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Estimated flooded areas of the Inner Niger Delta from 1960 to 2020 using the Height-Area-Volume (HAV) method.

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ABSTRACT
The Inner Niger Delta (DIN) is a vast wetland where socio-economic activities (agriculture, livestock breeding, fishing, navigation) are dependent on its fairly complex hydrological regime whose hydrodynamic functioning depends on river inputs from the upstream basins: the upper Niger and Bani. The flooding surface of the DIN is closely linked to its hydrological regime. It was calculated by the HAV (Height-Area-Volume) model during the study period from 1960 to 2020. The HAV model is designed on the basis of two modules: physical and hydrological. The design of the physical module resulted in the development of the HAV matrix of DIN, calculation engine of hydrological module. The hydrological module is designed on MATLAB; it calculates the variation in the volume of stored water and converts it into flooded surface area. During the study period, the maximum flood area in the DIN was estimated at 37,252 km² in 1967 compared to 8,466 km² in 1993. She is observed from mid-October until the end of December, i.e. a duration of at least three and a half months (3.5 months). The flooded area generally reaches its maximum in November in the DIN.

Keywords: Hydrological balance, Height surface volume curve, Interior Niger Delta, and Variability of the hydrological balance

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I. Introduction

An original space in the heart of the Sahel, the Inner Niger Delta (DIN) is an ecosystem of great ecological and economic importance, but also of remarkable ethnic diversity. The DIN supplies 15% of Mali's cereal production, 80% of national fishing, 30% of rice production, and waters and feeds 60% of the herds during the dry season [1]. Maintaining the balance between these different components is closely linked to the availability of water otherwise to its hydrodynamic regime (filling and emptying) totally dependent on the upper Niger basin and the Bani basin.

The area area of the DIN varies with the extension of hydrographic connections depending on the season and the hydraulicity of the years. It was more recently estimated at around 30,000 to 40,000 km2 [2] which is a reduction of 50% if we compare to the estimates of BRUNET-MORET and BRICQUET J.P [3, 4] which are respectively 80,000 km² and 74,000 km². These two authors worked on flows before the great drought of the 1980s.

Occurring since the 1970s, the African continent has been subject to an unprecedented drought [5, 6, 7], which has caused a significant drop in area and groundwater levels, particularly in Mali [8, 9]. This drop in water levels has caused a reduction in flooded areas in the DIN, leading to an ecological imbalance affecting the exploitation of resources by the populations of the area who live at the rhythm of its filling and emptying [10, 11, 12].

To find a solution to this imbalance, several recent studies have shown the importance of the annual extent of flooding on the productivity of the environment [13, 14, 15] and consequently on the wealth of populations [16, 10].

As a prelude to the results of recent studies on the flooded areas of the Delta and in the face of flow deficits in the Delta after the 1970s and the growth in water needs (Agriculture, livestock breeding, fishing, navigation etc.); Sustainable management of the Delta's water resources is essential and appears more than necessary for sustainable development of the region.

The objective of this article is to estimate the flooding area of the DIN based on its geometry and the river inputs from the upstream basins on which its hydrodynamic regime depends. Achieving this objective consisted of developing the DIN Height – Area – Volume (HSV) model. This is a first experience of a hydraulic model on the DIN. The prospects will be to establish a tool for estimating flood areas in the DIN.

II. Materials And Methods

II.1. Presentation of the study area

The Inner Niger Delta (DIN) or the Niger lake basin is geographically located between the parallels 17° and 13°N, and the meridians 2°30' and 6°30'W in the Sahelian zone in the center of Mali and the Niger river system, Fig.1. The first plains and depressions of the DIN appear a little before the confluence between the Niger and the Bani (in a Ké-Macina – Douna – Mopti triangle), and end at Koryoumé where all the flows have joined [2].

Topographically, the Delta is at a lower altitude than the waters of the upstream basins. These numerous plains and depressions give it the impluvium function before being the collector draining the water towards the rest of the Niger river system.

Its hydrographic network is dense with distributaries, flood plains and lakes on the right and left banks of the Niger. The Delta has two major hydrographic entities: the upstream Delta and the downstream Delta [17, 18, 19, 3, 20, 21, 22].

The upstream Delta is made up of two major branches, the Diaka and the Issa Ber, and circumscribed between the stations of Ké-Macina on the Niger, from Douna on Bani to the central lakes.

