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Surface runoff revitalization policy in the context of climate change in the Senegal River watershed

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Abstract: In the Senegal River watershed, hydroelectric infrastructure and land use have profoundly altered the hydrosystem, resulting in environmental imbalance. The aim of this study is to propose policy options for revitalizing surface runoff in the Senegal River watershed, using remote sensing, geographic information systems and spatio-temporal modelling tools, coupled with climate change indicators. Several types of data were used. The Land Change Modeler (LCM) model was used to simulate the data and make projections up to 2030 of land use in the Senegal River basin. In this study, the author chose three scenarios Business-As-Usual (BAU), Rapid Economic Growth (REC) or maximalist scenario and Coordinated Environmental Sustainability (CED) or medium scenario. The results show that the CED scenario offers hope that the restoration and preservation of plant resources is still possible to ensure the revitalization of surface flows in the Senegal River basin.

Keywords: *Runoff – revitalization – policy – climate change – Senegal River*

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1 Introduction

The impact of water resource variability on human activities has drawn the attention of many scientists and organizations around the world to the need to reconsider previous achievements. In addition to seeking a better understanding of the phenomenon, one of their primary objectives is to assess the impact of these changes on water resources. Several studies have already been carried out on continental, regional or sub-regional scales [1]. On the scale of the African continent, important studies have also been carried out, both in terms of recent climatic fluctuations [2]; [3] & [3] ; [4]; [5]; [1]; [6]; [7] and at regional level. These studies have made it possible to identify the manifestations of climate variability, in particular the drought observed over the past thirty years in the tropical African sub-region.
At the scale of the West and Central Africa window, while rainfall deficits are well established in the North, the effects of climate variability are less visible in the South, where resources are still significant in absolute terms

(fouta Djalon massif and the Gulf of Guinea). However, these can have a disastrous impact on the balance of ecosystems and compromise human activities. Numerous studies on climate variability in West Africa [8];[1] and the Senegal River basin [9] ; [10] ; [11], show that a trend towards drought began to emerge at the end of the 1960s.
Climatic variability has not been uniform over time. In the basin, it first affected the north, then gradually spread to the center and finally to the south. These rainfall anomalies, which have been observed for almost three decades, have had an exceptional impact on the northern and central parts of the basin. The rainfall deficit observed over several consecutive years has had repercussions on the flow of rivers and their tributaries in the basin, causing a considerable drop in their hydrological characteristics (average thirty-year flows, average ten-year flows, average annual flows, maximum average daily flows, low-water flows).

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Flow deficits seem to be amplified in some cases. Drought is generally perceived more in terms of its impact than its genesis, but scientific and technical data alone do not always seem to be sufficient to make perceptible the dramas experienced by the populations of regions affected by the vagaries of the climate (loss of herds, crop failure, famine, displacement of populations, malfunctions in the filling of reservoirs, etc.). All this has had serious consequences on the supply of water and hydroelectricity, affecting production capacity and endangering natural resources (surface water, groundwater, vegetation and wildlife, etc.). In this

In this the « Panta Rhei » context based on the dynamics of change between hydrology and society [12] appears to be a need to reinvigorate hydrological research in Africa. In West Africa, and particularly in the Senegal River basin hydrosystem, these spatial changes are reflected in the degradation of vegetation cover and hydrological imbalance from upstream to downstream of the basin. Thus, this hydrosystem is subdivided into three entities with particular characteristics.

The upper basin in its Guinean part, the "water tower" of the basin, appears to be the most environmentally preserved sector but, paradoxically, the one on which there is the most uncertainty for the coming years.

Around the Manantali dam, and as far as Bakel, the issue of existing or planned reservoirs or run-of-river power stations (Felou dam) is a major concern. These developments are not without impact, both positive and negative, on the environment, economic development, the presence of diseases and of course the management of water resources and their distribution downstream.

Further downstream, the valley is characterized by total dependence on inflows from upstream, which are only partially regulated. In this part, we note the consequences of the hydrological imbalance observed over the last forty years (a drop in water levels coupled with the artificialization of the environment) are the most flagrant. This imbalance has led to a loss of biodiversity and the drying up of wetlands in a sector that is in the process of desertification, made even more vulnerable by the increase in population and conflicts over land use. Faced with this continuous degradation of the vegetation cover, one wonders what the future of the Senegal River Basin landscape is.

