PRINT ISSN 1119-8362
Electronic ISSN 2659-1502

Full-text Available Online at
https://www.ajol.info/index.php/jasem
http://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 26 (12) 2059-2066 December 2022

Assessment of Infiltration Rates and Index Properties of Soil in a Flood Prone Community, Kogi State, North Central Nigeria

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ABSTRACT: The characteristics of Soil is one of the major factors that affect flooding. This study therefore was carried out to assess the infiltration rates and index properties of soil within a flood-prone community of Oforachi in Kogi State, Nigeria using appropriate standard methods. Data obtained showed that the average soil infiltration rate ranges from 1.89 – 3.24 cm/hr and the maximum infiltration rate range between 6.00 – 9.00 cm/hr, while the soil antecedent moisture content was between 15.00 – 42.48 %. Soil infiltration properties classification based on hydraulic conductivity and sieve analysis show that soils within the study area combine silt and clay characteristics which has strong relationship with the persistent flood experienced in the area.

DOI: https://dx.doi.org/10.4314/jasem.v26i12.21

Cite this paper as: ALFA, M. I; OWAMAH, H. I; ISHAQ, A; ADIE, D. B. (2022). Assessment of Infiltration Rates and Index Properties of Soil in a Flood Prone Community, Kogi State, North Central Nigeria. *J. Appl. Sci. Environ. Manage.* 26 (12) 2059-2066

Dates: Received: 31 November 2022; Revised: 21 December 2022; Accepted: 24 December 2022; Published: 31 December 2022

Keywords: Flood; Hydraulic conductivity; Infiltration rates; Index Properties; Soil

Flood which is a condition of partial or total inundation of an area of land which is usually dry has been a consistence menace in Nigeria with the event of 2012 and 2022 as the most severe in over 40 years of Nigeria's history (Alfa *et al.*, 2018a; Alfa *et al.*, 2019). This has been an annual occurrence in Oforachi, a community within the catchment of Ofu River for over two decades (Alfa et al., 2018b). Among other factors, the characteristics of soil has a great influence on runoff and flood occurrence (Vaezi *et al.*, 2010; Chifflard *et al.*, 2018). The soil receives water at the surface after rain, stores it for plant use or slowly releases it for ground water recharge through gravitational flow (Magdolf and Van Es, 2010). The ease with which the soil can do this is dependent on its infiltration rate as well as its index characteristics (Anni *et al.*, 2020). The infiltration rate of the soil is influenced by the soil type, structure and moisture content at the start of rain (Magdolf and Van Es, 2010; Anni *et al.*, 2020). A high infiltration rate will therefore result in lower runoff volumes. This is because runoff is produced when rainfall exceeds a soil's infiltration rate. An understanding of the soil infiltration and index characteristics is therefore an important pre-requisite to understanding the runoff characteristics and flood risk in a catchment. This knowledge will contribute to the management of the flood menace within the catchment. While previous studies (Alfa *et al.*, 2018c; Ogbozige and Alfa, 2019) had investigated the effect of land use/land cover changes on the runoff with the Ofu River catchment, no investigation on the soil characteristics has been carried out in the present study area to the best of our knowledge. This present study was therefore carried out to investigate the soil index and infiltration characteristics within the flood prone community of Oforachi in Kogi State.

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With the growing application of Remote Sensing and Geographic Information System in various fields, there is a possibility of obtaining soil characteristics for any part of the world which can be validated using information obtained from field observation. In recognition of the urgent necessity for improved soil and easily accessible global soil information especially in the context of climate change, the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) took the initiative of combining the recently collected vast volumes of regional and national updates of soil information into a new comprehensive Harmonized World Soil Database (Nachtergaele *et al.*, 2009). Consequently, the Harmonized Soil Database of the World was produced as a result of collaboration between the Food and Agriculture Organization of the United Nations, the :
International Institute for Applied Systems Analysis (IIASA), the International Soil Reference and Information Center (ISRIC), Institute of Soil Science, Chinese Academy of Science (ISSCAS) and the Joint Research Center of the European Union (JRC). Both remotely sensed soil characteristics and data obtained from field work are therefore employed in this present study. Therefore, the objective of this paper was to assess the infiltration rates and index properties of soil in flood prone community in Kogi State of North Central Nigeria.

