Modelling Seasonally Flooded Wetlands in the Semi-arid Sahelian Zone

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Abstract

A coupled one-dimensional (1D)/two-dimensional (2D) hydrodynamic modelling of the Inner Niger Delta wetlands (Mali) was carried out using LISFLOOD-FP. The inundation model was built using both field measurements and the Shuttle Radar Topography Mission (STRM) digital elevation model. The model was then calibrated against the 2001 flood data and validated against the 2005 flood data. Based on field measurements, the study has also reviewed the different components of water budget of Inner Niger Delta, and evaluated the behaviour in the seasonal cycle of flooding. The importance of evapotranspiration for losses in the wetland system was also investigated. More specifically, the model results show that the flooding of the seasonal floodplains of the Inner Niger Delta depends significantly on the river inflow, wetland topography, direct rainfall and evapotranspiration. The flood inundation model, although simple, was found to simulate satisfactorily different components influencing the inundation extent of the seasonally flooded wetlands, such as river hydraulics, wetland, inundation, evapotranspiration, direct rainfall, infiltration

***Key words**:* LISFLOOD-FP; Wetlands; Seasonal Floodplains; Inner Niger Delta; 1D/2D hydrodynamic model; Water budget; Evapotranspiration.

1. INTRODUCTION

The Inner Niger Delta is located in the semi-arid sahelian zone in central Mali. This zone is one of the largest wetland areas in the world, is defined by seasonal flooding and is responsible for the loss of large quantities of inflowing waters from the Niger River and its main tributary the Bani River.

According to the previous studies evaluating flow data in the Inner Niger Delta, approximately half of the inflowing waters are lost between the entrance and exit of the Inner Niger Delta (J.C.Olivry, 1993). Historical information about the Inner Niger Delta is available from studies carried out during the last century. Olivry (1993) investigated the hydrology of the inner delta of the Niger River. Bamba et al. (1996) investigated climate change and the variability of the water resources of the inner delta and upper Niger. Bricquet et al. (1997) described erosion and particulate transport by the Niger River, from the upper basin to the inner delta. Beukering et al. (2005) investigated the impact of water management on poverty and the environment in the Upper Niger River Basin. Gil Mahe et al. (1998) compared the interannual fluctuations of precipitation and discharge in the Bani catchment at Douna. Many studies were done also for elaborating different methods for estimating of inundated area in the inner Niger Delta. Poncet et al (1994) used topographical maps and aerial photographs. They compared the inundated area in 1955-1965 (36100 km^2) with the situation in 1970-1990. But Poncet et al. did not explicitly indicate the inundated area in extremely dry years on their map, they suggest it must have been as low as 8000-10000 km^2.

The hydrological model based upon evaporation for estimating the actual inundation area in the Inner Niger Delta was elaborated by Quensiere et al. 1994a, Olivry 1995). In this model the relationship between river discharge and water level was been determined for several hydrological stations along the Niger and can therefore be described accurately with third degree polynomials. Cisse & Gosseye (1990) elaborated the Agro-ecological model in which they followed yet another approach to determine the inundation area in the Inner Niger Delta. They based their analysis on the map of the PIRT (1983) where six different habitat types are distinguished. Orange et al. (2002a) evaluated the model of Cisse & Gossey and concluded that the model behaves relatively well. Remote sensing approach was used by Zwarts et al. (2003) to measure the inundated area directly. They established the relation between River flow and flooded area.

The flood plains are an important feature of the area in terms of their ecological and economic value (Petersen et al.(2010) . Detailed knowledge of their function, especially their flooding and drying mechanisms, which are the driving factors for vegetation growth and fish catch, is important for a full understanding of the system and future planning tasks for a good management, for example the impact of irrigation and reservoirs on the flooded surface have to be indicated. This study aims at determining a flood extent area and computing the evapotranspiration of Inner Niger delta wetlands using hydrodynamic model.

2. MATERIALS AND METHODS

2.1. Study Area and Data

The Inner Niger Delta constitutes one of the largest wetlands in the world and is situated in the sahelian zone in Mali. It is located between 13° 30’ and 17° 00’ latitude North and 2° 30’ and 5° 30’ longitude west.

