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Soil vulnerability to water erosion in the Baobolong catchment area (central-western Senegal): Remote sensing and GIS (Geographic Information System) approach

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Abstract

The 1140.94 ha Baobolong catchment area, located in the locality of Nioro du Rip (central-western Senegal), is subject to increasing anthropic action exacerbated by a changing climate. Its high vulnerability to water erosion has led to significant losses of agricultural land, housing, infrastructure and public buildings. The objective of this study is to develop a method based on the integration of satellite images (Sentinel-2A) and cartographic data in a Geographic Information System (GIS) for the identification and mapping of areas vulnerable to erosion. The approach uses erosion factors such as vegetation cover, slope, soil protection and soil type. The results showed that the two most dominant factors are vegetation cover and soil type. The resulting maps were integrated into a Geographic Information System (GIS) using an additive combination, resulting in a map of vulnerability to water erosion. Three classes of multifactorial vulnerability to water erosion have been distinguished: low to very low vulnerability classes covering 37% (422 ha) of the area, medium vulnerability classes covering 4% (41 ha) and high to very high vulnerability classes covering 59% (678 ha) of the basin. This map of soil vulnerability to water erosion is a decision support tool to guide decision-makers in soil conservation measures for sustainable development.

Keywords: *soils, water erosion, catchment area, Remote sensing, GIS.*

1. Introduction

Soil loss through erosion is the major process of soil degradation worldwide. Sub-Saharan Africa is no exception to this observation, with land losses due to water erosion causing problems in terms of development (Aké et al., 2012; Cissé, 2013).

In Senegal, soil erosion is a concern, as 77% of degraded land is degraded due to water erosion (Diop, 2008; Wade et al., 2008). In the Baobolong catchment area of Nioro du Rip, water erosion causes loss of habitable and/or arable land each winter. This results in gullies which, over the years, become more numerous, wider, longer and deeper. This situation naturally raises the concern of populations whose heritage is directly threatened. This leads to significant losses of agricultural land, housing, infrastructure and public buildings.

In this area, several studies have been devoted to understanding and quantifying the materials displaced by erosion (Albergel et al., 1995; Biaye et al., 2020; Diatta et al., 2001). So despite the many efforts made to combat erosion, the phenomenon is still a topical issue. Indeed, the implementation of effective soil conservation and restoration measures must first be preceded by a spatial assessment of the erosion risk.

In interactive decision-support systems, the coupling of remote sensing and geographic information systems (GIS) is best suited. It is then necessary to select the main factors of erosion and to use cartographic and statistical data in a GIS to visualise them. The aim of this study is to identify and map areas vulnerable to erosion in the Baobolong watershed.

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2. Materials and Methods

2.1 The study area

The Baobolong watershed is located between latitudes 13° 45′ 00″ north and longitudes 15° 48′ 00″ west (Fig. 1). The study area covers 1140.94 ha. It is an elongated depression; communicating with the Gambia and flooded for part of the year.

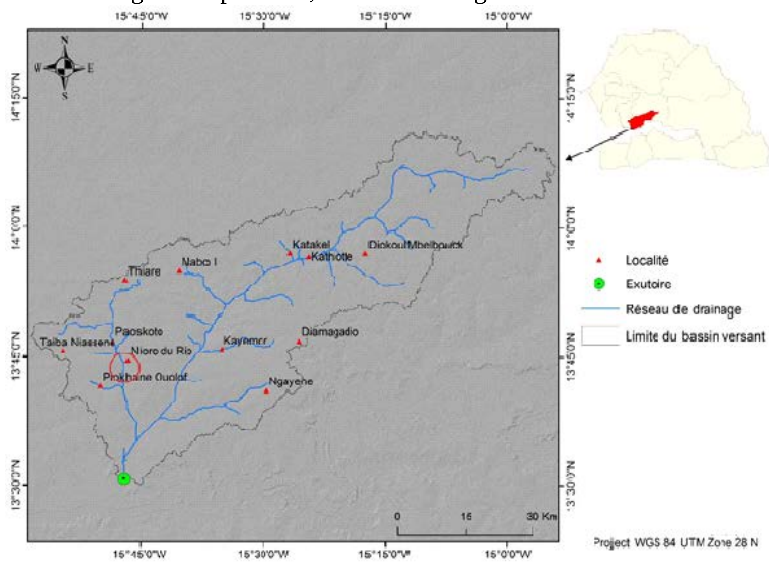

Fig. 1: The Baobolong catchment area

Geologically, the study area is located in the south-central part of the Senegalese-Mauritanian sedimentary basin. This basin is the result of the Jurassic separation of West Africa and North America. It is the largest (340,000 km^2) basin of the passive margin of the African Atlantic coast. It extends over nearly 1,400 km from Cape Barbas (Mauritania) to Cape Roxo (Guinea Bissau) through Senegal and Gambia. It covers three-quarters of the surface area of Senegal.

