Open Access Library Journal
2024, Volume 11, e11471
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Determination of Infiltration Rate in Developed Areas of Minna, Nigeria

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How to cite this paper: Otuaro, E.A., Musa, J.J., Kuti, A.I., Sunday, D.E. and Muhammad, A.G. (2024) Determination of Infiltration Rate in Developed Areas of Minna, Nigeria. *Open Access Library Journal*, **11**: e11471.
http://doi.org/10.4236/oalib.1111471

Received: March 22, 2024
Accepted: April 22, 2024
Published: April 25, 2024

Abstract

Infiltration is the process by which water on the ground surface enters the soil, and its capacity is the maximum rate of infiltration. Soil is a crucial component of agriculture, with properties varying due to connections between the atmosphere, living beings, parent material, and alleviation. A double ring with the inner and outer dimensions having diameters of 30 cm and 60 cm respectively. A core sampler of 50 mm in diameter and 50 mm high was used to collect soil samples from the study locations to determine the moisture content of the soil at each site. A 60-gram soil sample was collected from different plots, air-dried, weighed and passed a 0.0053 mm screen. The semi-built-up areas have significantly higher infiltration rates than built-up areas. The results from the study area of the semi-built-up area showed a bulk density of depths ranging from 1.20 g/cm^3 to 1.97 g/cm^3. The average moisture content of fifteen plots in the study area ranged from 7.14% to 17.07%. The soil texture ranges from 11.5% to 87.1% for sand, 2.53% to 60.75% for silt, and 4.43% to 38.25% for clay. It was concluded that preserving urban permeable areas, particularly forests, could help reduce urban flooding before it reaches flood-prone communities.

Subject Areas

Soil Science

Keywords

Bare-Land, Built-Up Infiltration, Soil, Water

1. Introduction

Soil is a crucial component of agriculture, with properties varying due to connections between the atmosphere, living beings, parent material, and alleviation [1]. It is essential to study soil attributes to determine the appropriate soil type for agriculture [2]. Land evaluations are a process used to assess the suitability of land for various uses, such as agriculture [3]. This data helps in selecting yields and related crops.

Infiltration is the process by which water on the ground surface enters the soil, and its capacity is the maximum rate of infiltration [4] [5]. It is measured in meters per day or over time. Infiltration capacity decreases with soil moisture content, and if precipitation exceeds the infiltration rate, runoff usually occurs unless there is a physical barrier.

Soil infiltration rate is determined by two factors: porosity and permeability [6]. Porous soil has coarse particles with large pores, while more porous soil loses water content quickly due to gravity [7]. Infiltration capacity is measured in meters per day or distance units over time. Understanding hydrological processes and their connections in land and soils is crucial for effective land-water resource management and planning. This study aims to determine the differential infiltration rate parameters in developed areas of Minna, Niger state.

2. Materials and Method

2.1. Study Area

Infiltration rates of Developed areas located at the Federal University of Technology, Minna Bosso Campus were measured using a double ring infiltrometer test. The study area is situated between Latitudes 9˚39'3.82"N to 9˚39'25.90"N, Longitude 6˚31'27.65"E to 6˚31'27.65"E at an elevation of about 400 m above sea level within Bosso Local Government Area of Niger State. The mean annual maximum and minimum temperature are 39.18˚C and 25.86˚C respectively while the mean relative humidity and rainfall are 56.28% and 130.0 mm respectively. Bosso Local Government Area is bordered by Shiroro to the North, Paiko to the East, Katcha to the South and Wushishi to the West [8]. Minna has two main distinct climates, rainy and dry seasons [9]. The rainy season begins in April and ends in October while the dry season starts in November and ends in March of the following year. The study area is known to have a basement complex and Nupe sandstones are the two separate geological zones that make up Niger State's geology. **Figure 1** shows the map of the study area and locations where the tests were carried out.

