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Water Erosion on the Thies Tray (Senegal): Study of the Factors of the Phenomenon using a Geotechnical Approach

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Abstract In this work, the objective is to contribute to a better understanding of the factors of water erosion in the Thiès tray through a geotechnical approach, particularly the relationships between the Hénin structural stability index, the Bouyoucos index and some geotechnical soil characteristics. Among other things, it aims to answer the question of whether water erosion in the area is linked to a problem of soil structure stability or due to a purely mechanical phenomenon dependent on runoff water? To do this, we undertook an experimental study consisting of soil characterization from the study area to the laboratory. A geotechnical prospecting campaign consisting of fifty (50) manual boreholes to a depth of forty (40) cm enabled to take two (2) samples per borehole (one between the level of the natural ground and twenty (20) cm and another between twenty (20) cm and forty (40) cm). Samples collected were subjected to the following test program: sieve analysis, consistency or Atterberg limits, sand equivalent test if limits are indeterminable, and Hénin structural stability test. The results obtained made it possible to establish the relationships between structural stability, the granulometric composition of soils (% sand, % fines), the consistency limits and the plasticity index on the one hand, and to make soil erosion maps from the structural stability indices of Benin and Bouyoucos on the other hand.

Keywords Thiès Tray - water erosion - grain size - structural stability - water erosion

1. Introduction

Senegal, like the other Sahelian countries, has been confronted for decades with a phenomenon of degradation of arable land as a result of water or wind erosion. This results in a loss of fertility and lower yields for food and industrial crops. Annual soil losses are estimated to average between five (5) and ten (10) tons per hectare in Africa [1]. The erosion process is generally characterized by three phases: a detachment or ablation phase, followed by a transport phase and a deposition or sedimentation phase. Water erosion, due to precipitation and resulting runoff, is a natural phenomenon affecting all soil types, in all climates and whatever the nature of their plant cover. Only its intensity and effects vary according to local conditions [2]. To fight against the erosion that is currently causing a lot of damage in the area including villages threatened [3], the loss of agricultural land [4], following the progressive gully [5-7] and aggregate deposits in the plains from trays), works have been made in the plates which corresponds to a first level of processing [8-9].

The Thiès tray, due to its topographic profile, is exposed to significant rainwater runoff, which contributes to an intensification of water erosion. The watershed of Kissane, our study area, located in the commune of Notto, has long been affected by the degradation of its land which has been gradually abandoned by farmers. Water erosion is the main cause and one of the objectives of this work is to contribute to a better understanding of the behaviour of the soil in our watershed in the face of this natural phenomenon.

This paper presents the results obtained using a geotechnical approach whose objective is to establish the relationships between soil erodibility, the Hénin structural stability index, the Bouyoucos index and certain geotechnical soil characteristics. The specific objective is to see if the structural stability of the soil is a determining factor in the water erosion observed in the area. The results of the soil tests carried out in the laboratory are analyzed locally, by characterizing the soil types and globally by drawing up erosion maps of the soils in the catchment area.

2. Presentation of the Study Framework

2.1. Site description

The study area is located in the center of the Thiès region in the commune of Noto (figure 1), more precisely in the Kissane catchment area. The area is mainly occupied by basins surrounded by hills that have been severely eroded by runoff.