The data used in this research was collected from various sources. Most of the meteorological data were acquired from the Direction Nationale de la Météorologie du Mali, river flow and water level were acquired from the Direction Nationale de l'Hydraulique du Mali. The satellite data was derived from the Shuttle Radar Topographic Mission STRM, which is the joint Project between NASA and NGA to map the earth's land surface in three dimensions at a high resolution. Google Earth was used for collecting the measures of the selected cross-section.

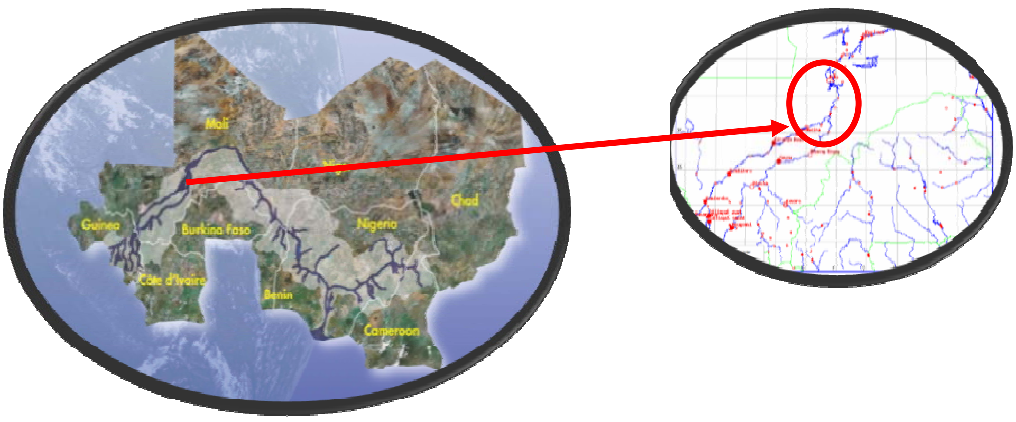
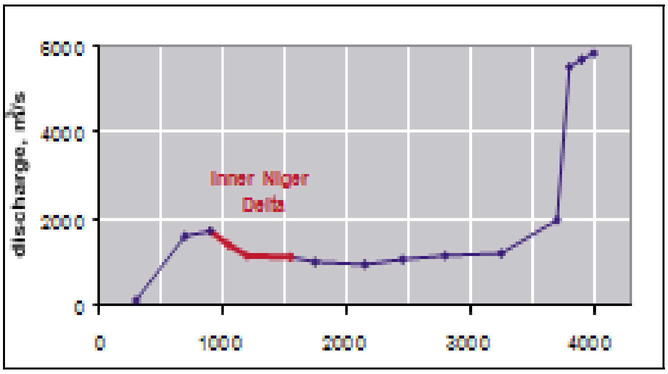


Figure 1: Niger river basin (source IRD, Niger-Hycos project)



distance(Km)

Figure 2: Average annual river discharge of the Niger as a function of the distance from its origin.

The Inner Niger Delta (indicated with a red line) is situated between Segou (900 km) and Toumbouctou (1500 km).(Leo Zwarts et al.2005).

