



3 FLOODING OF THE INNER NIGER DELTA

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3.1 Introduction

During the Great Drought, *La Grande Sécheresse*, in the early 1980s, the flooding of the Inner Delta shrank to less than one third of area inundated in the decades before. The inhabitants of the Inner Niger Delta dug channels and built dams and sluices to keep the water in the lakes and on the floodplains. Unfortunately, their efforts were mostly in vain because the flood level was insufficient during most of the recent years to cover the higher floodplains and fill the lakes.

The river flow of the Niger reaches a peak in September, bringing about the inundation of the Inner Delta. Chapter 2 already described how the peak flow of the Niger was rather minimal during the last decades and how part of this depression was due to irrigation by Office du Niger and management of the Sélingué reservoir. The analysis showed that about 6% of the peak flow in September is taken for irrigation of Office du Niger and about 20% is used to fill the Sélingué reservoir. What is the impact of this on the flooding of the Inner Delta? What will be the additional effect of the planned Fomi reservoir, which is nearly three times larger than the Sélingué reservoir? Before these questions can be answered, we have to describe how the flooding in the Inner Delta depends on the flood level and how both are related to the river flow. So far, the relationship between flooding and water level in the Inner Delta has only been quantified in an indirect way. Alternatively, satellite images can be used to directly measure the surface of the flooded area and link these data to the local water level.

The chapter is structured as follows. Section 3.2 elaborates on the existing estimates of inundated area in the Inner Niger Delta. For this purpose, various indirect methods, such as topographical maps, aerial photographs and agro-ecological models, are discussed. Next, remote sensing methods are applied to directly estimate the flooded area (Section 3.3). Specific issues discussed in this section are the selection procedure of satellite images, the distinction between land from water, and the coverage of the Delta. In Section 3.4 water maps are created for incoming and receding water, respectively. On the basis of these water maps, a digital flooding model is developed for different algorithms and elevations (section 3.5). Ultimately, the constructed models can be used to determine man-made impact of irrigation and reservoirs on the flooded surface of the Inner Delta, applying both the water balance and the statistical approach. (section 3.6-3.8). Finally, conclusions are drawn in section 3.9.



Orange et al. (2002a) evaluated the model of Cissé & Gosseye and concluded that the model behaves relatively well, but they detected a systematic underestimation of the inundated area. Therefore Orange et al. used a maximum water level of 610 cm at Mopti. By doing so, the model simulates variations of the inundated area between 6,000 km² in 1984 and 25,000 km² in 1955.

3.3 Remote sensing methods

Satellite images offer an opportunity to measure directly the inundated area. Mariko et al. (2002) analysed four NOAA-images from 1999. Although the resolution of NOAA-images is low with 1 x 1 km, a comparison of a series of images might be used as a direct measurement of the variation in the inundated area. Using a large number of Landsat images (resolution 30 x 30 m), Zwartz et al. (2003) conducted a similar approach for the Inner Niger Delta. This section is based on their work.

Separate land from water

Fig. 3.2 shows how Lac Débo looks like on a satellite image for two different days: February 1985 and February 2001. A selection has been made of three spectral bands (blue, red, green). The True Colour Composite clearly reveals where the ground is bare and where is vegetation. The image of February 1985 shows unmistakably what is water and what is land. This is not the case for the image of February 2001 because it remains unclear whether the green area is covered by water or not.

Land and water can be distinguished by selecting Landsat TM band 5 and 7. Water implies an algorithm of band 5 between 100 and 135 and band 7 between 70 and 90. All other values are land. This rule appears to work well. As shown in Fig. 3.2, most of the green area on the image of February 2001 must be considered as water which colours green because of floating vegetation.