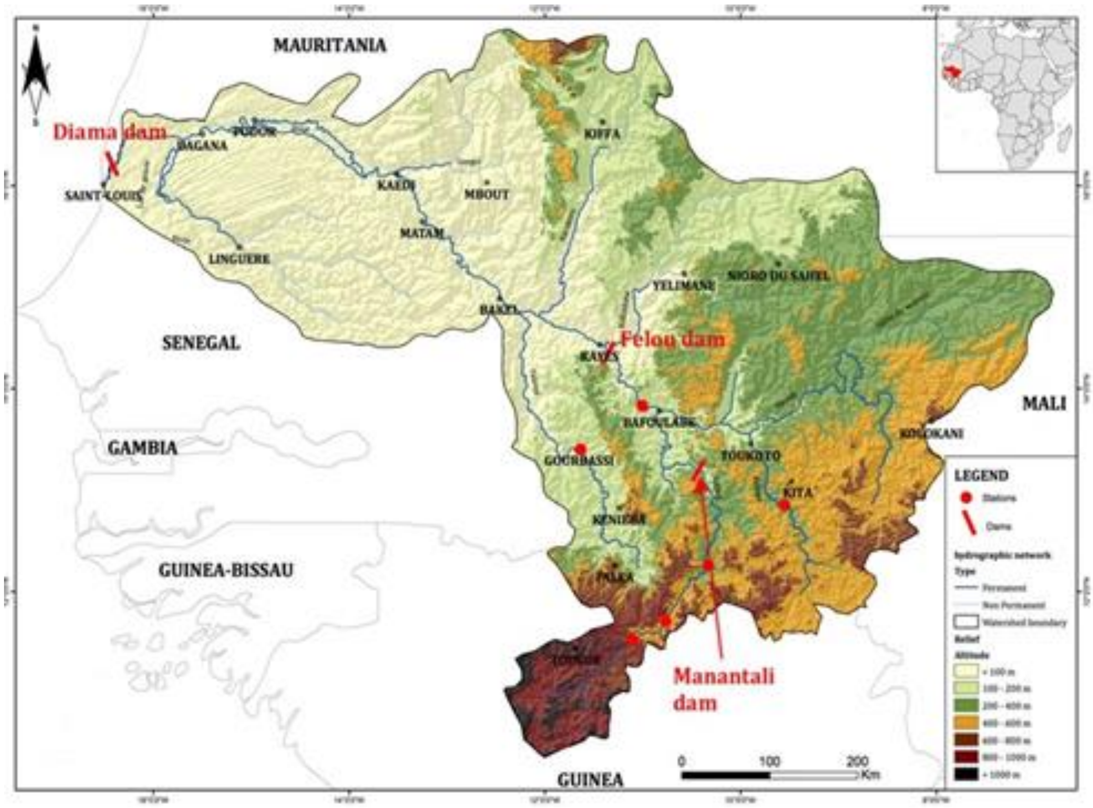
For several decades, modeling and projection of land use change has been a relevant toolfor decision support. It allows the analysis of territorial planning policies with the aim of evaluating and anticipating their environmental impacts [13] . The originality of this research lies in the fact that the modeling of land use dynamics will make it possible to monitor the evolutionary trend of the landscape and to find acceptable rules to ensure the revitalization of surface runoff in the Senegal River watershed.

2. Data and methods

2.1 Description of the study area

The Senegal River basin is located in the western part of Africa between latitudes 10°30' and 17°30' and longitudes 7°30' and 16°30'. With a surface area of approximately 325,000 km², it is drained by a 1,800 km long river which is subdivided into three main parts: the upper basin (from Fouta Djalon to Bakel), the valley (from Bakel to

Dagana) and the Delta (from Dagana to Saint-Louis). It is shared by four coastal states (Guinée, Mali, Mauritanie et Senegal) with several hydroelectric dams (Manantali et Felou) and hydro-agricultural (Diama) (Map 1).



Map 1: Overview of the Senegal River Basin

2.2 Data and materials

In this study, the data used to determine the dynamics of land use for a better understanding of the scenario that could contribute to a revitalization of the flows in the basin are recorded in Table 1.

Table 1 : The Senegal River Basin

Data	**Scale**	**Source**
Digital terrain model	5 m	Srtm/ersdac
Landsat	250 m	Modis terra
Soil type	250 m	Basegeo
Mean daily rainfall	71 years	OMVS

2.3 Methods

The prediction model used here is the Land Change Modeler (LCM) implemented in the Terrset software (formerly Idrisi). This model uses past and present knowledge of land use to predict the future. Several factors influencing land use changes have been integrated into this model. These include slope, altitude, soil type, distance to fields, distance to plantations and density.

