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RESEARCH ARTICLE

Land use Mapping of the Bandama Blanc Watershed: Implications for the Kossou Hydroelectric Dam (Côte d'Ivoire)

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ABSTRACT

Land use and Land Cover (LULC) plays a crucial role in the water cycle, directly influencing the availability and quality of water resources, which is essential for activities such as hydroelectric production and drinking water supply. Understanding the evolution of LULC is very important for the sustainable management of water resources. This study, therefore, takes a close look at the evolution of land use in the Bandama Blanc watershed in Côte d'Ivoire, an important region for the Kossou hydroelectric dam. Using Landsat ETM+ (2000, 2011) and OLI (2021) satellite images and supervised classification using the maximum likelihood algorithm, the results show high overall accuracy (97% to 99%) and a Kappa index ranging from 0.98 to 0.99, attesting to the reliability of the classifications obtained. Despite this, confusion persists between certain classes, in particular between savannah and crop/fallow and degraded forest areas. Spatio-temporal analysis reveals a regression in forest, savannah, and water surface areas in favor of habitats/bare ground and crops/fallow over the period 2000–2021. These changes are attributed to bushfires and population growth, which intensifies anthropogenic pressures such as slash-and-burn agriculture, livestock breeding, and hunting. Falling rainfall and sediment deposits in lakes are also contributing to the reduction in water surface areas. These results underline the need for sustainable management strategies to mitigate anthropogenic pressures and preserve ecosystems in the Bandama Blanc watershed.

Keywords: Bandama Blanc watershed, Kossou Dam, Land Use and Land Cover, Maximum likelihood.

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1. Introduction

Rapid changes in LULC, driven by intensive agriculture and increasing urbanization, are transforming natural ecosystems with major ecological and hydrological consequences. Intensive farming, for example, leads to the conversion of forests and wetlands to agricultural land, reducing the habitats available for local flora and fauna [1]. Urbanization is another major factor in land use change. The expansion of towns and villages encourages the transformation of natural areas into residential, industrial, and commercial zones. The exploitation of natural resources, such as mineral extraction, deforestation for firewood, and the collection of non-timber forest products, also puts considerable pressure on natural resources [2]. All these activities can lead to rapid deforestation, loss of vegetation cover, and soil destabilization [3], [4] Analysis highlights that changes in LULC can significantly alter critical hydrological components, such as surface runoff, groundwater recharge, infiltration, interception, and evaporation, with immediate or lasting effects, on a local and regional scale.

Hydrological regimes changes caused by LULC can have a significant impact on reservoirs, particularly those used for hydroelectric generation. In June 2017, flooding was reported at the Fayé hydroelectric dam [5]. This flooding is the result of the combined effect of extreme rainfall events and the occupation of areas at risk [flood zones] [6]. Increased runoff can also lead to soil erosion as water moves quickly over sealed surfaces, carrying away soil particles [7]. The eroded soil particles are then transported to watercourses and reservoirs by runoff. The resulting sedimentation can reduce the storage capacity of reservoirs [8].

The Bandama Blanc watershed in Côte d'Ivoire is home to the third largest hydroelectric dam in the country, the Kossou Dam [9]. Several studies on the dynamics of land use have been carried out in the Bandama Blanc catchment area [9]–[11]. Thus, [10] showed in his study that the regeneration of the woody cover was due to favourable human actions such as the management of the Mont Korhogo classified forest and the introduction of perennial woody crops in the Korhogo region. [9] and [11] have reported a decline in forest and savannah areas in favor of crops, fallow land, habitats and bare soil. These studies were carried out in sub-catchments of the Bandama catchment at Kossou. The Bandama catchment at Kossou [12] reports a dominance of deciduous forest and grassy savannah in 2013. [9]'s studies carried out on a larger scale in the Bandama catchment in Taabo showed that land use changed in favor of anthropized surfaces over the period 1988–2016. For the latter, LULC could alter the hydrology of the basin. The conversion of vegetated areas to agricultural land and urbanization can lead to an increase in the flow of watercourses, which is favorable to hydroelectric production but can have consequences for the power station system. Given the importance of land use, an analysis at the catchment scale is essential to fully understand its influence on the Kossou hydroelectric dam. The aim of this study is, therefore, to Analyse the past dynamics of land use.