The general topography of the study area is flat, with low plateaus, shallows and shallow troughs. The different geomorphological units are as follows (CSE, 2005):

- plateaus of 15 to 20 metres in altitude with a cuirass flush on the periphery and on the edge of the plateaus;
- connecting glazes which are convex-concave or convex surfaces notched into the laterites ;
- terraces made up of colluvium and thick alluvium, mainly sandy, silty on the surface and clayey at depth;
- shallows which are beds of dead valleys, the old beds of the tributaries of Baobolong.

The local climate is Sudano-Sahelian. It is marked by a dry season during which the trade winds circulate and a rainy season during which the monsoons circulate. The rainy season lasts 4 to 5 months (June to October) with maximum rainfall in July, August and September. The dry season lasts 7 months (November to May).

The vegetation is a savannah with trees and shrubs, presenting numerous woody and herbaceous species. In the lowlands and valleys, there are cashew and mango tree plantations.

In the study area, water erosion has increased over the years. The area of bare soil and gullying has increased considerably, which has dealt a blow to the agricultural vocation. Water erosion has caused immense damage as shown in the photos below (Fig. 2).

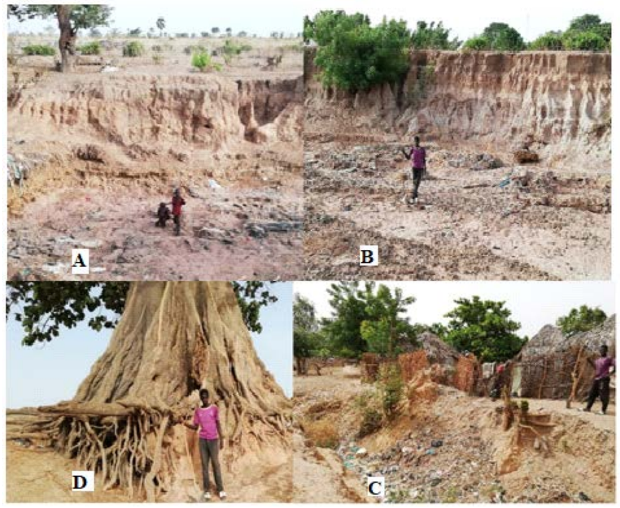

Fig. 2 (A, B, C and D): Water erosion damage in fields and habitats in the study area

2.2. Study methodology

The model chosen to map the areas vulnerable to water erosion in the study zone has been proposed by several authors (Saroufim, 2007; Yjjou et al., 2014; Payet *et al.*, 2012; Zouagui et *al.*, 2018; El Hage Hassan *et al.*, 2018).
The parameters governing water erosion used are vegetation cover, soil erodibility, slope and soil protection.
The combination of these factors is based on several data processing steps such as Sentinel-2A satellite imagery, topographic surveys and soil analysis.
The soil protection factor is generated by crossing the land use with the vegetation cover. These elements are extracted from the Sentinel-2A image acquired in April 2020 and downloaded from Google Earth Engine (GEE). GEE is a cloud-based platform for geospatial data analysis that gives the user the ability to work within a geospatial Big Data infrastructure. Sentinel-2A is equipped with a multispectral imaging sensor (MSI) consisting of thirteen spectral bands from visible to mid-infrared. The channels used are described in Table 1 below.