MATERIALS AND METHODS

Study Area: This study was carried out at Oforachi Community covering Oforachi Ward I and II in Igalamela/Odolu Local Government Area of Kogi State, Nigeria (Fig. 1).

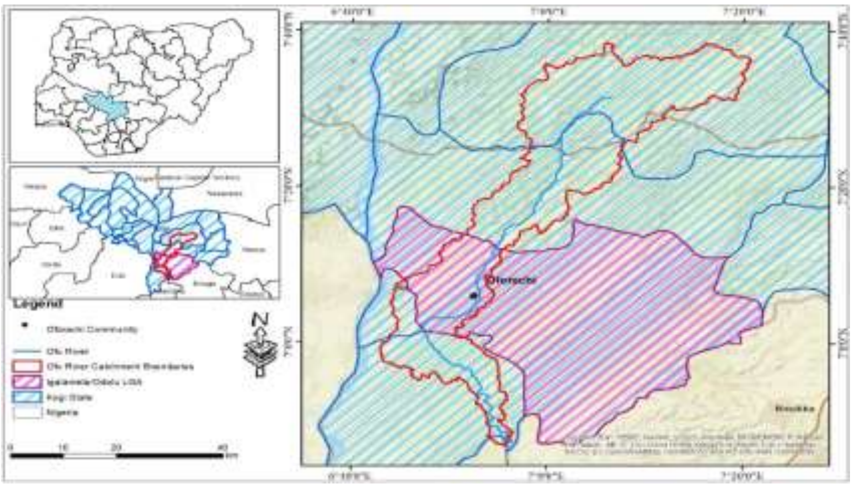

Fig. 1: Map of Study Area

It lies between longitudes 6º 49ˈ E and 6º 57ˈ E and latitudes 7º 06ˈ N and 7º 09ˈ N (Alfa et al. 2018d). The community lies along the banks of Ofu River, which is a perennial river flowing parallel in pattern to Imabolo and Okura Rivers. The trio forms a confluence before emptying into the famous Anambra River downstream (Gideon *et al.*, 2013). The area is nearly level to undulating with dominant slopes between 0 to 2% clay plains which are largely subject to seasonal water logging owing to impeded drainage (Alfa et al. 2018a). The land within the study area is predominantly used for agriculture. The community is divided into nine (9) human settlements with other scattered houses not within the defined settlements.

Collection of Remotely Sensed Soil Data: The soil characteristics of the entire catchment of Ofu River was extracted from the digital soil map of the World (DSMW) obtained from the FAO's website in GIS environment (Fig. 2). The detailed characteristics were obtained from the harmonized world soil database viewer version 2.1 also obtained from the FAO's website. Four soil layers with distinct characteristics were extracted for the entire catchment. A description of the soil types, the area covered and texture classes is presented in Table 1.

Table 1: Characteristics of Soil within Ofu River Catchment

SMU	FAOSoil Symbol	Area (km^2)	Name	Textured Class
1021	Af13-1a	975.61	Ferric Acrisols	Sandy loam
1567	Nd5-1a	259.77	Dystric Nitosols	Loam
1193	G2-2/3a	366.61	Gleysols	Clay Loam
677	Jd3-2a	2.59	Calcaric Fluvisols	Sandy Clay Loam

