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Infiltrating to Control Floods - Suitability of Infiltration Based Systems in Urban Sub-Sahara Africa

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Abstract: The research studies infiltration characteristics of soils of an urban Sub-Sahara African metropolis, specifically Accra, Ghana. It investigates the infiltration characteristics of the soils of the research area for a preliminary assessment of their suitability for infiltration based interventions to stormwater management. Data was collected from 91 locations on soil infiltration characteristics for hydraulic conductivity under near saturated conditions using Double Ring Infiltrometer, Inverse Auger Hole, and Turf Tec Infiltrometers and under unsaturated conditions using a MiniDisk Infiltrometer. The different infiltrometers were used on seven different soil groups. Unsaturated Hydraulic conductivity values had a median of 219.5 mm/h. Near saturated hydraulic conductivity for Double Ring was 42 mm/h, Inverse Auger Hole (645.2 mm/h) with Turf Tec being 140 mm/h. The results showed significant spatial variation (p=0.001, p=0.004) between the methods and soil types for the first thirteen locations and does not support homogenous hydraulic conductivity within soil groups. Soils had moderate hydraulic conductivity seen in drain times for Korle consociation (23.3 h) and Oyarifa-Mamfe complex (55.7 h) but others like Nyigbenya-Haacho (77.6 h), Fete-Bediesi (407.1 h), and Fete consociation (1282 h) had higher drain time. Near saturated hydraulic conductivity values were used to build an initial profile for the soil groups where Korle consociation and Damfa-Dome complex were classed under HSG A, Nyigbenya-Haacho complex as HSG C and the rest as HSG B. Soils like the Fete-Bediesi complex with relatively high drain time could be engineered to predefined moderately high hydraulic conductivity to ensure moderate infiltration characteristics for infiltration based stormwater management systems.

Keywords: Infiltrometer, Infiltration Rate, Hydraulic Conductivity, Drain Time, Soils

1. Introduction

Research over the years has established a strong relationship between urbanization and the incidence of floods [1-3]. Moreover, floods in urban areas especially in developing countries is increasing in frequency, extent and damage to life and property, becoming more extreme in their impact [2-7] reported that between 1970 and 2015 there were a total of 227 major flood events within the West African sub region resulting in 3,162 fatalities, 73.5% of which occurred from 2000 to 2015. Work by [8] on the incidence of flooding in Ghana's capital, Accra, confirmed the trend, showing that between 1960 and 2007, about 90 incidence of floods were recorded, with recurrence interval of 0.52years/flood. They estimated that between 1980 and 2010 floods resulted in about 400 casualties and economic loss of US$ 33.5 million [8]. These trends in flooding is a manifestation that the current system of stormwater management in urban areas based on the traditional hydrologically efficient conveyance systems is not working and is even worsening the situation [9-11]. In the developed world, this realization lead to the development of new systems of stormwater management in the 1970s which has proven to be better adapted to changing urban conditions, holistic and more environmentally friendly [12, 13]. One such system is the infiltration based system of stormwater management and flood control practiced as low Impact Development (LID).

Low Impact Development (LID) is a stormwater management strategy that seek to mitigate the impact of increased runoff and stormwater pollution using a set of on-site design practices to promote the use of the natural system for infiltration and reuse of stormwater [14]. These infiltration based systems may include infiltration wells [15, 16], percolation trenches [16-18], bioinfiltration ponds [19, 20], rain gardens, bioswale, detention basins [21-23]. They are developed as at-source-control integrated stormwater management techniques installed at critical locations within a watershed where their impact will be greatest in reducing runoff and erosion and improve base flow to surface water bodies [14, 20, 24]. However the effectiveness of any LID system is dependent on infiltration characteristics or the hydraulic conductivity of the soils in which the intervention is installed [20, 25, 26]. To address this challenge this research was set up to investigate the infiltrating characteristics of the soils of the study area to guide the introduction of infiltration based interventions. The first objective was to investigate the infiltrating characteristics of soils of the study area whilst the second looked at spatial variability in the infiltrating characteristics of the soils.

2. Infiltration Methods

Different approaches have been used in the literature to estimate hydraulic conductivity which can be under either saturated or unsaturated, direct or indirect, laboratory or field method, small scale or large scale methods to approximate the value of hydraulic conductivity of soils [25]. Small scale field methods include the use of Inverse Auger Hole, Single or Double ring infiltrometer [25, 27], Mini disk infiltrometer [27]. Large scale methods include drain line discharge, water table elevation, existing drainage tube wells, experimental fields [25]. While small scale methods serve for fast testing many locations and can be done relatively cheaply and quickly, large scale methods are tedious, difficult, rather expensive and time consuming, so various models have been developed [25, 28]. The models are used as quick and easy methods to obtain and estimate infiltration rate for the purposes of preliminary analysis on hydraulic conductivity for decision making [29]. But these models often over-simplify hydraulic conductivity which may lead to under-estimation, over estimation, inaccuracies and random errors [29, 30] making a direct field measurement the best alternative. Determination of hydraulic conductivity (K) by any of the methods identified in the literature can be by either correlation or hydraulic method. The correlation method uses a predetermined relationship between an easily determined soil property like texture and the K-value while the hydraulic method uses the relationship between infiltration rate and hydraulic head to calculate K [30]. In this study the hydraulic method was used to provide estimates on hydraulic conductivity [31] for various locations within the study area to serve as reference data for further work. Due to ease of use, the advantage of direct field measurement and limitation of time, the research adopted four small scale hydraulic methods: Double Ring Infiltrometer, Inverse Auger Hole infiltrometer (Plump-line method), Mini Disk Infiltrometer and the Turf Tec Infiltrometer.

The Double Ring infiltrometer method was used to derive hydraulic conductivity under near saturated field conditions. The method is used for areas where ground water table is absent and is the preferred choice for many in situ measurements of infiltration rate because it is suitable for almost any type of soil [32] cited In [25, 27, 33]. A major criticism of this method is that accuracy depends on actual moisture content of the soil, the process is time consuming [25], requires a lot of water to operate and that the method does not guarantee accuracy and effectiveness [31]. The Turf-Tec infiltrometer is similar to the double ring infiltrometer but with a smaller ring diameter (Figure 3, right). The equipment is portable, easy to use and require less amount of water. However its small diameter could lead to overestimation of infiltration rates which may affect the accuracy of the results [34, 35]. Conditions for use and set up of all four methods are described below.

