Natural Hazards (2023) 116:3447–3463
https://doi.org/10.1007/s11069-023-05818-0

ORIGINAL PAPER

Contribution of soil physical properties in the assessment of flood risks in tropical areas: case of the Mbo plain (Cameroon)

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Received: 24 November 2021 / Accepted: 4 January 2023 / Published online: 10 January 2023

Abstract

Flooding occurs when water is in excess and can no longer be evacuated normally. The nature of the soil has been identified as one of the major causes of flooding; hence, this study aimed is to show the influence of the physico-chemical properties of the soil on the recurrence of flooding in the Mbo plain. Four soil profiles were carried out on the alluviums according to the altitudes. These profiles were described, and undisturbed soil samples were taken. Then, measurements of the infiltration rate of water in the soil by the Porchet method were taken in sixteen sites. Finally, soil samples taken by auger and core sampling were studied in the laboratory. Physico-chemical parameters such as grain size, porosity, moisture, pH, compactness and organic matter were determined. Infiltration tests carried out in situ using the Porchet method revealed a hydraulic conductivity between 10^{-5} and 10^{-7} m/s, characteristic of a semi-permeable soil. This low value of permeability results from the morpho-structural arrangement and the chemical composition of the soils of the plain. These soils are hydromorphic, which means that they are constantly flooded and temporarily waterlogged. They are more or less sandy-clay on the surface, and very clayey at depth, generally from 25 cm. The very clayey soils at the base considerably slow down infiltration and act as a real barrier layer that prevents water from infiltrating, resulting to intense runoff. These soils are very porous and compact with a fairly high water content of up to 71%. This work allows us to conclude on the role of intrinsic soil properties on the genesis of floods in lowland areas. As in many plains in Africa and in the world, the nature of the soil in the Mbo plain is a natural predisposing factor to flood risks. The methods used can be applied in areas with the same characteristics as the Mbo plain.

Keywords Soils · Physico-chemical characteristics · Flooding · Infiltration rate · Mbo plain · Cameroon

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1 Introduction

Soil is the central element that defines the capacity of water to circulate either by infiltration or by runoff. This parameter depends on its structural, textural and chemical composition. Several works have focused on the physico-chemical analysis of soils related to water circulation, notably Leumbe et al. (2015) who define porosity as the central element that conditions the vertical infiltration of water from the upper parts to the lower parts. Delville (1996) believes that in addition to porosity, the permeability of a soil ensures the circulation and infiltration of water. These two parameters are closely related to the grain size composition of the soil solids and the way they are arranged with the organic matter (Montoroi 2012). Indeed, unlike sands which are inert grains with low water retention, clay-textured soils are not very permeable (Garba Mallam 2000). Organic matter improves soil structure by promoting the formation of aggregates and thus increases infiltration (Tisdall and Oades 1982; Stengel et al. 2009; Wiesmeier et al. 2012; Temgoua et al. 2014). Other authors such as Casenave and Valentin (1989) support the thesis that the decrease infiltrability of a soil is related to its surface condition and internal morphology. Wotling (2000) believes that the degree of soil moisture also influences the infiltration rate. In either case, the infiltration rate of water into the soil depends on its intrinsic characteristics. When the infiltration rate is considerably reduced, the risk of surface runoff increases, which can lead to flooding. Thus, for flooding to occur, the soil must be partially or fully saturated with water. The genesis of floods has been the subject of several studies in Africa and in the world in general. According to some authors, flooding result from the combination of several elements. These are soil, relief, hydrography with rain as a trigger (Leumbe et al. 2015; Zogning Moffo et al. 2015; Lamachere 1988). For others, flooding is due to land-use change and human activity (Tchotsoua 1996; Tchotsoua et al. 2007; Mendonça et al. 2015; Mwazvita et al. 2018; Sighomnou et al. 2012; Zehra et al. 2019; Ansar and Naima 2021). These works corroborate those of Montoroi (2012) who believes that the nature of the soil and its spatial distribution play a dominant role on the genesis of floods. This study was carried out with a view to further investigation in the involvement of soil in the aggravation of flood risks in a plain in a tropical zone. The Mbo plain in West Cameroon was chosen as a test site. Indeed, flooding is the most recurrent risk in this plain. These almost annual floods occur mainly between the months of August and September, with damaging effects on both the socio-economic and environmental levels.

2 Study area

The Mbo plain is located in the west of Cameroon, between 5° 05′ and 5° 25′ North latitude and 9° 50′ and 10° 10′ East longitude, with a surface area of 1394.78 km^2 (Fig. 1). The region has a Guinean equatorial climate with an average annual rainfall and temperatures of 2413 mm and 23.4 °C, respectively. The dry season runs from December to February and the rainy season from March to November. Geomorphologically, the Mbo plain is one of the numerous collapse basins which interrupt in place the continuity of the Cameroonian ridge in places (Tchotsua 1984; Bandji 1994). It is a vast alluvial basin of tectonic origin situated at 710 m altitude (Bourgeon 1979). It is surrounded to the SSW by the Manengouba massif, to the NNE by the Bambouto Mountains and to the East by the escarpment of the Western Highlands at Bafang, which rise between