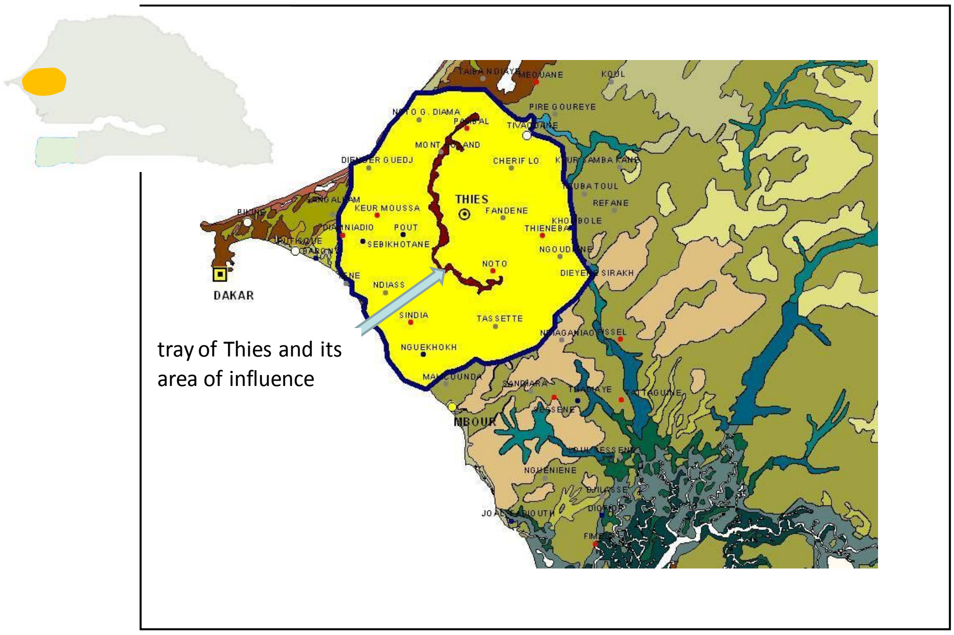

Figure 1: Location map of the study area

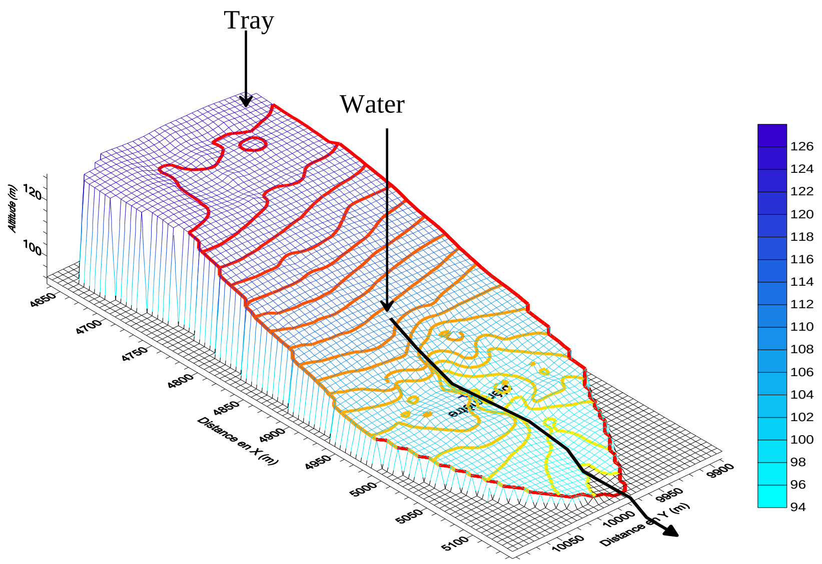

Figure 2: Kissane watershed

The 1:50 000 scale topographic maps available for the area did not allow us to delineate the Kissane watershed site of our present study. Thus, topographic surveys have allowed us to delineate our field of study and determine its topographic and hydraulic characteristics (Figure 2). This watershed is characterized by the presence of three parts: a first zone with fairly high altitudes (max. 138 m) constituting the plateau, a second constituting the slopes and a third the plain where the basin outlet is located. It is also important to note the existence of a non-perennial water source.

At the level of the village of Kissane, the consequences of water erosion are visible with a continuous gullying and even the appearance of new ravines (Figures 3 and 4). On the plains we are witnessing loss of land for agriculture; the land becoming unfit for cultivation due to the deposition of stones torn off by the strong runoff on the slopes (Figure 5).

Figure 3: Continuous gullying with presence of a water source

Figure 4: beginning of a new ravine at the foot of the Thiès tray at Kissane

Figure 5: Stones transported by runoff from the slopes to the plains

2.2. Climatic and soil characteristics

The Thiès region is characterized by a hot and dry Sudano-Sahelian climate with a single rainy season that extends from June to October with an annual average rainfall of about 450 mm over the last 32 years from 1982 to 2013 (Figure 6). Rainfall is often very badly distributed and irregular. The relatively low water conditions are aggravated by intense sunshine (10 hours per day) and high temperatures with an annual average of 30°C and maximum temperatures that can reach 40°C [10].

The soils in the study area are of three types: the tropical ferruginous soils (Dior) which cover almost all the eastern and central parts of the commune with an area estimated at around 60% of the land; the sandy-clay soils (Deck-Dior) located in the central part of the commune, represent 10% of the total surface area and the non-leached tropical ferruginous soils (Deck), lowland and watershed soils, they represent about 30% of the soils and are characterized by their fertility due to their water retention capacity).