2.2. Infiltration Rate Capacity

A double ring with the inner and outer dimensions having diameters of 30 cm and 60 cm respectively. The height of the infiltrometer used was 30 cm. This is in accordance with the study carried out by Musa and Egharevba [10] and Musa *et al.* [11]. The double-ring infiltrometer was installed into the earth where measurements were taken. The rings were carefully hammered into the ground by placing a wooden bar across each ring to protect the tops from damage. Areas

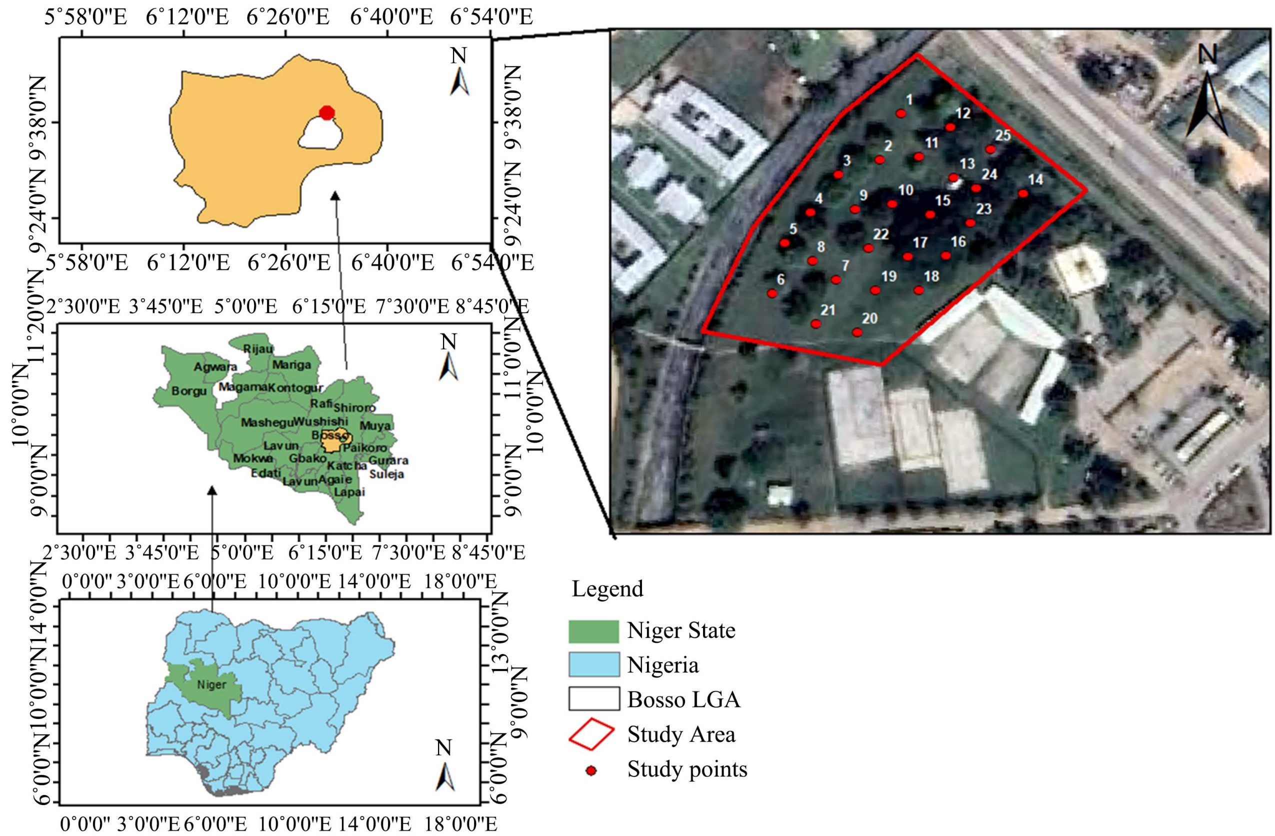


Figure 1. Map showing selected study area within FUT Minna Bosso Campus, Nigeria.

where grasses existed were carefully cleared such that the soils beneath were not disturbed.