Among the many types of results that the model can give, the indicators chosen to compare the scenarios between them are the following:

- The minimum guaranteed volume of the artificial flood (estimated at Bakel),
- The minimum flow at Bakel and at the control point downstream of the basin in order to ensure that the minimum flow set point for navigation is respected,

The maximum flow at Bakel in order to ensure the flood protection set point and the occurrence of exceedances of the 4500 m3/s threshold at Bakel.

- ✓ **Description of the different prospective scenarios**

Three scenarios have been developed to predict current trends in land use and change in order to facilitate decision making. The Business As Usual (BAU) scenario is a baseline scenario that assumes no new economic or environmental policies (no new regulatory dam: Manantali only).
The medium scenario or Coordinated Environmental Sustainability is to protect the remaining plant resources still in place. This is a scenario in which legislation andgovernment subsidies encourage the emergence of forestry (more plantations and agroforestry) and the protection of timber resources and also the construction of a new regulating dam (Koukoutamba). In the maximum scenario or Rapid Economic Growth, the destruction of tree and shrub cover is accelerated and the agricultural land is expanded (a trend towards catastrophe) and the number of dams in the basin is increased. In this scenario, the population and economic growth will be very high, resulting in increased environmental degradation with the construction of three additional control dams.

3. Results

3.1 Natural flow regime of the Senegal and its tributaries

The average flow of the Senegal River at Bakel is around 490 m3 /s. Its three (03) main tributaries have flows of around 240 m3 /s for the Bafing at Dibia, 80 m3 /s for the Baoulé Bakoye at Oualia and 80 m3 /s for the Falémé at Gourbassi.
The Senegal River's flow regime depends essentially on rainfall in the Upper Guinean Basin. The high-water season extends from August to October, and the most severe low-water periods occur from January to May. In Bakel, average flows were around 3,300 m3/s in September and 8 m3/s in May before the 1970s. Dependent on rainfall, these flows were significantly affected by the great drought (table 2).

Table 2: Variation in mean annual flows in the upper Senegal River watershed

		J	F	M	A	M	J	J	A	S	O	N	D
Before 1972	Flow (m^3/S)	159,1	91,0	46,5	19,1	7,5	95,7	648,5	2407,0	3341,9	1601,7	568,1	275,4
	Contribution (%)	1,7	1,0	0,5	0,2	0,1	1,0	7,0	26,0	36,1	17,3	6,1	3,0
Between 1972 and 1993	Flow (m^3/S)	68,4	43,4	34,0	23,6	24,8	56,0	382,5	1184,4	1563,6	726,7	290,1	121,2
	Contribution (%)	1,5	1,0	0,8	0,5	0,5	1,2	8,5	26,2	34,6	16,1	6,4	2,7

Runoff deficits seem to have been amplified after the great drought of the 1980s. The drought had terrible consequences for the populations of the regions affected by the vagaries of the climate (loss of herds, crop failure, famine, displacement of populations, malfunctions in filling reservoirs, etc.). All this has had serious consequences on the supply of water and hydroelectricity, affecting production capacity and endangering natural resources (surface water, groundwater, vegetation and wildlife, etc.).

3.2. Land use dynamics in 2007-2014 and 2014-2019

Analysis of the land use table for 2007, 2014 and 2019 shows a difference in the dynamics observed over the 2007-2014 and 2014-2019 sequences.

Table 3: Evolution of land use statistics in the Senegal River basin (2007 to 2019)

Land use categories	**Areas in 2007**		**Areas in 2014**		**Area in 2019**		**Differences (%)**	
	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	2007-2014	2014-2019
bare floors	15	49 400	22	67 990	24	78679	7,0	2
wet soils	22	71 880	20	66232	18	59 287	-2,0	-2
Forest and savannah	39	126 040	34	110 958	31,2	101 411	-5,0	-2
Crops and fallow land	13	43 200	15	46 710	18	60 130	2,0	3
Water	11	34 480	9	33 110	6	21492	-2,0	-3
Coef Kappa		0 ,80		0,78		0,87		

Total	100	325 000	100	325 000	100	325 000

Examination of Table 3 shows that the Kappa index from the processing of the land use indicators for each of the three classifications is above 75% (recommended threshold). This shows that these land use types are acceptable. In the context of climate change, we find that forest and savannah classes (02%); wetlands (-2%) and water areas (-3%) tend to decrease (Table 3). This decrease is mainly linked to the intensification of human activities and the irregularity of rainfall. With the advent of climate change in the basin, rainfall amounts would have decreased by 18% compared to normal, which is equivalent to a 40% decrease in runoff [10].
In terms of land use dynamics, forests and savannahs decreased by 5% during the period 2007-2014 compared to 2% for the period 2014-2019. Bare land and crops and fallow land increased by 7% and 2% respectively during the period 2007-2014 and 2% and 3% respectively during the period 2014-2019 (Table 3).