Coverage of the Delta

A Landsat scene covers an area of 180 x 180 km. To cover the entire Inner Niger Delta, one needs one image from the area between Djenné and Lac Débo

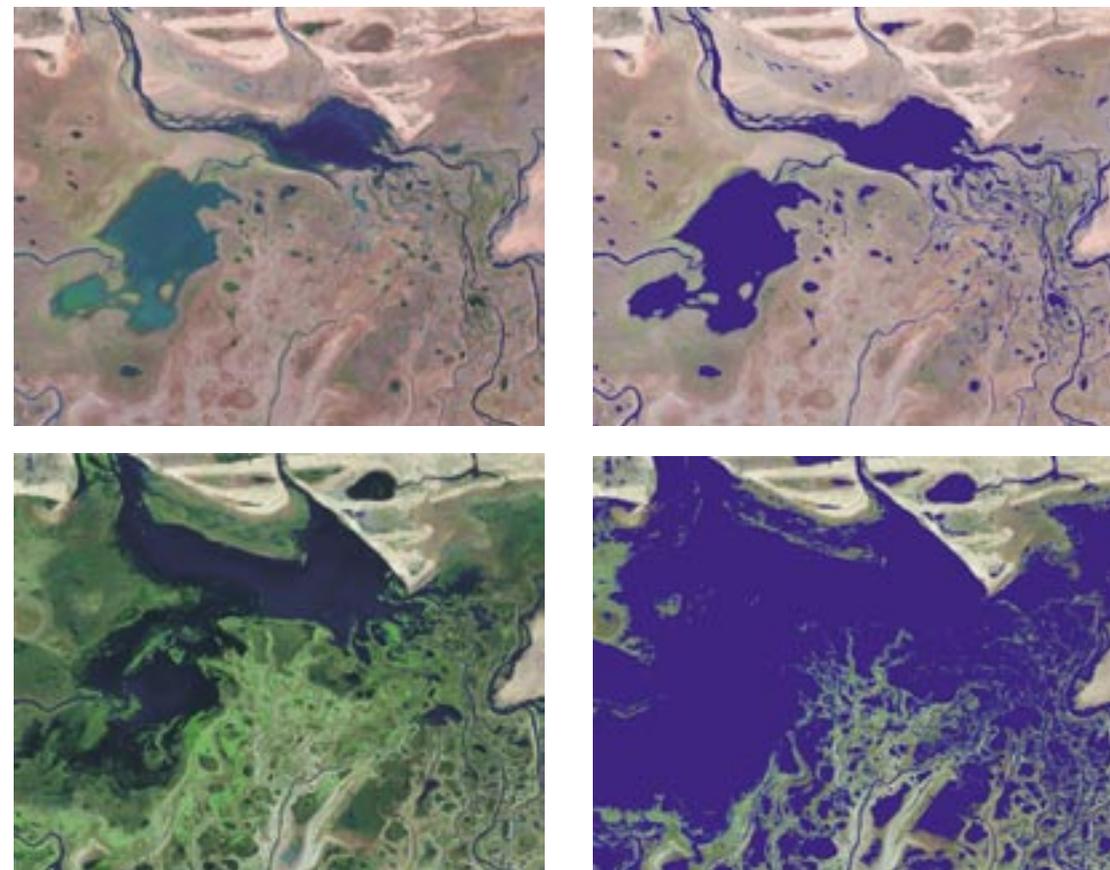


Fig. 3.2. True Colour Composite (left) and water map (right) of Lac Débo and Lac Walado on two different dates. Blue is water according to an algorithm (with the left picture as background). The four maps cover exactly the same area and measure 64.9 x 74.4 km. UTM Coordinates of NW-corner 333.7 x 1701.5 and of SE corner 407.1 x 1636.6.