2.3. Soil Moisture Content

A core sampler of 50 mm in diameter and 50 mm high was used to collect soil samples from the study locations to determine the moisture content of the soil at each site. With the use of a blade, the end of the core sampler was cut off, and the substance was immediately emptied into a container of known weight and secured [12]. The soil and the container were weighed and oven-dried for 24 hours at 105˚C degrees [13]. Equation (1) below was used to determine the soil's moisture content for each study location.

$$\text{Moisture Content of soil} = \frac{\text{weight of wet mass of soil} + \text{container}}{\text{weight of dry mass of soil} + \text{container}} \times 100 \quad (1)$$

2.4. Soil Texture

A 60-gram soil sample was collected from different plots, air-dried, and weighed. The sand fraction was preserved by a 0.0053 mm screen. The sedimentation process involved adding distilled water to the smaller soil fractions [14]. Clay and silt particles were suspended in the solution, followed by two hours of room temperature settling [15]. The sand and wet silt were dried in an oven at 105˚C and weighed before the suspended clay fraction was separated from the settling silt particles. The percentages of sand, silt, and clay were determined using the formulae presented in Equation (2).

$$w = \frac{MT}{VT} \tag{2}$$

where MT is the Total mass of soil, VT is the Total volume of soil and Dw is the Wet bulk density. The mass of oven-dry soil per unit volume of damp soil is known as "dry bulk density," and it is expressed as Equation (3).

$$Dd = \frac{MS}{VT} \tag{3}$$

where Ms is the Mass of the soil solid, VT is the Volume of the soil and Dd is the Dry bulk density.

$$\text{Sand}(\%) = \frac{\text{Oven dry sand mass}}{\text{mass of soil sample}} \times 100 \tag{4}$$

$$\text{Silt}(\%) = \frac{\text{Oven dry silt mass}}{\text{mass of soil sample}} \times 100 \tag{5}$$

$$\text{Clay}(\%) = 100\% - (\text{Sand} + \text{Silt})\% \tag{6}$$

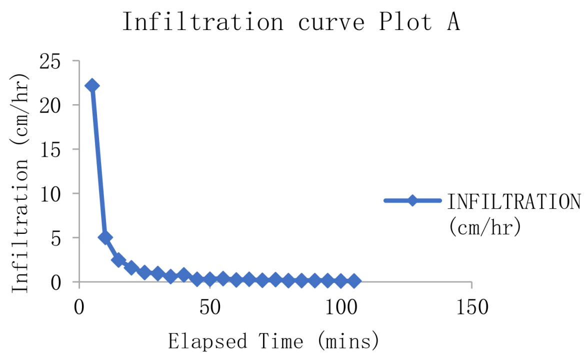
3. Results and Discussions

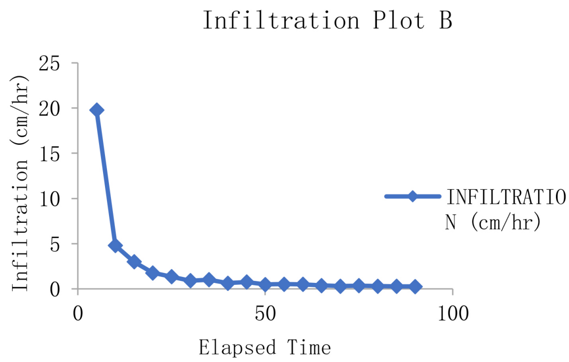
3.1. Soil Infiltration Rate

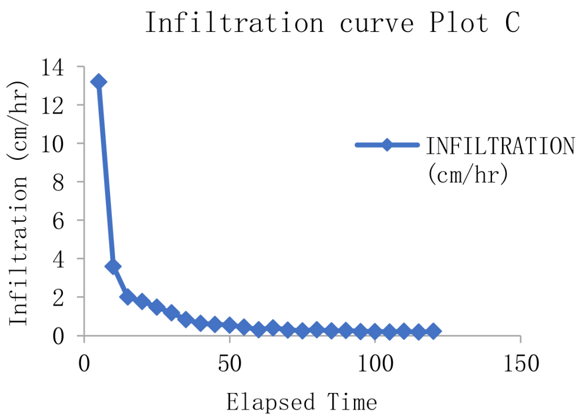
The study focuses on improving infiltration rates by using existing land use and land cover data. Ground-truthing of the land cover data was found to help determine relative infiltration capacities at the site [16] [17], with semi-built-up areas having significantly higher infiltration rates than built-up areas [17] [18] as observed in **Figure 2**. Trees can increase infiltration rates by increasing soil macropores and soil organic matter, while also taking up water with their root systems. During site visits, the study site was re-classified into places with high and low built-up areas. Not much difference was observed between the two classes as all the study areas had similar water intake rates as shown in **Figure 2**.

