Hydro-climatology: Variability and Change (Proceedings of symposium J-H02 held during IUGG2011 in Melbourne, Australia, July 2011) (IAHS Publ. 344, 2011).

Estimation of the flooded area of the Inner Delta of the River Niger in Mali by hydrological balance and satellite data

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Abstract The Inner Niger Delta in Mali is the largest flood plain of West Africa. It is an ecosystem where water regime, environmental dynamics and human activities (fishing, agriculture, livestock) are closely associated. It is home to a tenth of the population of Mali on an area of 35 000 km^2. Rational management of this wetland subjected to a dry climate is essential for sustainable development in the region. Since the drought began around 1970, the Delta has been facing a problem of sustainability of renewable natural resources. Management strategies of these resources depend on the extent of flooded areas, the annual variability of which is still largely natural. The prediction of the flood extent, varying with runoff of the rivers Niger and Bani, is an important venture. Thus the objective of this study is the estimation of flooded areas of the Delta from conventional water balance methods and from analysis of satellite images. We examine the variability of the hydrological regime and processes of storage and release in the Delta. We then present the method of evaluation of flooded areas, from low-resolution multispectral data (1 km) NOAA/AVHRR for the period 1990–2000, using a distinction between the open water surfaces, vegetation cover and flooded vegetation. We then determine the flooded areas by this method and compare them with previous estimates. Finally, to produce a model for spatial-temporal forecasting of flooded areas, we study the correlations between the heights of water levels at gauging stations in the Delta and the flooded areas.

Key words River Niger; West Africa; Inner Delta; flooded area; AVHRR

INTRODUCTION

The Inner Delta of the River Niger (NID) in Mali is the largest flooded area in West Africa, which covers an area of approximately 50 000 km^2 in Mali. It stretches SW–NE over 350 km between Ké-Macina and Douna to the south, and Timbuktu to the north (Fig. 1). Comprising a network of tributaries and distributaries, lakes and flood plains (Auvray, 1960; Galais, 1967; Brunet-Moret *et al.*, 1986) its hydrological functioning (Olivry, 1995) depends essentially on the hydrological regimes of the upper basins of the rivers Niger and Bani, whose sources are located in Guinea, Ivory-Coast and Mali, and on other morphological and climatic conditions specific to the NID, regulating flows and water balance. In this study we distinguish: the Southern Delta (SD), which extends from Ké-Macina and Douna to the central lakes Korientzé and Debo, and the Northern Delta (ND) downstream of these lakes, marked by a system of lakes on the right bank and left bank downstream the hydrometric stations of Akka, Awoye and Korientzé. We describe first the inter-annual and seasonal variability of the hydrological balance in the NID. Then we use NOAA/AVHRR images from 1990 to 2000 to map the flooded areas and link them with water heights at the main gauging station of Mopti, for simulations of flooded areas and predictions.

HYDROLOGICAL BALANCE

Monthly discharges are available for the gauging stations at the entry of the Delta (KeMacina & Douna), at the outlet of the central lakes (Aka on the main stream, Awoye on the secondary course and Korientze on the tertiary course – from west to east), and at the exit of the Delta at Timbuktu. The average input discharge for the common observation period 1955–1996 is approximately 1490 m^3 s^{-1}. The output discharge at Timbuktu is about 900 m^3 s^{-1}. The annual average total loss is about 40% of the average input discharge, 18.7 km^3, varying over the period between 24 and 48% (4 and 39 km^3) (Mahé *et al.*, 2009).