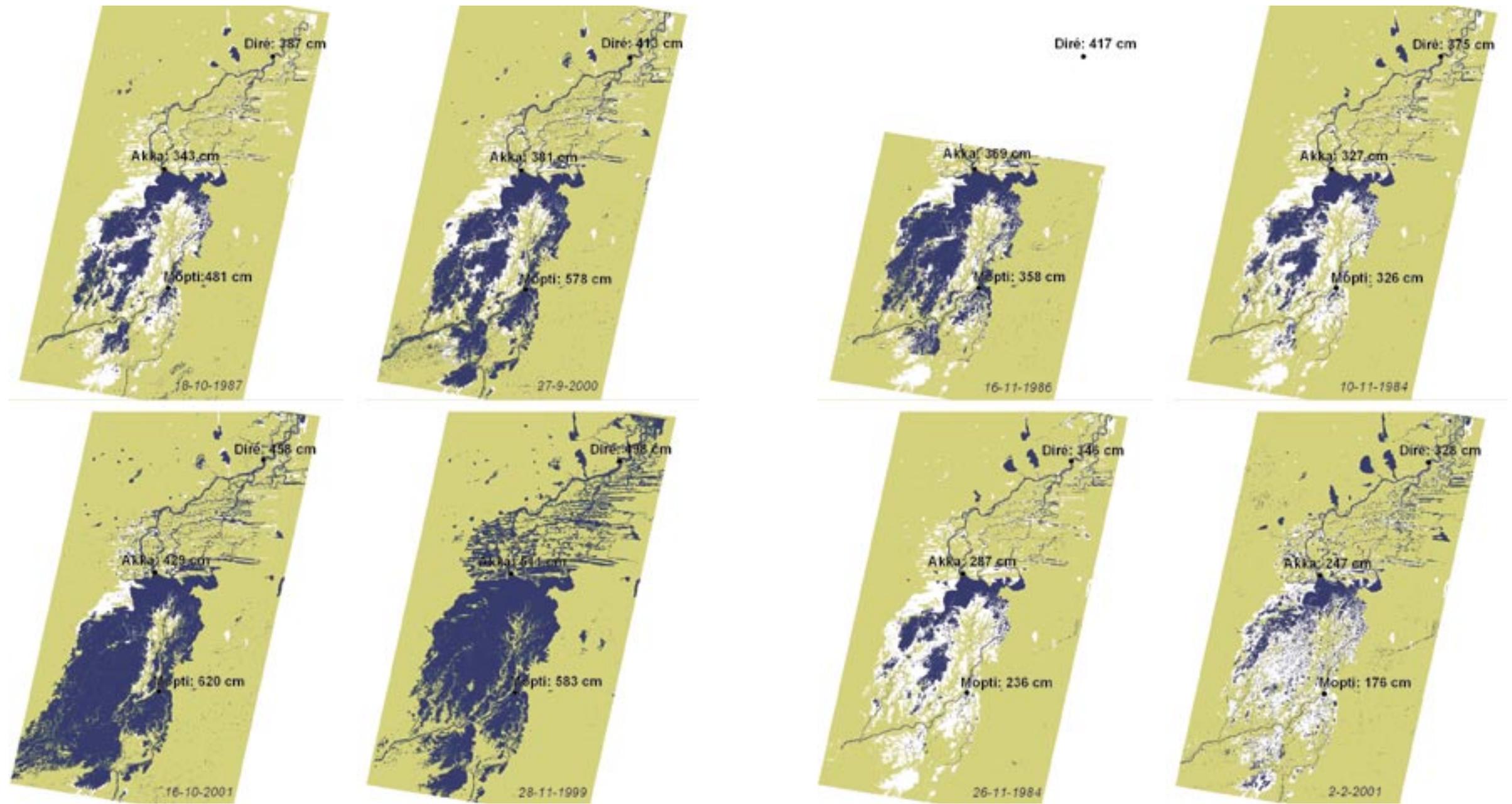
(path 197/row 50) and another north of Lac Débo up till Tombouctou (path 197/row 49). To get data from Lac Faguibine a third image (path 197/row 48) is required and two additional images from path 196 and 198 to cover the SW part near Ké-Macina and the NE part, east of Tombouctou. Fortunately, it was possible, at least for the images before 1999, to get a shift within the path. That is why image 197/49 and 197/50 with a shift 20% to the north was purchased. In this way, we are able to cover the upper northern part of the Inner Niger Delta, including Lac