3. Materials and Methods

3.1. Location

The study adopted part of the Greater Accra Metropolitan Area (GAMA), a densely populated urban area in Accra-Ghana as a case study. The site covers 5 administrative districts within GAMA and lies within Long. 5.804253 and 5.492637dd West and Lat. 0.527292 and-0.082525dd North, covering a total land mass of about 900 sq km. The climate is described as Coastal Savannah with two rainy seasons of unequal intensity, averaging 730–800mm per annum. The soils in the area have developed on thoroughly weathered parent material with alluvial soils and eroded shallow soils [36] with the entire drainage system flowing into the sea [37].

3.2. Experimental Design-Methods

The research was done *in situ* using double ring infiltrometer, MiniDisk Infiltrometer, Inverse Auger Hole infiltrometer (Plump-line method) and Turf Tec Infiltrometer. These were combined with auxiliaries like a GPS handset to locate position of sites (Figure 1), a Fijizu Camera to record the events, plastic bottles for water collection, a stop clock, and a field note book for taking records.

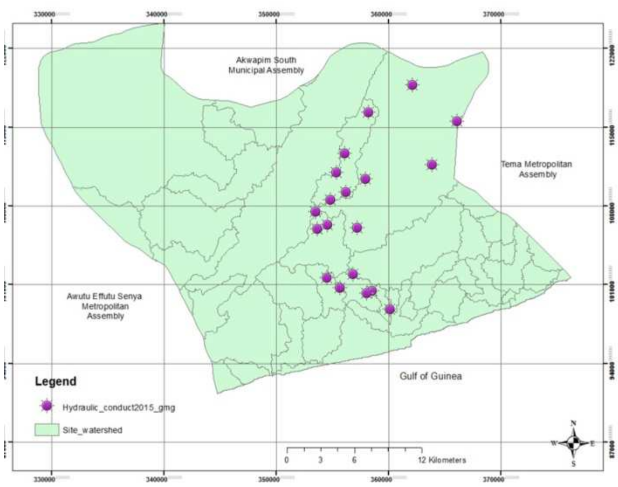

Figure 1. Map showing spatial location of infiltration rate test sites.

Data was taken on infiltration and time from a total of 91 locations, an average of 3hours spent per location. A stop clock and a field note book were used to record the time and change in volume.

3.2.1. Double Ring Infiltrometer

Double ring infiltrometer was used to derive hydraulic conductivity under near saturated field conditions. Two variants of the double ring infiltrometer were used in this research, the large ring type and the small ring type.

Setup: The setup of the large type double ring infiltrometer is composed of two concentric steel cylinders of between 50-60cm diameter outer ring (a), 30cm diameter inner ring (b) which are inserted manually into the ground to between 5cm - 10cm depth, a measuring bridge (c) and a measuring rod (d) with float calibrated in millimeters' (Figure 2, left).

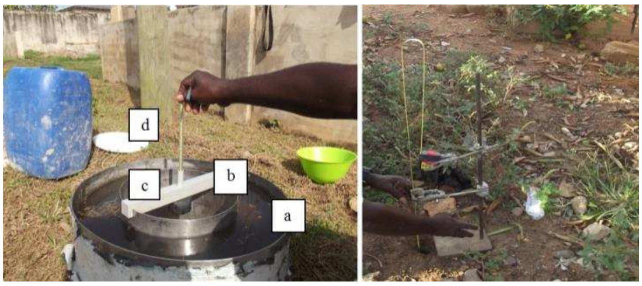

Figure 2. *Double Ring Infiltrometer field setup (left) Inverse Auger Hole Field Setup (right).*

Large plastic bottles were used to cart water from near-by wells, pipe stands or water reservoirs to fill the cylinders for the test in various locations. The two cylinders are filled with water and the water level in the outer cylinder kept approximately at the same level as the water in the inner cylinder [25].

Infiltration rate was determined by measuring the change in volume of water on the measuring rod in the inner cylinder within a specified time interval, until steady state had been reached sometime after the infiltration rate has stabilized, at which stage the recording ended [25]. The steady state of infiltration was assumed to have been reached when discharge changes were < 10%, over 5-minute interval [27, 33]. The main assumption here is that at the steady state when infiltration rate has stabilized, infiltration rates approximates the hydraulic conductivity [25]. This assumption though has been challenged [38], nevertheless its use yields a fair approximation to hydraulic conductivity of a soil media. In this research, the steady state assumption was used to calculate cumulative infiltration rate and using the Reduced Philips' equation, to calculate the hydraulic conductivity as well. The reduced Philips' equation [25] is stated as follows:

$$I = S * t^{\frac{1}{2}} + A * t \tag{1}$$

and

$$v = \frac{1}{2} s * t^{-1/2} + A \tag{2}$$

where I is cumulative infiltration,

v is intensity of infiltration (MT^{-1})

S is the Sorptivity ($MT^{-0.5}$)

A is a coefficient (MT^{-1})

t is time

At steady state Eq. (1) becomes

$$I = At \tag{3}$$

this implies that

$$A = \frac{I}{t} = K \tag{4}$$

Where K is the Hydraulic conductivity at near saturation. At steady state, the infiltration rate equals hydraulic conductivity when the sediments in the soil media are saturated [39]. Figure A1-A6 displays the relationship between cumulative infiltration and time as the test approaches steady state.

3.2.2. Hand-Held Soil Auger or Inverse Auger Hole method

This method was used for measuring on-site hydraulic conductivity in areas where the water table was very low or absent [25]. Measurement was made under fully saturated soil conditions and unsteady state condition [30, 40].

Set-up: This was carefully done as described by [30, 40]. Digging was vertically downward into the soil with a 60 mmØ soil Auger to a depth of 500mm. The digging was done to minimize compaction of the sides of the hole. The field set up is shown in Figure 2 (right).