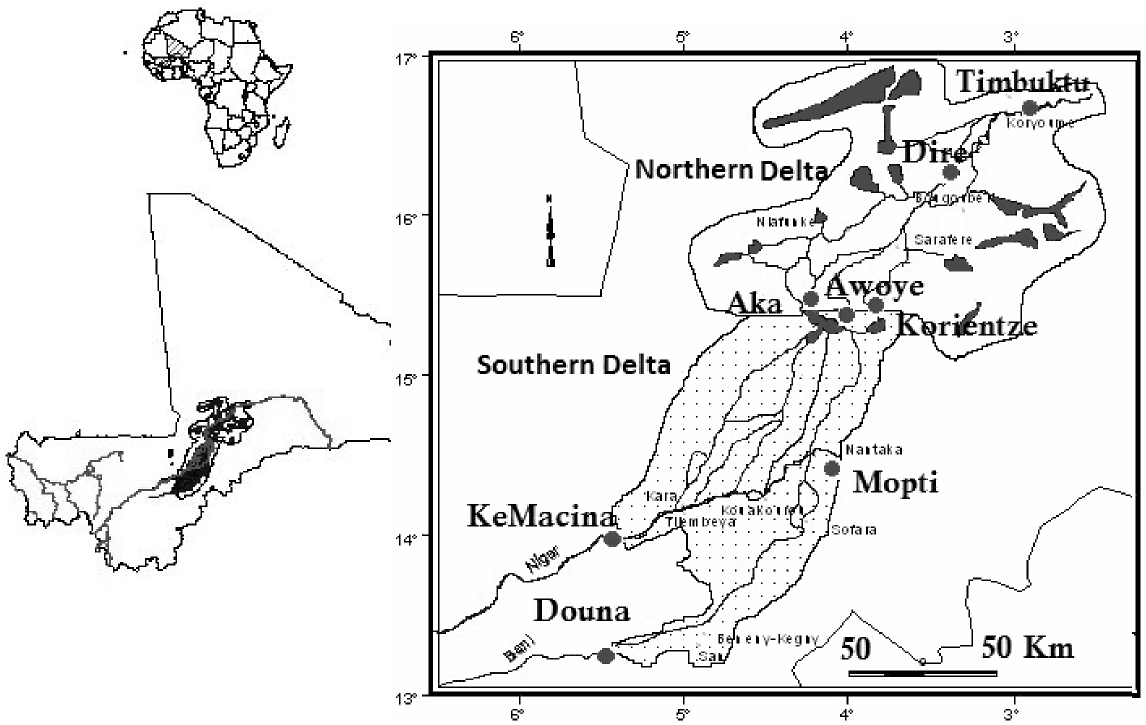
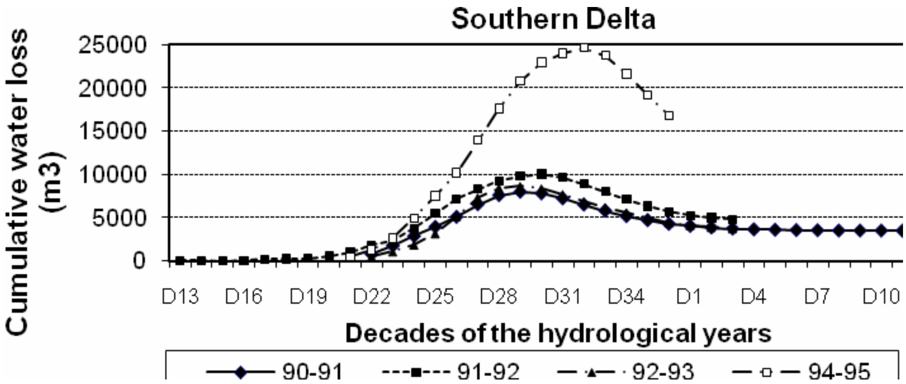


Fig. 1 The Inner Delta of the River Niger in Mali, and the maximum extension of the flooded areas (Mariko, 2004).

The rainfall in the region varies between 356 m and 682 mm, and averages 545 mm (Mahé *et al.*, 2009). The annual losses are in general greater in the ND (10.5 km^3) than in the SD (8.2 km^3); however the latter is five times as big in surface area. The specific loss (annual volume divided by the surface area) is therefore five times greater in the Northern Delta than in the South, when following the limits of the basin that were used, as outlined in Fig. 1. The total surface of the Delta basin is about 73 000 km^2. The SD functions like a transit plain where the flow is simply delayed. In the Northern Delta, the flooding recharges many lateral depressions where the water is trapped. Potential evaporation is also greater (higher temperatures, less cloud cover). During important overflows in the northern zone, the infiltration may also be higher, because the lands beyond the banks of the Niger River, are essentially made up of very sandy soils and sandhills. The total real evaporation above the Delta, calculated according to the hydrological balance (Mahé *et al.*, 2009), averages approximately 800 mm per year, but it may vary between 400 (1984/85) and 1300 mm (1924/25). This evaporation is the difference between flows at the Dire output and the sum of flows input (Ke Macina and Douna) and rainfall input over the Delta basin. This is if infiltration, which may be compensated by the rainfall, is not taken into account (Olivry, 1995).

