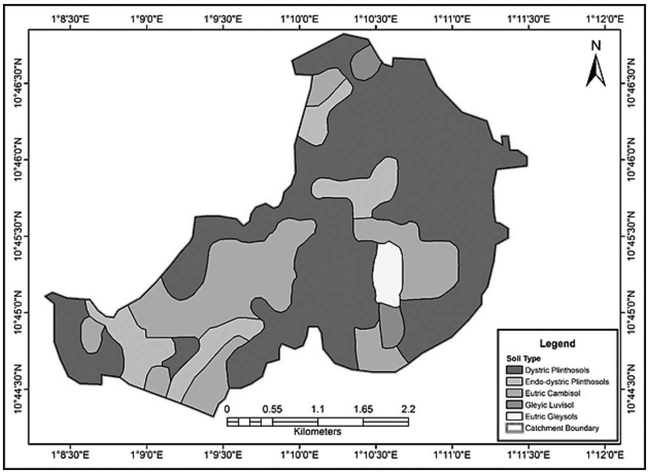

Figure 2.

scorea spp), oil and cash crops such as cotton (*Gossypium* spp), and pastoralism (livestock production).

Only a small amount of land is suitable for agriculture, livestock, and for dwellings in the Volta Basin of Benin due to poor nutrient status of the soil and limited availability of water. Despite these constraints, agricultural activities are rapidly expanding due to population growth, migration and accessibility.

Sample Collection

Field observations were made using toposequence method with clinometer during reconnaissance survey of Koupendri catchment. A total of 50 surface soil samples (0-30 cm) were collected at 10 m intervals from different soil types in the catchment to assess the effect of soil type on soil hydraulic properties and their spatial distribution or variability within the catchment.

Laboratory analysis/methods

Laboratory determination of particle size distribution, saturated hydraulic conductivity, Bulk density and Total Porosity

The particle size distribution of the < 2 mm size fraction of soil samples was determined using the hydrometer method described by Gee & Or (2002). Saturated hydraulic conductivity (Ksat) was determined by the constant head method using Eijkelkamp laboratory permeameter. It operates on the basis or the principle of difference in water pressure on both ends of a saturated soil sample and the resulting flow of water is measured for hydraulic conductivity determination. Darcy's equation for analysis of constant head method, as described by Youngs (2001) was used for the computation of Ksat

$$Ksat = \frac{Q\,.\,L}{(A\,.\,T\,.\,\Delta H)}\ , \qquad (1)$$

where Q is steady state volume of outflow from the entire soil column (cm^3), L is the length of soil column (cm), A is the interior cross-sectional area of the soil column (cm^2), T is the time of flow (sec), ΔH is the change in hydraulic head or the head pressure difference causing the flow (cm). The saturated weight of the core samples was taken before the analysis and weighed again after drying in the oven at a temperature of 105°C. The result obtained was used to calculate the bulk density and porosity. Bulk density was determined by core method as described by Blake & Hartge (1986) while total porosity TP (%) was computed from bulk density (Bd), using the equation below (Assumed particle density ps = 2.65 kg/m^3):

$$TP = \left(1 - \frac{Bd}{Ps}\right) x\ 100\ , \qquad (2)$$

where TP = total porosity, Bd = bulk density, Ps = particle density.

Determination of soil water retention characteristics

The soil water retention capacity or characteristics at 10 kPa or pF 2.5 (0.3 bar) and 1500 kPa or pF 4.2 (15 bar) was determined on core soil samples using the 08.03 pressure membrane apparatus or sandbox method (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) in 10 replicates for each of the soil types. The sand/kaolin box method is a standard method for measuring the pF curves, also called soil water retention characteristics, in a large soil moisture range from saturation (0 kPa or pF 0) to a dry state corresponding to an applied pressure of near 1500 kPa or pF 4.2. For the measurements, the core cylinders with a diameter of 3.5 cm and a height of 5 cm were placed on two sheets of nylon cloth and two sheets of cellophane, which have been saturated with tap water, by avoiding any air inclusion. We assumed equilibration when water drainage through the outlet had ceased usually lasting at least 4 days. Available water capacity (AWC) was calculated as the difference between water or moisture content at pF 2.5 (Field capacity) and moisture content at pF 4.2 (permanent wilting point).

In-situ measurement of Infiltration characteristics using Hood infiltrometer

In-situ measurement of infiltration characteristics until steady state was done using Hood infiltrometer (Figure 3) (UGT, Müncheberg, Germany), as described by Schwärzel & Punzel (2007). The infiltration measurement was replicated thrice in each of the selected land use and slope positions

Figure 3.