Hydraulic conductivity (K) values for the Inverse Auger Hole method was calculated based on [30, 40, 41] using the relation:

$$K = 1.15r \frac{\log\left(h_o + \frac{r}{2}\right) - \log(h_n + \frac{r}{2})}{t_n - t_o} \tag{5}$$

Where

$$\frac{\log\left(h_o + \frac{r}{2}\right) - \log(h_n + \frac{r}{2})}{t_n - t_o} = slope\ (Tan\emptyset)$$

where K = hydraulic conductivity (cm/s)

r = radius of Auger hole (3cm)

h_o = Depth at beginning at t_o

h_n = Depth of water level at time t_n

t_n = time since start of experiment

t_o = Start time (s)

For this research K was derived using the relation [30];

$$K = 1.15r\ x\ Tan\emptyset \tag{6}$$

Where TanØ is the slope of the graph Log (h_t+0.5r) against t (s)

Set-up: The set-up is as illustrated (Figure 1, right)

3.2.3. Mini Disk Infiltrometer

Set-up:—The infiltrometer was filled and operated as described by [42] and data taken by recording water loss from the stem (infiltration) at a defined time step when the infiltrometer is placed directly on the surface of the soil. The quantity of water lost was read in millimeters for a given time in seconds (s) using a stop clock and recorded in a field note book. The recorded data was later entered in an Excel spread sheet and summarized as cumulative infiltration, cumulative time, and square root of time. Analysis was by line graphs of cumulative infiltration against square root of time.

Unsaturated Hydraulic conductivity was calculated based on [42] using the formula;

$$k = C/A \quad (7)$$

where k is the unsaturated hydraulic conductivity,

C - is the slope derived from the graph of cumulative infiltration against square root of time curve. The curve takes the form of a quadratic equation of the relation:

$$y = ar^2 + br - c \quad (8)$$

where a and b are coefficients (Ref Figure A7-A12). Slope (C) was calculated from Eq. 8 using the relation;

$$C = 2ar + b \quad (9)$$

A - is a value relating the van Genuchten parameters for a given soil type to the suction rate, radius of the mini-infiltration disk and soil textural class read from tables [42]. The value of A was obtained from tables which combines soil textural class with the suction head. Information on the soil physico-chemical properties provided in a detailed soil series assessment was used to derive the textural class through the NRCS Soil Structure converter; an excel application. The suction head used was 2.0cm.

Figure 3. *Field set up for MiniDisk Infiltrometer (right) and set-up of Turf-Tec Infiltrometer (right) Source: Field Survey 2015, 2018.*

3.2.4. Turf-Tec Infiltrometer

Data analysis was done as has been explained under the Double Ring Infiltrometer.

3.2.5. Drain Time

Hydraulic conductivity values from all four methods were used to estimate drain time (based on a 25year design storm), using an infiltration well of 1.5 × 1.5 m size, designed to infiltrate a roof runof volume of 18.9m^3. The calculation of the drain time is based on Blansett [43].

3.3. Data Collection and Analysis

A number of on-site infiltration tests were carried out from November 2015 - December 2015, towards the end of the minor rainy season when the soil water content was close to field capacity, that is 1-3days between rainfall events, similar to what was reported by [28]. This period falls within the ideal summer test period recommended by [44] for carrying out infiltration tests mainly because soil characteristics during that period is more stable. A second set of data was taken in 2018 between October and November when the weather was relatively dry. The first set of data was taken with three instruments whilst the second set was taken with only one instrument, the Turf-Tec Infiltrometer. To account for spatial variation, data was collected from various locations dispersed within the study area [35]. Soil profile tests were also run in limited areas for a better understanding of the infiltration characteristics of the soils. The data collection area lies within a major catchment of the study area which supplies about 70% of runoff to the metropolitan area of Accra. Out of the 91 locations, three methods were used to collect data at once from the first thirteen locations but due to logistical challenges the process could not be extended to the rest of the study area. Mini Disk and the Turf Tec infiltrometers were used to cover the rest of the locations.

Statistical analysis was performed on the data to determine links, association and differences between different soil groups and infiltration methods using analysis of variance, summary statistics and boxplot in a Genstat software. A T-Test was performed to determine the effect of the different data collection periods on the results.

4. Results

4.1. General Overview

The proportion of data taken with the four different infiltrometers is shown in Figure 4. Data taken at the same time with the three infiltrometers (MiniDisk, Double Ring and Inverse Auger Hole Infiltrometers) for the first thirteen locations are summarized in Table 1.

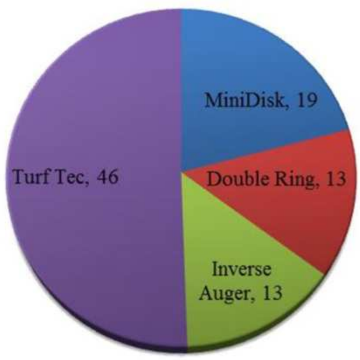

Figure 4. *Distribution of data among the data collection methods.*

Analysis of variance for hydraulic conductivity for these first thirteen locations showed significant differences between the three methods (p = 0.002) and also between soil types (p<0.001). Unsaturated Hydraulic conductivity values from the mini-Disk Infiltrometer ranged from 8 mm/h to 385.5 mm/h. Near saturated hydraulic conductivity values for the Double Ring Infiltrometer ranged between 12 mm/h and 120 mm/h, and was lower than that of the Inverse Auger Hole method which gave values of between 78.7 mm/h and 1722.4 mm/h. Among the three methods, Double Ring Infiltrometer produced the least variability with a Coefficient of variation (CV) of 67% and standard error of mean (SEM) of 9.7. The Inverse Auger Hole infiltrometer had the second lowest CV of 80.9% with a standard error of mean of 140.8. Among the soil types for this first thirteen locations, Oyarifa-Mamfe complex showed less variability with a CV of 92.6 and Standard error of mean of 27.3 compared with Fete-Bediesi complex with CV, 126.3% and SEM of 104.1.