The downstream Delta extends from the outlets of Lake Débo with three main draining axes (Issa Ber in the West, Bra Issa in the center, Koli-Koli the smallest in the East) to Diré. It is characterized by a very diffuse hydrographic network within an inter-dune sand system which limits the flooded areas [2].

II.2. Materials

This work was carried out with hydroclimatic data provided by the National Hydraulic Directorate (DNH) and National Meteorological Agency - Mali-Météo. The DIN Digital Terrain Model (DTM) and the new 1/200,000 scale topographic map of Mali were respectively obtained by downloading from the internet and from the Geographic Institute of Mali (IGM).

The hydrological data are the average daily flow rates from 1960 to 2020 from the hydrometric stations at the entrance to the DIN of Ké-Macina on the Niger and Douna on the Bani and at its exit at Diré.

Daily climate data from 1960 to 2020 (rainfall, minimum and maximum temperature, wind speed, air humidity and sunshine) come from the synoptic stations of Ségou, San, Mopti and Tombouctou. These stations are the most representative of the DIN and have the most regular chronological records.

The MNT has been uploaded to the NASA website http://gdex.cr.usgs.gov/gdex/ with a resolution of 30 m, i.e. a planimetric precision of 30 m and altimetric precision of 20 m per pixel.

Several software programs were used to obtain the results below, the main ones being: Google Earth Pro, Global Mapper v19, Arc-GIS v10.8, Khronostat v1.01 and MATLAB.

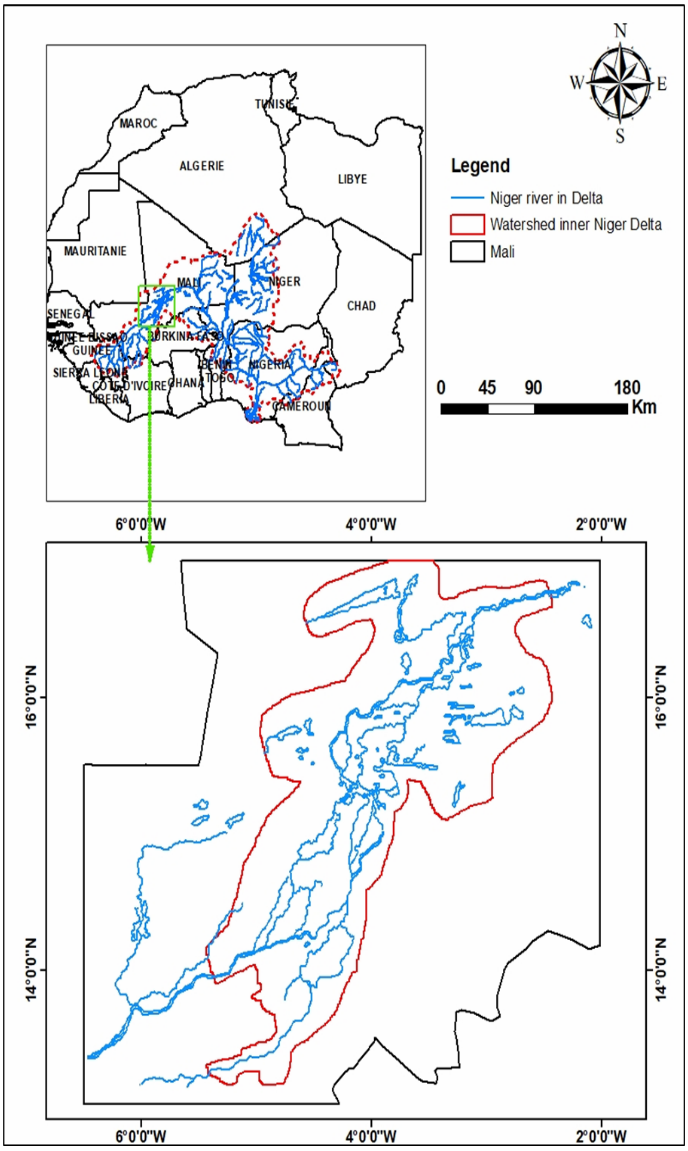


Figure 1: The geographical location of the interior Niger delta in Mali

II.3. Methodology

The data underwent preliminary processing. It consisted of arranging them in chronological order from 01/01/1960 to 12/31/2020 and calculating the missing data using linear correlation and extrapolation methods. The latter represented only 4% of the total data.

