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RESEARCH ARTICLE

LAND USE DYNAMICS AND SOIL VULNERABILITY TO WATER EROSION IN THE AGNEBY WATERSHED (IVORY COAST)

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Abstract

In Cote d'Ivoire, particularly in the Agneby watershed, forest degradati on increases the vulnerability of soils to water erosion. This study aims to analyze the impacts of changes in land use on the vulnerability of soils to water erosion in this watershed. The data used include a Digital Elevation Model (DEM), Landsat satellite images of scenes 196/055 from TM (December 20, 1987), ETM+ (09/02/2025) and OLI-TIRS (07/01/2020) scenes, as well as a FAO soil map at a scale of 1:500,000. The methodology is based on the classification of satellite images and the mapping of vulnerability to water erosion. The results indicate a decline in primary forest cover, which fell from 53.3% in 1987 to 4.4% in 2020. At the same time, the areas covered by mosaics of crops/forest and habitat/bare soil have expanded significantly. Between 1987 and 2020, these increased from 42% to 78.2% and from 1% to 16.4%, respectively. In 2020, 68.2% of the basin's area is occupied by soil classes that are highly vulnerable to water erosion.

Introduction:-

Cote d'Ivoire has experienced a significant loss of forest cover. It fell from 16 million hectares in 1960 to 12 million hectares in 1970, then to less than 3.5 million hectares in 2015. This represents a decline of around 90% between 1990 and 2020 (Ministry of Water and Forests, 2020). This significant degradation of forest cover will undoubtedly have repercussions on agriculture and contribute to the acceleration of specific phenomena, in particular the vulnerability of soils to water erosion. Water erosion develops more rapidly when vegetation cover is reduced (Yao, 2023). Vegetation plays a crucial role in intercepting part of the rainfall, thus limiting the impact of raindrops on the soil. As a result, the water that reaches the soil has less kinetic energy and can infiltrate more easily at the root level. In this context, it is imperative to conduct an in-depth study on the effects of land use dynamics on the evolution of soil sensitivity to water erosion in the Agneby watershed. The objective of this research is to analyze the impacts of these dynamics on soil sensitivity to erosion in this particular area.

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Materials and Methods:-

Presentation of the Agneby watershed:

Location of the Agneby watershed:

Located between latitudes 5°10' and 6°08' north and longitudes 3°50' and 4°41' west, the Agneby watershed is situated in southeastern Cote d'Ivoire and covers an area of 8,863 km² (Yao, 2023). It is drained by the Agneby River, a coastal watercourse that flows north-south (Kouakouet al., 2022).