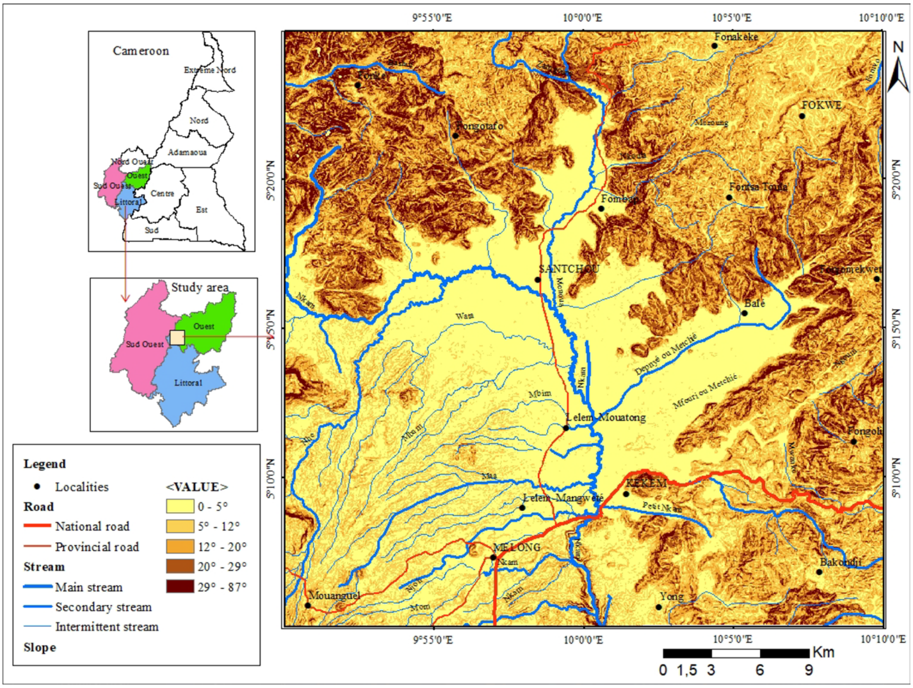

Fig. 1 Location and slope map of the study area

1200 and 2800 m (Bourgeon 1979; Wonanke 2002). At Mélong, a rocky sill locks the plain, serving as the base level for its dendritic and locally meandering hydrographic network (Nkam and Ménoua) (Bourgeon 1979; Nguiffo 2013; Djukem Fenguia 2017) (Fig. 1). Geologically, Mbo plain is made up of two major lithological units: (1) a granite-gneissic substratum made up of migmatites, granites, granodiorites and diorites, on which rest (2) volcanic formations (Dumort 1968). The recognised volcanic products are divided into: Ash and slag, basalts of the upper black series, trachytes and rhyolites associated with the middle white series (Gèze 1943). These two lithological sets are covered at the level of the plain by recent quaternary formations represented by alluvium, essentially clay and sand (Bandji 1994; Wonanke 2002). Soil types include gneiss soils, cliff bottom scree soils, granite soils, basalt soils and trachytes (Bandji 1994). These different types of soils are grouped into three levels of altitude, namely hydromorphic soils in the low altitude zone, humus soils in the medium altitude zone and ferralitic soils in the high altitude zone (Wonanke 2002).

3 Data and methods

The work was carried out in the field and in the laboratory. The field work was carried out during the dry season and consisted of hydraulic conductivity determination, description and collection of soil samples.

3.1 Hydraulic conductivity

It was determined at a depth of between 50 and 70 cm by the Porchet method (Porchet and Laferre 1935; De Beaucorps et al. 1987). The principle consists of following the infiltration of a quantity of water poured into the hole as a function of time. Using an auger of radius *R* (in metres), we dig a hole of a certain depth h_0 in the soil, fill it with water until it is saturated (about 20 min depending on the soil properties) and follow the infiltration of the water into the soil as a function of time *t*. A graduated ruler has been introduced into the hole in order to measure the decrease in the water level (Fig. 2).

According to Darcy's law, we can write

$$Q = K_{\text{sat}} \times S \times I \tag{1}$$

where K_{sat} is the permeability coefficient; *S* is the wetted surface of the soil (water infiltration surface) and *I* is the driving slope or load gradient.

The water infiltration surface is equal to the sum of the infiltration surface by the walls of the hole of expression $2\pi \cdot R \cdot z$ and the infiltration surface by the bottom of expression $\pi \cdot R^2$. In this case, we can derive the following relationship:

$$S = \pi \cdot R^2 + 2\pi \cdot R \cdot z \tag{2}$$

3.1.1 Simplifying assumption

It will be assumed that the walls of the holes are not smoothed and that the driving slope or gradient of the charges is equal to the unit ($I = 1$).

The flow rate of water in the hole of radius *R* is therefore reduced to the relation:

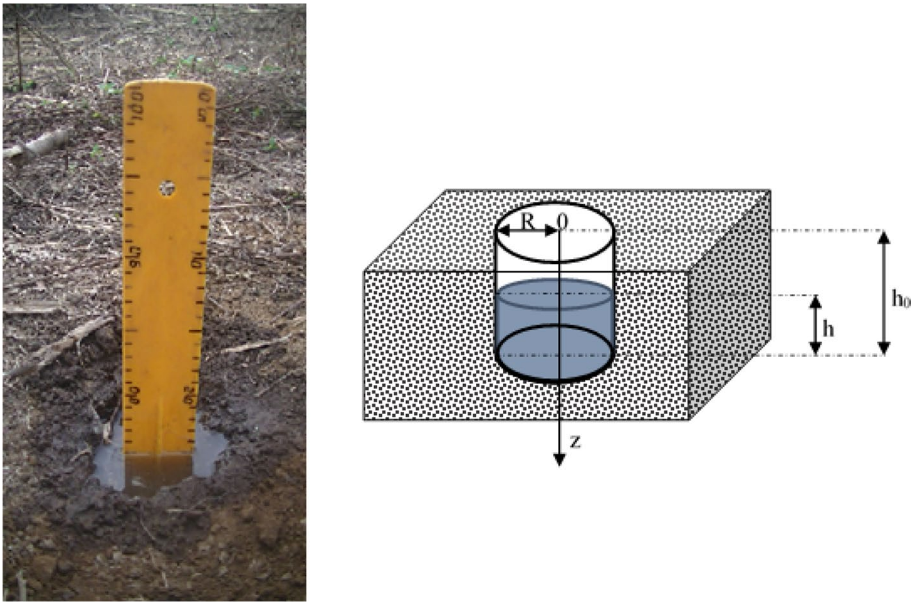

Fig. 2 Experimentation of Porchet method

$$Q = K_{\text{sat}} \cdot \left(\pi \cdot R^2 + 2\pi \cdot R \cdot z\right) = 2\pi \cdot R \cdot K_{\text{sat}} \cdot \left(z + \frac{R}{2}\right) \tag{3}$$

Assuming that the height of water in the hole is h and time t, let us denote by dτ, the small variation in time during which the water level drops in the hole by dz, dz being the height element corresponding to the small variations in time dτ.