Table 1. *Interactions between Soil type, methods and Hydraulic Conductivity values.*

Soil type	K1 (mm/h)	K2 (mm/h)	K3 (mm/h)
21. Oyarifa-Mamfe Complex	50.4	60	266.9
31. Oyarifa-Mamfe Complex	39.9	12	261.1
32. Oyarifa-Mamfe Complex	28.0	96	78.7
34. Oyarifa-Mamfe Complex	32.0		150.4
22. Danfa-Dome Complex	385.5	12	856.9
23. Fete Consociation	351.4	36	1722.4
25. Fete-Bediesi Complex	107	72	1113.8
26. Fete-Bediesi Complex	8	120	1161.8
27. Fete-Bediesi Complex	18.1	36	756.1
33. Fete-Bediesi Complex	120.1	24	181
36. Fete-Bediesi Complex	376.4	48	645.2
24. Nyigbenya-Haacho Complex	357.4	60	115.4
35. Korle Consociation	219.5	24	848.5

Soil type P-Value (0.004).
Methods P-value (<0.001).
Soil * Method P-Value (0.001).
Hydraulic Conductivity CV% 84.6, Standard error 18, 17.
Notes: K1 - Mini Disk Infiltrometer hydraulic conductivity; K2 - Double ring method hydraulic conductivity; K3 - Auger hole Method hydraulic conductivity CV – Coefficient of Variation.

Hydraulic conductivity values of the soil types between methods did not seem to be related. For instance, while Danfa-Dome complex gave the highest unsaturated hydraulic conductivity value for the Mini Disk infiltrometer (385 mm/h), it produced the lowest (12 mm/h) near saturated value for the Double Ring method. Oyarifa-Mamfe complex produced the second lowest value (28.0 mm/h) for the Mini Disk, but the lowest (12 mm/h) with the Double Ring method (Table 2). Fete-Bediesi had the lowest value with the Mini Disk method (8 mm/h), the second lowest (24 mm/h) for the Double Ring infiltrometer but second highest for Inverse Auger Hole method (1162 mm/h). The range of values for the Turf Tec infiltrometer was 4 mm/h and 900 mm/h with significant differences between soil types (p=0.048). A boxplot analysis based on the median showed significant differences between the four methods (Figure 5).

Table 2. *Preliminary classifying of the different soil groups into Hydrologic Soil Groups using minimum hydraulic conductivity values.*

Soil Group	Hydraulic Conductivity (mm/h)		Standard*	Hydrologic Soil Group
	Minimum	Maximum		
Danfa-Dome complex	48	198.7	> 36.1 mm/h	A
Fete-Bediesi complex	28	248.4	< 36.1 mm/h	B
Fete Consociation	20	443.5	< 36.1 mm/h	B
Korle consociation	54	924	> 36.1 mm/h	A
Nyigbenya-Haacho complex	14	834	< 14.5 mm/h	C
Oyarifa-Mamfe complex	20	124.2	< 36.1 mm/h	B

Note: Standard* obtained from United States Department of Agriculture publication on Hydrologic Soil Groups. Source: [45] Comparison between methods.

Comparing all four methods, the Inverse Auger Hole method with the highest median (645.2 mm/h) produced the second lowest CV (80.9%) but the highest SEM (140.8). The Double Ring Infiltrometer with the lowest median (42 mm/h) gave the lowest CV (67%) and the lowest standard error of mean (9.7) as confirmed with the small box size (Figure 5).

4.2. Differences Between Soil Types

Between the soil types, the widest variation in the median values was seen in Fete Consociation (979.9 mm/h) which was significantly different from Korle Consociation (360 mm/h), Fete-Bediesi complex (120.1 mm/h), Nyigbenya-Haacho complex (111.7 mm/h) and Oyarifa-Mamfe complex (60 mm/h) (Figure 6). Nyigbenya-Haacho and Oyarifa complex generated hydraulic conductivity values with the least variability (Figure 6). They also had the second highest CV (107.3%) and the lowest SEM of 28.1.

The slightly different periods in 2015 and 2018 within which data was taken with the Mini Disk, Double Ring, Inverse Auger Hole and Turf Tec infiltrometers did not show any significant differences from a T-Test at 5% (P=0.245) but an analysis of variance showed significant differences between the soil types (P<0.001) for the two periods (Data not shown). Interactions between the methods and the soil types were significantly different at 5% (p = 0.004).

Median drain time was calculated as 38.2 (h), 13 (h) and 59.8 (h) for the Mini Disk, Inverse Auger Hole and Turf-Tec infiltrometers respectively for all soil types. Comparatively, the drain time from the double ring infiltrometer was very high, (median of 2240 hours). Among the infiltrometer methods, the Inverse Auger Hole showed the lowest variability with a CV of 84.4% and standard error of mean of 6. The Turf Tec method produced the next lowest coefficient of variability of 126.4% and standard error of mean, 18.4. The Double Ring Infiltrometer produced the highest variability with CV 79.5% and standard error of mean, 691.7 (Figure 7).

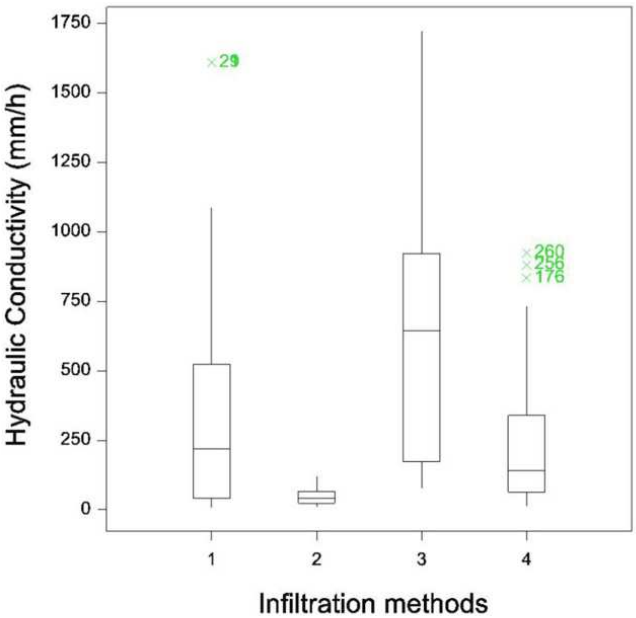

Figure 5. *Boxplot showing the relationship between the hydraulic conductivity values for MiniDisk (1), Double Ring (2), Inverse Auger Hole (3) and Turf Tec (4) Infiltrometers.*