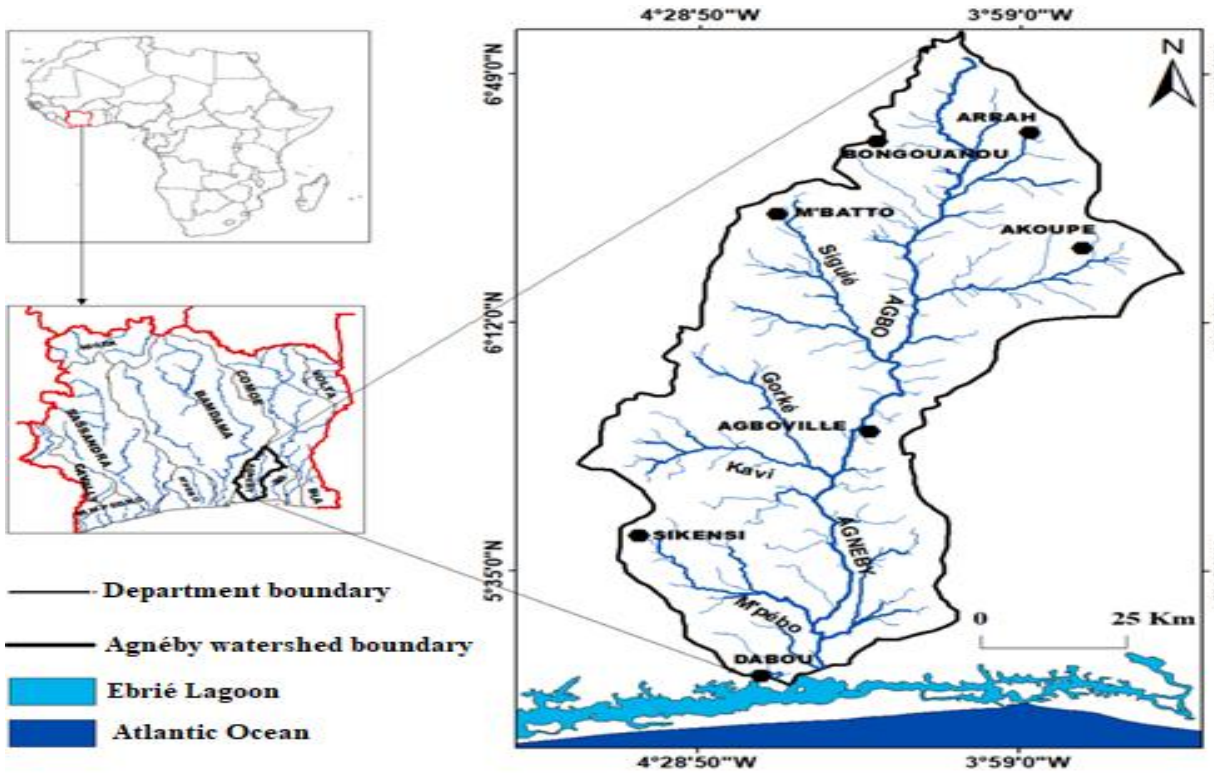


Figure 1: Geographic location of the Agneby watershed
(Source: Digital Terrain Model data, 2016)

Climate conditions from 2010 to 2020:

The climate of the Agneby watershed is tropical humid, characterized by two rainy seasons and two dry seasons (Yao J C, et al., 2025, p. 39). Rainfall varies between 1,000 and 2,000 mm/year, with 70% of this annual rainfall occurring between May-June and October-November. The average annual temperature is 27.2°C in the south and 27.8°C in the north (Yao et al., 2022, p. 104). February and March are the hottest months, while August is the coldest month across the entire basin.

Physical environment and population:

The relief of the Agneby watershed is characterized by altitudes ranging from 40 to 205 meters (Kone et al., 2019). The forest complex is dominated by a mosaic of crops and forest (Dibi-Anoh et al., 2022). In 2021, the population of the basin was estimated at over one million inhabitants. Agriculture is the main economic activity in the region, with cash crops predominating, occupying nearly 60% of cultivated land (Yao, 2023).

Study data:

The data used for this study comes from several reliable sources. These include the Digital Terrain Model (DTM). Landsat satellite images of TM (December 20, 1987), ETM+ (February 9, 2005), and OLI-TIR (January 5, 2020) scenes from indices 196/055. In addition, the FAO soil map produced at a scale of 1:500,000 in 1986 and cartographic data from rainfall stations in the basin collected from the Ivorian Center for Standardization Management (CIGN) were used.

Methods:-

Land use mapping:

Land use mapping was carried out in several methodological stages. First, image pre-processing was performed, consisting of a series of actions aimed at improving data readability (Konan, 2008). The next step was image processing, which began with the delimitation of the study area. Subsequently, visual identification based on color compositions (N'go, 2015) and the acquisition of field data made it possible to define six land cover classes: habitat/bare soil, primary forest, crop/forest mosaic, rubber tree, cocoa, and water body. The final step consisted of mapping land cover based on supervised classification using the “maximum likelihood” algorithm " algorithm (Kangah and Z. Koli Bi, 2015; Kangah et al., 2016; Melèdje, 2016; Noho et al., 2018; Ourega et al., 2019; Deguy, 2021).

The diachronic analysis of land use dynamics was established by calculating the rate of change (Soro et al., 2014; Diallo et al., 2019) according to the following equations:

$$\mathbf{T_{annual}} = \frac{(V_i - V_j)}{P*100} \quad ; \quad \mathbf{T_{global}} = \frac{(V_i - V_j)}{V*100}$$

Where: T (annual and global): the annual rate of change, Vi represents the value of the statistic for the final year, Vj the value of the statistic for the initial year.