The flow rate of the water in the hole becomes:

$$Q = -\pi \cdot R^2 \frac{dz}{d\tau} \tag{4}$$

The "−" sign of this expression is explained by the fact that Q is essentially positive, while the change in height h is negative.

So

$$2\pi \cdot R \cdot K_{\text{sat}} \cdot \left(z + \frac{R}{2}\right) = -\pi \cdot R^2 \frac{dz}{d\tau} \Leftrightarrow \frac{2K_{\text{sat}}}{R} d\tau = -\frac{dz}{z + \frac{R}{2}} \tag{5}$$

In this case,

$$\int_0^t \frac{2K_{\text{sat}}}{R} d\tau = -\int_{h_0}^{h} \frac{dz}{z + \frac{R}{2}} \tag{6}$$

Thus,

$$\frac{2K_{\text{sat}}}{R} t = -\ln\left(h + \frac{R}{2}\right) + \ln\left(h_0 + \frac{R}{2}\right) \tag{7}$$

Finally,

$$\log\left(h + \frac{R}{2}\right) = -\frac{2K_{\text{sat}}}{R \ln 10} t + \log\left(h_0 + \frac{R}{2}\right) \approx -\frac{2K_{\text{sat}}}{2,3.R} t + \log\left(h_0 + \frac{R}{2}\right) \tag{8}$$

Expression (8) shows that the characteristic resulting from this method is a straight line of global form $Y = AX + B$ *with* $Y = \log\left(h + \frac{R}{2}\right)$; $A = -\frac{2K_{\text{sat}}}{2,3.R}$;$X = t$ *and* $B = \log\left(h_0 + \frac{R}{2}\right)$ which is shown in Fig. 3.

Figure 3 represents the log (h + R/2) versus time curve on a semi-logarithmic scale. From the figure, we can establish the equality of the graphical and analytical slopes by the relation:

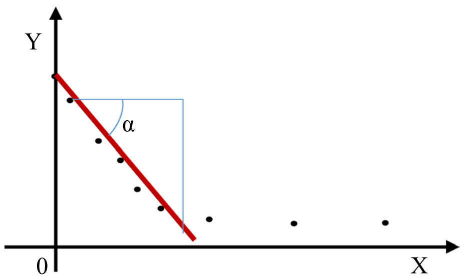

Fig. 3 log (h + R/2) versus time curve on a semi-logarithmic scale

$$-\frac{2K_{sat}}{2,3 \cdot R} = \tan\alpha \text{ that is to say } K_{sat} = -\frac{2,3 \cdot R \cdot \tan\alpha}{2} \quad (9)$$

In this study, the test was conducted at 16 representative sites (P1–P16). All holes were sized at 3.5 cm diameter.

3.2 Soil sampling and analysis

A landscape analysis and soil survey of pits (1.5 m long × 1 m wide) from 100 to 300 cm and more in depth taking into account lithology and morphology was carried out. These pits were described in detail according to the FAO soil profile description guide (FAO 2006). Subsequently, soil samples were taken from the walls of the pits, taking into account the different horizons and phases, and other samples were taken using the auger. A total of 44 soil samples were analysed in the laboratory for physico-chemical parameters. The following parameters were determined: grain size, porosity (*n*), compactness (*c*), water content, pH water and organic matter.

4 Results

4.1 Macroscopic description of pedological wells

In the plain, two (02) typical soil profiles were made according to the altitudes (Fig. 4).

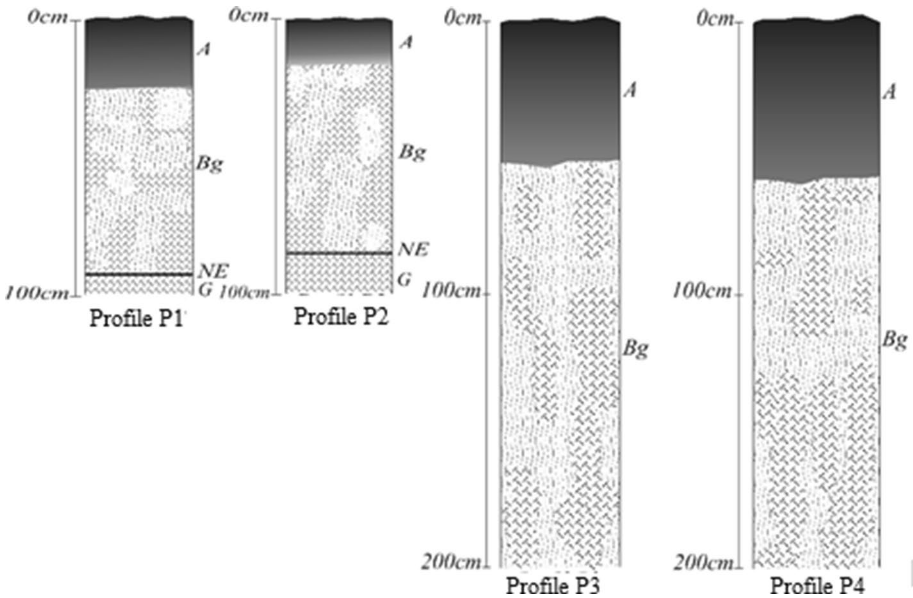

Fig. 4 Soil profile made on alluvium

4.1.1 Type 1 profile

This typical profile is found in the lowlands at the heart of the plain between altitudes 706 m and 711 m. These lowlands are occupied by a temporally flooded pseudo-steppe. This profile is differentiated from top to bottom by three horizons:

Horizon A 0–23 cm, fine soil that varies from black (10YR 2/1) to very dark grey (10YR 3/1). This horizon is very thick, not very compact, fine polyhedral with a clayey-silty texture and clayey-sandy in places. It has a very dense root system with significant biological activity; few green and blue patches at the base of these horizons (reduced or iron-depleted areas) and a distinct and regular lower boundary.