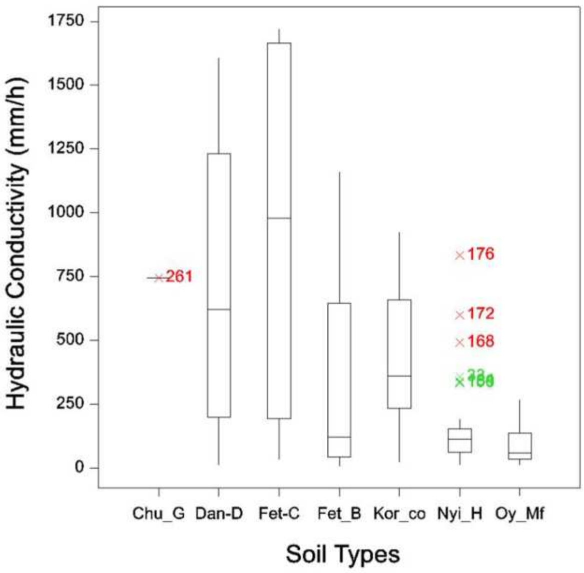

Figure 6. *Boxplot showing how Hydraulic Conductivity values relate to the different soil types.*

Notes: Chu_G (Chuim Gbegbe consociation), Dan-D (Danfa-Dome complex), Fet-C (Fete Consociation), Fet-B (Fete-Bediesi complex), Kor_co (Korle Consociation), Nyi_H (Nyigbenya-Haacho complex) and Oy_Mf (Oyarifa-Mamfe complex).

Among the 7 soil types and based on the three near-saturated infiltrometer methods, Nyigbenya-Haacho complex generated a median of 77.6 hours, CV of 165.1% and the lowest standard error of mean of 44.1 (Figure 8). Fete-Bediesi produced the lowest CV (128.7%), but a high standard error of mean (425.4). The drain time for the soil groups range from median 23.1 hours (Korle consociation), 55.6 hours (Oyarifa-Mamfe complex), 77.6 hours (Nyigbenya-Haacho complex), 407.1 hours (Fete-Bediesi complex). The highest drain time (3845 hours) was from Danfa-Dome. (Chuim-Gbegbe complex was ignored in the analysis because of its very limited coverage).

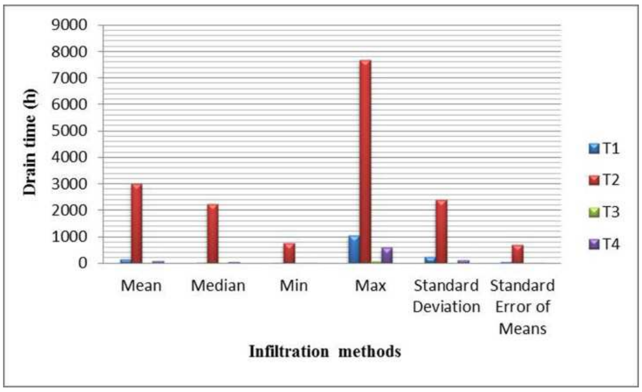

Figure 7. *Summary of Drain time by the four infiltrometer methods.*

Notes: T1 (MiniDisk), T2 (Double Ring), T3 (Inverse Auger Hole) and T4 (Turf Tec) Infiltrometers.

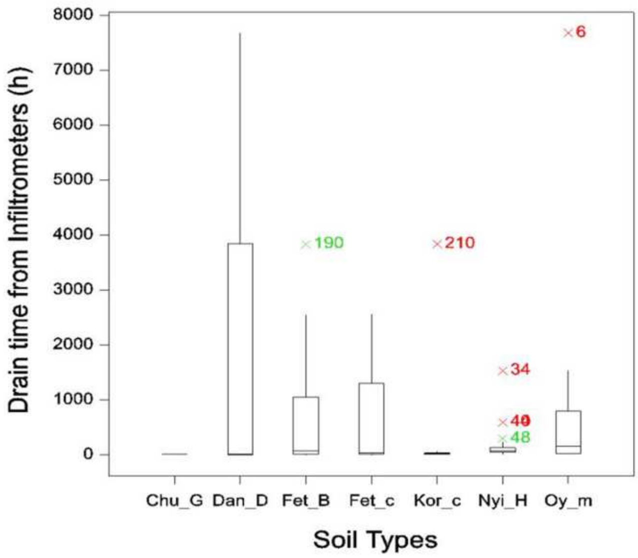

Figure 8. *Summary of Drain Time for the different soil types.*

5. Discussion

The results seem to support the observation that different methods used to determine hydraulic conductivity yield different results with very little correlation between the methods [25, 40, 46]. The different soil types may have contributed to the variation in the hydraulic conductivity values as evidenced in the high CV (> 79.1%). The results suggest non-homogeneity within soil types and methods across spatial locations, as was similarly observed by [25, 47]. This negates suggestions from Ghartey that spatial characterization of soil physical properties such as hydraulic conductivity can be used as a means to locate homogeneous areas within a watershed [48]. Unsaturated hydraulic conductivity values from the Mini Disk were lower than the near saturated values obtained with the Inverse Auger Hole method. This support observations on unsaturated hydraulic conductivity and near saturated hydraulic conductivity by [47, 49] who explain that as soils become more saturated, hydraulic conductivity increases and that values under near saturated conditions are generally higher than under unsaturated conditions. Unsaturated hydraulic conductivity from the Mini Disk were however higher than values from the Double Ring and the Turf Tec infiltrometers (Table 1). This difference cannot be explained purely on the performance of the different methods due to the unbalanced nature of the data collection process where all four methods could not be used to collect data from the different locations at the same time. The extent of soil disturbance in those locations could also explain the difference because areas exposed to heavy compaction, or serious erosion usually have lower hydraulic conductivity compared with natural soils with less disturbance [50]. Near Saturated Hydraulic conductivity values from both Double ring and Inverse Auger Hole methods were within the range of 0.04 mm/h and 1374 mm/h reported by [51]. The results also lies within the range of values quoted for clay soils (0.0072mm/h) and gravels (11,160 mm/h) by [25]. The Inverse Auger Hole method produced higher hydraulic conductivity values (median of 645.2mm/h) which is above the range quoted as acceptable for infiltration based systems [26]. According to [52] soils with infiltration rate of 6.86 mm/h or lower are not suitable for infiltration based systems and that minimum infiltration rate should be between 13.2mm/h – 61.2mm/h. For the Inverse Auger Hole method the high values (Figure 5) obtained could be due to improved infiltration conditions with the setup which involved breaking into the soil horizons to a depth of 500 mm. This could have removed any crusting's and might have penetrated into the transmission zone where moisture content is also fairly uniform [47].