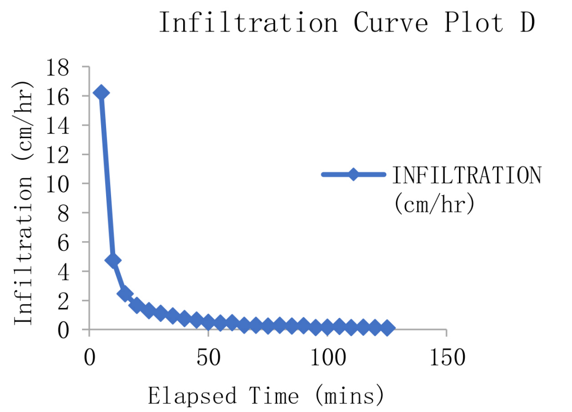
The study also found that available soil survey data on soil texture or time since development is not sufficiently attuned to soil conditions. The common practice of adding sandy soil to mitigate construction activities likely causes soil textures to not match soil survey data, leading to inaccurate predictions of infiltration rates as observed in plots I and O of the study area. Development-related changes to soil texture may also explain why time since development a poor indicator of infiltration is.

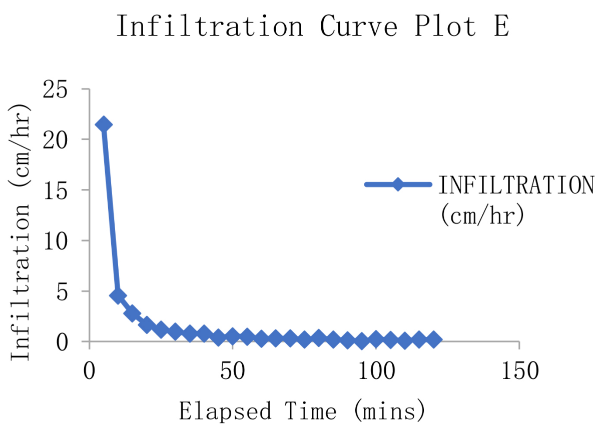
Despite urban soil infiltrating 99% of precipitation events in most cases, portions of this watershed experience persistent stormwater challenges. These challenges may be due to the extent of impervious cover throughout the watershed which is similar to the findings of Musa and Egharevba [10], but the connectivity of impervious surfaces likely plays a critical role. The low infiltration capacities across the study area indicate that disconnecting impervious surfaces could be a

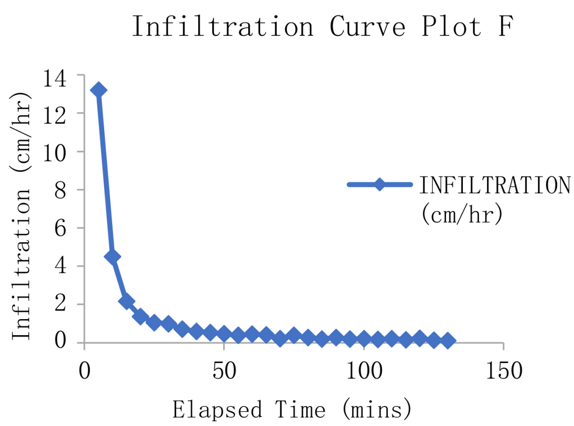

Infiltration curve Plot A
Infiltration (cm/hr)
25
20
15
10
5
0
0
50
100
150
Elapsed Time (mins)
INFILTRATION (cm/hr)