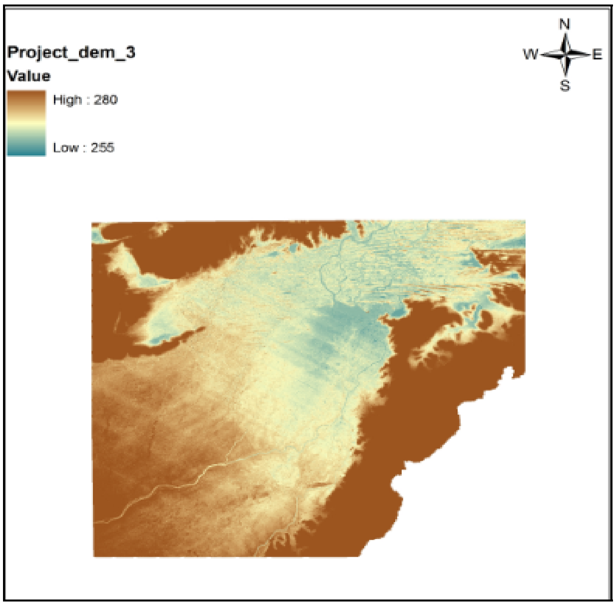


Figure 3: Digital elevation model of Inner Niger Delta

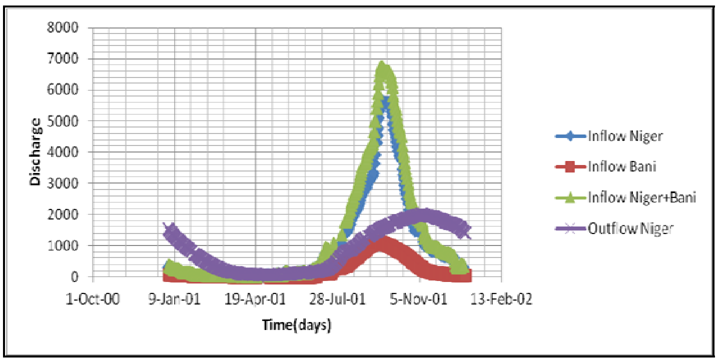


Figure 4: Observed flow in Inner Niger Delta for 2001 event

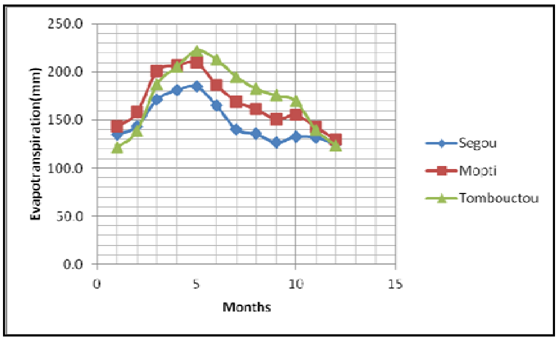


Figure 5:Average observed Evapotranspiration in Inner Delta 1983-1998

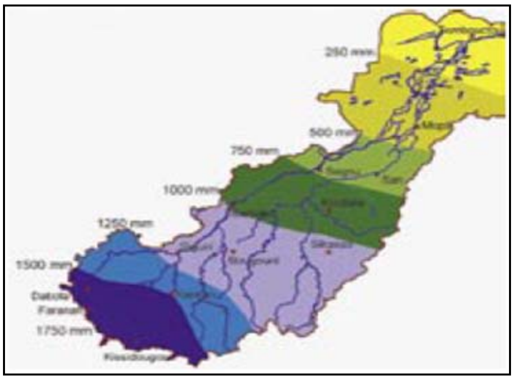


Figure 6: Annual precipitation (mm/year) in the basin of the Upper Niger, the basin who include the Inner Niger Delta (Quensiere et al.1994a).

2.2. Data Pre-Processing

Hydrodynamic modelling is often faced with challenges brought about by limitations in the quality of available data. The quality of data has a direct impact on the output of the model. It is therefore important to check the quality and consistency of the input data. For this research, data pre-processing was done before the start of the model setup. It included: checking the consistency of the meteorological and flow data, checking for missing data, and controlling the DEM

2.2.1. Filling in missing values

The goal of any infilling technique is the production of a complete data set which may then be analysed using complete data inferential methods (Little and Rubin,1987). This is turn, generally leads to better estimates of the mean and variation of the data set. In filling the missing values, the mean value Infilling was used.

2.3. Flood Inundation Modelling

In this study, the LISFLOOD-FP code (Bates and De Roo, 2000) was used. The code developed by the School of Geographical Sciences, University of Bristol (UK), provides a general tool for simulating fluvial flood spreading, with output consisting of raster maps of water depth and flow velocity in each grid square at each time step and, in the case of fluvial flooding, the predicted stage and discharge hydrographs at the outlet of the reach. For fluvial situations, the 3.4.0 version of LISFLOOD-FP solves the kinematic or diffusive approximations to the one-dimensional St. Venant equations to simulate the passage of a flood wave along a channel reach. Once bankfull depth is exceeded, water moves from the channel to adjacent floodplain sections where two dimensional (2D) inundation is simulated using a Manning-type equation and a storage cell concept applied over a raster grid. The model therefore assumes that flood spreading over low-lying topography is a function of friction. The model is designed to take advantage of recent developments in remote sensing of topography such as airborne laser altimetry or airborne Synthetic Aperture Radar interferometry, which are now beginning to yield dense and accurate digital elevation models over wide areas.