Flooding interannual variability

The flood lasts longer in the ND than in the SD from 1 "decade" (10 days) (during dry years) to 2 or 3 decades (during wet years). The flood starts 2 decades later in the ND than in the SD (more than 2000 m^3 of losses), and it also ends later, by 4 to 5 decades. From hydrological balances between gauging stations it is possible to get water losses between the different parts of the Delta. The average annual losses of water in the Delta are of approximately 29.5 km^3 from 1955 to 1971, and 11.4 km^3 during the period 1972–1996 (Mahé *et al.*, 2009). The much smaller loss of water in the Delta during the dry period comes both from the dramatic reduction of input flows from the Niger River and from the much smaller flooded area, leading to reduced evaporation.



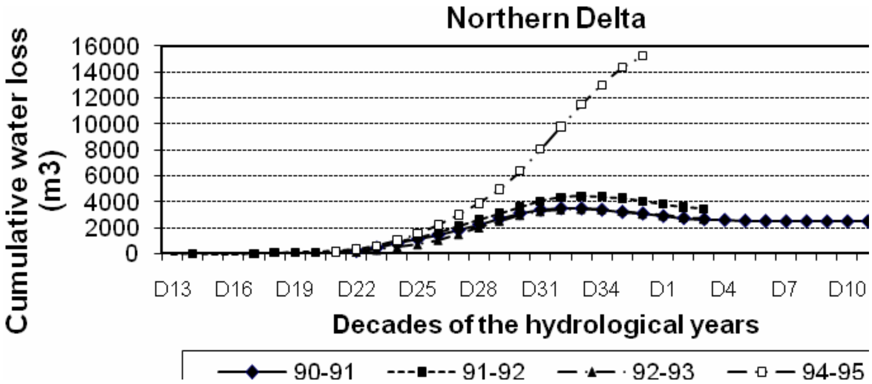


Fig. 2 Decadal (10-day periods) cumulative water loss in the Northern and Southern Delta for dry and wet years. Filling (up) and restitution (down) phases. The hydrological year starts in May.

METHODS

Study of the flooded surfaces using NOAA/AVHRR images

We use NOAA/AVHRR images selected over a period of 11 years (1990–2000). The study period begins with four dry years 1990–1993, followed by a succession of wet or medium years, among which 1994 and 1999 were the wettest. The images were preprocessed in decadal syntheses at AGRHYMET, which is equipped with a receiving station and a processing chain of raw NOAA/AVHRR data. The number of images that meet the selection criteria – the delta must be in the centre of the image where the resolution is close to 1 km, and no clouds – do not exceed 10% of archived data examined. The spectral channels operated are Red (R 0.58–0.68 μm) and the near infrared (NIR 0.73–1.1 μm), mid infrared (MIR 3.55–3.93 μm) and two thermal channels (IRT4 10.3–11.3 μm and IRT5 11.5–12.5 μm). The NDVI (Normalized Difference Vegetation Index) defined by the ratio (NIR – R)/(R + NIR) is calculated.

The delineation of flooded areas is made from processed images according to three main phases: a preprocessing to reduce noise, the composition of channels in the form of indices (IB – brightness index $IB_T = \sqrt{(MIR^2 + IRT4^2 + IRT5^2)/3}$, NDVI and RC (IRT4/NIR)), and comparing these indices to extract information according to the classification of objects to identify (Mariko *et al.*, 2003; Mariko, 2004).

RESULTS

Flooded areas as seen by NOAA

Among many results detailed in Mariko (2004), Fig. 3 shows images of the maximum flooded surfaces in the autumn of each year compared to the water height in Mopti. In Fig. 3, black is open