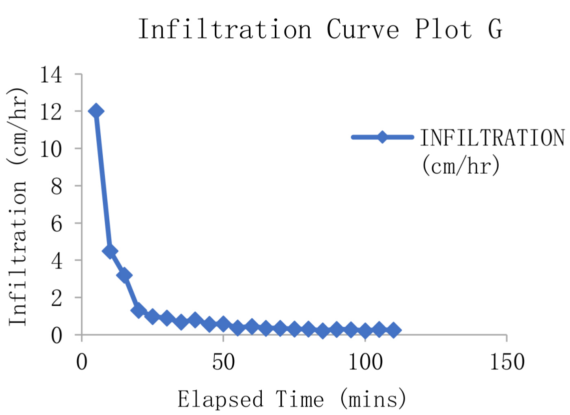

Infiltration Plot B
Infiltration (cm/hr)
25
20
15
10
5
0
0
50
100
Elapsed Time
INFILTRATIO N (cm/hr)

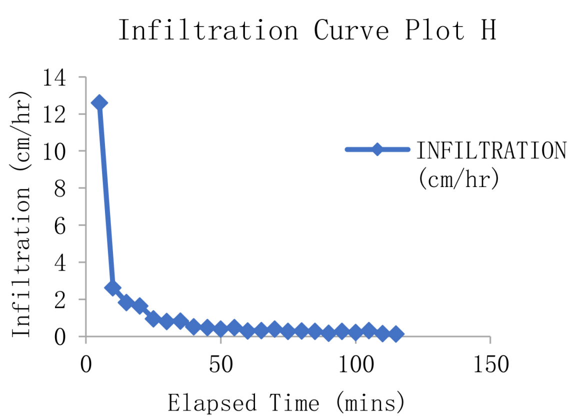

Infiltration curve Plot C
Infiltration (cm/hr)
14
12
10
8
6
4
2
0
0
50
100
150
Elapsed Time
INFILTRATION (cm/hr)


Infiltration Curve Plot D
Infiltration (cm/hr)
18
16
14
12
10
8
6
4
2
0
0
50
100
150
Elapsed Time (mins)
INFILTRATION (cm/hr)


Infiltration Curve Plot E
Infiltration (cm/hr)
25
20
15
10
5
0
0
50
100
150
Elapsed Time (mins)
INFILTRATION (cm/hr)


Infiltration Curve Plot F
Infiltration (cm/hr)
14
12
10
8
6
4
2
0
0
50
100
150
Elapsed Time (mins)
INFILTRATION (cm/hr)


Infiltration Curve Plot G
Infiltration (cm/hr)
14
12
10
8
6
4
2
0
0
50
100
150
Elapsed Time (mins)
INFILTRATION (cm/hr)


Infiltration Curve Plot H
Infiltration (cm/hr)
14
12
10
8
6
4
2
0
0
50
100
150
Elapsed Time (mins)
INFILTRATION (cm/hr)