LISFLOOD-FP has been extensively tested for several transnational catchments – amongst them the Meuse and the Oder. For these catchments high resolution data were available, particularly in terms of river dimensions. Flood risk on a European scale is another main application of the LISFLOOD-FP model, currently used as part of the European Flood Alert System (EFAS).

It is important to mention that LISFLOOD-FP gave good results in modeling the Amazonian wetlands. In particular, Wilson et al. (2007) showed that the channel–wetland exchange correctly predicted by LISFLOOD-FP was higher than that predicted by using Muskingum routing (Richey et al., 1989).

2.3.1. Model calibration (2001 Event)

We could use the inundation map derived from satellite imagery,to calibrate the model (Di Baldassare et al. (2009). In this method, the model that predicted a flood outline which closely resembled the image should be selected as the best. Due to the unavailability of relevant imagery, it was not possible to adopt such a method in this research. As discussed above, a number of studies have already been done for evaluating the flood extent area in the Inner Niger Delta. Zwarts et al. (2005) established the relation between river flow and flooded area by the function

$A = 24.497\ Flow^{0.765}$,

where: *A* is the inundated surface on the area, and
Flow is the average river discharge (m^3/s) for the entrance Inner Delta (Niger+Bani) in August-October

This formula was used to calibrate the model in this research. According to the formula, the maximum inundated area for 2001 flood event is 14,119 km^2 for a flow of 4058 m^3/s

Therefore the model calibration was carried out by running LISFLOOD-FP using a uniform floodplain Manning's coefficient in the range 0.04-0.08 $m^{-1/3}$s, and a channel Manning's coefficient in the range 0.02-0.03 $m^{-1/3}$s.

The optimum area was found by simulating the entire season (6 months) and using a uniform floodplain Manning's coefficient of 0.08 $m^{-1/3}$s, and a channel Manning's coefficient of 0.02 $m^{-1/3}$s.

Reclassification of extent area

The reclassification is the process of taking input cell values and replacing them with new output cell values. To consider infiltration in the model, we assumed a soil water recharge value of 350 mm (Petersen and Fohrer, 2010), which is simulated by neglecting the first 0.35 m of flooding. This value was varied when carrying out sensitivity runs. Using the ArcGIS spatial analyst extension, the model area had a new surface with a total of 1643100 cells. By multiplying this number with the unit surface of the cell, the definitive area became 13309 km^2, still very close to the "observed" value of 14119 km^2 (5.7% absolute error).