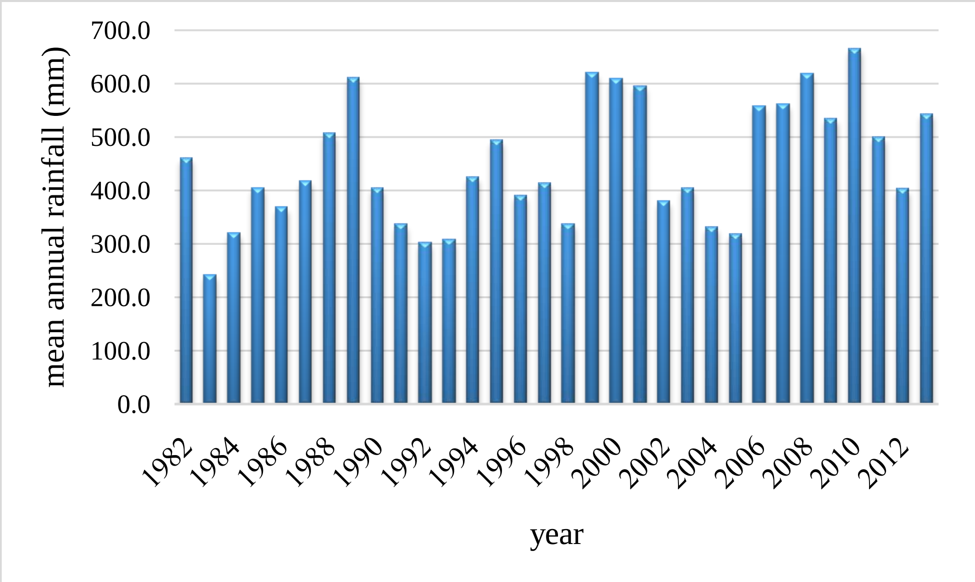

Figure 6: Annual Rainfall Distribution

3. Materials and Methods

The methodological approach adopted was implemented in different phases including site visits, topographic surveys, hydrological studies, geotechnical sounding campaign and soil characterization in the laboratory. Thus, a geotechnical prospecting campaign consisting in the realization of fifty (50) manual soundings of a depth of forty (40) cm made it possible to take samples at a rate of two (2) per sounding (one between the level of the natural ground and twenty (20) cm and another between twenty (20) cm and forty (40) cm). The samples were subjected to the following test program: the grain size analysis, the limits of consistency or Atterberg, the sand equivalent test if the limits are indeterminable and test of structural stability of Henin. The results obtained made it possible to establish on the one hand the relationships between the granulometric composition of soils (% sand, % fines) and structural stability and on the other hand between structural stability, consistency limits and plasticity index.

3.1. Experimental study: Sampling and theory

A geotechnical prospecting campaign consisting of fifty (50) manual boreholes to a depth of forty (40) cm was carried out [2]. In each hole, two (2) samples were taken between the natural ground level and twenty (20) cm and forty (40) cm. If, on the other hand, the soil encountered is homogeneous, only one sample is taken from the 0 cm - 40 cm horizon.

3.2. Geotechnical tests

3.2.1. Sieve analysis

The granulometry or granulometric analysis of a soil is its decomposition into various fractions according to the size or diameter of the grains that compose it. It is a statistical analysis of the grains included in the different granular fractions (standard NF P 94 056).

The results are presented in the form of granulometric curves shown in Figure 7.

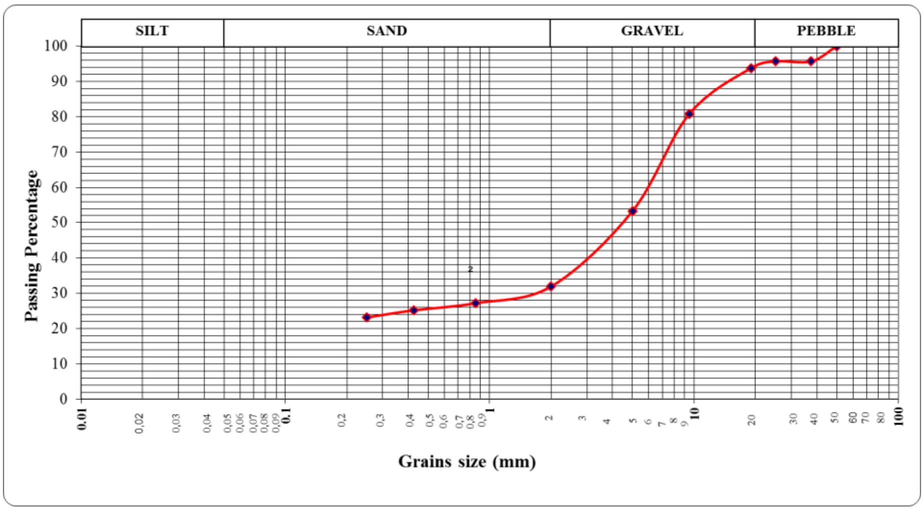

Figure 7: Soil sample granulometric curve Borehole No. S32

Soils containing more than 50% fine sand (particles with diameters between 50 and 100 microns), a percentage of clay and a low organic matter content are very erodible [11]. According to the USCS soil classification system, the samples taken in the boreholes are composed of 45% clay gravel (GC) 25% silty sand (SM) 21% clay sand (SC) 9% very plastic clay (CH).

3.2.2. The consistency or Atterberg limits

The consistency limits or Atterberg limits are the water contents that delimit the 4 consistency states: solid without shrinkage, solid with shrinkage, plastic and liquid [12]. We thus have three water content limits (when the latter decreases): the noted liquidity limit which is that for which the soil passes from the liquid state to the plastic state The plastic limit which is that for which the soil passes from the plastic state to the solid state with withdrawal; The shrinkage limit which is that for which the soil passes from the solid state with shrinkage to the solid state without shrinkage.