Horizon BCg 23–85 cm, a variegated pseudo-gley level with two non-distinct phases of a dominant grey colour (10YR 5/1), made up of very few red, ochre spots (oxidised or iron-enriched zones) and numerous green, blue spots (reduced or iron-depleted zones), not very compact and of a massive structure with a clay texture, with strong claying characterised by intense reduction phenomena due to temporary waterlogging linked to the rise in the water table. It is a Pseudo-gley horizon.

Horizon G 85–100 cm 75–100 cm, alluvial level with a variegated appearance, with red, ochre (oxidised or iron-enriched zones) and green, blue (reduced or iron-depleted zones) spots. This horizon is characterised by intense reduction phenomena due to temporary waterlogging. Claying gives this soil profile the name Clayey.

In short, the soils of this profile type 1 are very thin, not very evolved and not very differentiated with an organic-mineral level that rests directly on the clay level, with intense claying. We also note the presence of a water table at the base of the profile. It therefore defines a type A/Cg profile.

4.1.2 Type 2 profile

This profile is characterised with an altitudes between 720 and 730 m. It is differentiated by two horizons from top to bottom:

Horizon A 0–61 cm, varying in colour from greyish brown (2.5YR 5/2) to dark reddish grey (5Y3/1). It is a fine revamped soil with a medium to coarse lumpy, sandy-clay texture with a coarse polyhedral structure and low compaction in places. This horizon is very thick, with very few healthy roots and few coarse elements (millimetre to centimetre gravels), not very porous, with a diffuse and regular lower limit.

Horizon BCg 61–200 cm, mottled alluvial deposit with pseudo-clay consisting of two non-distinct phases. Dark yellowish brown (10YR 3/6), clayey with massive structure, not very compact. These horizons are made up of numerous fine-sized concretions and contain a large number of red and ochre spots (oxidised or iron-enriched zones) and few green and blue spots (reduced or iron-depleted zones), with weak claying characterised by intense oxidation phenomena due to temporary waterlogging linked to seasonal fluctuations in the water table. This is a pseudo-clay horizon.

In total, the soils along this type 2 profile are thick, poorly developed and poorly differentiated, with an A horizon lying directly on the BCg horizon. They therefore define a type A/Cg profile.

4.2 Soil permeability

The hydraulic conductivity in the plain decreases considerably with time. After a certain period of time, the hydraulic conductivity does not change, which shows that the soil has reached a saturation point, making it impermeable (Fig. 5).

The calculation of the different hydraulic conductivity values based on Eq. (9) leads to the results shown in Table 1. According to this table, the hydraulic conductivity values are between 10–5 and 10–7 m/s. Such a value between 10–5 and 10–7 m/s is indicative of a very low permeability and allows to classify these soils as semi-permeable.

4.3 Study of physico-chemical parameters

Laboratory analyses of the soil samples provided physico-chemical parameters and particle size (Table 2).

Across the plain, bulk density varies from 0.42 to 1.22 g/cm^3 (Table 2). This value results in a fairly high total porosity (over 60%). There is a slight increase in porosity with depth. Compactness values are high throughout the profile (16–58.91%) and generally higher in the surface horizons.

Clay (9.5–71.5%) and sandy (13–72%) fractions are abundant in these soils, followed by silts (5–51.5%). The sandy fractions are more abundant at the surface, while the clayey ones are more abundant at depth. The silty fraction is more abundant at depth except in a few profiles.

The textural triangle (Fig. 6) indicates that the soils in the plain are classified as clayey (A), sandy-clay (AS), silt–clay (AL), sandy-clay (SA) and silty-sand-clay (LSA).

The acidity of the plain soils increases from surface to depth (Table 2). The water content of the soils is quite high throughout the plain. These soils are also poor in organic matter.

5 Discussions

5.1 Soil classification

Studies conducted on the soils of the Mbo plain show that these soils are essentially hydromorphic. Indeed, hydromorphic soils are soils whose genesis and evolution occur either under water, or in an environment where water is in excess, so that hydrological factors have played a predominant role in paedogenesis and have induced a morphology that prevails over all other classification characteristics (Bourgeon 1979; Khouma 2000; Keita 2000; Worou 2000; Charreau and Fauck 1965). These soils are generally very saturated with water and therefore can't intercept rainfall and thus favour runoff to the detriment of infiltration. This type of hydric soil resembles that of many swampy alluvial plains (Leumbe et al. 2015; Garba Mallam 2000; Keita 2000; Youssouf and Lawani 2000; Khouma 2000; Worou 2000; Barbery and Gavaud 1980; Vizier 1984; Charreau and Fauck 1965; Dasylva et al. 2019). Hydromorphic can direct the evolution of organic matter and under certain types of vegetation, cause its accumulation (Keita 2000). Compared to studies conducted in Mali (Keita 2000) and Togo (Worou 2000),