Table 1: Spectral and spatial characteristics of the satellite image used

Sensor	Date of acquisition	Tapes	Resolution
MSI	April-May	2-Blue	10 m
		3-Green	
		4-Red	
		5- Vegetation classification	20 m
		6- Vegetation classification	
		7- Vegetation classification	
		8- Near Infrared	10 m

Vegetation cover is obtained by calculating the Normalized Difference Vegetation Index (NDVI). All factors are resampled at the same spatial resolution and projected in the same reference system WGS 1984, UTM Zone 28N.
The topographic surveys were carried out using appropriate equipment such as Differential GPS (DGPS), which offers the possibility of generating a high-precision digital terrain model (DTM) using interpolation techniques. This operation made it possible to extract the slope.
The erodibility factor (K) is a function of soil texture, structure, organic matter content and permeability. Experiments on different soil types have led to the statistical development of an equation for the calculation of this factor (Wischmeier and Smith, 1978):

K = 1/100 * [2.1 * M 1.14 * 10-4 (12 - A) + 3.25 (B -2) + 2.5 (C - 3)
Where:
M = (% fine sand + % silt) * (100 - % clay)

A = percentage of organic matter
B = permeability code
C = structure code

We used the geological substrate map and the land use map to identify homogeneous units. Soil samples were then taken from these units (17 samples) and analysed in the laboratory to determine the erodibility factors K which are divided into 4 classes:
If: K> 0.45; Class 1, very high erodibility ;
If: 0.45 > K > **0**.35; class 2, high erodibility ;
If: 0.35 > K > **0**.25; class 3, medium erodibility ;
If: K **<** 0.25; class 4, low and very low erodibility.
In order to produce the multifactorial vulnerability map to erosion in the basin, the different thematic maps (erodibility, slope, vegetation cover and soil protection) were cross-referenced according to the general principles used by Le Bissonnais et *al. (*2004).

3. Results

3.1. The vegetation cover map (C)

The spatial distribution map of the vegetation cover index (Fig. 3) shows that the areas most sensitive to erosion have a low to very low density of vegetation. They mainly cover the upstream part of the catchment area and represent 83% (953.43 ha) of the catchment area.
Low to very low vegetation cover is encountered in cattle runs, degraded rangelands and on completely bare and uncultivated soils. High to very high vegetation cover is found downstream of the catchment area, in annual crops (cereals, extensive agriculture), in reforested areas, in lowland areas and arboriculture. It represents only 17% (190.03 ha) of the catchment area.

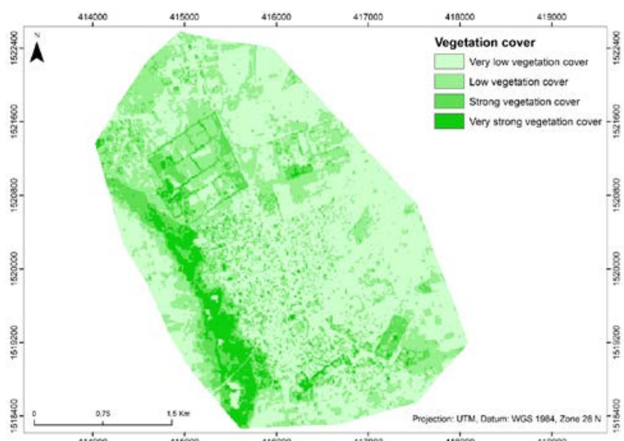

Fig. 3: The vegetation cover map

3.2. Map of the slopes

The study area has a wide range of slope values from 0.3% to 15%. The fig. 4 shows that steep to very steep slopes (8%) are concentrated in the north-west and south-east parts of the catchment area. They characterise the glacis.
Low to very low slopes (92%) are distributed over the whole basin, but are more concentrated in the south of the basin. They characterise the plains and alluvial terraces. Generally speaking, the catchment area does not offer any clear breaks in the slope; the slopes are regular, not very long and fairly gentle.

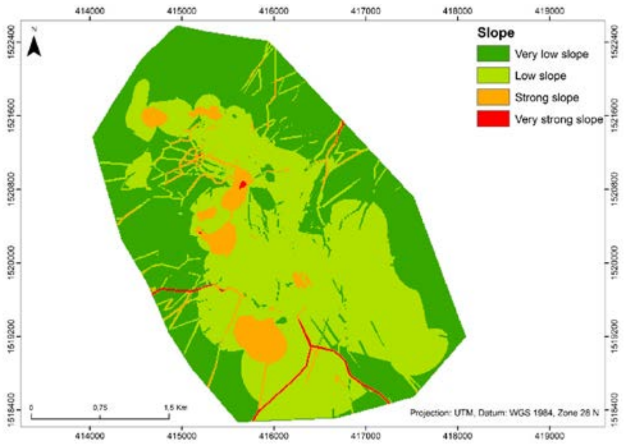

Fig. 4: The slope map

3.3. The soil protection map

The fig. 5 shows the heterogeneity of soil protection. The strong to very strong protection class is estimated at 59% (677 ha) of the total area of the basin. It is concentrated in the centre and south of the basin. It is more or less superimposed on habitat and arboriculture.
The low to very low protection class occupies 41% (465 ha) of the basin. It characterises bare, deforested and uncultivated areas. It is found along the lowlands and on the north-eastern slopes of the basin.