2. Materials and Methodology

2.1. *Description of Study Area*

The Bandama blanc catchment area, with the Kossou hydroelectric dam as its outlet, is located in Côte d'Ivoire (West Africa). It is a sub-catchment of the Bandama River. It covers an area of 32,400 km^2, representing around 33% of the total surface area of the Bandama watershed, and stretches from the north to the center of Côte d'Ivoire. This elongated rectangular basin has a perimeter of 1020 km [12]. The white Bandama River rises at an altitude of 480 m between the towns of Boundiali and Korhogo in the north of the country [12]. This area, with its distinctive hydrological and geographical features, is also at the heart of agricultural and pastoral activities. Hydro-agricultural activities, which include irrigation and water management for agriculture, are essential for food security and rural development. Pastoral practices, including animal husbandry and grazing management, play a vital role in the local economy and the livelihoods of rural communities. The watershed plays a crucial role in draining the waters of the Kossou hydroelectric dam. Located in the center of Côte d'Ivoire (Fig. 1), Lake Kossou is the largest artificial lake in the country.

2.2. *Data*

The spatio-temporal dynamics of land cover were monitored using satellite images from satellites with a spatial resolution of 30 m. Three images from sensors in the Landsat series were used (Table I). These images are divided into five scenes (Fig. 2) and can be downloaded from http://earthexplorer.usgs.gov/.

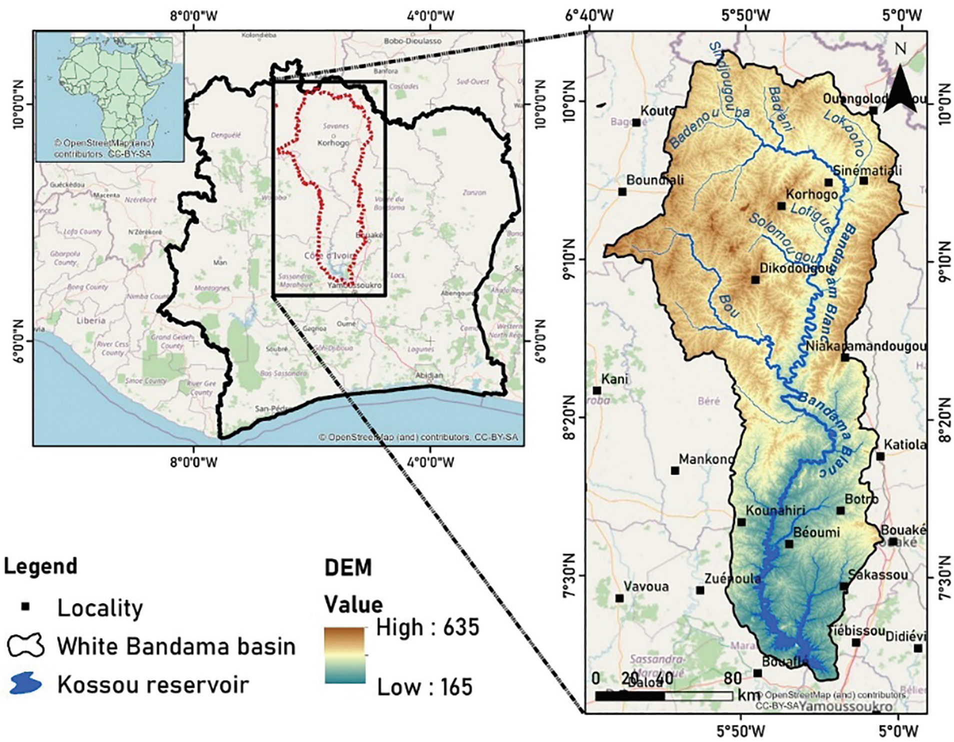

Fig. 1. Bandama basin location of Kossou.

TABLE I: Characteristics of the Images Used

Satellites	Sensor	Spatial resolution (m)	Acquisition date
LANDSAT 7	ETM+	30	16/01/2000
LANDSAT 7	TM	30	20/12/2011
LANDSAT 8	OLI	30	16/12/2021

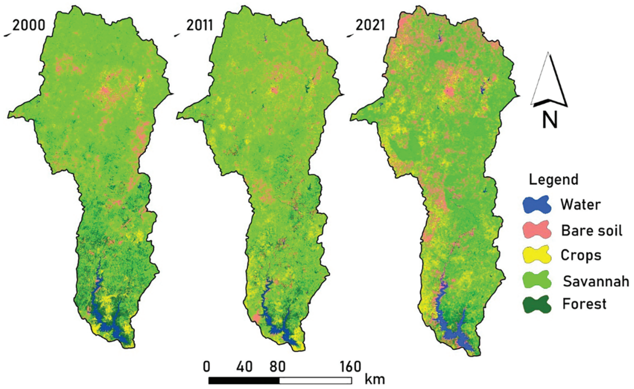

Fig. 2. LULC map of the Bandama Blanc catchment for 2000, 2011 and 2021.