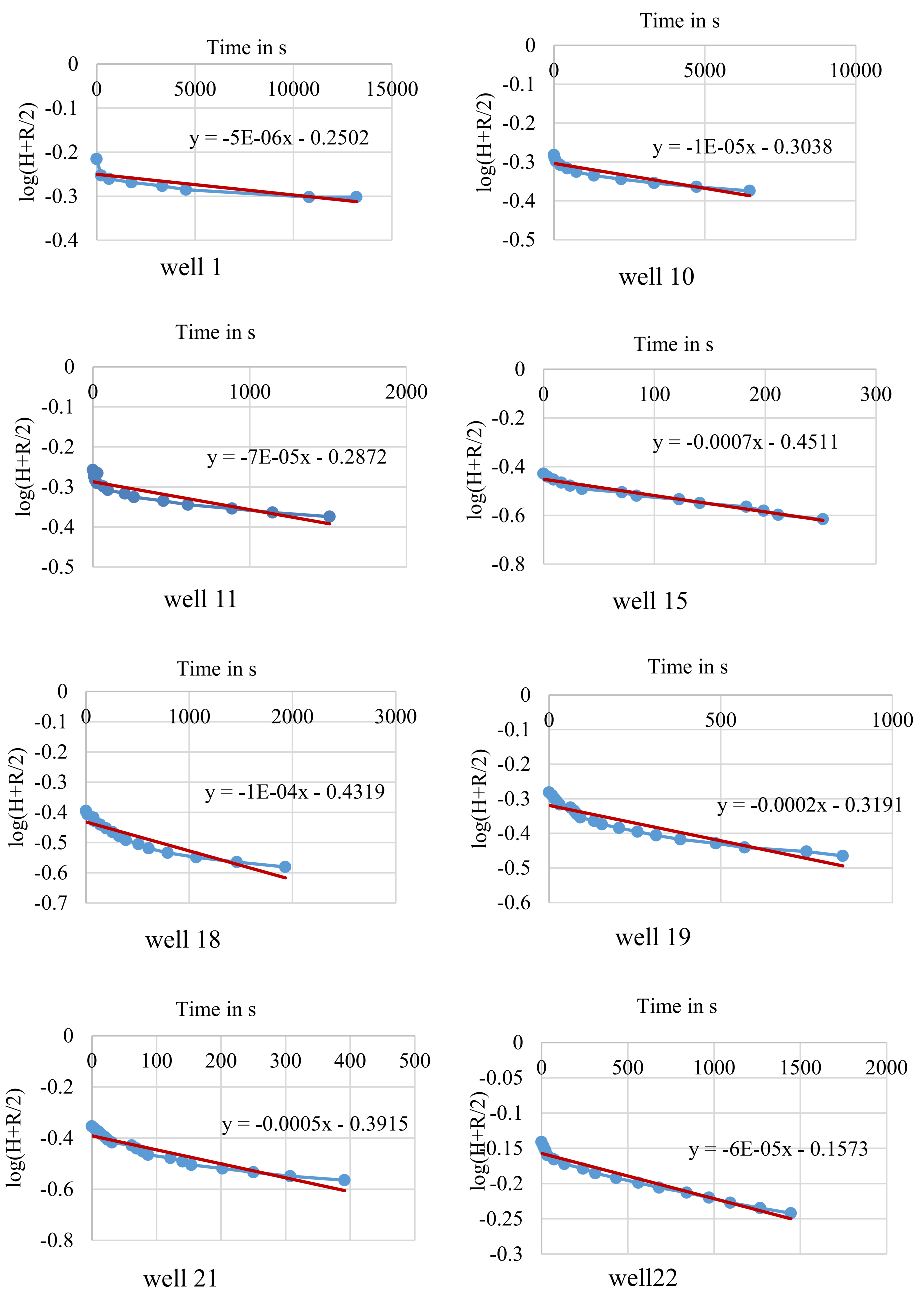

Fig. 5 Graphs showing the general behaviour of soil permeability in the plain

the hydromorphic soils of the Mbo plain are mineral or low-humus hydromorphic soils (less than 8% organic matter). The dark colour found in most of the profiles indicates that these soils are rich in organic matter.

