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Relationships between water level at hydrological stations and inundated area in the River Niger Inner Delta, Mali

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Abstract The River Niger Inner Delta is a wide natural seasonal flood plain in Mali, where the two main streams of the River Niger gather. This area is only poorly influenced by hydraulic managements, thus the inundation dynamic is mostly natural. Many people live in this humid area, and their activities depend on the date of arrival of the flood peak, and of its duration. But the Inner Delta is very large, and there is a long delay of several weeks or months between the arrival of the flood at the Delta entry, and the occurrence of the flood at its exit. Previous studies using the low resolution AVHRR/$NOAA_{14}$ satellite data, over the years 1990–2000 described the space–time propagation of the flood and of the inundated vegetation cover. These images help to study the relationships between the inundated areas and the water levels at several hydrological gauging stations, which have data series long enough and which cover several regions inside the Delta. The values of flooded areas obtained from both regional and local approaches are close, but always greater for the local approach. The results seem closer to the observations with the regional approach. Finally, we propose the reconstruction of possible past flooded areas from these relationships.

Key words Inner Delta; River Niger; flooded area; regionalisation; water level

INTRODUCTION

The River Niger Inner Delta is located in Central North Mali (Fig. 1). It is a wide flood plain seasonally flooded by the River Niger overflow. The River Niger regime is still mostly natural (Hassane *et al.*, 2000) as there are only a few dams on the river. The rainfall diminution over the basin since the 1970s has considerably reduced the inundation area (Mahe *et al.*, 2009, 2011). Now there are several projects for dams in the countries upstream of the basin which will lead to a reduction of the flood peak and the average water level in the river (Lienou *et al.*, 2010) if the projects are realized.

In order to simulate the future impact of the modification of the river regime on the extension of the flooded area, a previous study has determined a relationship between the water levels at one gauging station (Mopti in Mali) and the inundated areas (Mariko, 2004; Mahe *et al.*, 2011). The relationship is of quite good quality. But, as there is a delay of several weeks, or months some years, between the beginning of the flood in the south of the Delta, and the end of the flood at the north exit of the Delta (near Timbuktu in Mali), we want to study the relationships between inundated areas and water levels at the local scale within the Delta, searching for possible better relationships at the local scale, which could improve the prediction of inundated areas.

THE STUDY REGION AND DATA

The region of the River Niger Inner Delta stretches in the middle of Mali, West Africa, between the towns of KeMacina and Douna in the south, and the city of Timbuktu in the north (Fig. 1). The Delta is composed of two main areas: in the southern/upstream part the flood stretches over large flooding plains, and in the northern/downstream part, the flood circulates between narrow bands of ergs oriented east/west, and fills lateral depressions on both banks of the river (Fig. 2). These natural lakes can store very large amounts of water over several years (Auvray, 1960).

The water levels for the gauging stations come from the National Direction of Hydraulics in Bamako, Mali, for which metadata, as well as contours of the basins, can be extracted from the SIEREM database (Boyer *et al.*, 2006). The flooded area values come from previous studies (Mariko, 2004, Mariko *et al.*, 2003, 2013).