The results suggest that spatial characterization of hydraulic conductivity values cannot be used to delineate homogeneous areas within the study area, and this supported by other writers such as [21, 53, 54]. They cautioned that the hydraulic properties of urban soils are extensively modified by construction, compaction and erosion thus any observed values from standard field tests may not necessarily reflect anything close to either pre-development or post-development conditions, affecting reliability. Also for a country like Ghana, [48] posited that there is limited information on variability in physico-chemical properties of soils under the different land use systems to allow conclusive generalizations. Further, there has been challenging conclusions to the effect of soil variability on hydraulic conductivity [55]. These reservations notwithstanding the researcher is of the view that the results from the four methods is consistent with values reported in the literature under various soil and climate conditions and will serve as a good basis for further work. The results from all four methods suggest moderate hydraulic conductivity values for the seven soil types which will make them suitable for infiltration based stormwater systems, howbeit with some level of engineering to increase hydraulic conductivity in places. This is related to the general assumption that *insitu* soils with low hydraulic conductivity are not suitable for infiltration based stormwater management systems [52] and require modification to improve performance.

Implication for infiltration based stormwater management

Soils of the study area are known to have high clay content, more than 30% being common [56] which increases with depth [57], the highest level being in the subsoil [58]. Nyibgenya-Haacho and Oyarifa-Mamfe complex have similar characteristics as they are derived from the same parent material [59, 60]. They are known to be prone to hard pan formation in areas where the soil has been exposed to the elements over prolonged periods [56, 59, 61]. The observed difference in their hydraulic conductivity values could be due to the presence of hard pan developed especially in the Nyigbenya-Haacho complex. This is confirmed by soil profile tests run by the researcher for limited areas of the research area with Nyigbenya-Haacho complex which showed hard pan formation at 1.2 m depth. Since the soil profile tests could not be extended to the other soil types it is difficult to extend this point.

Using the minimum values obtained from the three near-saturated infiltrometers as stated in USDA Hydrologic Soil Groups (HSG) document [45], the soil groups were given a preliminary classification (Table 2). The classification of Nyagbenya-Haacho under HSG C is supported in the literature by [62, 63]. The same cannot be said for Oyarifa-Mamfe complex, an Acrisols which has been classified as C based on work done by [62, 63] and data from the Harmonized World Soil Database site [64]. Also using the Phillips approach [65] Damfa-Dome complex is classified as HSG D. These differences in hydrological soil groupings is not strange as soils in urbanized areas keeps changing under different land cover conditions [66], from physical processes like erosion [54] and even within the same soil type [25, 47].

Among the near saturated infiltrometer methods, Oyarifa-Mamfe produced the lowest Infiltration rate (median, 52 mm/h) followed by Nyigbenya-Haacho complex (median, 98 mm/h). The highest was from Korle consociation (median, 356 mm/h). The low infiltration rate places Oyarifa-Mamfe within the minimum infiltration rate range for infiltration based systems for stormwater management as stated in the Bioretention Manual [52]. Soils with low infiltration characteristics can be improved for infiltration based interventions to control floods [67, 68] through the introduction of media with predefined hydraulic conductivity (engineered soil) greater than 200 mm/h [26]. In addition to using engineered media, Dietz suggests that in areas where *insitu* soils have low hydraulic conductivity of between 13.2mm – 61.2mm/h [52], a thick reservoir of coarse aggregate can be installed to increase storage capacity and allow longer time for temporarily stored stormwater to infiltrate [69]. This could be overlaid on the *insitu* low hydraulic conductivity soil to ensure high run-off infiltration rate [70]. Work has been done to define composition of engineered soils for infiltration based stormwater management systems for different geographic and climatic locations [71-73]. The best engineered soil media should be chiefly of sandy texture, highly permeable to allow infiltration of runoff [52] and should have hydraulic conductivity sufficient to drain stormwater runoff quickly enough to provide capacity for subsequent storms [52, 74]. This should be combined with depth with the composition varied to accommodate projected increases in runoff from impervious areas [75].

The design of any infiltration based system may be guided by Le Coustomer's classification in relation to how pervasive the problem of erosion is on a site. In a study [26] found that infiltration based storm-water management systems can be grouped into two, those designed with an initially high hydraulic conductivity (> 200 mm/h) and those designed with an initially low hydraulic conductivity (< 20 mm/h). He found that those designed with initially high hydraulic conductivity quickly deteriorates, thus a better option will be to design with a moderately high hydraulic conductivity.

There are advantages to the use of media with high hydraulic conductivity, though. Soils with high hydraulic conductivity values have good drainage [41] resulting in reduced drain time for any designed and strategically installed infiltration based systems for stormwater management [76]. The drain time which is the period between a rainfall event and the time ponding is observed on the surface of the soil [47] has direct bearing on the design and sizing of infiltration based interventions for stormwater management. From the results the good drain time recorded by Korle (median, 23.1 hours) which outperformed all other soil types, including Oyarifa-Mamfe complex (median, 55.7 hours) and Nyagbenya-Haacho (median, 77.6 hours) which showed moderate drainage characteristics is critical to reducing ponding time for infiltration based systems [76]. The performance of Korle consociation and Oyarifa-Mamfe complex falls within the standard 24-72 hours drain time suggested for draining infiltration-based systems to prevent environmental problems [77, 78].