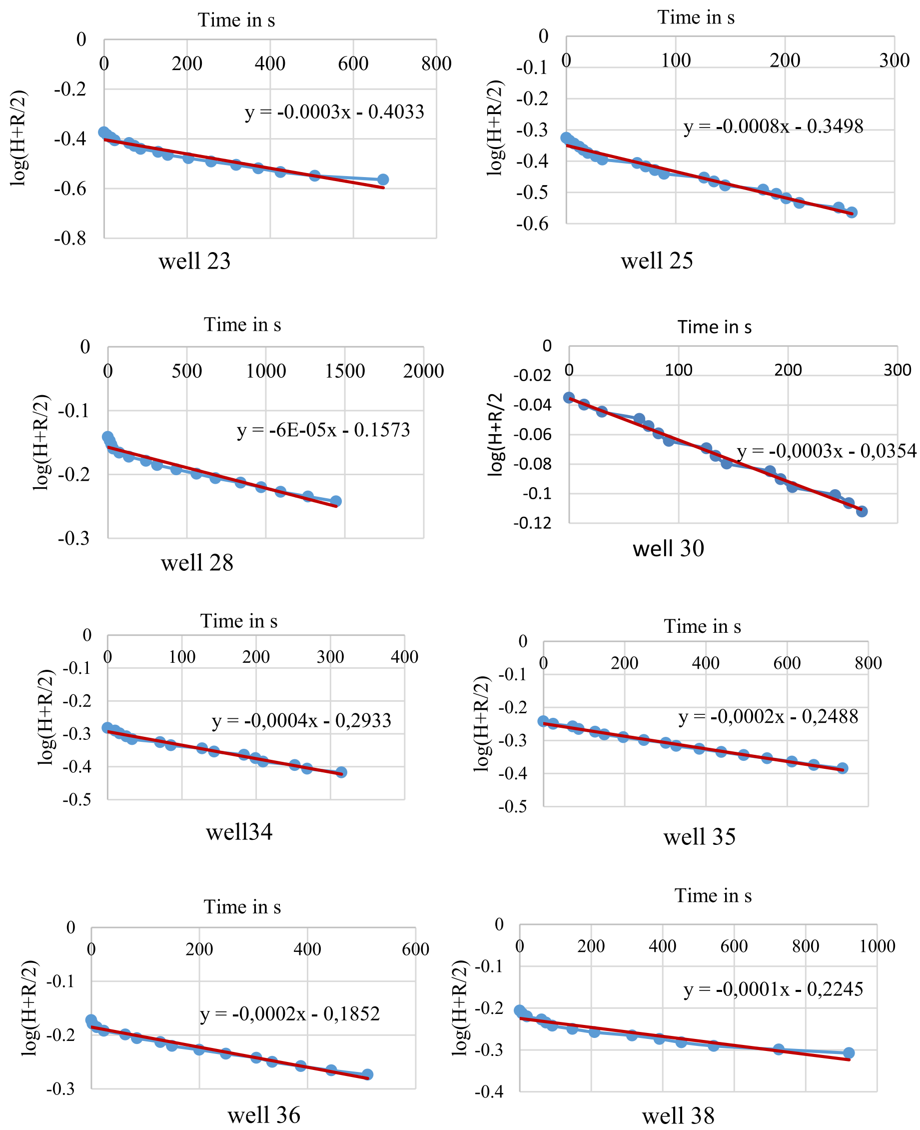

Fig. 5 (continued)

5.2 Physico-chemical parameters

In the Mbo plain, hydromorphic soils are located in the low-lying areas and are formed on clay-sand-loam alluvium. They have a texture marked by sandy minerals (about 60%) on the surface and a clay fraction that reaches 41% at depth, generally from 25 to 30 cm. This high clay content in the deeper horizons combined with a high silt content considerably reduces the infiltration of surface water resulting to flooding. Compared to the studies of Bachelier (1952), the alluvial soils of the Mbo plain form the banks of the Nkam and

Table 1 Evaluation of soil permeability (*Source*: Musy and Soutter 1991 cited in Barraud 2006)

Well	*K* value in m/s	Soil type	Degree of permeability	Type of training
Well 1	5.0313×10^{-7}	Very fine sand, coarse loam to clay loam	Medium to low	Semipermeable
Well 10	2.5875×10^{-7}			
Well 11	1.8113×10^{-6}			
Well 15	1.8113×10^{-5}			
Well 18	2.5875×10^{-6}			
Well 19	5.175×10^{-6}			
Well 21	1.2938×10^{-5}			
Well 22	1.5525×10^{-6}			
Well 23	7.7625×10^{-6}			
Well 25	2.07×10^{-5}			
Well 28	1.2938×10^{-6}			
Well 30	7.7625×10^{-6}			
Well 34	1.035×10^{-5}			
Well 35	5.175×10^{-6}			
Well 36	5.175×10^{-6}			
Well 38	2.5875×10^{-6}			

Menoua rivers and are generally sandy-silt with a clay horizon located at depths of 30 cm and above. These results are similar to those obtained on the soils of the Maga plains in Cameroon (Leumbe et al. 2015), Niger (Garba Mallam 2000), Mali (Keita 2000), Benin (Youssouf and Lawani 2000), Khouma 2000; Charreau and Fauck 1965; Dasylva et al 2019), Togo (Worou 2000) and Burkina Faso (Barbery and Gavaud 1980) unlike the soils of Tahiti (Wotling 2000) which have a clay to clay-silt texture.

The soils of the plain are very acidic (pH = 3.6–6) at depth, like those of the hydromorphic soils of Burkina-Faso (Barbery and Gavaud 1980) and of the agricultural valley of the Commune of Ziguinchor in Senegal (Dasylva et al. 2019). They are poor in organic matter. Organic matter favours aggregation and thus increases infiltration. The low content of this element in the soil reduces the capacity of the plain soils to infiltrate rainwater, which leads to flooding. Compared to the studies conducted by (Youssouf and Lawani 2000), the hydromorphic mineral soils of Benin have a weakly acidic to basic pH (5.5 and 7) with a low organic matter content (1–6%). Also, in the Maga plain in the Far North of Cameroon (Leumbe et al. 2015), the soils have an organic matter levels below 1%, which makes the soil more impermeable. As in the soils of the Maga plain (Leumbe et al. 2015) where the aggregates are very stable and do not favour water infiltration, the soils of the Mbo plain are very porous and compact. Water is therefore concentrated on the surface because the deeper horizons are compact. The humidity of these soils is very high (over 40% in several horizons), this is due to a high density of drainage and the presence of a sub-surface water table which rises progressively under the effect of abundant and frequent rainfall to reach its maximum level (Bourgeon 1979; Bandji 1994). This high moisture content results in a poor permeability between 10–5 and 10–7 m/s because they are generally very waterlogged and constantly flooded. Compared to the studies of Wonanke (2002), the soils of the Mbo plain are made up of sandy-clay alluvium with low permeability (10–4 to 10–6 m/s). They are not very permeable due to their clayey nature which does not favour the infiltration of