The plasticity index, is defined as the difference between the limits of liquidity and plasticity, is given by the following expression:

$$I_P = w_L - w_P \tag{1}$$

The Atterberg limits determined with the Casagrande apparatus have respective maximum and minimum values 20 and 183 for the liquidity limit; 14 and 61 for the plasticity limit and 6 and 122 for the plasticity index. Test results for some boreholes are presented in Table 1.

Table 1: Atterberg limits

Sample N°	**S7-1**	**S7-2**	**S8-2**	**S9-2**	**S10-2**	**S14**	**S15-1**	**S16-1**	**S16-2**	**S18-1**
Horizon (cm)	20-40	20-40	20-40	20-40	20-40	0-40	0-20	20-40	20-40	20-40
Liquidity limit	20,5	36,1	22,4	35,3	30,3	28,9	23,2	21,6	20,1	26,3
Plasticity limit	15,8	20	15,6	19,2	18,6	24,5	14,7	14,6	15,5	14,8
Plasticity index	4,6	16,1	6,8	16,2	11,7	14,3	8,6	6,9	4,6	11,5

3.2.3. Henin's structural stability test

The structural stability of soils is an essential element of their resistance to erosive phenomena, reason for which structural stability tests are among the most reliable indicators of soil erosion [13]. The Henin test has the advantage of simultaneously integrating the action of several destructuring agents (bursting and swell-dispersion) [14], [15]. It allows the determination of a Hénin structural stability index of defined by:

$$I_S = \frac{Fraction\ \phi < 0{,}02\,mm}{\frac{Ag_A + Ag_B + Ag_E}{3} - 0{,}9\,S_g} \tag{2}$$

In this expression I_s represents the structural stability index of Hénin; Ag_E is the weight fraction of aggregates with a diameter greater than 0.2 mm remaining after immersion in water of an untreated sample; Ag_A is the weight fraction of aggregates with a diameter greater than 0.2 mm of sample respectively pretreated with alcohol; Ag_B is the weight fraction of aggregates with a diameter greater than 0.2 mm of sample respectively pretreated with benzene, and S_g is the particle size fraction with a diameter between 0.2 and 2 mm (coarse sand). The higher the I_s value (it varies globally between 0.1 and 100), the more the soil tends to disintegrate, to clog under the effect of water circulation, which reduces the filtration speed, so that these two parameters vary in the opposite direction. The Hénin structural stability test was performed on all samples and the results show that the structural stability index for Hénin varies between 0.03 (borehole S11-2) and 2.22 (borehole S45-2) with an average value of 0.59. They are presented in Table 2.

Table 2: Hénin Structural Stability Test Results

Sample N°	Horizon (cm)	Stability index	Sample N°	Horizon (cm)	Stability index
S1	0-40	1.34	S15	0-40	0.34
S2-1	0-40	0.13	S16-1	0-20	0.3
S2-2	20-40	0.32	S16-2	20-40	0.38
S3	0-40	0.07	S17	0-40	0
S4	0-40	0.553	S18-1	0-20	0.39
S5	0-40	0.051	S18-2	20-40	0.52
S6	0-40	0.391	S19-1	0-20	0.6
S7-2	20-40	0.35	S19-2	20-40	1.47
S8-1	0-20	0.27	S20	0-40	0.88
S8-2	20-40	1.85	S21-1	0-20	0.93
S9	0-40	1.13	S21-2	20-40	0.56
S10	0-40	0.13	S22	0-40	0.36
S11-1	0-20	0.12	S23	0-40	0.71
S11-2	20-40	0.03	S24	0-40	0.71
S12-1	0-20	0.39	S25	0-40	0.38
S12-2	20-40	0.3	S26	0-40	0.27
S13	0-40	0.04	S27-1	0-20	1.05
S27-2	20-40	0.99	S43-1	0-20	0.6
S28	0-40	0.33	S43-2	20-40	1.18
S29	0-40	0.74	S44	0-40	0.44
S30	0-40	0.33	S45-1	0-20	0.77
S32	0-40	0.74	S45-2	20-40	2.22
S33-1	0-20	1.17	S46	0-40	0.38
S33-2	20-40	1.67	S47	0-40	0.36
S34	0-40	0.8	S48	0-40	0.38
S36	0-40	0.87	S49	0-40	0.49
S37	0-40	1.61	S50	0-40	0.35
S38	0-40	1.43	S46	0-40	0.38
S39	0-40	0.32	S47	0-40	0.36
S40	0-40	0.39	S48	0-40	0.38
S41	0-40	0.26	S49	0-40	0.49
S42	0-40	0.6	S50	0-40	0.35