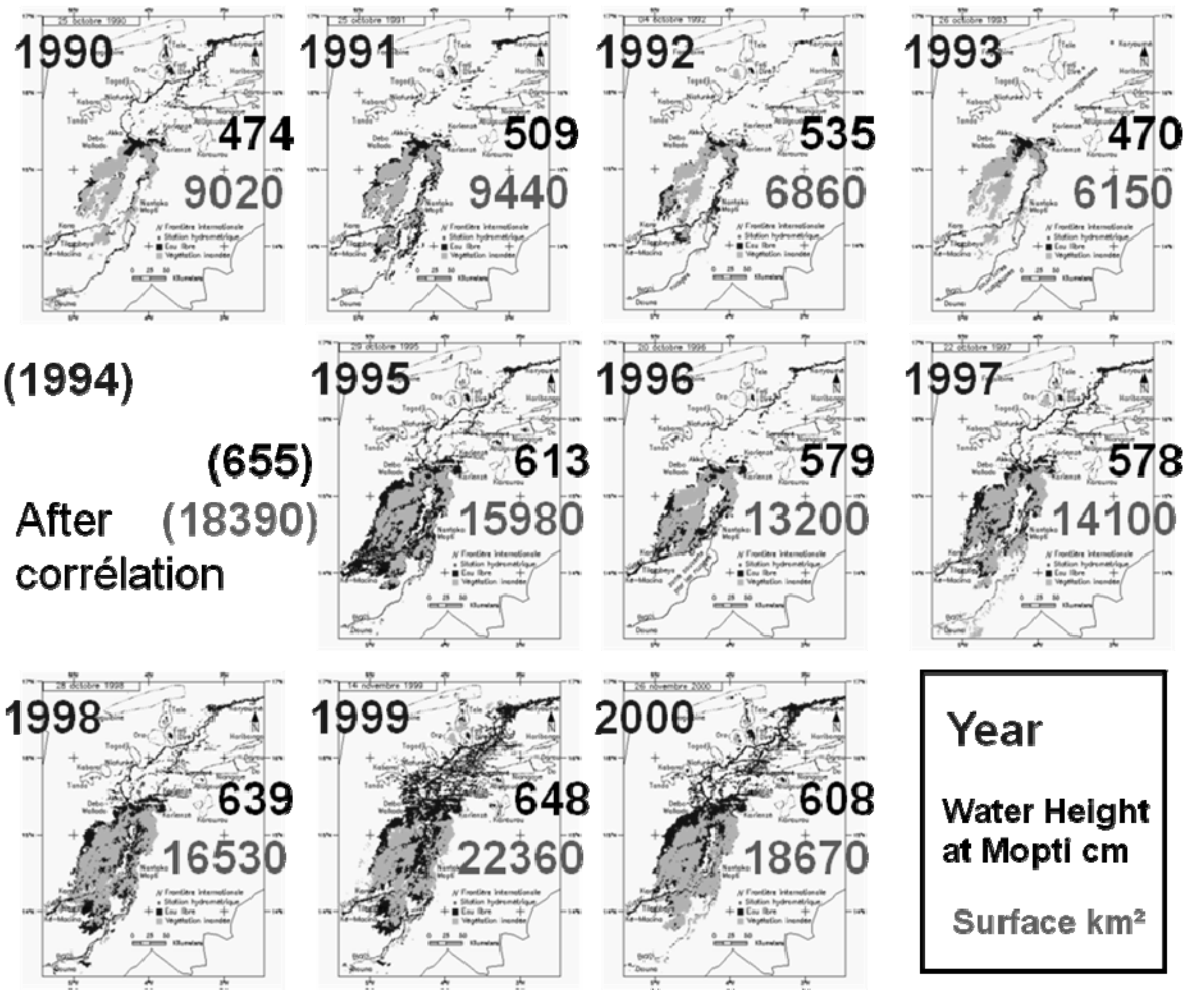


Fig. 3 Map of the maximum flooded areas at the Autumn of each year, compared to the water height at the Mopti gauging station. Inundated vegetation in light grey and black is for open water. The flooded surfaces given correspond to the near annual maximum flooded area in the NID.

water, and grey is the inundated vegetation. In autumn, the flooding area is maximum in the SD, and close to the maximum in the ND, where the flood peak is reached a few weeks later. The figures for the maximum flooded areas are then slightly underestimated. The figure for 1994 is given according to the correlations shown in Fig. 4.

Indeed, not all the dates could be observed due to lack of images and/or presence of clouds. However, these values seem quite consistent with those obtained from the empirical model of water balance used in other studies (Orange *et al.*, 2002). However in an earlier study, surfaces obtained by Olivry (1995) reach 14 500 and 15 200 km^2 in 1990 and 1991, respectively, from a method based on the hydrological balance at several gauging stations in the Delta.

Relations between water heights and flooded area: predictability

Figure 4 gives the correlations between the water height at Mopti and the flooded surfaces. The regression is better for the SD but is still good for the whole area. Several regional correlations can be calculated, but the best results are obtained with Mopti. This relation can be used to predict the flooded surfaces in the north according to the level of the flood at Mopti several weeks in advance, due to the delay between the peak flood in Mopti and Dire.