Source: www.fao.org

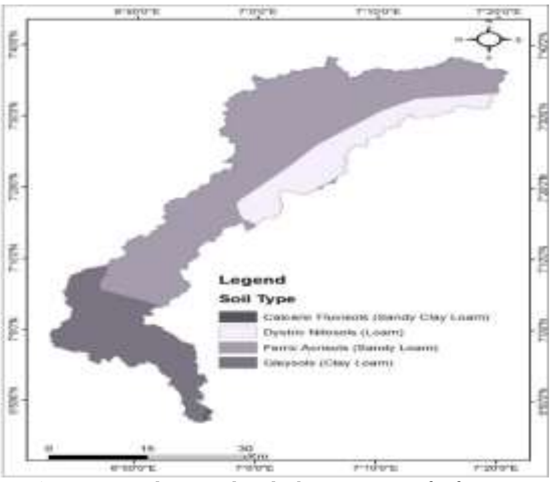

Fig. 2: Remotely Sensed Soil Characteristics of Ofu River Catchment www.fao.org

Assessment of Soil Infiltration and Index properties: In situ and ex situ soil analysis for determination of infiltration rates and index properties were conducted on soil samples collected from ten (10) locations in Oforachi (Fig. 3).

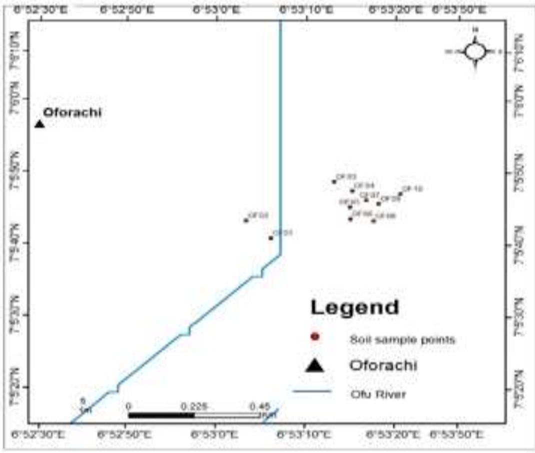

Fig. 3: Location of Soil Sample Collection points at Oforachi

Apart from the infiltration test and part of the Antecedent Moisture content measurement that were carried out in-situ.

Determination of Soil Infiltration Rates: The double ring infiltrometer method was used for the in-situ infiltration measurement. This method has been described previously by Arriaga *et al.* (2010). The infiltrometer consisted of an outer ring of 35 cm diameter and inner ring of 20 cm diameter. The height of both rings was 27 cm. The sizing of the infiltrometer followed the design method described previously by Parr and Bertrand (1960). The fabrication of the rings was made using 1mm mild steel sheets. Both rings were hammered 15 cm into the soil with a plank to protect the surface of the ring from damage during hammering. The test began by pouring water into the inner ring to an appropriate depth and at the same time, adding water to the space between the two rings to the same depth as quickly as possible. The time when the test began was recorded and the water level on the calibration was noted. After two (2) minutes, the drop in water level in the inner ring was recorded and water added to bring the level back to approximately the original level at the start of the test. The water level outside the ring was maintained similar to the one inside to prevent lateral flow. Each infiltration test lasted four (4) hours with cumulative time intervals; 2, 5, 10, 20, 30, 45, 60, 90, 120, 150, 180, 210 and 240 minutes. The cumulative infiltration depth at the elapsed time was recorded.

Estimation of Saturated Hydraulic Conductivity: The analysis of the field data was done based on Philip's infiltration model expressed in Eq. (1) (Philip, 1957).

$$i(t) = St^{1/2} + At \qquad (1)$$

Where; *i(t)*=Cumulative infiltration at cumulative time *t* (cm); *t*=Time (s); *S*=Sorptivity (cm/hr$^{1/2}$); *A*=Transmisivity or permeability coefficient

Values of cumulative infiltration, *i(t)* and time, *t* were obtained from field measurement while the sorptivity, *S* and permeability coefficient, *A* were determined using the method of least square between the field measured cumulative infiltration and the calculated cumulative infiltration. The saturated hydraulic conductivity, *K* (ms^{-1}) as a function of the transmisivity or permeability coefficient, *A* and a constant *m* (2/3) was calculated using Eq. (2).

$$K = \frac{A}{m} \qquad (2)$$

The value of saturated hydraulic conductivity, *K* was used to classify the respective soils based on the CSN 721020 classification table (Holubík *et al.*, 2016).