The flood area is calculated using the HSV model. The model makes it possible to calculate the daily volume of water stored (hydrological balance) in the DIN and convert it into flat water area (flooded area) and water height. The model is composed of two modules: a physical module and a hydrological module. The physical module is designed on the geometry and topography of the Deltaic basin aiming to establish an HSV matrix and the hydrological module is based on the processes of calculating the volume of stored water and its conversion into water height and water area flood.

In order to simplify the model, the deltaic zone is considered as a black box of which we are only interested in the input and output parameters to establish its hydrological balance. The hydrological balance corresponds to the volume of water stored or lost in the flow in Diré at the outlet of the DIN.

2.3.1- Physical module:

The physical module was designed from 13 transverse profiles equidistant by 50 km on the longest hydrographic network of the Delta (the main branch of the Niger from Ké-Macina to Diré). All of the profiles are produced on the DIN Digital Terrain Model (DTM), after superimposing the DIN hydrographic network on the DIN, Fig.2

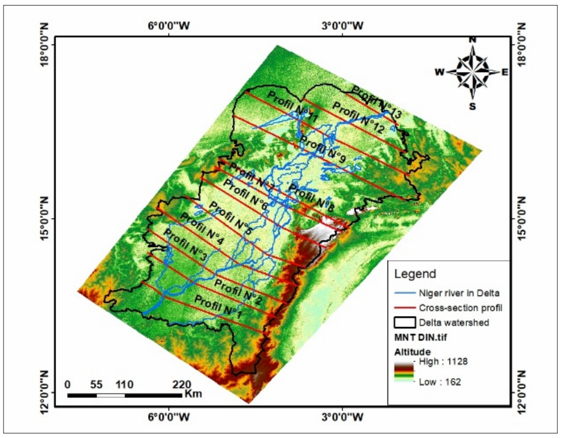
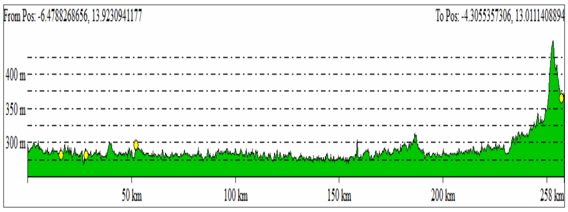
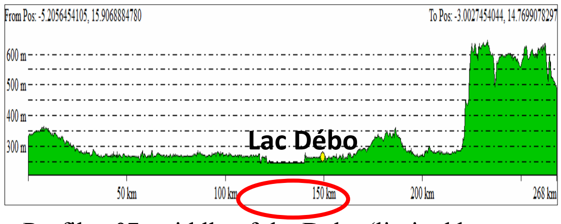


Figure 2: The digital terrain model of the interior Niger delta with transverse profiles and the hydrographic network.

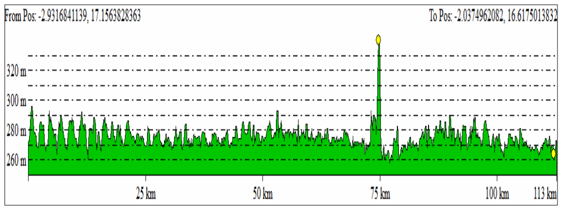
The Global Mapper v13.2 software allowed the creation of profiles from the DEM. Figure 3, Fig.3 below shows profile no. 1 which is located at the entrance to the DIN; profile n°7 is in the middle by the way by Lake Debo and profile n°13 located at the exit of the DIN.



Profile n°1: the entrance to the Delta



Profile n°7: middle of the Delta (limited between upstream and downstream)



Profile n°13: the exit from the extreme North Delta after Diré.

Figure 3: Cross-section profiles of the delta

(Global Mapper)

In order to minimize errors in the altitudes of the DEM. The DEM has been superimposed on the new 1/200,000 topographical map of Mali. A correlation is established between around fifty points on the new topographic map of Mali and the MNT with a correlation coefficient of around 98%; which made it possible to adjust all the altimeter points of the MNT, Fig.4.