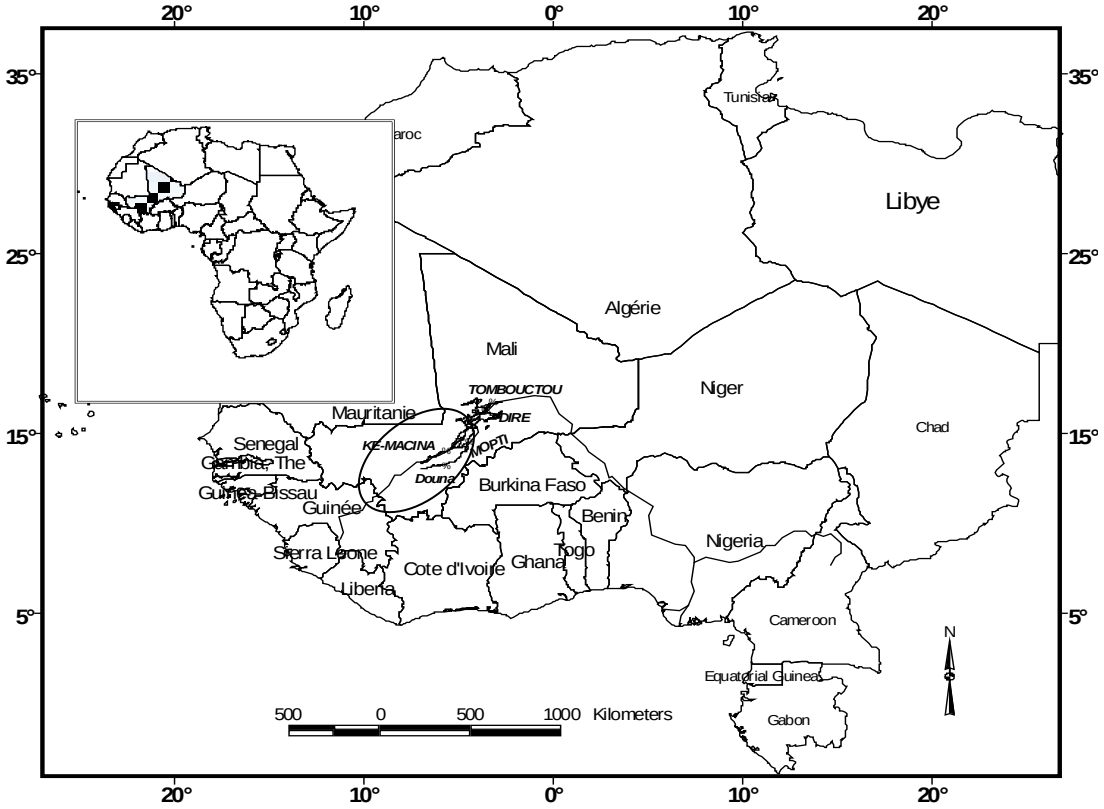

Fig. 1 Location of the River Niger Inner Delta in Mali, West Africa.

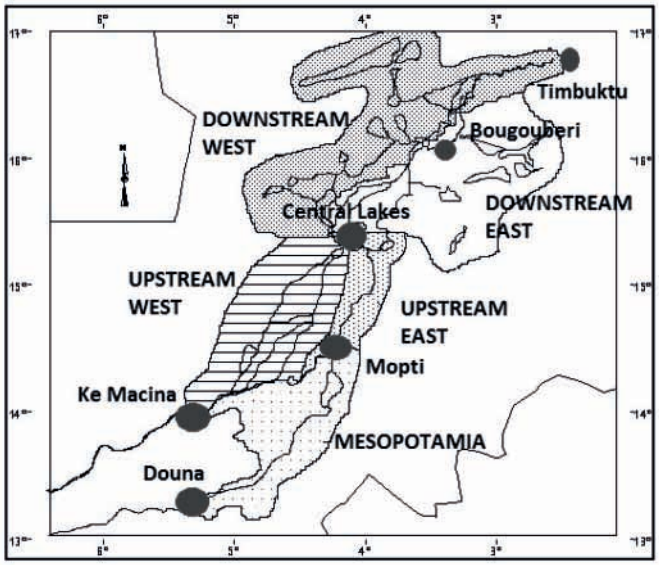

Fig. 2 Location of the five sub-regions in the Delta and the main gauging stations.

DELINEATION OF THE LOCAL AREAS

The Delta is subdivided into five local divisions (Fig. 2). They correspond to natural limits combined with the location of the main gauging stations. The Mesopotamia region is located upstream of the Mopti gauging station, along the Bani River and south of the River Niger, up to the stations of Douna on the Bani and KeMacina on the Niger. This inundated plain between the Bani and River Niger is called Mesopotamia.

Downstream of KeMacina and Mopti lies the main flood plain of the Delta called the Diaka, from the name of the main river flowing northward out of the main Niger stream on the left bank. Along this plain several branches flow out of the main stream, heading north, and rejoining in Wallado Lake, just south of Debo lake; we called it the Upstream West region. North of Mopti the main stream of the River Niger flows toward Debo Lake, inundating a smaller plain with no connection with the Diaka; we called it the Upstream East region. Both Upstream West and East regions are limited to the north by a string of great lakes; Lakes Wallado and Debo gather the waters from the Diaka stream and most of those of the main River Niger stream. Korientze Lake is flooded by water flowing from the main River Niger stream on its right bank. Out of the Lakes, towards the north, the western stream, named Issa Ber, flowing out of Debo Lake is the largest, and concentrates 80% on average of the Niger water. We delineated the Downstream West region as the whole left bank of this main stream, from Debo Lake to the exit of the Delta near Timbuktu (Koryoume is the name of the gauging station, at the harbour of Timbuktu) including the natural lakes of the left bank. The Downstream East region includes two smaller streams flowing out of this central lakes area: the Bara Issa River flows out of the Debo Lake and is about 15% of the total River Niger discharge, and the Koli Koli River provides 5% of the total River Niger discharge out of the Korientze Lake; this region also includes the right bank natural lakes flooded periodically by these streams.