TABLE II: Types of Land use Category in the Bandama Catchment Area in Kossou

N°	Category	Descriptions
1	Water	Rivers, lakes and reservoirs.
2	Degraded forest	Shrubby forest.
3	Bare soil	Cities, villages, bare soil, roads.
4	Savannah	Vegetation composed of trees and shrubs, scattered shrubs and thick grasses.
5	Crops/fallow	Land areas of agricultural activity (maize, mango, cotton, cashew nuts, vegetables), fallow land and areas with sparse vegetation.

2.3. *Methodology*

2.3.1. *Definition of Category Types*

According to [13], the definition of the types of land cover categories takes into account the research objectives and must respect certain conditions, such as the actual conditions of the study area and the technical conditions of the satellite images used. In this study, the selected classes are presented in Table II.

2.3.2. *Land Cover Mapping*

2.3.2.1. *Image Processing*

Image calibration is the first stage in satellite image processing. It is used to normalize the images (Landsat ETM+ and OLI) in order to reduce the atmospheric influence and the earth's curvature on the image [13]. Radiometric and atmospheric corrections were then made to eliminate disturbances caused by the presence of gas and dust. These elements can absorb and/or reflect certain wavelengths, thereby altering the spectral properties of the radiation. The second stage consists of mosaicing the five scenes (197/053, 197/054, 197/055, 198/053, and 198/054) covering the Bandama watershed at the Kossou hydroelectric dam to create a single image from the initial images.

The mosaicking method used is 'Seamless Mosaic' on ENVI software. Finally, the last step consists of extracting the Bandama watershed at the Kossou hydroelectric dam using the 'Subset Data from ROIs' tool in the ENVI software.

2.3.2.2. *Supervised Classification*

Color composition is the first stage in supervised classification. The aim of this operation is to synthesize the information in order to clearly distinguish the different types of land cover. It involves combining the information from three strips by displaying them simultaneously in the three primary colors (red, green, and blue). After several combinations, the 7-4-3 and 4-3-2 color compositions were chosen for the Landsat 8 and 5 images, respectively, as they offer the best discrimination of land cover types. Image sampling consisted of defining regions of interest (ROIs), which are portions of images selected by the user, each ROI representing a thematic category that may include one or more samples. The ROIs for this study were determined on the basis of field visits and the literature. The classification method was then carried out using the maximum likelihood algorithm, which calculates the probability of each pixel belonging to a given class. Finally, the classification results were validated using the parameters calculated from the confusion matrix, namely overall accuracy and the Kappa coefficient. The confusion matrix presents the image classification accuracy statistics, in particular, the misclassification rate between the different classes, expressed in pixels and as a percentage.

2.3.2.3. *Change Analysis*

The percentage area [14] and percentage change [15] were calculated as follows:

$$\%S = \frac{S_c}{S_t} \times 100 \qquad \text{and} \qquad Tg = \frac{DS}{S_t} \times 100$$

where $\%S$ is the percentage of the area of a given class, S_c is the area of a given class, and DS is the variation in the area of a land-use unit between $t1$ and $t2$.

$$DS = S2 - S1$$

where $S1$ represents the area of a land-use unit at date $t1$, $S2$ is the area of the same land-use unit at date $t2$, and S_t is the total area of all the units. A positive value indicates an increase, while a negative value indicates a decrease in the area of a land-use unit.

3. Results

3.1. *Evaluation of the Accuracy of the Classifications of the Bandama Catchment Area*

The evaluation criteria for the various land use maps are overall accuracy and the Kappa coefficient. The overall accuracies obtained are 95.49%, 92.49%, and 93.80%, respectively, for 2000, 2011, and 2021 images. The Kappa coefficients are 0.95, 0.90, and 0.94 for the 2000, 2011, and 2021 images, respectively. These criteria demonstrate

TABLE III: Confusion Matrix (Percentage) for the 2000 Land Use Map

		Verification pixels				
Affected pixels (Classification)	Class	Water	Bare soil	Savannah	Degraded forest	Crops
	Water	99.93	0	0	0	0
	Bare soil	0.05	99.03	1.30	0	0
	Savannah	0.02	0.97	98.05	0.07	0.24
	Degraded forest	0	0	0.55	99.92	0.08
	Crops	0	0	0.1	0.01	99.68
	Total	100	100	100	100	100