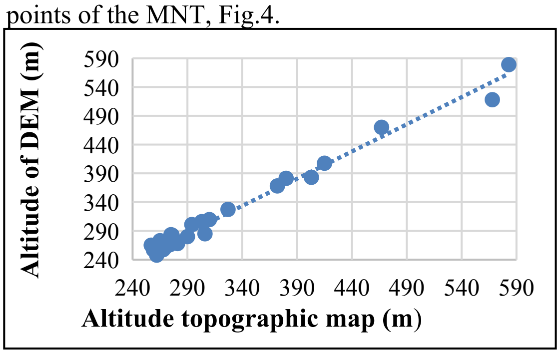


Figure 4: Correlation between the altitudes of the DEM and the topographic map of Mali

Then all 13 profiles were smoothed by calculating an average altitude over each 25 km throughout the profile, Fig.5. This made it possible to facilitate the calculations of the HSV matrix.

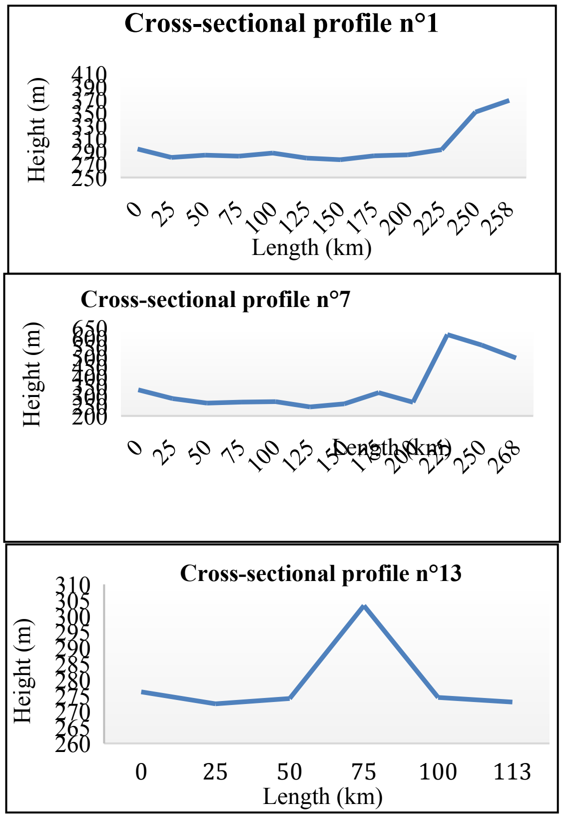


Figure 5: Cross-section profils simplify at the entrance (n°1), middle (n°7) and exit (n°13) of the delta.

2.3.2- Hydrological module

The hydrology module is designed to calculate the daily quantity of water stored in the DIN. The principle of calculation is based on the continuity equation (1).

(1)

The inputs are the daily flow rates of the Niger River at Ké-Macina (Q1) and the Bani tributary at Douna (Q2), expressed in m^3/s and 5% of local daily precipitation (P) of the Delta in mm. The outputs are the daily flow rates from the Dire hydrometric station (Q3) on the Niger and the daily evaporation (Ep) mm also, Fig.6.

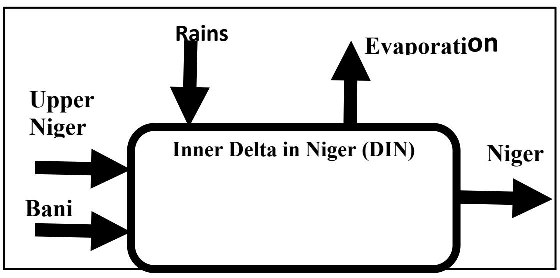


Figure 6: Simplified diagram of the delta operation

Evaporation from the body of water (mm/year) is expressed as a function of air saturation deficit and wind speed. According to Dalton's law in 1802: the evaporation rate of a body of water is expressed as a function of the saturation deficit (quantity of water (ps-pe) that the air can store, which corresponds to dryness of the air), and wind speed.
This law is formulated according to the following relationship (2)

(2)

With
E: the evaporation rate in (mm/day);
Pe: the effective or real pressure of water vapor in the air in kPa
Ps: the saturated vapor pressure or vapor pressure at the temperature of the evaporating area in kPa
K: is a constant f(u): the proportionality factor, depending on the wind speed u in m/s
So theoretically the stock is calculated by the formula (3)

(3)

The stock is expressed in cubic kilometers per day (km^3/j). Rainfall (P) and evaporation on the body of water (Ep) are converted into volume units (km^3). Q1, Q2 and Q3 are respectively the average daily flow rates of the Ké-Macina, Douna and Diré stations in (m^3/s) are also converted to (km^3) per day.
The calculation of the stock variation from day d to d+1 and the successive extrapolation of heights into areas then into volumes in the calculation of the stock variation are carried out by an algorithm designed on MATLAB: scripting language emulated by a development environment of the same name; it is used for purposes of numerical calculation. Developed by the company The MathWorks. It is developed in four phases.
1era Step: Reading Data
After arranging the data on Excel, reading the data involves checking the timeline of the model input data (Q1; Q2, Q3, P1 and Ep) from 1960 to 2020 day to day.
2th Step: Calculation of initial values (ST_i, H_i and St_i)
The initial stock is calculated using input data from the first day of the series (01/01/1960). Using the HSV matrix, the algorithm translates the initial stock calculated into height and water area by extrapolation (4).