Determination of Soil Index Properties: Soil samples were collected from ten (10) locations within the Oforachi and transported to the Geotechnical Engineering Laboratory in The Department of Civil Engineering, Ahmadu Bello University, Zaria for the determination of soil index properties. The tests carried out were Moisture contents, Atterberg limits and Sieve analysis. The tests were carried out according to standard methods for soil analysis and classified according to American Association of State Highway and Transportation Officials (AASHTO) and Unified Soil Classification Systems (USCS) described previously (Moreno-Maroto *et al.*, 2021).

Assessment of the Relationship between Soil Type and Flood Risk: The soil characteristics extracted from the digital soil map of the world and verified via field measurement were overlaid on the flood risk maps determined and reported previously (Alfa *et al.*, 2022) in order to assess their relationship.

RESULTS AND DISCUSSIONS

Soil Infiltration Rates and Saturated Hydraulic Conductivity: A comparison of the infiltration rates of the soils with their respective antecedent moisture contents (AMC) is presented in figure 4, which shows that OF-03 has the lowest antecedent moisture content of 22.51 (%) while OF-06 has the highest AMC of 42.48 %. This probably explains the low infiltration rates obtained for all the samples. Furthermore, the saturated hydraulic conductivity as well as corresponding classifications is presented in Table 2. Based on this, the soil is classified predominantly as low plasticity Soil with clayey characteristics.

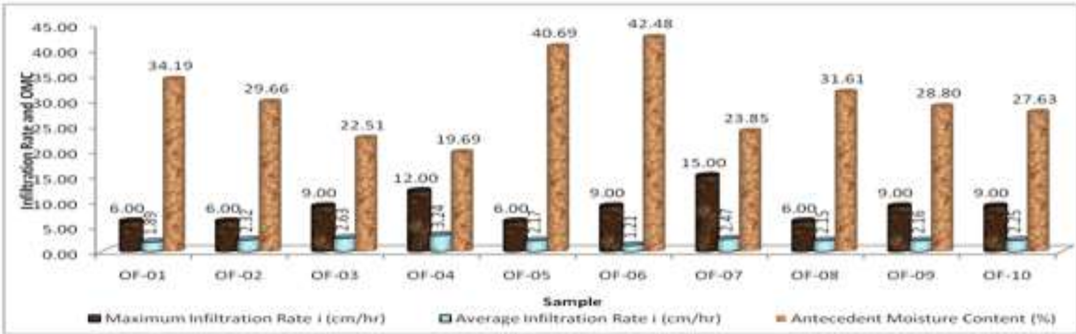

Fig. 4: Maximum Infiltration Rate, Average Infiltration Rate and Antecedent Moisture Content

Table 2: Soil Classification based on Saturated Hydraulic Conductivity

Sample	K (m/s)	Description	Classification
OF-01	-2.01136×10^{-06}	Highly Impermeable	Low plasticity soil with Clay characteristics
OF-02	-2.35862×10^{-06}	Highly Impermeable	Low plasticity soil with Clay characteristics
OF-03	-3.30082×10^{-06}	Highly Impermeable	Low plasticity soil with Clay characteristics
OF-04	-3.53072×10^{-06}	Highly Impermeable	Non plastic soil with Clay characteristics
OF-05	6.68813×10^{-07}	Lowly (poorly) Permeable	Low plasticity soil with characteristics of sandy loams, loamy sands or clayey sands
OF-06	-1.47864×10^{-06}	Highly Impermeable	Low plasticity soil with Clay characteristics
OF-07	-2.69122×10^{-06}	Highly Impermeable	Non plastic soil with Clay characteristics
OF-08	-2.16694×10^{-06}	Highly Impermeable	Low plasticity soil with Clay characteristics
OF-09	-1.84564×10^{-06}	Highly Impermeable	Low plasticity soil with Clay characteristics
OF-10	-2.5993×10^{-06}	Highly Impermeable	Low plasticity soil with Clay characteristics

Soil Index Properties: The results of the Atterberg-limits tests and sieve analyses as well as their corresponding soil classifications are presented in Tables 3 and 4, respectively.