6. Conclusion

The main purpose of the research was to provide a preliminary analysis for a general knowledge of the hydraulic properties of soils of the study area to inform the introduction of infiltration based interventions to address the problem of flooding. Although data collected was not comprehensive, the areas covered represent important catchments which supply about 70% of runoff to the metropolitan area. Hydraulic conductivity of soils of the area fell within a wide range between the four different infiltrometer methods with median values of 219.5mm/h, 42mm/h, 645.2 mm/h and 140 mm/h for the Mini Disk, Double Ring, Inverse Auger and Turf Tec infiltrometers respectively. Among the four infiltrometers the Inverse Auger produced the highest near saturated hydraulic conductivity values, ranging between 78.7 mm/h and 1722 mm/h. The results showed that soils of the study area have moderate infiltration characteristics to support an infiltration based system for stormwater management. This is confirmed by the low drain-time of 23.1 h for Korle consociation and 55.7 h for Oyarifa-Mamfe complex, which will ensure drainage within a maxi of 72 hours. The rest of the soils had drain time greater than 72 h. Results from the near saturated infiltrometers, using minimum hydraulic conductivity values were used to provide an initial classification of the soils into hydrological groups where Korle consociation and Damfa-Dome complex were classed HSG A, Nyigbnenya-Haacho complex as HSG C and the rest as HSG B. Based on these limited findings it may be necessary to design specially prepared engineered soils not only to improve the hydraulic properties of the soils for faster drainage but to counteract the effect of depth on hydraulic conductivity. This will also help address the problem of non-homogeneity due to modification of the soil from urbanized activities. Such engineered soil media with predefined hydraulic conductivity may be necessary to improve the infiltrating qualities of soils with low drain-time such as Nyigbenya-Haacho (77.6 h), Fete-Bediesi (407.1 h), and Fete consociation (1282 h). The research takes the position that the design of engineered soil media for infiltration based systems should adopt a medium initial hydraulic conductivity approach; this way the effect of erosion resulting in sedimentation will not be too drastic to affect the long term performance of the system. The design of an appropriate engineered soil media with medium hydraulic conductivity should follow a reiterative process of trial and error and should be such as not to sacrifice the ability of the infiltration based system to perform the key function of draining away stormwater quickly enough to accommodate the next storm event. Finally, this preliminary information about infiltration characteristics of the soils can be combined with soil depth to guide the sizing of infiltration based interventions such as infiltration wells, percolation trenches, bio-infiltration ponds, bioswales, and detention ponds for stormwater management and flood control.

7. Recommendation

As has been shown very little work has been done on the infiltration characteristics of soils in the research area. Future work can focus on how infiltration characteristics of the various soils vary with depth and land cover types over a more extensive area.

Appendix

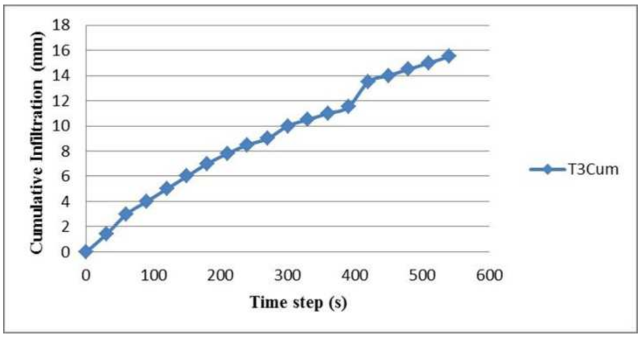

Figure A1. *Cumulative infiltration (saturated) graphs for Oyarifa-Mamfe complex.*

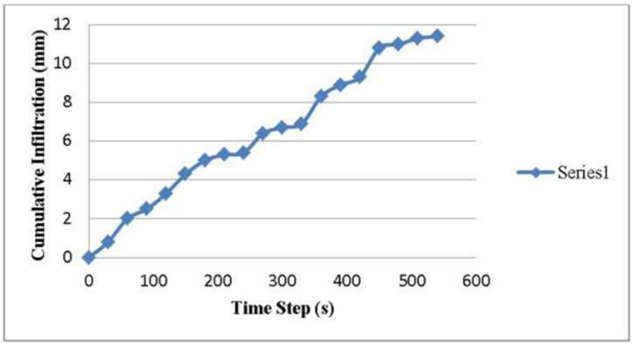

Figure A2. *Cumulative infiltration (saturated) graphs for Danfa-Dome complex.*

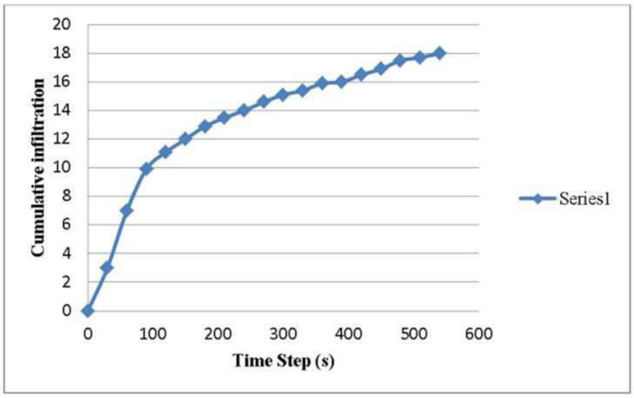

Figure A3. *Cumulative infiltration (Saturated) graphs for Fete consociation.*

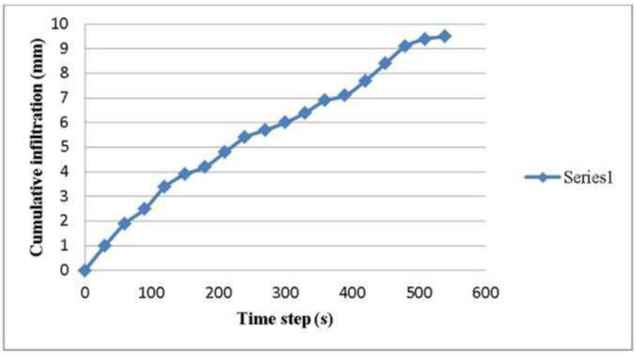

Figure A4. *Cumulative Infiltration (saturated) graphs for locations Oyarifa-Mamfe.*