TABLE IV: Confusion Matrix (Percentage) for the 2011 Land Use Map

		Verification pixels				
Affected pixels (Classification)	Class	Water	Bare soil	Savannah	Degraded forest	Crops
	Water	100	0	0	0	0
	Bare soil	0	98.13	0.7	0	0
	Savannah	0	1.76	78.21	0.83	0.02
	Degraded forest	0	0.10	0.19	87.13	0
	Crops and fallow land	0	0. 02	21.1	12.04	99.98
	Total	100	100	100	100	100

TABLE V: Confusion Matrix (Percentage) for the 2021 Land Use Map

		Verification pixels				
Affected pixels (Classification)	Class	Water	Bare soil	Savannah	Degraded forest	Crops
	Water	99.81	0	0	0	0
	Bare soil	0.19	99.82	0.44	0.03	0.02
	Savannah	0	0.18	99.56	0.22	0
	Degraded forest	0	0	0	99.72	0
	Crops	0	0	0	0.03	99.98
	Total	100	100	100	100	100

the quality of the classification of the different land cover maps. Low confusion rates (less than 2%) can be noted overall for the different land cover maps for 2000, 2011, and 2021. However, high confusion rates between certain land cover classes were observed in 2011. A confusion rate of 21.3% was observed between the savannah class and the crop and fallow land class, and a confusion rate of 12.01% was observed between the savannah class and the degraded forest class on the 2011 image. Tables III–V show the confusion matrices for the 2000, 2011, and 2021 land cover maps, respectively.

3.2. *Land Cover Mapping for the Years 2000, 2011 and 2021*

Supervised classification of Landsat images using the maximum likelihood algorithm produced land cover maps for the years 2000, 2011, and 2021 (Fig. 2). Analysis of the maps shows that the savannah class is predominant on all three land cover maps. In 2000, the savannah class represented more than half of the surface area of the study catchment, with a percentage coverage of 62.76% of the total surface area. This class is followed by the Habitats and Degraded Forest classes with respective areas of 16.48 and 13.48%. The Crops/Fallow Land and Water classes are the lowest, with areas of 4.78% and 2.51%, respectively. In 2011, the classes did not change significantly. In 2021, the Savannah class will account for less than half of the total surface area of the basin, with a percentage of 44.08%, followed by the Habitats/Bare Soils class, which will occupy 34.91% of the total surface area (Fig. 3).

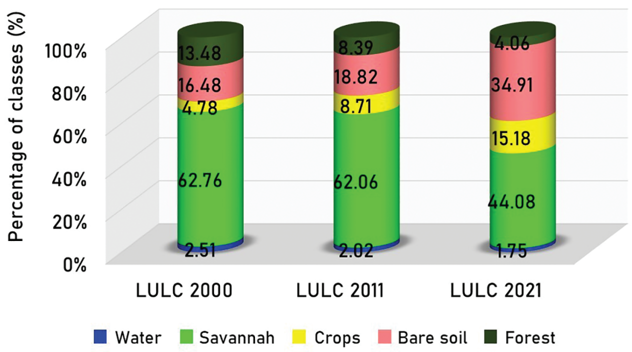

Fig. 3. Percentage of land use classes in 2000, 2011 and 2021.

3.3. *Analysis of Changes in Land Use*

Figs. 4 and 5 show, respectively, the overall changes in land use over the periods 2000 to 2011 and 2011 to 2021 in the Bandama Blanc catchment:

- From 2000 to 2011, the water, savannah, and degraded forest classes saw more loss than gain in their surface area, with rates of change of 19%, 1%, and 38%, respectively, compared with their surface area in 2000. The habitat/bare soil and cropland/fallow classes have seen more gains than

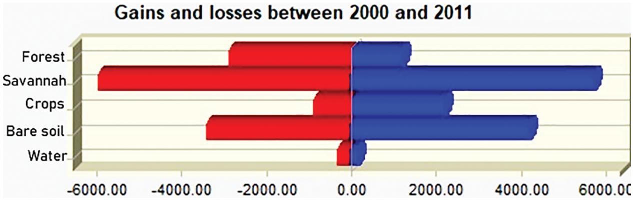

Fig. 4. Land use gains and losses in the Bandama Blanc catchment over the period 2000–2011.

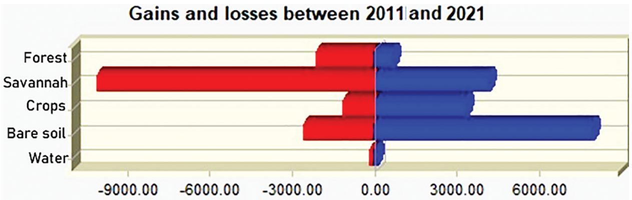

Fig. 5. Land use gains and losses in the Bandama Blanc catchment over the period 2011–2021.

losses in their 2000 areas, with rates of 14% and 84%, respectively.