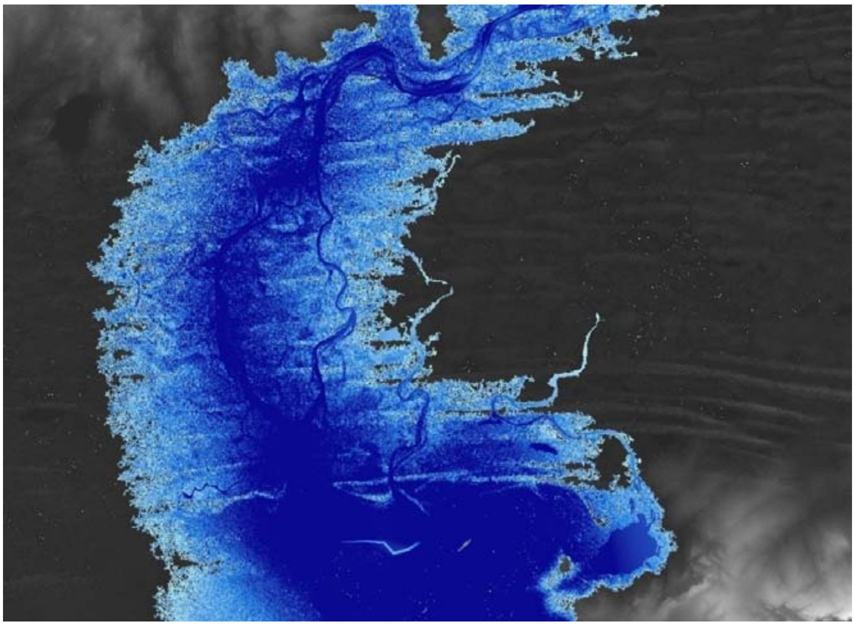


Figure 7: The downstream of the inundation map at Akka including Lake Debo

2.3.2. Model validation (2005 Event)

After calibration, a model needs to be systematically tested against independent observations to assess its accuracy under different circumstances. In this way the model is validated, that is, the performance of the model in situations as close as possible to those used in practice is assessed (Klemes, 1986). Model validation denotes the establishment of legitimacy (Oreskes et al., 1994) or its operational adequacy (Klemes, 1986). This model was validated by running the calibrated model using the 2005 data event without changing the model parameters.

Evaluation was performed in a way similar to the model calibration, that is, using the formula for the flooded area above. This generates an area flooded of 11368 km^2, for a flow of 3057 m^3/s. After reclassification the flooded area becomes 12465 Km^2 , for which the absolute error is 9.6% .

3. RESULTS AND DISCUSSION

3.1. Water Budget

The general water budget is the sum total of inflows and outflows of water from the entrance and the exit of a wetlands region. The components of a water budget are shown in the equation 1. Each component has a relative importance in maintaining wetlands and varies both spatially and temporally, but they all interact to create the hydrology of an individual wetland (Carter et al. 1997**).**

The simplified water budget for this case study is based on the following equation:

$$V_1 + V_2 + P = V_3 + Losses \quad (1)$$

where V_1: inflow Niger River
V_2: inflow Bani River
P: Precipitation
V_3: outflow Dire

Losses: Evapotranspiration + Infiltration-Groundwater inflow+ Groundwater outflow-Others stream

$V_1=\sum_{i=1}^{365}(Q_{1,i}*24*3600)$ (2)

$V_2=\sum_{i=1}^{365}(Q_{2,i}*24*3600)$ (3)

$V_3=\sum_{i=1}^{365}(Q_{3,i}*24*3600)$ (4)

where $P=((P_1+P_2)/2)*A$ (5)

P_1: Segou station

P_2: Mopti station

A: Maximum area from LISFLOOD-FP

The summarized results of equations show:

$V_1+V_2 = 40.711 km^3$

$V_3 = 27.506\ km^3$

$A=13309\ Km^2$

$P=7.93\ Km^3$

Losses=21.135 km^3

3.1.1. Discussion

-The general water budget results of inner Niger delta shows that approximately 43.5% of entrance water are lost.

-The flooding of the seasonal floodplains of the Inner Niger Delta depends significantly on the river inflow, wetland topography, direct rainfall and evapotranspiration

3.1.2. Water budget modelling

A data driven model was built using sfitt toolbox of Matlab in order to establish the relationship between precipitation, discharge and loss.

The method: consisted of the following steps (decribe them in words)

Rainfall file;

Find the average rainfall of the two stations then find the rainfall in m3/d by multiplying the daily rainfall by the area

Discharge file

Compute the total discharge Q1 + Q2, determine the outflow Q3

In the same file compute the loss in m3/d and then convert it to mm/d

Then using Matlab code, the following model if derived:

F(x, y) = a + b*x + C*x^2 + d*y + e*y^2

The coefficients with 95% confidence bounds:

C = 1.383e-005 (1.304e-005, 1.461e-005)
a = -11.97 (-18.34, -5.609)
b = 0.03771 (0.03299, 0.04243)
d = 5.367 (4.521, 6.214)
e = -0.1061 (-0.1383, -0.07392)

The goodness of fit is given by the following parameters:

SSE: 1.135e+010
R-square: 0.9082

Adjusted R-square: 0.9081
RMSE: 1.808

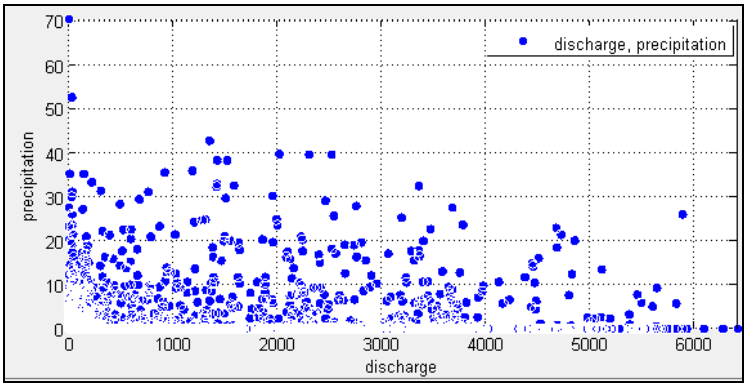


Figure 8: Relation discharge, precipitation

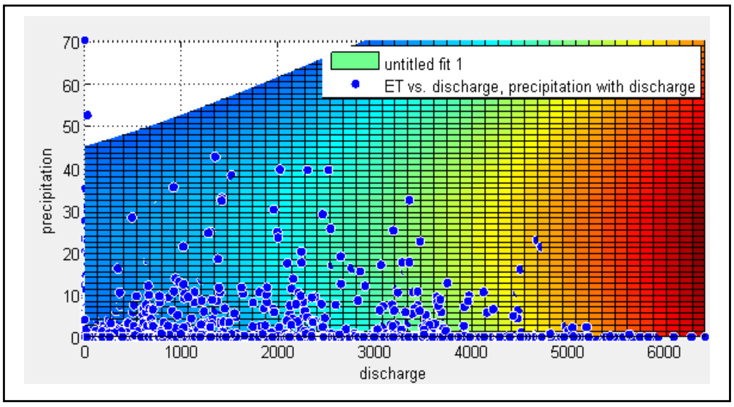


Figure 9: Relation, loss, discharge, precipitation

3.2. Evapotranspiration Calculations

In this research the local evapotranspiration for Inner Niger Delta was calculated based on meteorological records of monitoring stations located within the delta and the seasonally flooded area from LISFLOOD-FP model. The Penman-Monteith method (Allen et al., 1998) was used in a spread sheet calculation to determine the evapotranspiration under given conditions. Values used in the calculation were selected from 1998 to 2008. The average values used for calculation for this period are shown in table below.

Table 1: Parameters and values used for average evapotranspiration calculations using the Penman-Monteith method.

Months	Wind speed	Temperature	Net radiation	Relative humdity
	[m/s]	[°C]	[W/m2]	[%]
1	1.9	23.2	57.4	33.0
2	2.7	23.3	62.1	25.5
3	3.6	23.9	58.2	27.5

Table 2: Evapotranspiration output using using the Penman-Monteith method.

Months	days/ month	Rn	es	Δ	ea	δe	ra	ET_0	ET_0
	[Days]	[W/m2]	[Pa]	[Pa/°C]	[Pa]	[Pa]	[s/m]	[mm/s]	[mm/month]
1	31	44.16	2835.96	171.33	935.87	1900.09	82.4	5.13E-05	137.3
2	31	47.84	2861.76	172.69	729.75	2132.01	58.0	7.05E-05	188.7
3	31	44.79	2958.13	177.75	813.48	2144.64	43.5	8.24E-05	220.6

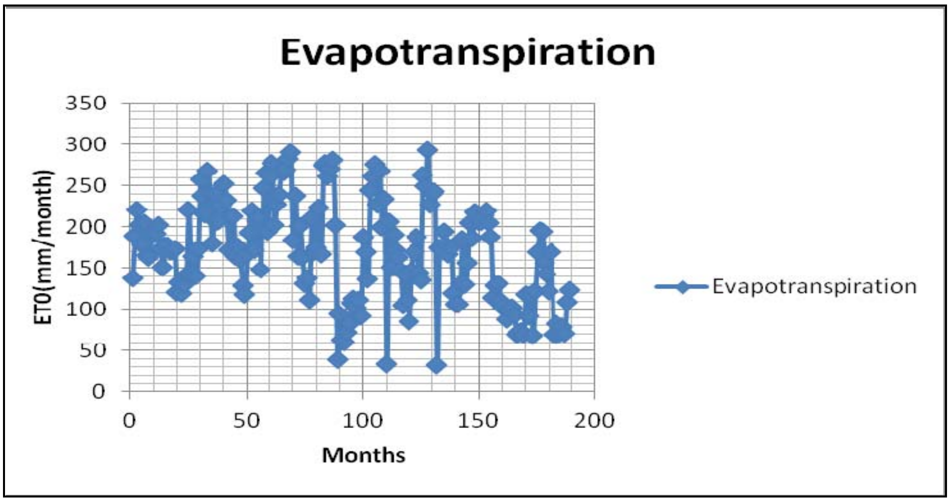


Figure 10: Computed mean monthly ET in Inner Niger Delta, using data from 1998 to 2008