Table 3: Soil Classification based on Results of Atterberg Limits Tests Conducted

Sample	Atterberg Limits			
	Liquid Limit	**Plastic Limit**	**Plasticity Index**	**Class**
OF-01	28.86	23.87	4.99	ML-Silt
OF-02	26.96	25.14	1.82	ML-Silt
OF-03	31.4	14.07	17.33	CL-Lean Clay
OF-04	Non-Liquid	Non-Plastic	Non-Plastic	-
OF-05	18.54	15.63	2.91	ML-Silt
OF-06	49.84	33.86	15.98	ML-MH (Silt to Elastic silt)
OF-07	Non-Liquid	Non-Plastic	Non-Plastic	-
OF-08	31.52	27.18	4.34	ML-Silt
OF-09	24.82	17.36	7.46	CL-ML-Silty clay
OF-10	27.45	20.16	7.29	CL-ML-Silty clay

Based on the three classifications shown in Tables 2 to 4, it can be seen that the soils tested combines silt and clay characteristics. This probably confirms the digital soil map of the world's (DSMW) classification of the soil within the sample locations as sandy loam. The plotted sample locations were overlaid on the DSMW as shown in Fig. 5. This shows that the classification based on the DSMW actually reflects the soil characteristics of Ofu River Catchment.

Table 4: Soil Classification based on the Sieve Analysis Results

Sample	Sieve Analysis Results									Classification	
	Cu	Cc	% Fine (Passing #200)	Fine sand		Medium sand		% Coarse Sand	% Sand (Total)	USCS	AASHTO
				% passing #40	% Fine sand	% passing #10	% Medium sand				
OF-01	5.6	0.86	41.85	86.9	45.05	97.9	11	2.1	58.15	SM - Silty Sand	A-2-4 (Silty sand)
OF-02	31.11	1.07	50.55	84.1	33.55	97	12.9	3	49.45	ML - Sandy silt	A-2-4 (Silty sand)
OF-03	13.08	1.37	37.35	94	56.65	99.6	5.6	0.4	62.65	SC-Clayey Sand	A-2-6 (Clayey sand)
OF-04	11.08	1.66	25	78.5	53.5	98.5	20	1.5	75	SW - Well Graded Sand	A-3 (fine sand)
OF-05	4.59	0.78	32.45	85.2	52.75	99.1	13.9	0.9	67.55	SM-Silty sand	A-2-4 (Silty sand)
OF-06	135	2.67	42.2	71.4	29.2	83	11.6	17	57.8	SM - Silty Sand	A-2-7 (Clayey sand)
OF-07	8.06	1.38	22.4	65.1	42.7	79.5	14.4	20.5	77.6	SW - Well Graded Sand	A-3 (fine sand)
OF-08	25.33	0.63	32.5	71	38.5	96.1	25.1	3.9	67.5	SM-Silty sand	A-2-4 (Silty sand)
OF-09	44.55	7.42	21.55	55.1	33.55	97.2	42.1	2.8	78.45	SC-SM-Silty or clayey sand	A-2-4 (Silty sand)
OF-10	171.43	0.67	44.2	80	35.8	98.2	18.2	1.8	55.8	SC-SM-Silty or clayey sand	A-2-4 (Silty sand)