Table 2 Physic and chemical characteristics of the soils

	Samples	Horizon (cm)	Physical parameters								Chemical parameters	
			S (%)	Si (%)	C (%)	Da (g/cm^3)	Dr	H (%)	Porosity	Compactness (%)	pH water	OM (%)
P1	P1-1	0–25	57.0	16.0	27.0	0.95	2.55	22.94	62.76	37.24	4.8	4.94
	P1-2	25–60	27.0	32.0	41.0	0.96	2.63	25.77	63.44	36.56	5.3	1.21
P10	P10-1	0–25	40.0	23.0	37.0	1.08	2.56	24.06	47.70	52.30	4.9	4.60
	P10-2	25–50	25.0	22.0	53.0	1.02	2.57	32.27	51.98	48.02	5.3	3.76
P11	P11-1	0–20	27.0	20.0	53.0	0.99	2.47	34.4	45.41	54.59	4.9	8.92
	P11-2	20–53	31.0	15.0	54.0	0.95	2.50	38.88	54.49	45.51	4.9	7.66
P15	P15	0–35	33.5	27.5	39.0	1.20	2.56	15.30	54.66	45.34	5.1	4.60
P18	P18-1	0–20	52.5	19.0	28.5	1.14	2.57	15.90	56.99	43.01	5.0	4.20
	P18-2	20–38	51.5	16.5	32.0	1.21	2.61	12.87	54.48	45.52	4.9	1.84
P19	P19-1	0–30	41.0	27.0	32.0	0.98	2.52	20.48	53.17	46.83	4.7	6.53
	P19-2	30–50	27.0	20.0	53.0	1.04	2.57	26.9	55.33	44.67	4.8	3.76
P21	P21-1	0–25	37.5	40.0	22.5	1.09	2.58	16.35	58.94	41.06	5.4	3.55
	P21-2	25–42	44.0	18.5	37.5	1.04	2.60	24.40	60.92	39.08	5.6	2.36
P22	P22-1	0–45	33.0	51.5	15.5	0.82	2.52	36.86	69.18	30.82	6.6	6.30
	P22-2	45–70	26.5	34.0	39.5	0.90	2.57	36.92	66.19	33.81	5.4	4.20
P23	P23	0–45	40.0	39.0	21.0	0.95	2.57	41.64	56.22	43.78	5.2	3.76
P25	P25-1	0–45	69.0	14.5	16.5	1.01	2.61	34.92	61.97	38.03	5.3	1.97
	P25-2	45–60	64.5	5.0	30.5	0.98	2.62	42.93	62.86	37.14	5.7	1.58
P28	P28-1	0–25	29.0	18.0	53.0	0.95	2.47	25	52.39	47.61	5.1	8.92
	P28-2	25–40	44.0	31.0	26.0	1.13	2.56	21.35	38.04	61.96	5.3	4.60
P30	P30-1	0–30	69.0	19.5	11.5	1.25	2.58	8.32	52.96	47.04	5.3	3.42
	P30-2	30–60	64.0	24.0	12.0	1.07	2.57	18.91	59.52	40.48	4.7	3.86
	P30-3	60–90	76.0	15.0	9.0	1.16	2.60	19.25	56.19	43.81	5.5	2.43
P34	P34-1	0–40	56.5	31.0	12.5	1.30	2.56	9.10	50.91	49.09	4.4	4.41
	P34-2	40–50	43.0	28.0	29.0	1.17	2.59	16.93	55.85	44.15	4.6	2.87

Table 2 (continued)

	Samples	Horizon (cm)	Physical parameters								Chemical parameters	
			S (%)	Si (%)	C (%)	Da (g/cm^3)	Dr	H (%)	Porosity	Compactness (%)	pH water	OM (%)
P35	P35-1	0–25	35.0	39.0	26.0	1.18	2.58	12.79	55.57	44.43	4.9	3.31
	P35-2	25–40	52.0	25.0	23.0	1.20	2.63	20.86	54.88	45.12	5.1	0.88
	P35-3	40–55	62.5	19.5	18.0	1.05	2.59	25.00	60.55	39.45	4.8	3.20
P36	P36-1	0–35	47.5	36.0	16.5	1.16	2.58	20.11	56.42	43.58	5.2	3.64
	P36-2	35–65	6.5	37.0	56.5	0.92	2.55	36.50	65.41	34.59	4.3	5.08
P38	P38-1	0–20	52.5	41.0	6.5	0.97	2.59	33.94	63.57	36.43	5.4	2.76
	P38-2	20–40	47.5	47.5	5.0	0.86	2.55	55.13	67.70	32.30	4.4	4.97
	P38-3	40–60	23.5	72.5	4.0	0.92	2.57	46.71	65.36	34.64	4.9	4.19
Profile 1	HA	0–30	32.5	34.0	33.5	1.04	2.54	19.98	60.69	39.31	5.6	5.65
	HB1	30–65	28.5	21.0	50.5	0.98	2.59	29.03	63.14	36.86	5.5	2.89
	HB2	65–300	24.0	24.0	52.0	0.84	2.61	45.77	68.36	31.64	5.4	1.97
Profile 2	HA	0–55	35.0	34.5	30.5	1.03	2.53	3.84	61.01	38.99	6.0	5.78
	HB1	55–195	34.0	19.5	46.5	1.11	2.58	6.69	58.25	41.75	6.4	3.42
	HB2	195–395	52.5	19.0	28.5	1.09	2.60	10.68	59.02	40.98	6.5	2.63
	HBC	395–500	72.0	15.5	12.5	1.22	2.61	6.84	54.05	45.95	6.3	1.84
Profile 3	HA	0–23	53.0	37.5	9.5	0.42	2.41	77.74	84.00	16.00	4.4	11.82
	HB	23–70	14.0	32.0	54.0	1.00	2.60	40.55	62.15	37.85	5.2	2.63
Profile 4	HA	0–50	71.0	18.0	11.0	0.88	2.54	27.61	66.78	33.22	4.8	5.52
	HB	50–190	41.0	27.5	31.5	0.98	2.57	25.73	63,18	36,82	5.4	3.94

S sand, *Si* silt, *C* clay, OM organic matter, *Da* apparent density, *Dr* real density, *H* water content