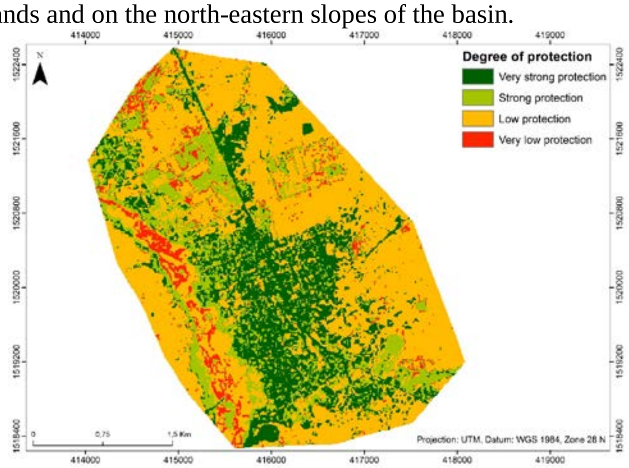

Fig. 5: The soil protection map

3.4. The soil erodibility map

The catchment area shows varied erodibility (Fig. 6). The degree of low to very low erodibility is estimated at 59% (672 ha) of the total area. It occurs at the northern and southern extremities of the catchment area and at the shallows and terraces.
The degree of strong to very strong erodibility represents 41% (471 ha) of the surface of the basin. It is found on the north-eastern and south-eastern slopes.

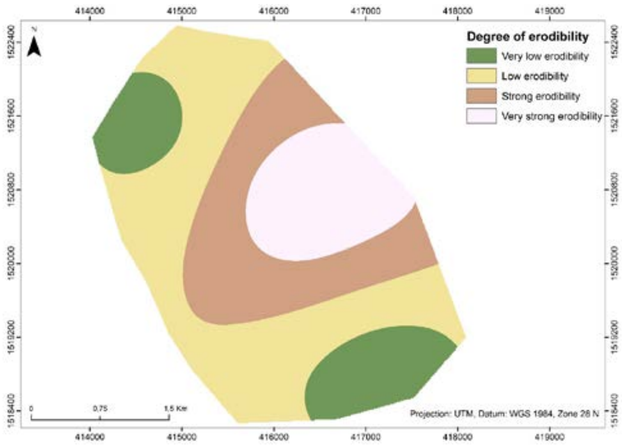

Fig. 6: The soil erodibility map

3.5. The soil vulnerability map

The soil vulnerability to erosion map (Fig. 7) was obtained by integrating data on slope, soil erodibility, soil protection and vegetation cover. It highlights:

- an area of low to high vulnerability, characterised by low slopes (0-2%) and low soil erodibility (K < 0.25). This zone is mainly made up of hydromorphic soils near the lowlands and brown soils in the centre of the basin. It represents 37% (422 ha) of the total area.
- an intermediate vulnerability zone where the susceptibility to erosion is low and soil erodibility is very high (K> 0.45). These are ruby soils and poorly evolved soils found in the west and south of the study area. This vulnerability class constitutes about 4% (41 ha) of the total area of the basin.
- an area of high to very high vulnerability, covering the upstream and a large part of the basin; it represents 59% (678 ha) of the basin. It is generally characterised by steep slopes (> 15%), very high soil erodibility (K> 0.45) and degraded plant cover. The soils are tropical ferruginous soils and beige soils. Also affected are the unstable edges of the deep and wide ravines, which are characterised by the steepest slopes in the area.