3.2.4. Bouyoucos Index

Soils most susceptible to erosion are sometimes defined as soils with a predominance of silt (0.002-0.05 mm) and fine sand (0.05-0.2 mm) fractions or, alternatively, a silt content between 40 and 60%. As these criteria do not take into account the important role of clay colloids, clay content is sometimes preferred as a soil erodibility criterion, with particularly sensitive soils for clay contents between 10 and 30%. The Bouyoucos index has the advantage of including the three granulometric fractions constituting the fine earth and is expressed by the relation:

$$I_{bou} = \frac{\% Sable}{\% Argile + \% Silt} \quad (3)$$

From the results of the sieve analysis test, we calculated the Bouyoucos index I_{bou} using equation 3. The results obtained show that the Bouyoucos index calculated from the granulometric analysis performed on our samples ranges between 0.63 (borehole S33-2) and 7.24 (borehole S13) with an average value of 2.90. They are presented in Table 3. However, the assessment of soil erodibility on the basis of textural criteria is relatively limited in scope, as other factors play an important role in soil cohesiveness forces, particularly soil moisture content.

Table 3 : Bouyoucos index

Sample N°	Horizon (cm)	Bouyoucos index	Sample N°	Horizon (cm)	Bouyoucos index
S1	0-40	3.55	S23	0-40	2.52
S2-1	0-40	4.83	S25	0-40	2.10
S2-2	20-40	1.83	S26	0-40	3.15
S3	0-40	6.69	S27-1	0-20	1.41
S	0-40	4.82	S27-2	20-40	3.35
S5	0-40	6.14	S28	0-40	4.64
S6	0-40	2.55	S29	0-40	3.91
S7-2	20-40	4.55	S30	0-40	1.86
S8-2	20-40	1.37	S31	0-40	0.89
S9	0-40	2.17	S32	0-40	1.09
S10	0-40	6.58	S33-1	0-20	1.66
S11-1	0-20	3.35	S33-2	20-40	0.63
S11-2	20-40	5.67	S34	0-40	2.43
S12-1	0-20	5.17	S36	0-40	3.06
S13	0-40	7.24	S37	0-40	0.76
S14	0-40	1.61	S38	0-40	0.71
S15	0-40	4.23	S39	0-40	3.92
S16-1	0-20	5.24	S40	0-40	2.95
S16-2	20-40	3.83	S41	0-40	2.24
S17	0-40	5.23	S42	0-40	2.3
S18-1	0-20	3.26	S43-2	20-40	0.85
S18-2	20-40	2.02	S44	0-40	2.49
S19-1	0-20	2.40	S45-1	0-20	1.30
S19-2	20-40	1.09	S45-2	20-40	0.69
S20	0-40	4.66	S46	0-40	3.07
S21-1	0-20	1.95	S47	0-40	2.7
S21-2	20-40	1.63	S48	0-40	2.80
S22	0-40	2.48	S49	0-40	2.10
			S50	0-40	3.0

4. Results and Discussions

The laboratory tests made it possible to determine the textural classes of the soils, their consistency limits and the structural stability index of Hénin and Bouyoucos. The results obtained thus enabled us to map soil erodibility at the Kissane watershed level based on the structural stability indices of Hénin, the consistency limits and the Bouyoucos index. Figure 8 shows the soil erodibility map based on the structural stability index of Hénin.

It allows to highlight that the highest stability index values are found on the slopes. This part of the watershed is characterized by its fairly steep slope which results in an increase in rainfall runoff velocity.

By examining the stability indices of Hénin ranging between 0.03 and 2.22, we note that the erosion in the Kissane catchment area is largely due to its relief. Indeed, when the logarithm in base 10 of the stability index is lower than 1 ($Log_{10}Is < 1$), we are in the presence of very stable soils. Thus, we can say that water erosion in the Kissane catchment is mainly due to a purely mechanical phenomenon linked to rainwater runoff.

Figure 9 shows the soil erodibility map based on the Bouyoucos index. It also shows that the highest index values are found on the slopes where runoff is most pronounced.