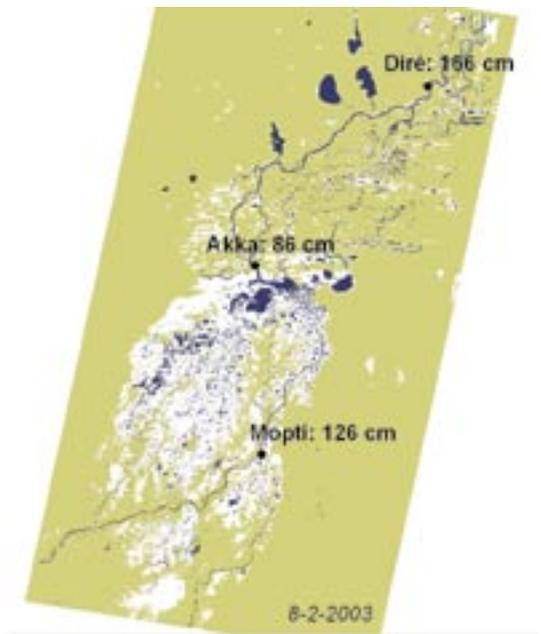
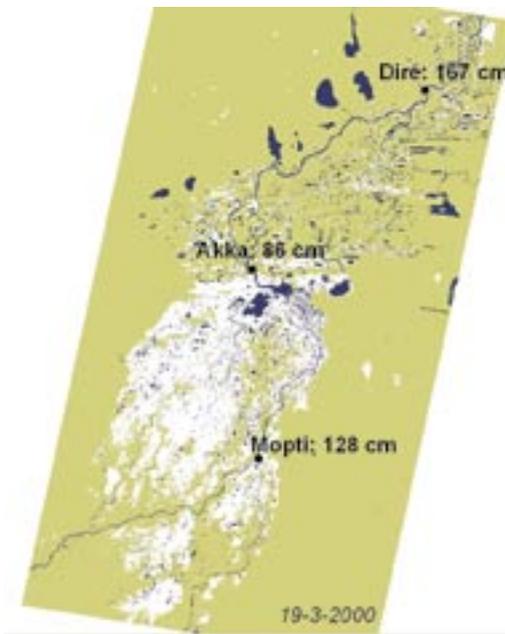
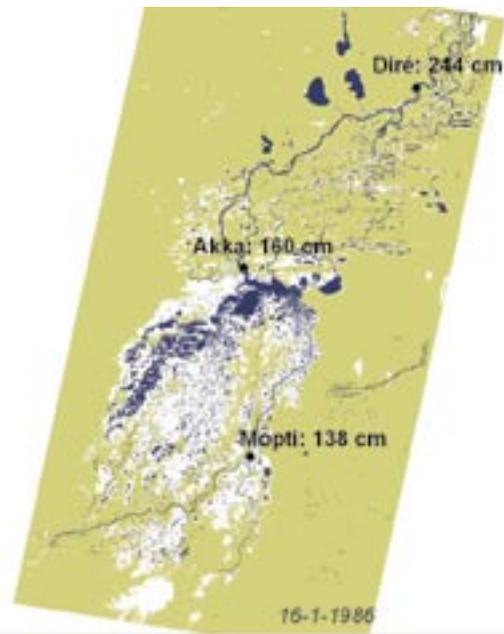
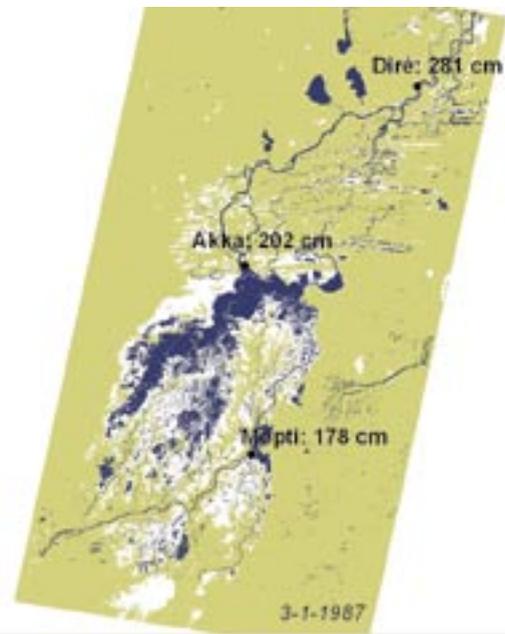
Faguibine, although part of the southern section had to be sacrificed. Fig. 3.3 shows the coverage of the two images without the shift of 20% northwards.