EXPLORING THE RELATIONSHIPS BETWEEN WATER LEVELS AND INUNDATED AREAS AT THE LOCAL SCALE

Figure 3 is from Mahe *et al.* (2011) and recalls the relationship between the water level at Mopti and the flooded area on the whole Delta. The points used to draw this correlation were observed during 1990–2000, which were for most of them rather dry years.

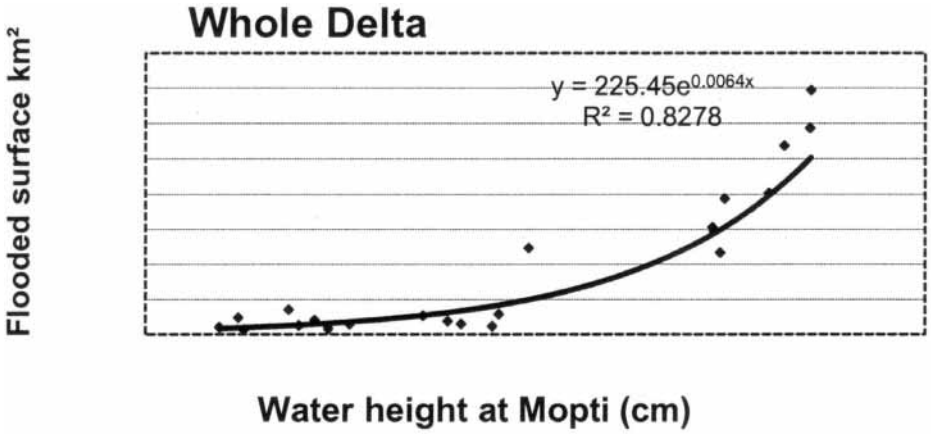

Fig. 3 Correlation between the water height at Mopti and the flooded areas in the whole Delta. Years 1990–1996 (from Mahe *et al.*, 2011).

Thus the maximum flooded area is limited in that case to <15 000 km^2, while larger flooded areas are reported for humid years (Auvray, 1960; Orange *et al.*, 2002; Mahe *et al.*, 2009), up to 35 000 to 40 000 km^2. According to this relationship, the flooded area for the water level of about 600 cm or more at Mopti is poorly documented, but should increase rapidly.

The correlations for each of the five sub-regions within the Inner Delta, from observations over the years 1990–2000 are shown in Fig. 4. The flooded areas are extracted from the same images that were used for the correlation presented in Fig. 3.

The correlation coefficients for each region are given at the top of each graph. There are several other stations that can be correlated with the inundated areas in each region, and we tried the correlations with 11 other ones along the river: Douna and Sofara on the Bani River;