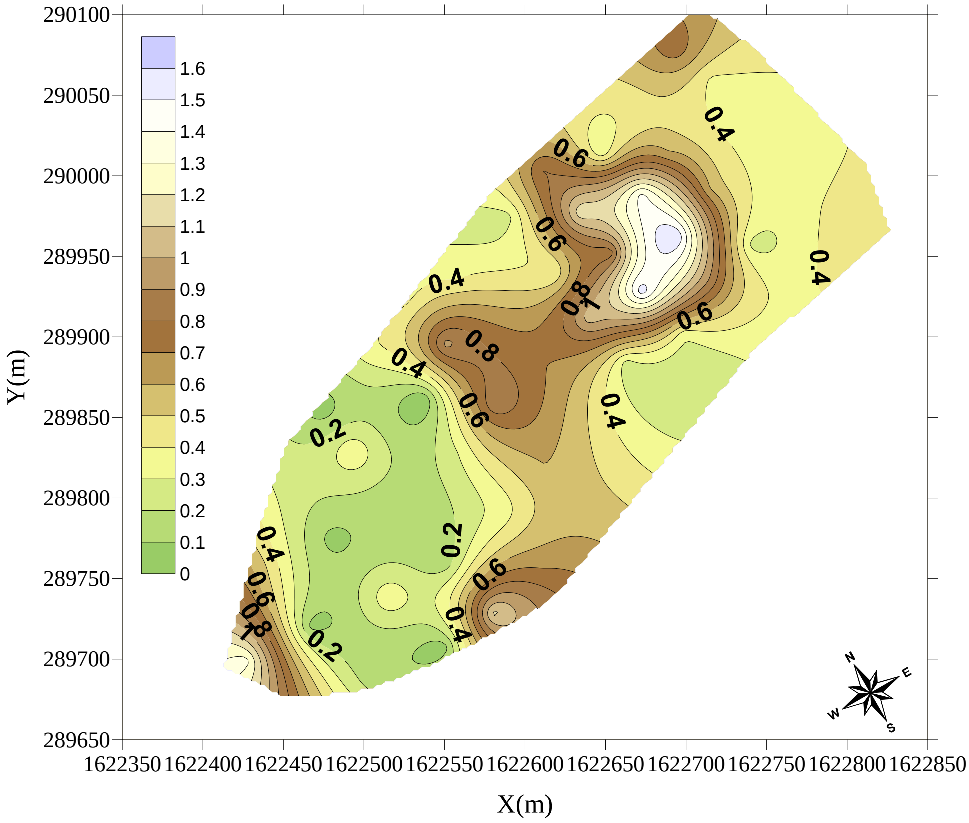

Figure 8: Soil erodibility map based on Hénin structural stability index

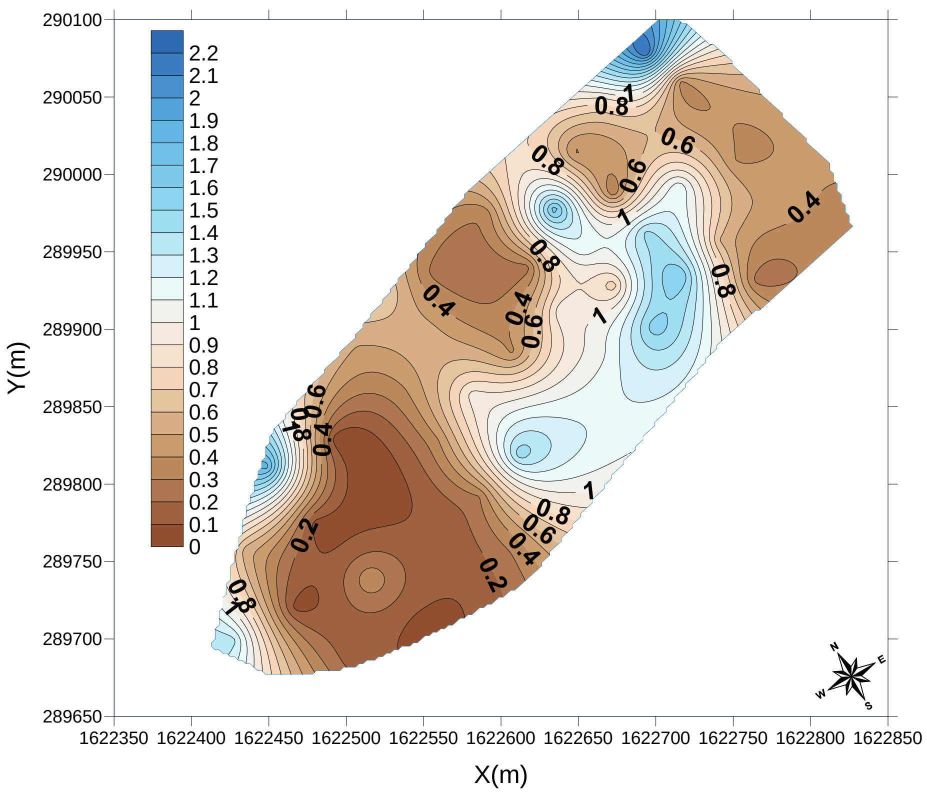

Figure 9: Soil erodibility map based on the Bouyoucos index

Figure 10, based on the liquidity limit, highlights two distinct zones, the southern part of the watershed and the outlet. They are characterised by fairly high liquidity limit values that decrease towards the North.