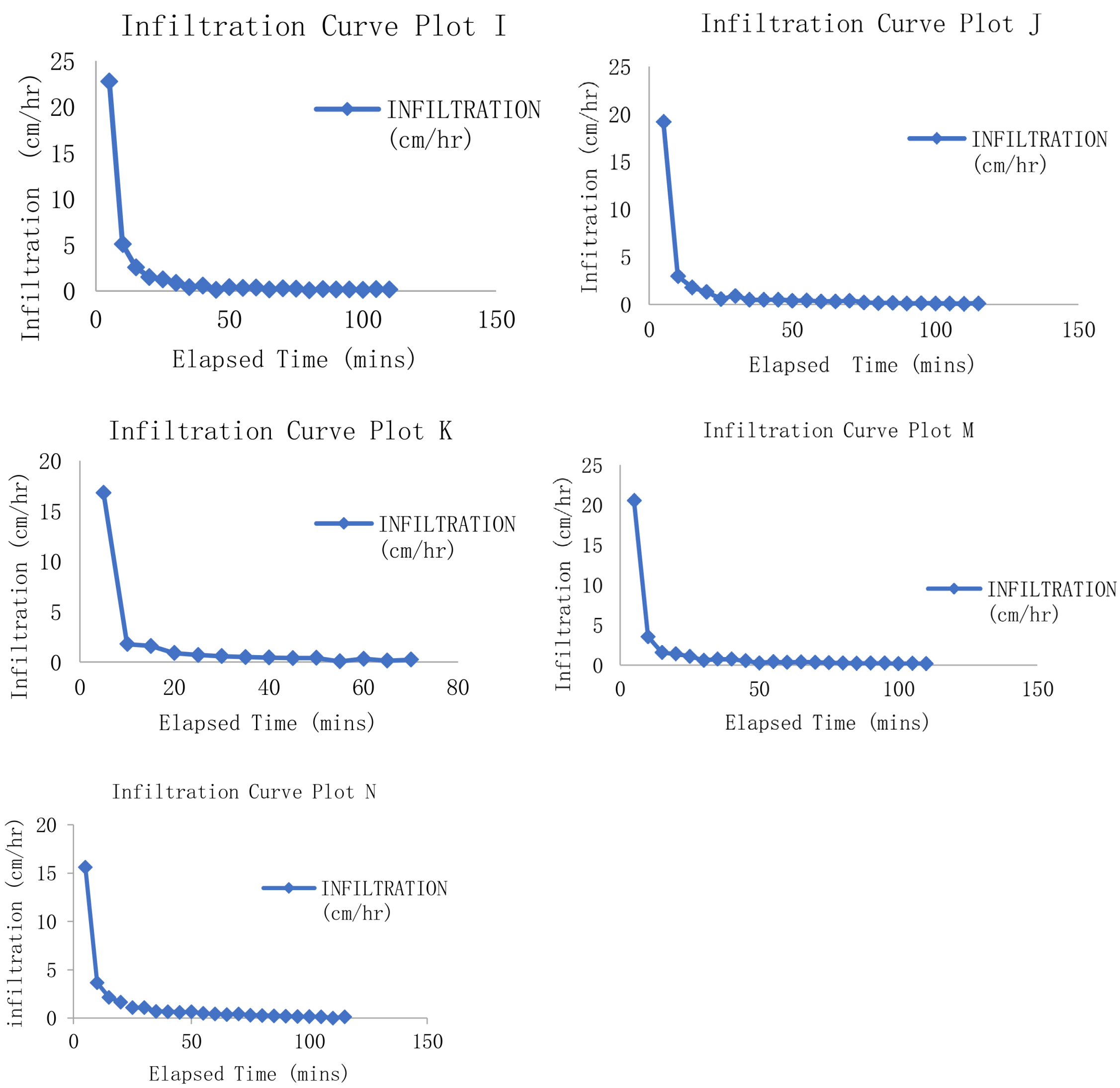


Figure 2. Soil infiltration rates for randomly selected developed areas in Bosso, Niger State.

a helpful strategy in areas of sandy soils, which may be less compact than in some urban settings. Prioritization for such interventions could be developed by analysing potential connections between imperious areas and areas with high infiltration capacity using the random-forest infiltration maps approach.

3.2. Bulk Density

The study examines the soil's bulk density from fifteen plots, ranging from 0 - 30 cm to 0 - 60 cm, to determine its wet and dry basis and micro-pore spaces for air and water movement. The results show that wet bulk density is higher (**Table 1**). Soil compaction significantly impacts productivity and is a severe agricultural issue [19]. Bulk density is a crucial variable, as it is connected to soil compaction and other physical, chemical, and biological characteristics [20]. The results from the study area of the semi-built-up area showed a bulk density of depths ranging from 1.20 g/cm^3 to 1.97 g/cm^3. However, the results are slightly in line due to the study being conducted on a cultivated area, where the value ranges from 1.6 g/cm^3 to 1.9 g/cm^3. The differences in results may be due to differences in soil type, localities, core ring volume, and sample depth, which may be related to the variation in bulk density values.

Table 1. Soil bulk density.