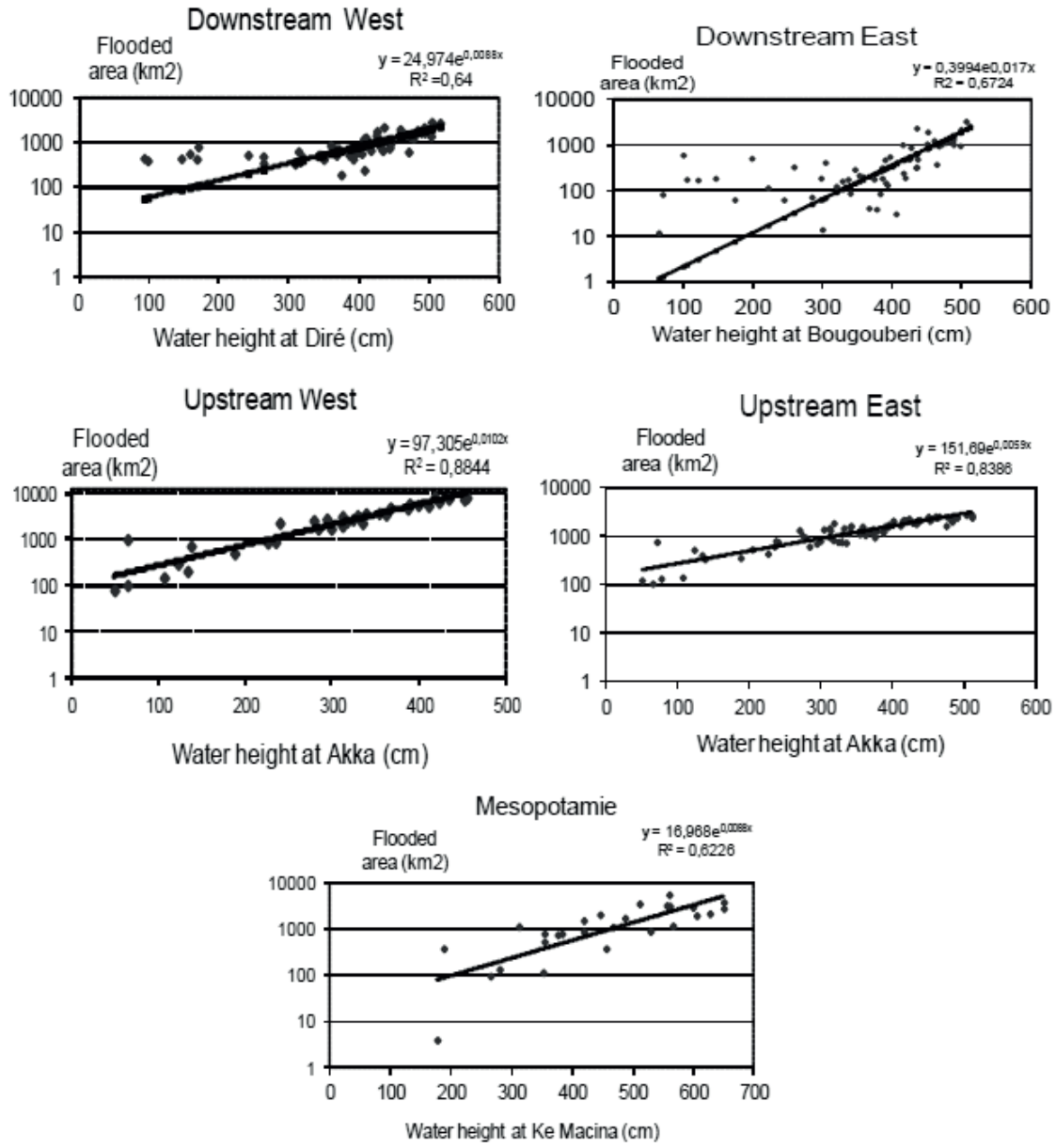

Fig. 4 Correlations between flooded areas (Y axis, km^2) and water level at gauging stations (X axis, cm), for the five sub-regions of the Delta: from top to bottom, and left to right: Downstream West, Downstream East, Upstream West, Upstream East, Mesopotamia.

Tilembeya upstream of Mopti on the River Niger; Kara on the Diaka River, downstream of KeMacina on the left bank; Awoye, Sah and Sarafere on the Bara Issa River downstream of the Lake Debo; Korientze on the Koli Koli River downstream of the Lake Korientze; Tonka and Niafunke on the Issa Ber River, downstream of the Lake Debo; and Koryoume on the main River Niger stream at the north exit of the Delta. We present only the best results. Good correlations are obtained for the Upstream West and East regions, with the gauging station of Akka, at the outlet of Lake Debo, controlling 80% of the total discharge of the River Niger. A good correlation is also obtained for the Downstream East region with the water levels of the Bougouberi station. But this station is no longer observed, and the correlations with all other stations are not good. The results for the other regions are not of good quality. We also tried correlations with combinations of time series of two gauging stations, without any significant improvement.