The Landsat satellite follows a track SSW – NNE. It does not always exactly produce the same images. There was a deviation of maximally 12 km to the west or the east. A zone of 178 km wide was always covered and all 23 images together covered a zone of 195 km wide. Row 49 + 50, including the 20% shift to the north, give a coverage of 380 km long.



Fig. 3.5. Water maps of the Inner Delta for 24 dates, based on 24 satellite images of the southern half and 19 images of the northern part. The water levels at Mopti, Akka and Diré are indicated. The maps are ranked by increasing and decreasing water level in Akka for incoming and receding water, respectively.

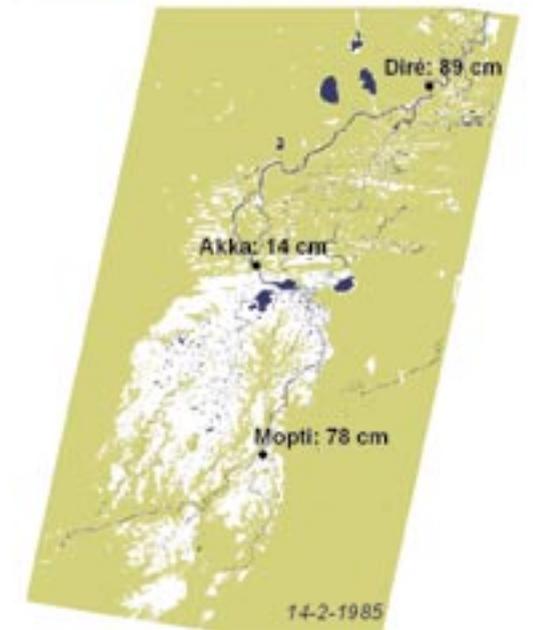
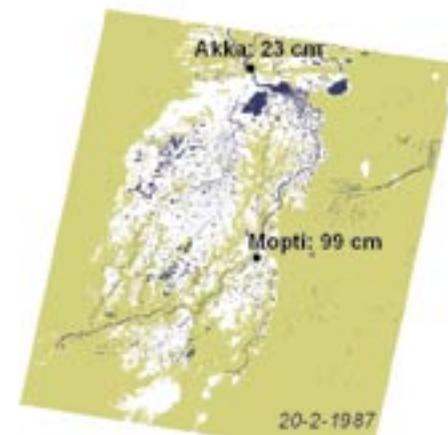
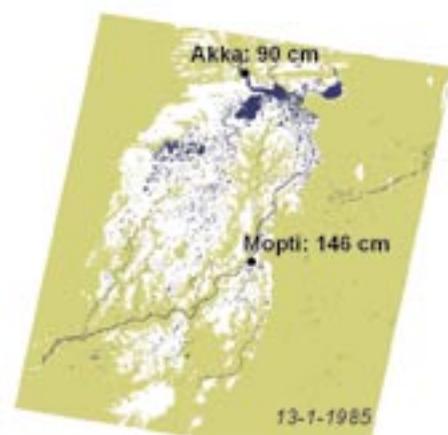
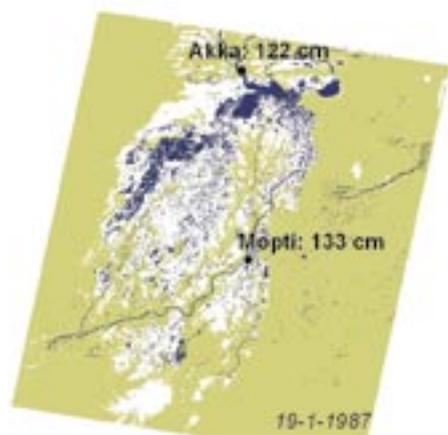