(4)

(Vx, Vy); (Hx, Hy); (Sx, Sy) are elements of the HSV matrix.

3[th] Step: Initial Stock Correction (ST_i)
It consists of converting precipitation and evaporation into volume of water. Precipitation is added to the initial stock and evaporations are subtracted from the sum. The conversion from millimeter of precipitation and evaporation to the unit of volume of water is done by multiplying these parameters by the initial flat area of the water. Thus the corrected initial stock is the arithmetic sum of the inputs and outputs of the system (5)

(5)

(V'x, V'y); (H'x, H'y); (S'x, S'y) are elements of the HSV matrix. H1 and S1 are calculated by extrapolation.

4[th] Step: Assessment

The Balance Sheet consists of calculating the variation in stock at daily time intervals. In the algorithm; step 3; the corrected initial stock corresponds to the stock of day. The transition from day d to d+1 requires resuming steps 2 and 3 with the data from d+1. Finally, the variation in the Stock or the daily hydrological balance is calculated by the expression (6).

(6)

The boundary conditions of the model are: when the initial stock is less than zero (Vj 0) we take Vj equal to zero for the following reasons: infiltration and drying up of groundwater are not taken into account in this hydrological balance.

III. Results and discussions

III.1. Results

The HSV matrix is obtained from the physical module which is a mesh of the DIN including profile no. 7 (reference profile of the HSV model) which passes through the dimension 246 m the lowest point in the DIN. The inter-profile areas are calculated at every 5 m of height until covering all of the Delta profiles at height 296 m. Thus from level 246 m to level 296 m, Table.1; the flat areas of the water are calculated at every 5 m of altitude and the corresponding volume between the flat areas are obtained by multiplication of the areas at the average inter-profile depths.

Table 1: The HAV matrix of the Inner Niger Delta based on the corrected DEM.

Water height (m)	Flat water areas (km²)	Water volume (km³)
246	0	0
251	1125	6
256	3125	21
261	4250	43
266	12146	82
271	26488	214
276	49051	459
281	80802	863
286	95370	1340
291	112667	1904
296	117511	2491

During the study period from 1960 to 2020, the maximum flood area in the DIN varied from 37,252 km² in 1967 to 8,466 km² in 1993. Table 2 below shows that the flood areas in the DIN are very variables which proves a standard deviation around the mean.

The flooded area in the DIN is dependent on the volume of water stored otherwise from the hydrological balance; the minimum flooded areas appear between the end of June and the end of July as do the minimum daily volumes of water stored in the DIN. Consequently, the month of July is considered the low water month in the DIN where all the spreading water joins the minor bed of the main branch of the Niger River, from the entry to Ké-Macina until the exit of the DIN to say. As for the maximum areas; they are observed from mid-October until the end of December; this is the period of maximum spreading of water from the deltaic basin. It lasts at least three and a half months (3.5 months). The month of November is the most frequent when the flood reaches its annual maximum. During the study period, flooding in the DIN reached its maximum 13 times out of 61 in October, 29 times out of 61 in November and 19 times out of 61 in December, i.e. 21% in October, 48% in November and 31% in December.

During the study period, the variability of flood areas in the DIN, Fig.7; shows that during the 1960s, flooded areas exceeded 37,000 km² with an average greater than 34,000 km². However, an acute decrease in the curve is observed from the 1970s until 1993 corresponding to the decades 70, 80 and 90 which are characterized by severe drops in flooded area ranging from 4.8%, 47.8% and 53% respectively. 1% compared to the 1960s. On the other hand, slight improvements are noted in the 2010s and 2020s compared to previous decades but they are still in deficit of 52.7% and 52.5% respectively compared to the 1960s. Overall after the 1960s the DIN experienced an average drop in its flooded area of 42.2%.