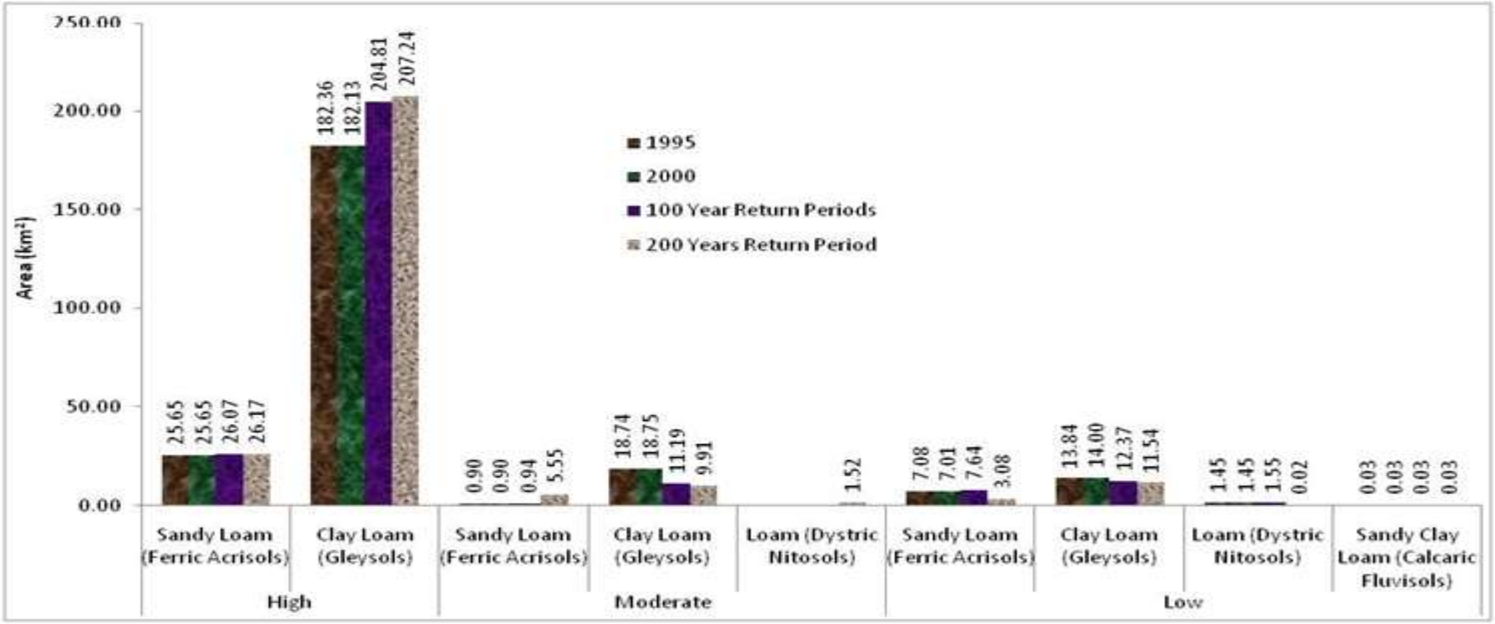

Fig. 6: Area Covered by the Soil Types within the respective Risk Zones in km^2**.**

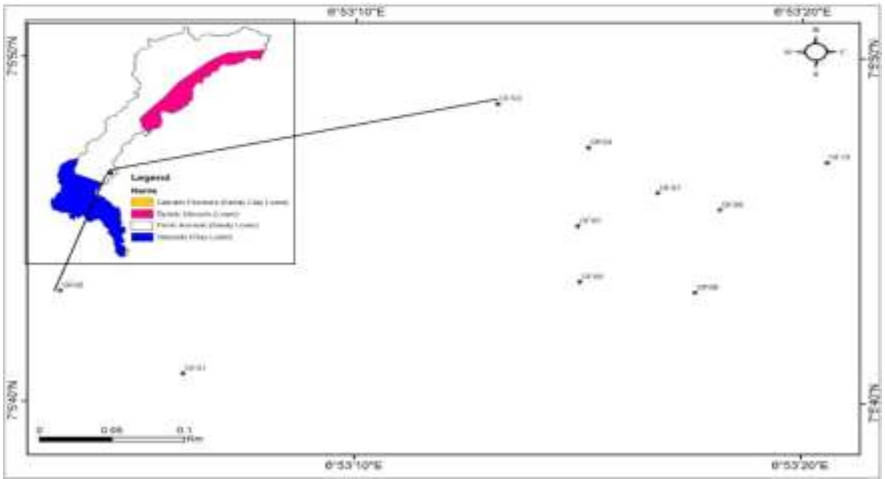

Fig. 5: Comparison of Soil Analyses Results with the Digital Soil Map of the World