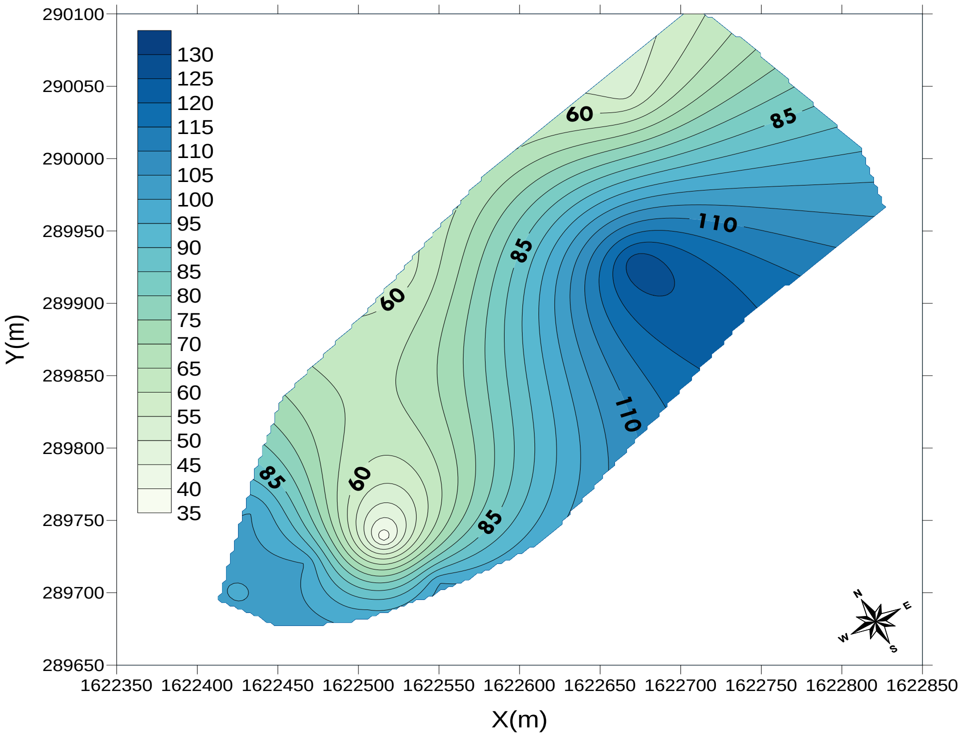

Figure 10: Liquidity Limit Map

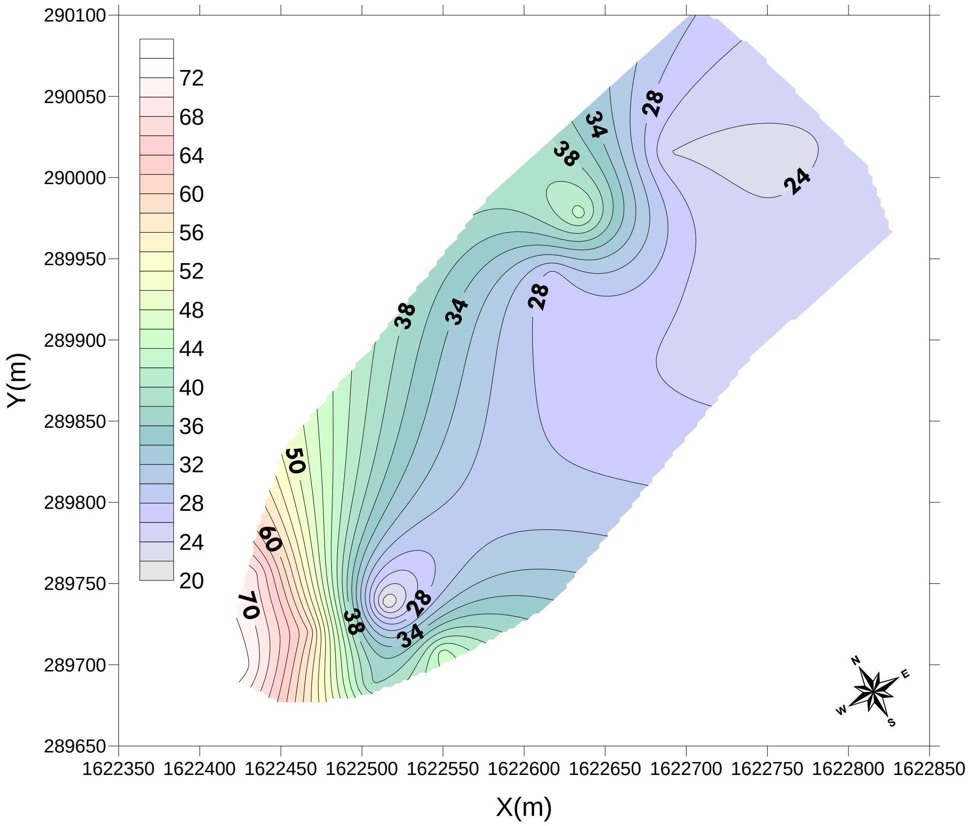

Figure 11: Plastic limit map

Figure 11 based on the plasticity limit shows that the highest values occur in the vicinity of the outlet. Indeed, the sedimentation phenomenon is more intense in this part of the watershed, which explains the predominant presence of clay particles. The two figures (10 and 11) allow, in the case of a Summary Preliminary Draft, to have a good idea of the plasticity and liquidity limit values.