COMPARISON BETWEEN LOCAL AND REGIONAL APPROACH

The flooded areas obtained from the correlations are presented in Table 1. There are no available data for 1994, as the images of the flood period were not available at the AGRHYMET centre of Niamey, where the data processing was realized. The areas obtained for each local division are summarized to be compared to the area obtained from the regional correlation. The regional approach always gives lower areas, with an increasing difference as the water level increases. Compared to the raw results of flooded areas that were used for the correlation, the regional approach seems to give better results than the local one. But this result is to be considered with caution, as previous studies, not based on satellite image processing, used to give larger flooded areas than those obtained during this study (Olivry, 1995).

Table 1 Flooded areas obtained from the correlations between water levels and flooded areas of Fig. 3 for the regional approach, and of Fig. 4 for the local approach, in km^2.

	Regional correlation area km^2	Local correlations area km^2
1990	9025	10 344
1991	9400	9683
1992	6855	7938
1993	6165	7049
1994	No data	No data
1995	16 463	16 821
1996	13 198	15 966
1997	14 103	16 380
1998	16 533	19 042
1999	22 359	26 301

The regional approach is used to reconstruct the past probable flooded areas, on the basis of the Mopti water levels (Fig. 5, black dots). These values are compared to two other sets of values that were estimated previously, by Orange *et al.* (2002) on the basis of an agro-ecological model (black squares), and by Olivry (1995) according to a water balance of the Delta. But according to several studies, e.g. Poncet & Troubat (1994), the maximum inundated area should not exceed 30 000 km^2, which seems not to be exceeded by using the correlations of this study.

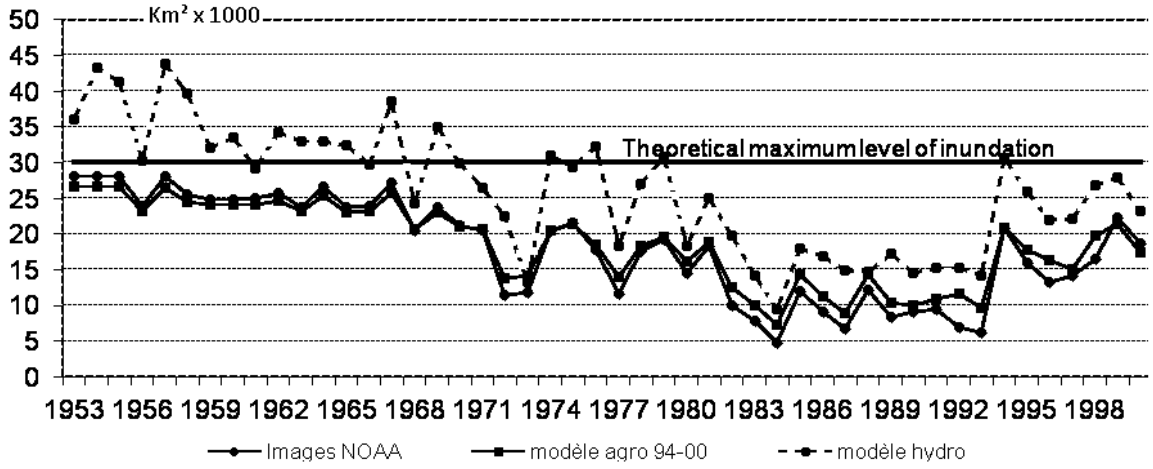

Fig. 5 Simulated flooded areas in 10^3 km^2 according to the correlation of this study (black dots), the agro-ecological model (Orange *et al.*, 2002) (black squares), and the water balance model of Olivry (1995) (dotted line).

CONCLUSION

The set of NOAA-AVHRR images processed by Mariko (2004) for the period 1990–2000 was used to assess the flooded areas on the River Niger Inner Delta in Mali. For each available image the open water area and the area of vegetation upon water were summarized to obtain the inundated area. For each year we determined the maximum flooded area. We also used all the points to correlate with the water levels at the main gauging stations of the Delta. Thus correlations were established between flooded areas and water levels for the whole Inner Delta in a regional approach, and for five local regions for the local approach.

For the downstream East and West regions, the relationships between water heights below 300 cm at the gauging stations and the flooded areas seem not to be represented satisfactorily by the linear correlation model used. Moreover the flooded area seems the same whatever the water height. But this has a limited impact on the study as we are interested in the maximum flooded areas occurring for the highest annual levels always over 400 cm.

The results given by the local approach are of similar quality to that of the regional approach, between 6000 km^2 and 26 000 km^2, but the results given by the regional approach would seem more reliable, compared to the observed results.

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