S/N	Stations	Soil depth (cm)	Bulk Density	Average Bulk Density
1	A	0 - 30	1.56	1.41
		0 - 60	1.26	
2	B	0 - 30	1.53	1.57
		0 - 60	1.61	
3	C	0 - 30	1.20	1.50
		0 - 60	1.80	
4	D	0 - 30	1.49	1.40
		0 - 60	1.30	
5	E	0 - 30	1.58	1.47
		0 - 60	1.35	
6	F	0 - 30	1.72	1.62
		0 - 60	1.52	
7	G	0 - 30	1.97	1.72
		0 - 60	1.47	
8	H	0 - 30	1.68	1.64
		0 - 60	1.60	
9	I	0 - 30	1.78	1.62
		0 - 60	1.46	
10	J	0 - 30	1.62	1.45
		0 - 60	1.28	
11	K	0 - 30	1.69	1.48
		0 - 60	1.27	
12	L	0 - 30	1.42	1.57
		0 - 60	1.72	
13	M	0 - 30	1.25	1.44
		0 - 60	1.62	
14	N	0 - 30	1.95	1.80
		0 - 60	1.65	
15	O	0 - 30	1.23	1.42
		0 - 60	1.60	

3.3. Soil Moisture Content

Soil moisture content, a crucial component of the soil's three-phase systems, significantly influences its mechanical properties, consistency, compatibility, cracking, swelling, shrinkage, and density. The average moisture content of fifteen plots in the study area ranged from 7.14% to 17.07% (**Table 2**). The developed area of the Bosso campus has a similar moisture content to previous research by Musa *et al.*, [21], which found a moisture content of 10% to 13%. This suggests that the soil is dry, as low moisture reduces cohesiveness among particles,

Table 2. Show the soil moisture content of the fifteen plots.

S/N	Samples	Soil Depth (CM)	Weight of container (g)	Weight of container + sample (g)	Weight after oven-dry (g)	Moisture content (%)	Average moisture content (%)
1.	A	0 - 30	24. 66	222.71	199.13	13.51	13.82
		0 - 60	24.55	224.29	199.57	14.13	
2.	B	0 - 30	22.73	270.60	235.22	16.64	15.25
		0 - 60	23.11	266.22	236.65	13.85	
3.	C	0 - 30	24.24	216.49	195.35	12.35	10.54
		0 - 60	24.57	214.33	199.10	8.72	
4.	D	0 - 30	24.66	242. 32	225.40	8.43	8.99
		0 - 60	23.42	243.25	224.12	9.54	
5.	E	0 - 30	22. 73	220.57	198.86	12.33	11.35
		0 - 60	23.15	218.46	200.11	10.37	
6.	F	0 - 30	24.23	227.25	212.34	7.93	7.14
		0 - 60	22.96	225.56	213.45	6.35	
7.	G	0 - 30	24.66	265.19	232.42	15.77	13.44
		0 - 60	24.13	260.74	237.29	11.10	
8.	H	0 - 30	22.73	223.53	199.68	13.48	12.86
		0 - 60	24.51	227.77	205.62	12.23	
9.	I	0 - 30	24.24	252.37	228.57	11.65	13.16
		0 - 60	23.91	255.42	225.82	14.66	
10.	J	0 - 30	24.66	212.41	191.20	12.73	12.10
		0 - 60	23.23	215.55	195.76	11.47	
11.	K	0 - 30	22.73	274.75	237.65	17.26	17.07
		0 - 60	24.56	271.13	235.53	16.87	
12.	L	0 - 30	24.24	255.24	229.96	12.29	13.47
		0 - 60	23.86	256.99	227.22	14.64	
13.	M	0 - 30	24.66	262.24	230.43	15.46	13.30
		0 - 60	24.11	259.22	235.66	11.14	
14.	N	0 - 30	22.73	215.61	193.65	12.84	12.46
		0 - 60	23.24	210.52	190.33	12.08	
15.	O	0 - 30	24.24	233.82	212.48	13.99	12.74
		0 - 60	23.79	236.22	214.32	11.49	

making them more dispersible by water and erosion agents. The infiltration rate is higher when the soil is dry, as low moisture reduces the cohesiveness of particles.