Vulnerability of soils to water erosion:

Soil vulnerability to water erosion corresponds to the degree of exposure of soils to this phenomenon (Deguy, 2018). In the Agneby watershed, this vulnerability was mapped using the methodology developed by (Yao, 2023) (Figure 2).

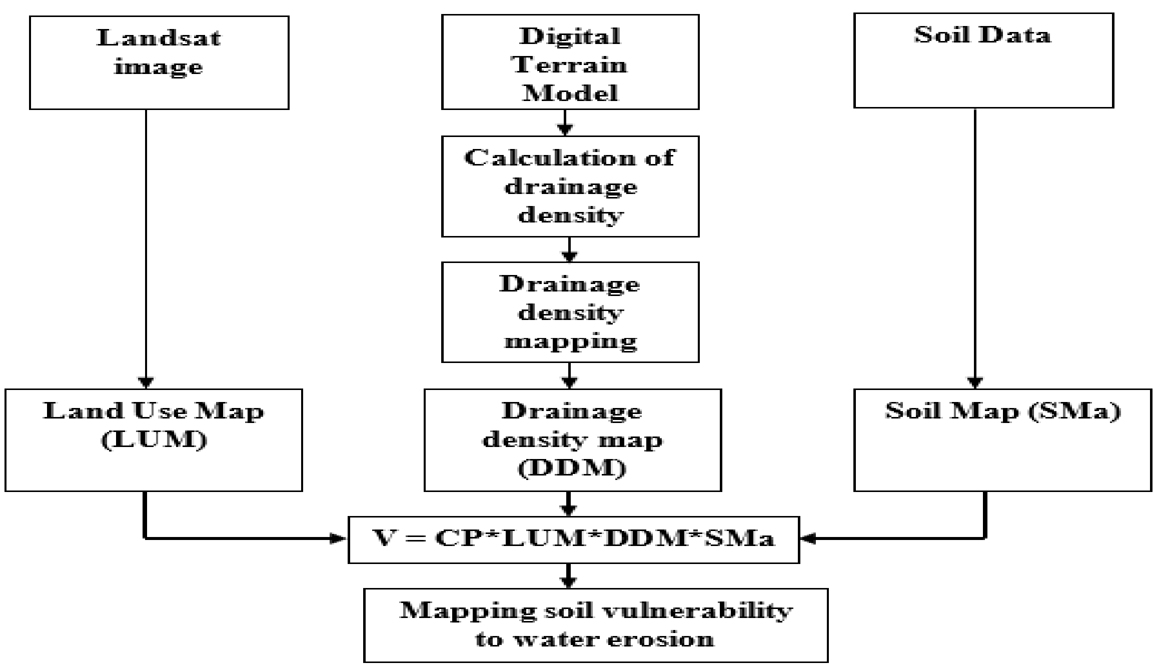


Figure 2: Methodology for mapping soil vulnerability to water erosion in the Agneby watershed
Source: Adapted from Yao, 2023.

Results:-

Land use mapping:

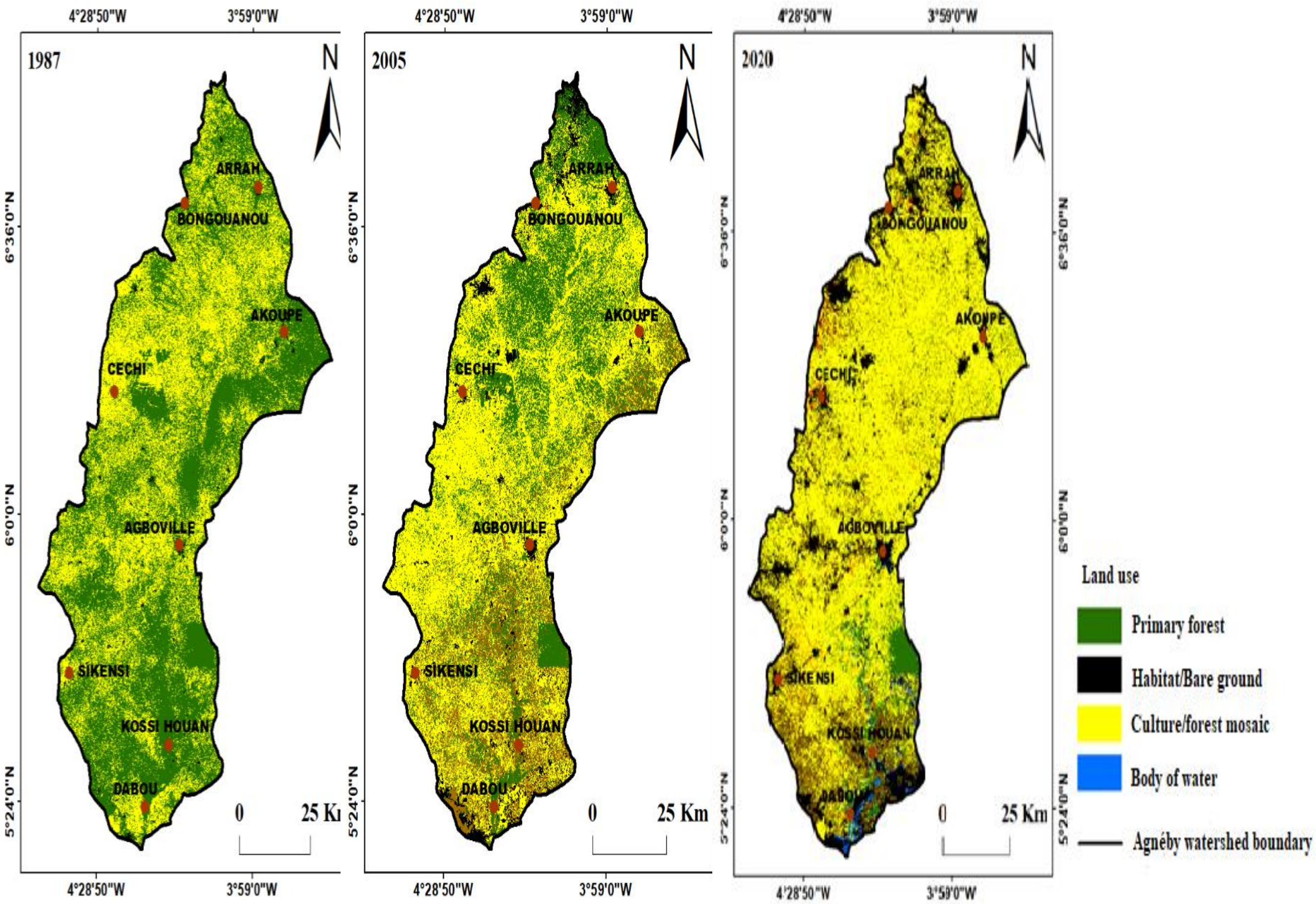
Surface condition:

Land use is illustrated in Figure 3. The main land use categories identified are: primary forest, crop/forest mosaic, habitat/bare soil, and water bodies (Figure 3).

The 1987 land use map highlights the predominance of primary forest in the Agneby watershed. This forest cover includes forest reserves as well as ordinary forests. The presence of forest was marked throughout the basin, with the exception of the north-central half and the extreme south of the basin. The crop/forest mosaic includes degraded forests, fallow land, and crops (notably oil palm, rubber, cocoa, coffee, and food crops). It was mainly located in the south and the north-central half of the basin. The habitat/bare land class includes modern and precarious habitats, bare land (open spaces with no buildings), and land undergoing subdivision or construction. Their presence was less marked. Water bodies refer to the hydrographic network and all areas where water is present (Figure 3).

The land use map produced in 2005 shows characteristics that are significantly different from those of the 1987 map. Whereas in 1987, the mosaic of crops and forest was mainly concentrated in the extreme south and the north-central half of the basin, it now occupies a dominant position throughout the basin. This vegetation class is mainly found in the south and center of the basin. In contrast, primary forest has gradually disappeared, concentrating mainly in the forest reserves located in the north, center-west, and southeast of the basin.

Figure 3: Land use from 1987 to 2020 in the Agneby watershed
Source:Images Landsat TM 1987,ETM 2005 et OLI-TIRS



The habitat/bare soil class, although less widespread, is beginning to become visible and is gradually spreading throughout the area. Water bodies were virtually absent from the 2005 map (Figure 3).