Spatial distribution/Mapping of Soil Hydraulic Properties

The ArcGIS 10.6 software with spatial analyst extension was used to prepare the soil hydraulic properties map. The interpolation method employed was Inverse Distance Weighting (IDW). IDW and ordinary kriging have been considered by (Zhu & Lin, 2010; Sun et al., 2012) to be the most reliable interpolation methods. The following equations (3 and 4) were used for IDW interpolation methods as detailed in (Yao et al., 2013):

$$\omega i = \frac{{}^{1}/_{d_i^2}}{\sum_{i=1}^{n} {}^{1}/_{d_i^2}}, \tag{3}$$

where d_i is the distance between the estimated point and the observed point.

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}[Z(x_i) - Z(x_i + h)]^2, \tag{4}$$

where x_i and $x_i + h$ are sampling locations separated by a distance h, and $Z(x_i)$ and $Z(x_i + h)$ are the observed values of variable Z at the corresponding locations.

Statistical Analysis

The data collected were subjected to a one-way analysis of variance (ANOVA) procedure appropriate for an experiment in completely randomized design (CRD) using GENSTAT Discovery Software statistical package (Edition 4) (Genstat, 2012). The means of the main effects of soil type were compared for significant differences using the Fisher's Least Significant Difference (LSD) as described by Obi (2002). Differences were accepted at a significance level of $p \leq 0.05$.

Results and Discussion

Soil textural characteristics

The clay, silt, fine and coarse sand fractions were presented in Table 1. The highest values of fine sand and coarse sand fractions were recorded in Dystric Plinthosols and Endo-Dystric Plinthosols respectively which gave rise to highest total sand fractions (53.67 and 54.50%) for the two soil types respectively. The dominant nature of sandy texture in these soil types indicated the suitability of the soils for plant growth having bulk density less than 1.6 g cm^{-3}. Silt content fraction is greater than the clay content fraction in all the soil types and this can be attributed to the skeletal composition of the parent material which reflect that the soil is less weathered and thus, at less advanced stage of development. This was also reported by Moraru et al. (2020) for soils in Danube River Basin. The textural classes were mostly Sandy Loam for Dystric and Endo-Dystric Plinthosols, Silty Loam for Eutric Cambisol and Loam for Eutric Gleysols and Gleyic Luvisol soil types.

Main effect of soil type on soil physical / hydraulic properties of Koupendri Catchment

The physical and hydraulic properties of the soils of Koupendri Catchment as influenced by soil types are shown in Table 2. The result showed that bulk density was significantly higher in the Eutric Cambisol soil type. In all the soil types, bulk density value is above the optimal value of 1.40 g cm^{-3} for healthy plant and root growth. This could be attributed to soil compaction caused by continuous and intensive pastoral activities and cultivation for many years and poor soil structure (Azuka et al., 2015). The findings of Junge (2004) and Sintondji (2005) are similar to this result

Table 1. Soil Textural Properties of Koupendri Catchment

Soil Type	Fine sand, %	Coarse sand, %	Total sand, %	Silt, %	Clay, %	Textural Class
Dystric Plinthosols	23.08	30.59	53.67	37.67	8.67	Sandy Loam
Endo-Dystric Plinthosols	26.46	28.04	54.5	37.5	8	Sandy Loam
Eutric Cambisol	14.94	9.36	24	59	17	Silty Loam
Eutric Gleysols	18.45	24.05	42.5	44	13.5	Loam
Gleyic Luvisol	21.42	28.08	49.5	42.5	8	Loam

Table 2. Main Effect of Soil Type on Soil physical / hydraulic properties of Koupendri catchment

Soil Type	BD, $g\ cm^{-3}$	Ksat, $cm\ hr^{-1}$	Steady state, $cm\ min^{-1}$	TP, %	pF 2.5	pF 4.2	AWC
Dystric Plinthosols	1.59	9.8	1.51	40.13	15.12	8.06	7.07
Endo-Dystric Plintho-sols	1.56	21.9	1.76	42.44	18.87	10.52	8.36
Eutric Cambisol	1.77	17.1	1.15	32.07	19.26	9.76	9.5
Eutric Gleysols	1.61	17.9	1.4	39.4	24.8	12	12.8
Gleyic Luvisol	1.6	8.6	0.98	39.79	18.75	9.34	9.4
F-LSD $_{(0.05)}$	0.08	9.91	0.37	3.14	3.54	2.1	1.89

AWC= available water capacity, BD= bulk density, Ksat = saturated hydraulic conductivity, TP = Total Porosity, pF 2.5= water content at field capacity, pF 4.2 = water content at wilting point.

that reported high BD values for Terou-Igbomakoro catchment in central Benin.

Saturated hydraulic conductivity, steady state infiltration rate and total porosity values were highest in the Endo-Dystric Plinthosols whereas the lowest values of saturated hydraulic conductivity and steady state infiltration were obtained from Eutric Luvisol soil type. Eutric Cambisol soil type recorded lowest value of total porosity. The variation across the different soil types in the values of Ksat, Steady state and TP might be attributed as differences in the particle size distribution (Tabor et al. 2017).