Table 6: Inter Profile Characteristics of Soil within the Risk Zones

SMU	Name	Share in SMU (%)	Sand Fraction (%)	Silt Fraction (%)	Clay Fraction (%)	Silt+Clay Fraction (%)	Texture	Gravel Content (%)
				Top Soil (0 - 30 cm)				
1021	Ferric Acrisols (DS)	60	78	12	10	22	sandy loam	4
	Lithosols (ASI)	20	43	34	23	57	loam	26
	Plinthic Acrisols (ASI)	20	47	30	23	53	loam	35
	Average		56	25	19	44		22
				Sub Soil (30 - 100 cm)				
	Ferric Acrisols (DS)	60	65	12	23	35	sandy clay loam	10
	Lithosols (ASI)	20	-	-	-	-	-	-
	Plinthic Acrisols (ASI)	20	36	27	37	64	clay loam	19
	Average		51	20	30	50		15
				Top Soil (0 - 30 cm)				
1193	Gleysols (DS)	35	38	40	22	62	loam	4
	Gleysols (ASI)	35	16	31	53	84	clay (light)	7
	Fluvisols (ASI)	30	39	41	20	61	loam	4
	Average		31	37	32	69		5
				Sub Soil (30 - 100 cm)				
	Gleysols (DS)	35	37	35	28	63	clay loam	5
	Gleysols (ASI)	35	21	27	52	79	clay (light)	1
	Fluvisols (ASI)	30	41	39	20	59	loam	8
	Average		33	34	33	67		5
				Top Soil (0 - 30 cm)				
1567	Dystric Nitosols (DS)	60	76	13	11	24	sandy loam	4
	Lithosols (ASI)	20	43	34	23	57	loam	26
	Orthic Acrisols (ASI)	20	49	27	24	51	sandy clay loam	10
	Average		56	25	19	44		13
				Sub Soil (30 - 100 cm)				
	Dystric Nitosols (DS)	60	62	13	25	38	sandy clay loam	4
	Lithosols (ASI)	20	-	-	-	-	-	-
	Orthic Acrisols (ASI)	20	40	24	36	60	clay loam	10
	Average		51	19	31	49		7
				Top Soil (0 - 30 cm)				
677	Calcaric Fluvisols (DS)	60	49	32	19	51	loam	4
	Dystric Nitosols (ASI)	20	44	33	23	56	loam	11
	Plinthic Gleysols (ASI)	20	42	37	21	58	loam	7
	Average		45	34	21	55		7
				Sub Soil (30 - 100 cm)				
	Calcaric Fluvisols (DS)	60	52	28	20	48	loam	8
	Dystric Nitosols (ASI)	20	35	24	41	65	clay (light)	26
	Plinthic Gleysols (ASI)	20	36	30	34	64	clay loam	10
	Average		41	27	32	59		15

SMU-Soil Mapping Unit; DS-Dorminant soils; ASI-Associated soils with inclusions *Source: Extracted from Harmonised World Soil Database*

Relationship between Soil Type and Flood Risk: Furthermore, the soil types within the respective risk zones are presented in Fig. 6 while the inter profile soil characteristics for the respective soil types are presented in Table 5. It can be observed from Fig. 6 that the predominant soil type within the high risk zone is Gleysols (Clay loam) covering areas of 182.36 km^2, 182.13 km^2, 204.81 km^2 and 207.24 km^2 for year 1995, year 2000, 100 years return period and 200 years return period respectively. These areas represent 72.93 %, 72.87%, 77. 40 % and 78.18 % of the total flood risk extent for year 1995, year 2000, 100 years return period and 200 years return period respectively. The inter profile characteristics presented in Table 6 shows that the combined fractions of silt and clay in Gleysols are 69 % and 67 % for the top soil and the sub soil respectively. This high clay-silt content explains why the flood risk within that zone is high. It means that the ability of the soil to permit infiltration is low thus resulting in runoff and consequently, flooding.

Conclusion: The infiltration rates and index properties of soil within Oforachi were determined using both remotely sensed soil data and those obtained from field studies. The predominant soil within the community were found to be of silty clay characteristics which has strong relationship with the persistent flood experienced in the area.

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