Land use in 2020 marks a significant change. The mosaic of crops and forest, which remains predominant, has continued to expand, becoming the main vegetation feature of the basin at the expense of primary forest. The latter is now only present in a few forest reserves such as Petit Yapo in the southeast and in the form of forest islands around the Agneby River in the south of the basin. The habitat/bare soil class has also undergone a remarkable change, concentrating around the large cities of the Agneby watershed. As for water bodies, they are now only found in the extreme south of the basin (Figure 3).

Surface state dynamics from 1987 to 2020:

The dynamics of the surface area of the Agneby watershed are presented in Table 1. The primary forest underwent a significant decline in surface area between 1987 and 2020. Initially estimated at 53.3% in 1987, its area decreased to 30% in 2005 and then to 4.4% in 2020. This decline represents 86% between 2005 and 2020. This indicates that nearly three-quarters of the forest disappeared over a period of 33 years. The mosaic of cultivated land and forest and habitat/bare soil has expanded dramatically. In fact, occupying 42% of the basin in 1987, the area of the crop/forest mosaic increased to 64% in 2005, then reached 78.2% in 2020. This represents an increase of 86% between 1987 and 2020. The habitat/bare soil class, meanwhile, represented an area of 1% in 1987. This area increased to 5% in 2005 and reached 16.4% in 2020. The increase is therefore 93% between 1987 and 2020 (Table 1).

Table 1: Land use dynamics from 1987 to 2020 in the Agneby watershed

Land use classes	1987 (%)	2005 (%)	2020 (%)	Overall rate of change (1987-2020) (%)	Nature of the change
Virgin forest	**56,3**	30	4,4	**92,1**	Negative
Culture/forestmosaic	42	**64**	**78,2**	86	Positive
Habitat/bareground	1,7	6	17,4	**93**	Positive

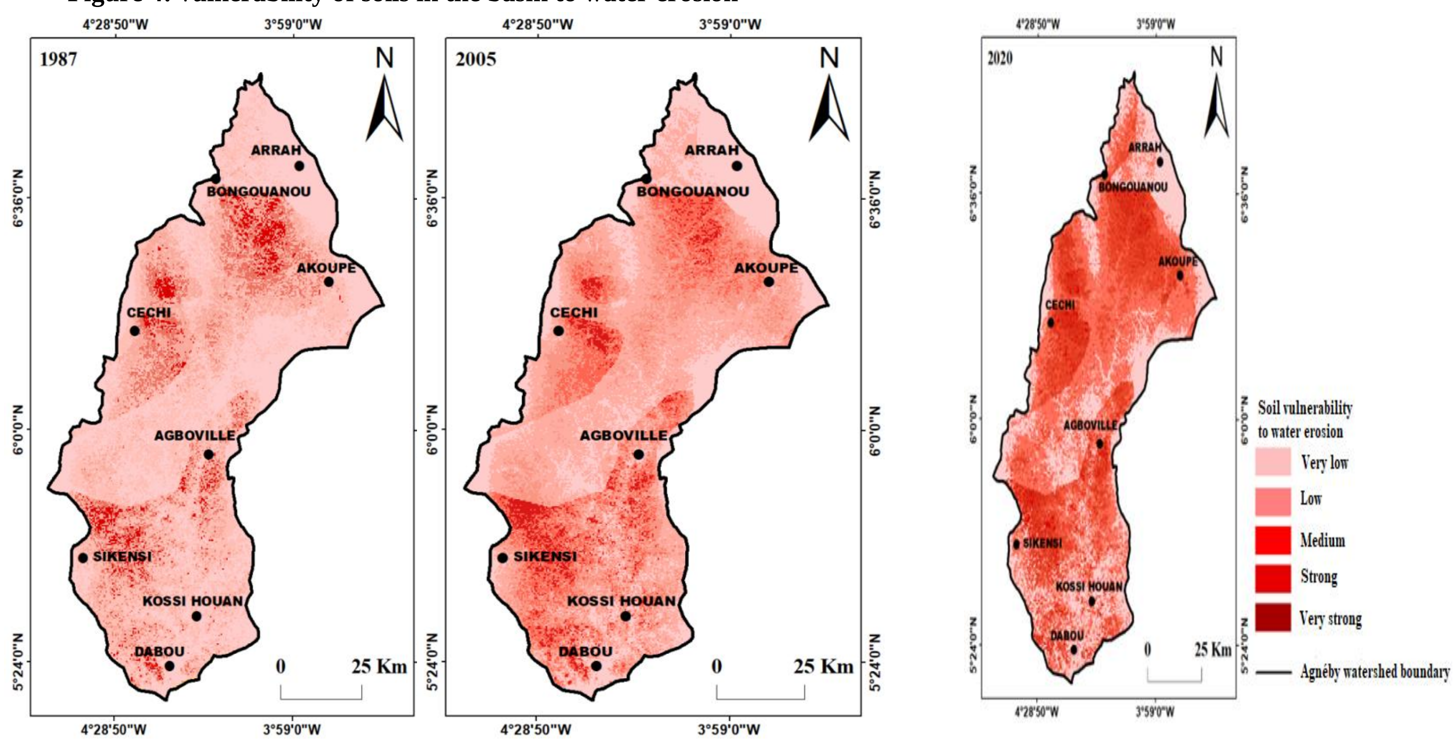
Source: Landsat TM 1987, ETM 2005, and OLI-TIRS 2020 images