The Eutric Gleysols soil type significantly recorded highest values of pF 2.5 (24.80), pF 4.2 (12.00) and AWC (12.80). This could be caused by differences in evaporation, total porosity and soil water retention capacity (Mcbeath et al., 2012; Li et al., 2016) among soil types. The AWC is commonly defined as the amount of water held between field capacity (pF 2.5) and permanent wilting (pF 4.2) point (Soil Science Division Staff, 2017). The soils of Koupendri catchment have been reported by Azuka et al. (2015) to have higher SOM, an important factor contributing to AHC, and could potentially contribute about 2.2 % to 12.5 % of the AWC.

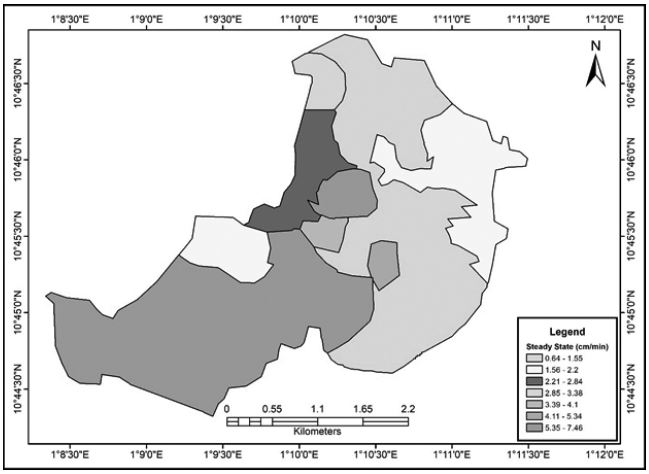

Figure 4.

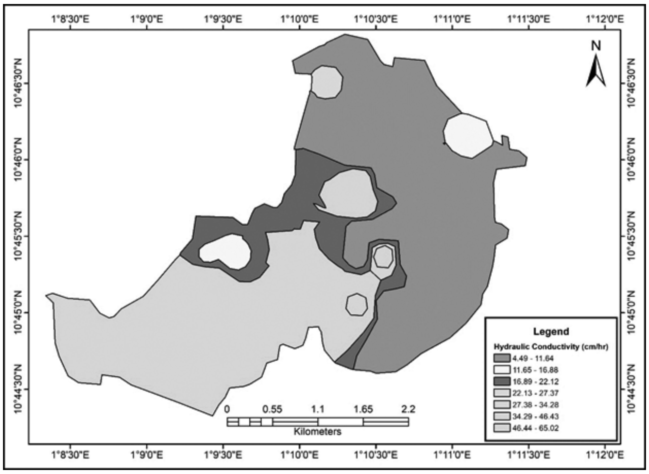

Figure 5.

Spatial Distribution Pattern of Soil Hydraulic Properties in Koupendri Catchment

The pattern of spatial distribution of hydraulic properties in Koupendri Catchment are presented in Figures 4 and 5. The number of soil samples, the distance between sampling points and the interpolation technique used are factors that affect the prediction of spatial distribution for soil properties (Kravchenko, 2003; Xie et al., 2011). The spatial distributions patterns of the soil hydraulic properties obtained from IDW interpolation technique are broadly consistent and exhibit a block and ladder-shaped spatial distribution pattern.

The results generally showed an increasing trend in steady state infiltration rate and saturated hydraulic conductivity with zonal distribution from northeast to southwest. The highest values occurred in the southwestern corner. The different soil types in the study area may have caused the variation in Ksat and Steady state infiltration rate. However, saturated hydraulic conductivity is associated with soil types, land uses, positions on landscape, preferential flow, depths, instruments, and methods of measurement and experimental errors (Stockton & Warrick, 1971). Moreover, saturated hydraulic conductivity may be affected by additional factors such as vegetation cover, bio- and human activities (Abaci & Papanicolaou, 2009). The lower values of saturated hydraulic conductivity in the southeastern part can lead to formation of an impeding layer and may lead to perched water tables, development of interflow and flooding.

Conclusion

Soil hydraulic properties of surface soils as affected by soil types were investigated in Koupendri Catchment located northwest of Benin Republic, West Africa. Soil hydraulic properties were significantly ($p<0.05$) affected by soil types. Inverse Distance Weighting interpolation method revealed high spatial variability of steady state infiltration rate and saturated hydraulic conductivity. The map revealed that areas of high values of steady state and saturated hydraulic conductivity were located in the southwestern region whereas the southeastern portion showed the lowest steady state and saturated hydraulic conductivity which may lead to formation of perched water table, development of interflow and flooding.

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