3.3 Implementation of the prospective land use simulation

The combination of the transition matrix adapted to the different scenarios Business As Usual, DEC and CER resulted in the prediction tables 2030 (Table 4) and the statistics on the area of the land use categories (Table 4).

Table 4: Evolution of land use statistics in the Senegal River basin (2030)

Land use categories	**occupation sol 2019**		**Scenario BAU**		**Scenario CER**		**Scenario DEC**	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
bare floors	78679	24,21	78679	24,2	79348	27,0	87679	24,4
wet soils	59 287	18,24	59 287	18,2	59 725	18,4	56 287	17,3
Forest and savannah	101 411	31,2	101 411	31,2	103 382	31,4	104 411	32,13
Crops and fallow land	60 130	18,5	60 130	18,8	60 054	18,5	61 131	18,81
Water	21492	6,61	21492	6,6	20491	6,3	19492	6,0
Total	325 000	100	325 000	100	325 000	100	325 000	100
Coef Kappa	0,87		0,87		0,89		0,79	

Table 4 shows that in the Business-As-Usual (BAU) scenario (reference scenario), the areas of forest and savannah are static compared to the 2019 reference year. The area of plantations, crop-fallow mosaics and settlements will increase by 0.3% respectively compared to the other two scenarios. The areas of dense forests, open forests and wooded savannahs, and wooded and shrubby savannahs will be significantly transformed into crop-fallow mosaics. Thus, the conversion of these lands into cultivated areas is expected to occur mainly in the less hilly parts around the “Baoule reserve”.
In the Rapid Economic Growth (REC) scenario, crop-fallow mosaics will change by a considerable (exagerated) 0.3 percent of the baseline area of occupation. The consequence is a more pronounced regression of natural vegetation formations than that observed in the BAU and DEC scenarios. In the coordinated environmental sustainability (CES) scenario, we assumed that land use is regulated by environmental protection policy over the period 2019-2030. Dense forests and shrub and tree savannahs declined by only -0.27% respectively compared to the 2019 baseline. Plantations, crop-fallow mosaics and settlements will increase by 0.31% respectively. The expansion of the area of open forest and wooded savannahs would mainly come from tree and shrub savannahs.
In this coordinated environmental sustainability (CES) scenario, the area of forest and savannah has increased significantly (1.61%) compared to the baseline scenario. This indicates that the environmental protection policy would play a positive role in the conservation of natural plant resources. Furthermore, this policy has encouraged both agriculture and an increase in forest area.

Figure 2 shows the monthly flow values in Bakel for the three scenarios, ranked in ascending order. Of the 71 years' x 12 values (i.e. 852 values), only the first 100 values corresponding to the minima in Bakel are shown.
The minimum flow of 300 m3/s is almost always met (only 10 to 15 months out of the 852 values of the chronicle, see the flow at Bakel lower than 300 m3/s); the frequency of failure on this constraint is thus lower than 2%; From the reference scenario to the maximalist scenario, we progressively see an increase of these minimum flows.