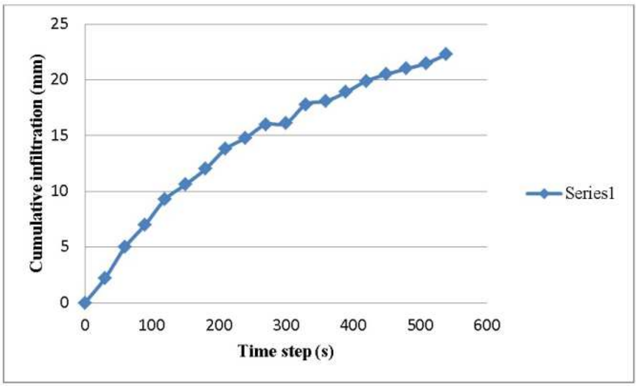

Figure A5. *Cumulative Infiltration (saturated) graphs for Oyarifa-Mamfe.*

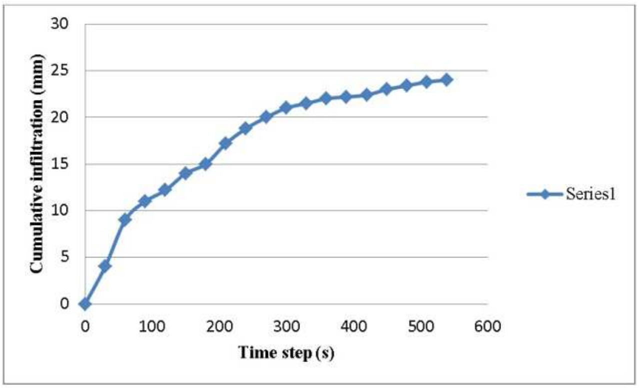

Figure A6. *Cumulative Infiltration (Saturated) graphs for Korle consociation.*

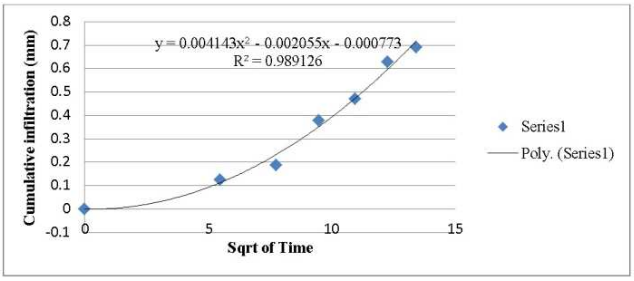

Figure A7. *Cumulative Infiltration (Unsaturated) graphs for Nyigbenya-Haacho complex. Note Sqrt is Square root.*

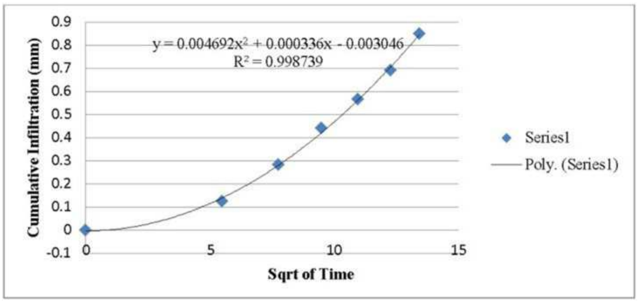

Figure A8. *Cumulative Infiltration (Unsaturated) graphs for Korle consociation.*

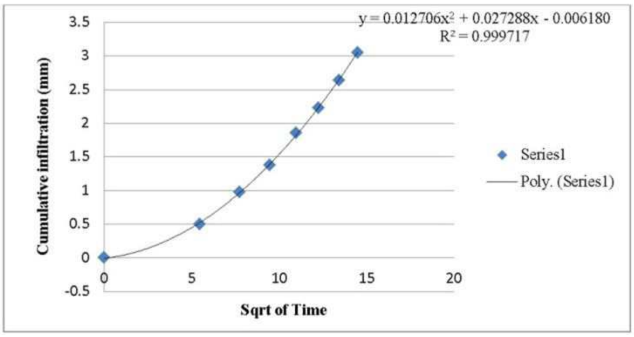

Figure A9. *Cumulative Infiltration (Unsaturated) graphs for Fete-Bediesi.*

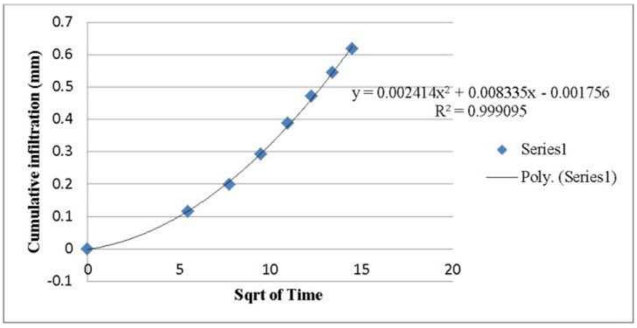

Figure A10. *Cumulative Infiltration (Unsaturated) graphs for Chuim-Gbegbe association.*

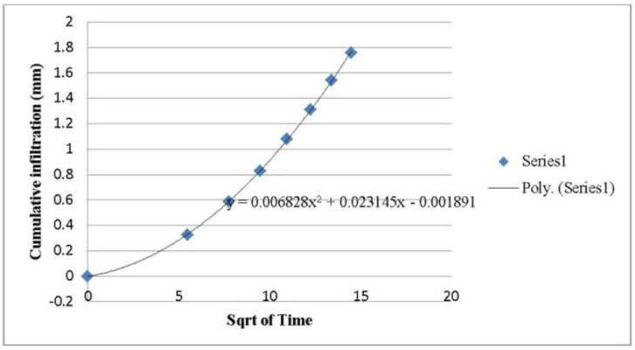

Figure A11. *Cumulative Infiltration (Unsaturated) graphs for Fete-Bediesi complex.*

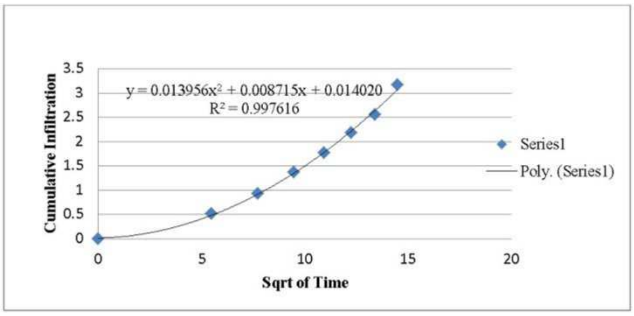

Figure A12. *Cumulative Infiltration (Unsaturated) graphs for Fete-Bediesi complex.*

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