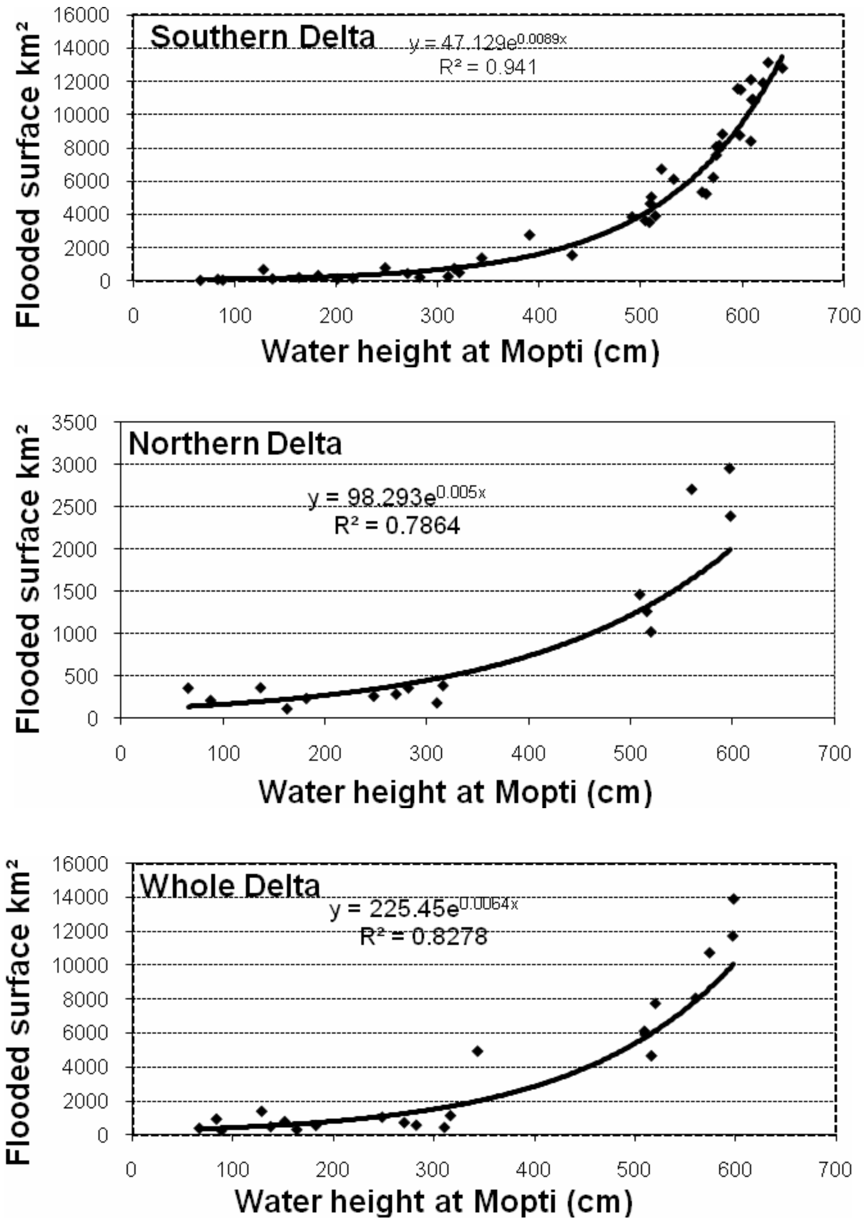


Fig. 4 Correlation between the water height at Mopti and the flooded surfaces in the Southern Delta (top), Northern Delta (middle), and the whole Delta (bottom); years 1990–1996.

CONCLUSION

The regime of the flood in the river Niger Inner Delta will soon be modified due to big dams proposed for the Upper Niger basin, which are being studied (Mahe *et al.*, 2011). Several studies have focused on this problem (Chamard *et al.*, 1997; Kuper *et al.*, 2002). But none of them could refer to a solid knowledge of the flooded surfaces. It was thus important to increase our knowledge about the natural flood. In a first part we studied the hydrological balance in the Delta, showing that the water losses are more important in the north than in the south, which is quite surprising due to the greater extent of the flooding in the south than in the north. Then we used NOAA images to delineate the extent of the flooded area in the NID, between 1990 and 2000. The series of flooded surfaces are finally correlated with the water height at the Mopti station. This relation is useful for the prediction of flooded surfaces several weeks in advance in the Northern Delta.

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