- From 2011 to 2021, degraded forests, savannahs, and water will have declined considerably compared with the other classes, with variations of 52%, 29%, and 13%, respectively. Crops/ fallow land and habitats/bare ground increased by 74% and 86% compared with the 2011 area.

4. Discussion

4.1. *Evaluation of Land Cover Classifications*

The satellite images (Landsat, ETM+ from 2000 and 2011, and OLI from 2021) were classified using the maximum likelihood algorithm. The overall accuracy values vary from 97% to 99% between 2000 and 2021. The Kappa index varies from 0.98 to 0.99. These evaluation criteria show that the maps obtained in this study are statistically acceptable. According to [14], a classification with a kappa index of between 50% and 75% is considered valid. However, although these results are statistically acceptable, it should also be noted that there was confusion between certain land cover classes, particularly in 2011. A 21.3% confusion was observed in the 2011 image between the savannah class and the crop and fallow land class; another 12.01% confusion was observed between the savannah class and the degraded forest class, again in the 2011 image. For [11], the lightly cultivated savannah class can interfere with the shrub savannah or crop classes. This confusion would, therefore, result from the similar radiometric behavior of these classes [1].

4.2. *Spatial and Temporal Dynamics of Land Cover*

The analysis of land cover at different dates (2000, 2011, and 2021) has highlighted the different processes of landscape change over the period 2000–2021. There has been a decline in forest, savannah, and water areas in favor of anthropized areas such as habitats/bare ground and crops/ fallow land. In fact, over the period 2000–2021, the loss of forest area was essential to the benefit of savannah, crops/ fallow land, and habitats/bare ground. These same results were also obtained by [1], [11], and [15] on the Bandama basin as well as [16] on the Lobo watershed and [17] on the Agneby and Boubo basins. For some of these authors, [1] and [15], bushfires, which are fairly common practices in this basin, are one of the causes of these landscape changes. Studies by Koffi [18] have shown that fires are more abundant in the northern sectors than in the southern sectors of Côte d'Ivoire. Furthermore, [16], [17], and [19] emphasize in their work that population growth is a factor in the disappearance of forest landscapes. Anthropogenic pressures exerted by populations through their settlement and certain practices such as slash-and-burn agriculture, livestock rearing, and hunting are thought to contribute significantly to the many fires observed in the dry season. In addition, the reduction in the surface area of water bodies is thought to be the result of the drop in rainfall in the basin observed by [9], [15], and [20], as well as sediment deposits in the lake bottoms highlighted in studies by Kamagaté [1], Avakoudjo *et al*. [21], Obahoundje *et al*. [22] and Koffi *et al*. [23].

4.3. *Contribution and Future Studies*

In addition to providing critical information for land management, this study reveals significant implications for hydroelectricity. Land use changes, particularly the conversion of forest areas to agricultural land and the expansion of anthropized habitats, have a direct impact on the hydrological regimes of the watershed. An increase in runoff and river flow rates can be beneficial for hydroelectric production by increasing water availability. However, this can also pose challenges for sediment management and the sustainability of hydroelectric infrastructure, such as the Kossou dam. Specifically, the increase in runoff due to the reduction of vegetated areas can enhance erosion and sediment transport, leading to reservoir siltation and reducing their storage capacity. This necessitates frequent dredging interventions, thus increasing maintenance costs and decreasing the efficiency of dams.

Moreover, managing flow fluctuations becomes more complex, especially during periods of heavy rain or prolonged drought, impacting the regularity of hydroelectric energy production. Understanding these dynamics is crucial for optimizing water resource management and ensuring the sustainability of hydroelectric production in the region. It is essential to consider land use changes in the planning and management of hydroelectric infrastructure to minimize negative impacts on energy production and the environment.

5. Conclusion

The analysis of land cover changes from 2000 to 2021 revealed significant landscape transformations, with a decline in forest, savannah, and water areas in favor of anthropized areas such as bare ground and agricultural land. These changes were driven by factors such as bushfires, population growth, and anthropogenic pressures, including slash-and-burn agriculture, livestock rearing, and hunting. The study also emphasizes the critical implications of these land cover changes for hydroelectricity. Increased runoff and river flow, while beneficial for water availability, pose challenges for sediment management and the sustainability of Kossou hydroelectric dam.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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