Soil vulnerability to water erosion in the Agneby watershed:

Soil vulnerability assessment:

Figure 4 illustrates the evolution of soil vulnerability to water erosion in the basin between 1987 and 2020. In 1987, areas with low vulnerability (very low and low) were mainly located in the north, center, and southeast of the Agneby watershed. In contrast, areas with high vulnerability (medium, high, and very high) were more prevalent in the north-central and south-central parts of the basin (see Figure 4). In 2005, there was a notable change in the distribution of soil vulnerability levels to water erosion in the Agneby watershed. Areas with high vulnerability (medium, high, and very high) increased considerably in size, occupying mainly the north and south of the basin. Areas with low vulnerability (very low and low) are now scattered throughout the basin (see Figure 4). In 2020, the degree of soil exposure to water erosion in the Agneby watershed became particularly worrying. More than half of the basin is now covered by areas of high vulnerability.

Figure 4: vulnerability of soils in the basin to water erosion



Source: FAO data, 1986; Landsat images: 1987, 2005, 2020, DTM, 2016

These are mainly located in the north, center, and south of the basin. Areas of low vulnerability (very low and low), which are increasingly rare, are now concentrated only in the extreme south and northeast of the basin (Figure 4).

Soil vulnerability dynamics:-

The dynamics of soil vulnerability to water erosion in the Agneby watershed are presented in Table 2. Areas with low sensitivity (very low and low) saw a decrease in their surface area between 1987 and 2020. In 1987, these areas covered 69% of the total area of the basin. This proportion fell to 57.7% in 2005 and then to 37.2% in 2020, representing a decline of 17.4% between 1987 and 2005 and 35.1% between 2005 and 2020. On the other hand, areas of high sensitivity (medium, high, and very high) saw their surface area increase dramatically between 1987 and 2020. In 1987, they covered 31% of the basin. This proportion rose to 42.3% in 2005 and reached 62.8% in 2020. The increase was 26.7% between 1987 and 2005, then 32.6% between 2005 and 2020.

Table 2: Dynamics of soil vulnerability to water erosion from 1987 to 2020 in the Agneby watershed

Soil erosion vulnerability classes	**1987 (%)**	**2005 (%)**	**2020 (%)**	**Overall rate of change (1987-2020) (%)**	**Nature of the variation**
Low (very low and low)	**69**	57	37,2	**46,4**	Negative
Strong (medium, strong, and very strong)	31	43	62,8	**93**	Positive

Source: FAO data, 1986; Landsat images: 1987, 2005, 2020, MNT, 2016

Relationship between land use dynamics and changes in soil vulnerability in the Agneby watershed:

Land use dynamics have a considerable influence on the evolution of soil vulnerability to water erosion in the Agneby watershed (Table 3). In 1987, forest covered 56.3% of the total area of the watershed, i.e., more than half of its surface area. During the same period, soil classes with low vulnerability to water erosion (very low and low) covered 69% of this area. In contrast, soil classes with medium and high sensitivity (high and very high) to water erosion processes accounted for 31% of the area (Table 3).