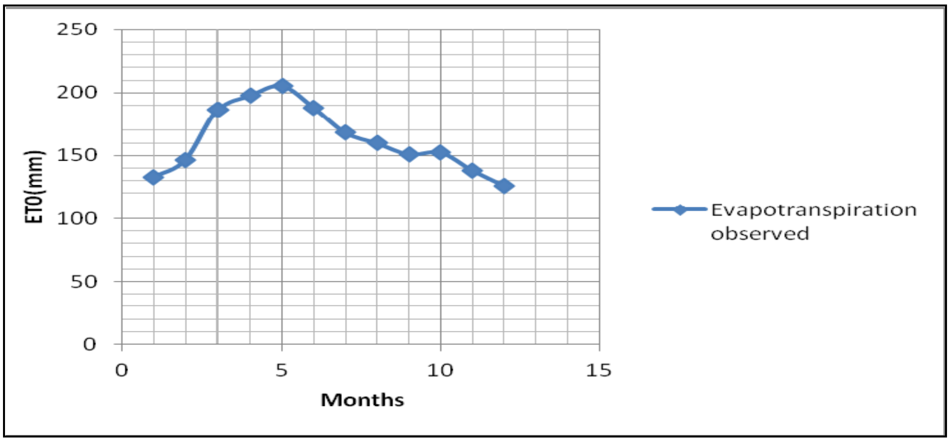


Figure 11: Observed mean monthly ET in Inner Niger Delta (1983-1998)

Average evapotranspiration for the 1998-2008 periods was calculated at 170.4 mm/month using the Penman-Monteith equation, an approach successfully used by Jacobs et al. (2002) and Portoghese et al. (2007) to assess the evapotranspiration of natural vegetation. The result provides a good match to the observed value 162.92 mm/month.

4. CONCLUSIONS

A 1D/2D LISFLOOD-FP model was set up to simulate the Inner Niger Delta wetlands area in central Mali. Based on comparisons with measurements and previous studies, the model was found capable of simulating the inundation extent of the seasonal flooded Inner Niger Delta between the entrance of the Delta, Kirango station on Niger river and BenenyKegny on Bani river and the Delta exit at Dire station.

The main findings of the study include:

- The SRTM DEM can be used to support large scale inundation modelling, when there is no need for detailed floodplain mapping. This confirms the recent findings of Petersen and Fohrer (2010).
- LISFLOOD-FP is able to simulate the diverse processes involved in the seasonally flooded wetland (river hydraulics, wetland, inundation, evapotranspiration, direct rainfall, infiltration).
- The performance of the LISFLOOD-FP model can be said to be good (absolute error of 5.7% in calibration and 9.6% in validation). The model estimated the extent of inundation with good agreement with observations.
- Flooding of the seasonally inundated area was found to be directly related to the flows entering the delta at Kirango on Niger river and BenenyKegny on Bani river. It can be assumed that the relationship is highly dependent on the long-term flow regime.
- The results of the hydraulic model were used to make a simplified evaluation of the water budget as well as compute the evapotranspiration of the region.
- A data driven model was built using the sfitt toolbox of Matlab, for establishing the relation between precipitation, discharge and total loss in the water budget equation.
- Average evapotranspiration for the 1998-2008 periods was calculated using the Penman-Monteith equation.

The model was calibrated explicitly for the Inner Niger Delta and delivers good results for the area, though further refinements and calibration would be necessary for areas further upstream or downstream. The results of this study can be used for future assessments, including sediment transport towards the flood plains and further assessment of infrastructural plans, including dike construction projects and potential water withdrawal schemes, which, depending on the amount of water diverted, may have a significant impact.

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