3.4. Soil Textural Class

The study examines the soil texture of fifteen plots in a developed area, focusing on its impact on physical, chemical, biological, and hydrological activities. The results of particle size analyses revealed two major soil types: sandy loam and loamy sand. The sandy loam soil type covers 63% of the area, while the loamy sand type covers 32%. The soil texture ranges from 11.5% to 87.1% for sand, 2.53% to 60.75% for silt, and 4.43% to 38.25% for clay (**Table 3**). The results differ from a previous study by Musa *et al.*, [21], which found values ranging from

Table 3. Shows the soil textural class of the fifteen plots.

S/N	Stations	Soil Depth (CM)	% Sand	% Silt	% Clay	Textural class
1.	A	0 - 30	71.00	13.66	15.34	Sandy loam
		0 - 60	32.15	53.63	14.22	Silty loam
2.	B	0 - 30	76.10	7.20	16.70	Sandy loam
		0 - 60	21.65	38.64	39.71	Clay loam
3.	C	0 - 30	72.40	14.60	13.00	Sandy loam
		0 - 60	77.21	15.39	7.40	Loamy sand
4.	D	0 - 30	83.10	10.25	6.65	Loamy sand
		0 - 60	81.25	7.56	11.19	Loamy sand
5.	E	0 - 30	78.12	7.73	14.15	Sandy loam
		0 - 60	58.12	23.44	18.44	Sandy loam
6.	F	0 - 30	66.76	18.20	15.04	Sandy loam
		0 - 60	87.10	2.53	10.37	Loamy sand
7.	G	0 - 30	71.16	14.22	14.62	Sandy loam
		0 - 60	25.18	36.57	38.25	Clay loam
8.	H	0 - 30	63. 15	23.70	13.15	Sandy loam
		0 - 60	60.31	22.30	17.57	Sandy loam
9.	I	0 - 30	80.25	15.32	4.43	Loamy sand
		0 - 60	35.23	31.95	32.82	Clay loam
10.	J	0 - 30	82.28	9.36	8.36	Loamy sand
		0 - 60	50.42	21.03	28.55	Sandy clay loam
11.	K	0 - 30	65.90	8.93	25.17	Sandy clay loam
		0 - 60	11.50	49.40	39.10	Silty clay
12.	L	0 - 30	79.55	6.36	14.09	Sandy loam
		0 - 60	25.15	60.75	14.10	Silty loam
13.	M	0 - 30	71.40	16.16	12.44	Sandy loam
		0 - 60	35.51	30.83	33.66	Clay loam
14.	N	0 - 30	80.11	5.74	14.15	Sandy loam
		0 - 60	65.20	4.28	30.52	Sandy clay loam
15.	O	0 - 30	68.52	13.28	18.10	Sandy loam
		0 - 60	72.33	3.25	24.15	Sandy clay loam

46.0% to 76.20% for sand, 11.30% to 23.50% for silt, and 11.0% to 30.0% for clay. The sand percentage is almost in line, but higher in various studies conducted on uncultivated land. This results in a higher infiltration rate due to the low silt and clay percentage, enhancing the soil's overall performance.

4. Conclusion

Infiltration rates in built-up and semi-built-up areas are crucial for understanding urban hydrology and sustainable water management. In densely populated areas with impermeable surfaces, infiltration rates are typically lower, leading to issues like urban flooding, decreased groundwater recharge, and water quality issues. However, commonly used infiltration models for rainfall-runoff modelling fail to accurately represent the highly variable infiltration rates of urban soils. This may result in overestimation of runoff in models that use infiltration estimations. A different approach to estimating urban infiltration measurements may be necessary. Capitalizing on the high infiltration rates of some soils, especially those in lightly managed urban permeable areas and urban forests, could reduce harmful impacts of runoff from neighbouring impervious surfaces. Information about the relative infiltration capacity of urban landscapes could be useful in planning and zoning, particularly in expanding urban areas. Preserving urban permeable areas, particularly forests, could help reduce urban flooding before it reaches flood-prone communities. Understanding and managing infiltration rates in built-up and semi-built-up areas is essential for achieving resilient and environmentally sustainable urban environments. Collaboration between urban planners, engineers, policymakers, and communities is essential for implementing effective strategies to enhance infiltration, mitigate flood risks, and promote water sustainability in urban areas.

Conflicts of Interest

The authors declare no conflicts of interest.

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