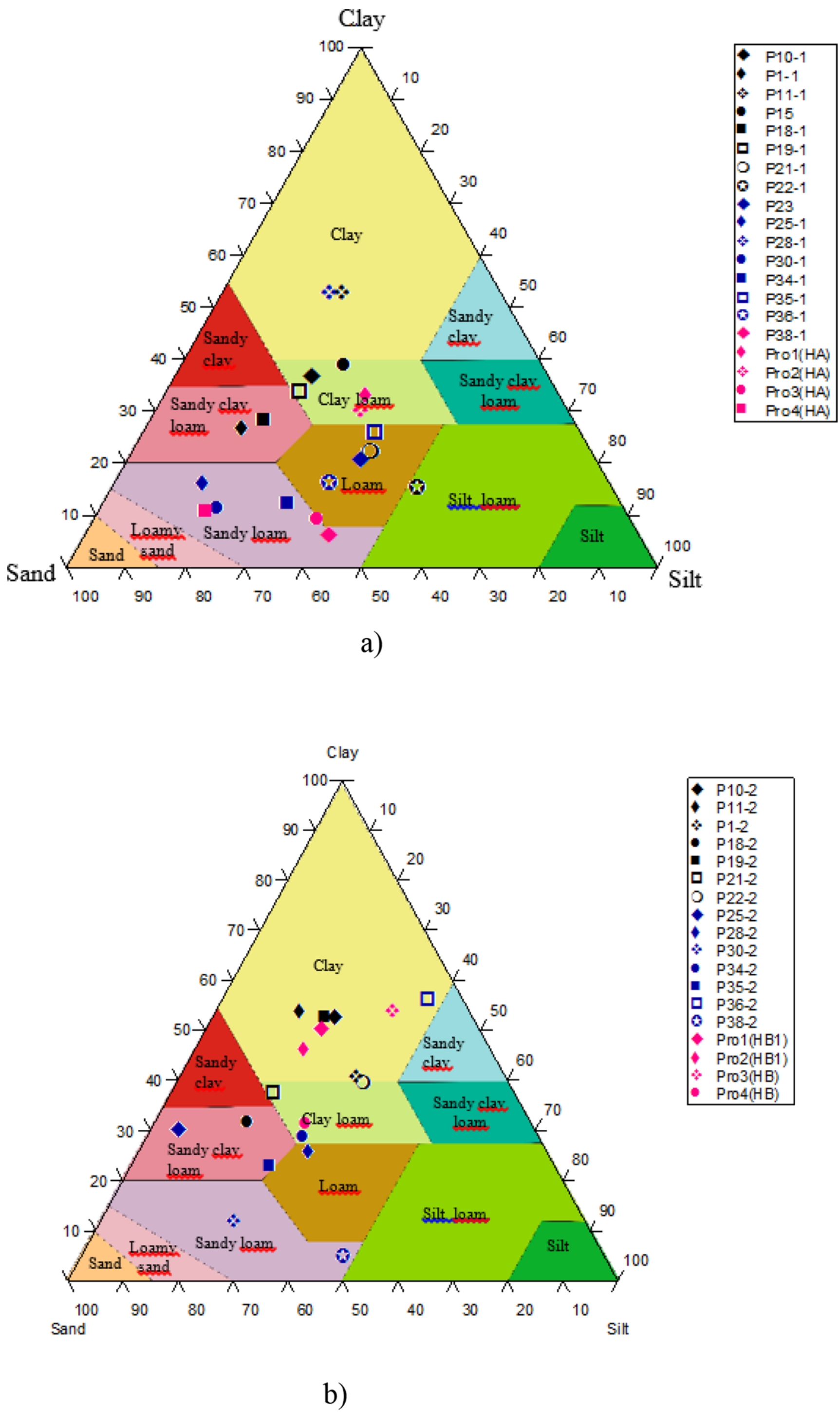

Fig. 6 Determination of the soil texture of the Mbo plain: **a** surface; **b** depth

rainwater. Consequently, the soils of the plain become saturated very quickly after the first rains. This result is similar to that obtained by Murhula et al. (2019) on the soils of the city of Bukavu in DR Congo (2.96 0.10–5 m/s). Furthermore, this permeability is in contrast to that of the ferralitic soils of Tahiti (Wotling 2000) where the permeability is higher than 20 mm/h. This is due to the fact that unlike Tahiti, the soils of the Mbo plain are very rich in clays with a fairly high water content.

Ultimately, the lack of water absorption by the soils due to low infiltration capacity, previous saturation and low thickness of the surface horizons is one of the main causes of flooding in the Mbo plain.

6 Conclusion

The main objective of this study was to assess the influence of the physico-chemical properties of the soil on the recurrence of floods. It was found that the soil of the Mbo plain has a direct impact on the formation of floods. Indeed, the morpho-structural description of the soil profiles showed that these soils are of hydromorphic type with a sandy-clay texture at the surface and a clay proportion that becomes very high as the depth increases. This high content of clay minerals in the soil is the main cause of flooding in the Mbo plain because these clays considerably reduce the speed of water infiltration and consequently favour runoff to the detriment of infiltration. A laboratory analysis of the physico-chemical properties of these soils shows a fairly high water content and compactness. In addition, these soils are poor in organic matter and very acidic at depth. All these different elements are in one way or another responsible for the increase in the risk of flooding because they make the soil more impermeable. In sum, flooding in the Mbo plain is due to a previous saturation of the soils which prevents the water arriving in the plain from infiltrating, and to a low infiltration capacity of the soils due to their physicochemical properties which are favourable to flooding. This phenomenon is similar to that of many alluvial plains.

Author contributions SNDF carried out the research plan, collected and analysed data, methodology and investigation review and editing, formal analysis and writing original draft; visualisation and supervision by DGN.

Funding No funding was received to assist with the preparation of this manuscript.

Availability of data and materials The data used to support the findings of this study are available from the corresponding author upon request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

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