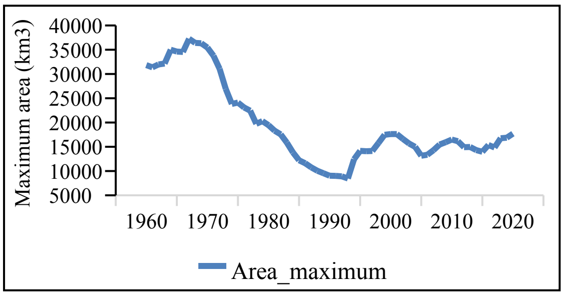


Figure 7: Variability of flood areas in the interior Niger delta from 1960 to 2020

III.2. Discussion

Among the work carried out on the DIN, the most recent ones are largely devoted to the modeling of flood areas for reasons of understanding the hydrological functioning of the DIN but also for economic reasons therefore the main activities (agriculture, fishing and breeding) of the area are linked to the extent of the flooding. How it works hydrological of the DIN is influenced by three (03) factors: the increase in the population, the developments in hydro agriculture and climate change which we do not mastery not yet know the consequences on hydrology you participate.

The estimate of flooded areas in the DIN has already been the subject of numerous studies, including the use of satellite images of the NOAA/AVHRR/MODIS type, the agro-ecological model, topographical and thematic maps, aerial photography and hydrological balance. All these studies have shown that the flooded areas vary depending on the hydraulicity of the year and can reach up to 40,000 km², the maximum found in the literature [19]. Studies that have not taken into account years of good hydraulicity, that is to say years before 1970, such as the work of Mariko et al. 2013 and Ogilvie et al. 2015, give much smaller maximum flooded areas than those which focused on the wet period; years before 1970, Table 3.

The HSV model covers a good part of the wet period and the entire drought period of the century and extends until 2020. The comparison of the flooded areas between the different models cited above and those of the HSV model made it possible to conclude that: The models having taken into account the wet period (from 1950 to 1960) estimated the maximum flooding area of the DIN strictly greater than 35,000 km², the majority of which was around 40,000 km². On the other hand, models of the dry and wet period from the end of the 1990s to the 2000s showed that the maximum flooding area in the DIN is strictly less than 30,000 km². The models which are interested in the three (03) periods (humid, dry and dry-humid) such as the HSV model have varying areas of maximums strictly greater than 30,000 km² and minimums which can reach up to 6,000 km², unlike the agro-ecological model whose maximum flooding area during wet periods is underestimated compared to that of other models.

During the period 1990 to 2000, Fig. 8. The maximum flooding areas calculated by the HSV method are very close to those estimated by NOAA images with the exception of the years 1994 and 1999. The hydrological and agro-ecological models have flooding areas very close to each other. of others. They represent more than double the areas estimated by the HSV model. However, it is observed despite the difference between the calculation hypotheses; the four (04) models follow the same trend of variability of flood areas.

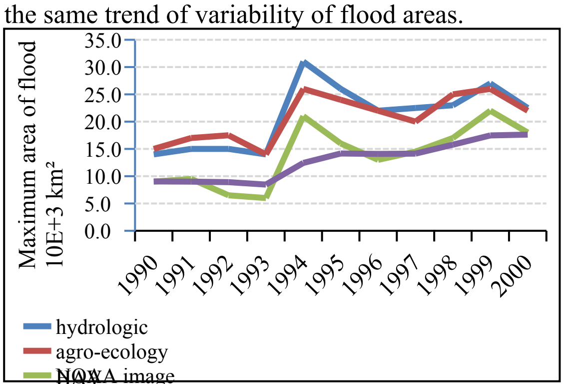


Figure 8: Comparison of maximum flooded areas, according to flood models and NOAA images, during the period 1990-2000 in the interior Niger delta (Mariko, 2003).

The HSV model was the first physical model experiment of the DIN; correlations are established between it and the other models during the period 1990 to 2000. These correlations aim to assess the results of the HSV model.

The Correlation results are very satisfactory with correlation coefficients R^2 at 91% and 81% respectively for the NOAA image model and the agroecological model Fig 9. On the other hand, with the Hydrological model the correlation is not good ($R^2 = 0.54\%$). When the flooded area in 1994 of the hydrological model is not taken into account the correlation coefficient becomes 84%. Indeed the value of the flooded area of 1994 of the hydrological model is an extreme value. The hydrological model, although it gives good approximations of floodable areas for medium and low hydraulic conditions, is proven invalid for high hydraulic conditions (very high water). The maximum areas obtained in this condition are too overestimated compared to the other models cited. Furthermore, the assumptions of base oversimplify the operation of the DIN.