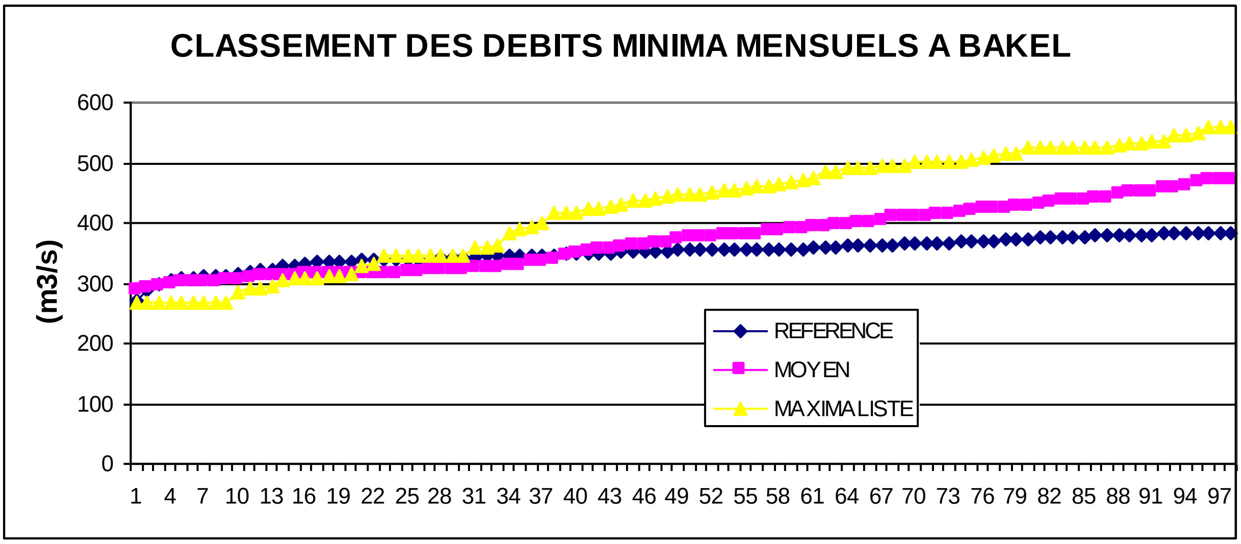


Figure 2: Ranking of monthly minimum flows by scenario (Source: OMVS, 2011)

- ✓ **Flood support**

The results of the simulations show that the commissioning of new dams in the basin results in a reduction of the average annual volume transiting through Bakel. This is due to the volumes lost by evaporation in the reservoirs, which amount to 1.1 to 2.1 billion m3/year on average.
Compared to the Reference scenario, the Medium scenario contributes to improved artificial flood support, which guarantees a floodplain area of 50,000 ha in almost 9 years out of 10.
In contrast, the Maximum scenario contributes to a lesser extent to the support of the artificial flood. The guarantee of a floodplain area of 50,000 ha is only 7 to 8 years out of 10.
Over the simulated period (1950-2021), the Rock flood is guaranteed approximately 1 year out of 2 for the Reference (BAU) and Medium (DEC) scenarios and approximately 4 years out of 10 for the Maximum scenario (CER).

4. Discussion

In summary, the trend of regression of the woody landscape in favor of cultivation and bare spaces observed since 2007 has also been observed in several reports of the "***Organisation pour la Mise en Valeur du fleuve Sénégal***", despite the fact that the specificity of the types of land use has not been the subject of an in-depth study. Moreover, this degradation mainly affects areas of dense vegetation. The use of these deforested areas makes it possible to benefit from new fertile land and thus to increase agricultural production. As a result, deforestation leads to a loss of biodiversity due to the destruction of many natural habitats.
The different prospective scenarios designed here take into account the different socio-economic activities developed in the Senegal River basin [14]. Overall, the evolutionary trend of plant formations in this study is regressive, while that of anthropogenic formations evolves gradually. In this BAU scenario, the areas of crop mosaics and fallows remain static compared to the reference year. The catastrophic scenario (CER) predicts that natural vegetation formations will regress in favor of anthropogenic ones. This is in line with the SDAGE report for the year 2025. The Coordinated Environmental Sustainability (CES) scenario, which combines preservation of vegetation cover with agricultural activities, makes the basin states and OMVS responsible for controlling deforestation and subsidizing domestic gas to replace firewood or developing alternatives for transforming typha into charcoal. By preserving biodiversity, the DEC scenario could ensure a sustainable flow in the Senegal River basin.

Conclusion

In conclusion, the authors note that the Senegal River catchment area has undergone significant spatial dynamics between 1986 (installation of dams) and 2019. The changes observed occurred in different ways during the different periods. Overall, this environment has seen its natural vegetation formations, notably dense forests, open forests and wooded savannahs, reduced in favor of anthropogenic formations such as mosaics of crops and fallow land, plantations and agglomerations. This spatial dynamic of the landscape is mainly explained by anthropogenic pressures.

The prospective approach used in this study has made it possible to understand and show the future of the territories by 2030. The LCM dynamic model used for the simulation makes it possible to observe changes in land use according to the scenario used. It should be noted that, whatever the scenario, the surface area of crop and fallow land mosaics, built-up areas and plantations is increasing. This landscape, on which the survival of the population depends, is evolving in the direction of degradation. If the current trend is not reversed, the situation will worsen by 2030 and could become irreversible. However, the results obtained with the Coordinated Environmental Sustainability (CES) scenario show that there is hope. Beyond the exploitation of timber resources and the expansion of agricultural land, to improve food security, it is essential to put in place strategies for the sustainable management of the natural resources of this environment. Decision-makers and actors in charge of territorial management must therefore take these results into account in their decision-making.

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