Figure 12 established on the basis of the plasticity index shows that the highest values are found near the outlet. The sedimentation phenomenon is more intense in this part of the watershed, which explains the predominant presence of clay particles.

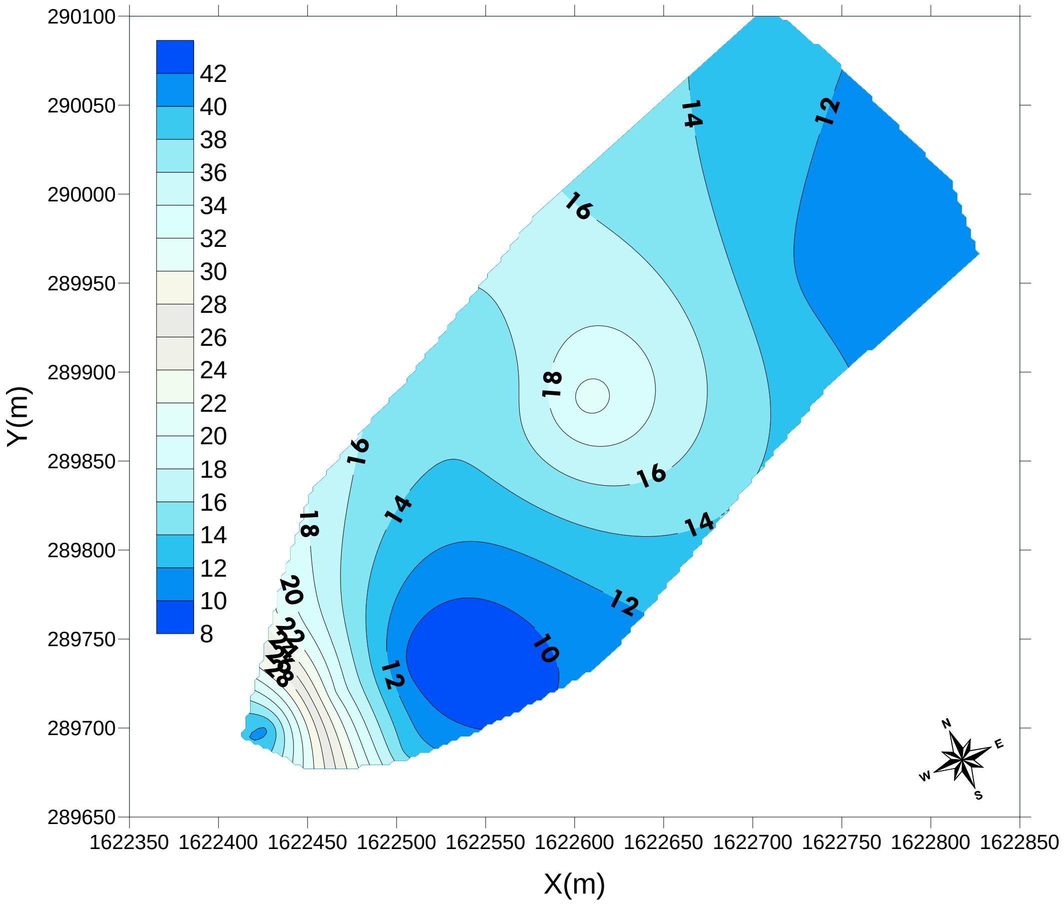

Figure 12: Plasticity index map

This map also allows, in the case of a Summary Preliminary Draft, to have a good idea of the values of the plasticity index.

5. Conclusion

Through this study, we have tried to contribute to a better understanding of the reasons for hydric erosion in the Thies tray by favouring a geotechnical approach, which has enabled us to establish certain relationships between the structural stability index of Hénin, the Bouyoucos index and some geotechnical soil characteristics. The experimental phase, consisting of a geotechnical prospecting campaign consisting of fifty (50) manual boreholes distributed over the Kissane watershed, made it possible to characterize the soils in the study area in the laboratory. For each sample, we determined the particle size composition by sieving, the consistency or Atterberg limits or sand equivalent, the Bouyoucos index and the Benin structural stability index. The results obtained highlighted the relationships between the consistency limits and the structural stability index of Hénin and Bouyoucos but also the correlation between these two indices. This work also enabled us to produce two soil erosion maps based on the Hénin structural stability index and the Bouyoucos index and three maps of the consistency limits and plasticity index. The values of the stability index of Hénin obtained between 0.03 and 2.22 allow us to conclude that the phenomenon of water erosion in the Kissane catchment is not due to a lack of structural stability but rather results from a purely mechanical phenomenon linked to intense runoff due to the topographic profile.

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