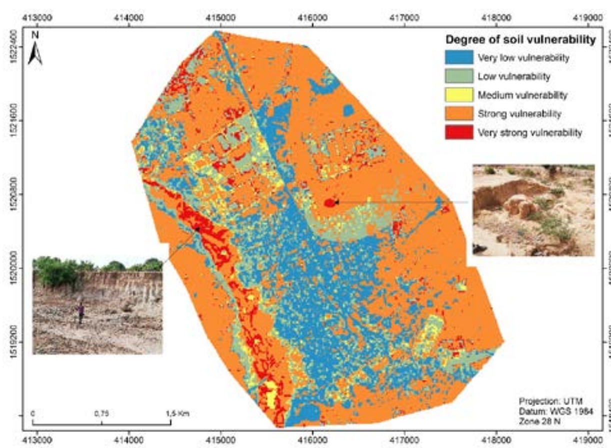

Fig.7: The soil vulnerability map

4. Discussion

The upstream part of the catchment area is characterised by fairly steep slopes (> 15%) and a predominance of silty soils and strong erodibility (0.45 > K > 0.35). This favours water erosion. In fact, the richer the soils are in silt, the more unstable the aggregates are; a crust is formed, followed by runoff and soil loss (Roose, 2004). The silty particles (2-50 µm) have a weak cohesion between them and this facilitates their detachment and favours the formation of a crust of threshing. Moreover, their small size makes them easily transportable by runoff water (Dautrebande *et al.*, 2006).

The upstream part of the basin has almost no protective vegetation cover, which is the most effective parameter for reducing erosion risk (Roose *et al.,* 2008b).

In the centre of the basin, despite marked erodibility, the habitat reduces soil loss. In this part of the basin, the high vulnerability of the soils is due to grazing areas characterised by a settling of the surface horizon which increases runoff (Sabir *et al.,* 1994). This often leads to gullying of fields downstream.

Downstream of the basin, the slopes become gentle and the vegetation abundant; it is a zone of sedimentary accumulation. There is a high degree of erosion, probably due to the geological formation covering these areas. These are in fact non-cohesive sediments (sandstone and clays) sensitive to water erosion.

The different maps of erosion factors show a clear concordance between the distribution of the different classes of erosion risk and that of the classes of soil erodibility and vegetation cover. These two parameters can be considered as determining factors in the erosion process in the catchment area. Indeed, according to Fournier (1967), in the absence of plant cover, the characteristics of the surface horizons play a primordial role in the initiation and development of erosion, in particular the structural stability and permeability of the soil.

Although the slope factor is a determining factor in the assessment of vulnerability to erosion, it is nonetheless a predominant factor in this basin. Indeed, despite a low slope ($p < 2$) along the lowlands, the soils are very eroded. This means that with a low slope, the action of the rains is sufficient to trigger erosion (Annabi, 2005; Fournier, 1967; Roose, 2002).

When the soil is completely covered, erosion is low, whatever the slope (Roose, 1994). Roose *et al* (2010) showed that erosion can occur in areas of low vulnerability (slope between 0 and 2%). In these cases, the erosion is sheet erosion, without the formation of gullies or ravines, as runoff water is unable to concentrate.

The results of this study show that the local geology plays a major role in the sensitivity of the rocks to water erosion. The geological formations in the study area are essentially non-cohesive sandstones and clays outcropping over more than 2/3 of the catchment area and have a high erodibility. The results of this work complement those of previous work in the study area (Hathie, 2003; Ndoye, 2006; Sow, 1995; Biaye *et al.,* 2020) and confirm the qualitative contribution provided by this model on soil vulnerability.

5. Conclusion

This work has shown the value of using remote sensing and GIS to study soil vulnerability. The results of this approach revealed that soils in the Baobolong catchment area are subject to the combined effect of several erosion factors: slope, vegetation cover, soil protection and soil type. But the two dominant factors are vegetation cover and soil type.

The combination of the different erosion factors has made it possible to distinguish three (3) classes of soil vulnerability to water erosion: low to very low vulnerability classes covering 37% (422 ha) of the area, medium vulnerability classes covering 4% (41 ha) and high to very high vulnerability classes covering 59% (678 ha) of the basin.

The vulnerability map obtained is a document that will help in decision-making and will contribute to the rational use of the area's land and monitor areas at risk.

The results obtained will also make it possible to detect areas with weak or strong protection and consequently black areas that urgently require reforestation to fix and stabilise the soil (Druais, 2009; Le Bissonnais *et al*., 2004).

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