In 2005, the proportion of forest had fallen to 30%. During this period, the areas classified as low vulnerability increased to 57% of the basin. Conversely, the areas classified as high vulnerability reached 43% of the basin's area (Table 3). In 2020, there was virtually no forest cover (4.4%) in the watershed. During this period, high vulnerability classes increased to 62.8% of the watershed area, while low sensitivity classes covered only 37.2% of the same area.

Table 3: Relationship between land use and soil vulnerability to water erosion in the Agneby watershed

Soil vulnerability classes to water erosion	**1987 (%)**	**2005 (%)**	**2020 (%)**
Low (very low and low)	**69,9**	**57**	37,2
Strong (medium, strong and very strong)	31	43	**62,8**
Land use	**1987 (%)**	**2005 (%)**	**2020 (%)**
Primaryforest	**56,3**	30	4,4
Culture/forestmosaic	42	**64**	**78,2**
Habitat/baresoil	1,7	6	17,4

Source: FAO data, 1986; Landsat images: 1987, 2005, 2020, DTM, 2016

Discussion:-

The primary forest has declined by 92% in area over 33 years in the Agneby watershed. Today, forest cover remains only in protected areas, which are also in a state of degradation. These observations are corroborated by the work of the Ministry of Water and Forests carried out in 2020, which concluded that 12 million hectares of forest were lost between 1960 and 2000. According to (Melèdje, 2016), the forest in the Bia watershed exists mainly in the form of islands, thanks to the presence of parks and reserves covering 16.25% of the watershed's surface area. Deguy (2021) specifies that the primary forest has suffered a 36% decline in area in the Lobo watershed. Furthermore, studies by Yao et al. (2020) on the Gourou watershed in Abidjan show that, due to the progressive urbanization of this city, the primary forest has been replaced by bare habitats/soil, covering 11.70% of the Gourou basin in 2017.

The vulnerability of soils to water erosion in the Agneby watershed increased significantly between 1987 and 2020. The areas classified as highly vulnerable (medium, high, and very high) increased from 31% to 41% and then to 62.8% in 1987, 2025, and 2020, respectively. These heavily leached ferralitic soils are increasingly vulnerable to water erosion due to urban development and agricultural expansion, particularly cash crop cultivation. These results confirm those of Deguy (2021), who observed high vulnerability to water erosion in the Lobo watershed in 2014, where areas of high vulnerability covered 85.78% and 88.12% of the area in 1986 and 2014, respectively.

The degradation of primary forest exposes soils to greater erosion. Forest cover acts as a natural barrier against water erosion (Roose and De Noni, 2004). Conversely, the Bia watershed, located in southern Cote d'Ivoire, is not as vulnerable to water erosion (Melèdje, 2016). In this basin, the dominant class is the low vulnerability class, representing 84.92% of the basin's surface area. This result can be explained by the particular geomorphological structure of the basin, which is mainly located at low altitude. In contrast, the relief of the Agneby watershed is characterized by slopes often exceeding 40 m, representing more than 60% of the basin, with slopes sometimes reaching 250 m in altitude. These rugged reliefs make the soils in this area particularly susceptible to water erosion.

Conclusion:-

The vegetation of the Agneby watershed is mainly dominated by a mosaic of crops and forest, which, in terms of land use, represents 78.2% of the area in 2020. Furthermore, the forest has undergone accelerated decline in terms of area within the watershed, reaching only 4.4% of the total area in 2020. This substantial degradation of forest cover has undeniably affected the evolution of soil vulnerability to water erosion.

The degree of soil exposure to this phenomenon in the Agneby watershed is particularly worrying, since more than half of its territory is now covered by areas highly sensitive to water erosion. In 2020, highly sensitive classes dominated the basin, representing 62.8% of its area. As a result, the basin is increasingly vulnerable to water erosion processes.

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