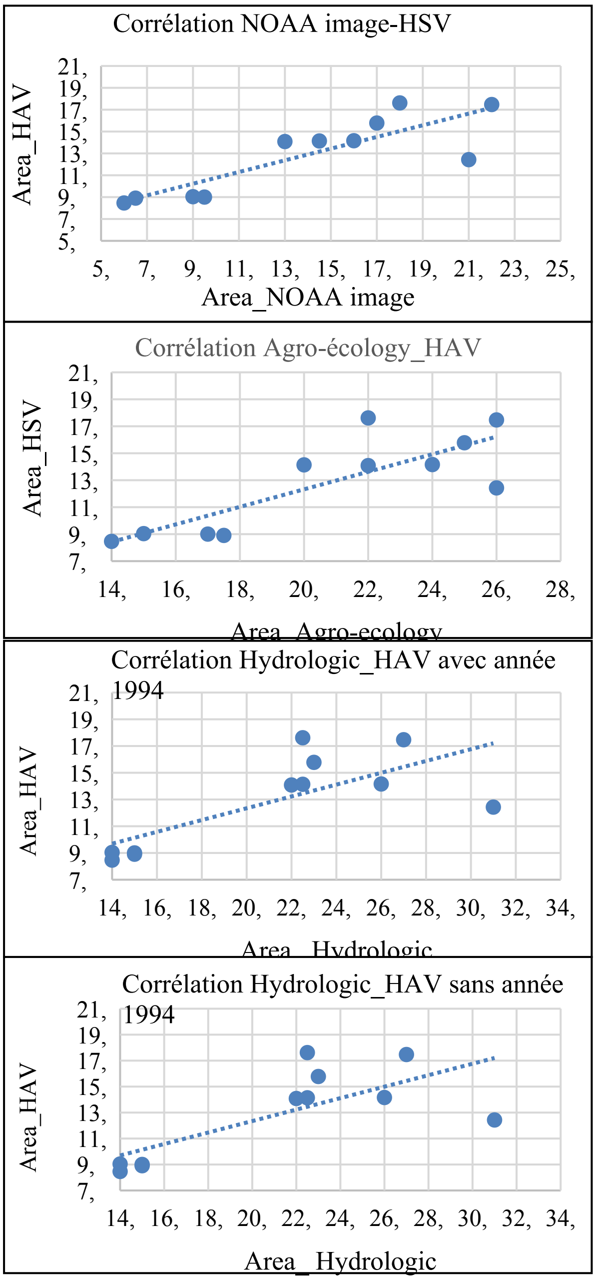


Figure 9: Validation by correlation of the HAV model with other flooding models of the interior Niger delta

IV. Conclusion

Estimation of the flooding area of the DIN was carried out on the basis of two modules which constitute the HSV model: a physical module configured on the topography and the main hydrographic network of the DIN and a hydrology module designed for the calculation of the variation in the volume of daily water stored (daily hydrological balance) in the DIN. The physical module made it possible to establish the HSV matrix. This matrix isthe backbone of the calculations of the variation of daily stocks of the hydrological module.

The data used are the average daily flow rates at the entrances (hydrometric stations of Ké-Macina and Douna) and the exit of the Delta at Diré and the climatic data (precipitation and evaporation on the body of water) at the most representative synoptic stations in the Delta (stations of San, Ségou, Mopti and Tombouctou). The evaporation of the body of water is calculated by the empirical formula of Dalton in 1802.

The results obtained show that the flood areas in the Delta are dependent on the variation in the hydrological balance. So from 1960 to 2020; the daily flood areas in the DIN varied from 37,252 km² from November 20, 1967 to 84,366 km² from January 1 1993 which corresponds to pic water stress of the century throughout the Niger River basin.

The analysis description of maximum daily flood areas from 1960 to 2020 watch that they are very dispersed around the mean with a standard deviation of 8461.

In revenge the results were compared with the results of other models such as the hydrological model, Agro-ecological and NOAA images. Despite the simplifying assumptions of the HSV model; it presents a very good correlation with these models for estimating flood areas in the DIN.

In conclusion, the HSV model with these two physical and hydrological modules and despite its basic simplifying assumptions allows a good estimate of the flooded areas of the DIN.

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