Diré: 206 cm

Diré: 167 cm

Diré: 104 cm



3.4 Water maps

The 24 water maps have been ranked by water level in Akka: rising for incoming water (Table 3.1) and decreasing for falling water (Table 3.2). At the extreme low water level of -2 cm in Akka (8 July 1985), large water bodies were only found in Lac Debo and Lac Korientzé in the central part of the Delta. Lac Walado fell nearly completely dry with little water left in the northern and southern part of this lake. In the north, Lac Horo still contained water. The situation was not much different at a water level of 77 cm (10 June 2001) and 140 cm (6-8-1984): Lac Debo and Lac Korientzé were slightly larger, while Lac Walado and Lac Fati were already (partly) filled with water. The southern Delta started to be flooded at a water level of 166 cm (28-7-2001) and

Table 3.1. Satellite images during incoming water. The water level in Mopti, Akka and Diré is given, as well as rainfall in Mopti (data IER): the number of foregoing days without rain, the rainfall (mm) in the fortnight before and the cumulative foregoing rainfall (mm) in the rainy season.

Date	water level (cm)			rain in time before		
	Mopti	Akka	Diré	dry days	rain in 14 days	total rain
8-jul-1985	137	-2	20	1	63.2	137.3
10-jun-2001	132	40	86	2	4.5	14.6
6-aug-1984	269	140	170	0	50.7	168.4
28-jul-2001	339	166	191	1	85.2	182.4
13-sep-1986	473	271	300	2	49.6	269.8
26-aug-2000	478	294	320	0	84.2	252.2
2-oct-1987	444	317	357	32	0.0	231.5
25-oct-1984	435	331	367	24	0.0	330.7
18-oct-1987	481	343	378	48	0.0	231.5
27-sep-2000	578	381	413	3	58.6	316.7
16-oct-2001	620	432	458	6	0.7	301.7

more so at 271 cm (13-9-1986) and 294 cm (26-8-2000). However, even at a water level of 381 cm (27-9-2000) still large parts of the southern Delta were not yet covered, while the northern Delta was still dry at 429 cm (16-10-2001).

Nearly the entire southern and middle part of the Inner Delta was covered by water as well as parts of the northern region, at a water level of 511 cm in Akka (28-11-1999). Within the southern half, only the highest terrains, the levees along the Niger itself, the Diaka and the several Mayos were dry. When the water level had decreased to 369 cm (16-11-1986), water was still found around Pora, between the Niger and the Bani and along the Niger north of Mopti. The most extensive areas still covered by water were found in the central part of the Inner Niger Delta: west of the Diaka (Plaines de Seri), east of the Diaka (along the Mayel Kotia, Mayo Togoro and the Diarenndé) and further north the entire zone around Lac Débo, Walado and Korientze. At a still lower water level of 202 cm on the scale of Akka (3-1-1987), the majority of the floodplains were dry, except for the Plaine de Seri, and the adjacent Walado-Débo-Korientze complex. At a further decre-

ase of the water, the Plaine de Seri got dry at a water level of 122 (19-11-1987) or 90 cm (13-1-1985), by which only Débo-Walado and Lac Korientze were still covered by water. During a water level of 23 cm (20-2-1987) and 14 cm (14-2-1985), Walado and Korientzé were still about the same size, but Lac Débo had become much smaller.

three images from June and July. Since 1984 Lac Faguibine was never completely filled with water. There were only three images on which the SE part was covered by water (16-1-1986, 3-1-1987, 19-3-2000). Lac Faguibine was fully dry on 2-2-2001. That is remarkable, because the maximal water level in Diré in the preceding months had

Table 3.2. Satellite images during receding water. Water level in Mopti, Akka and Diré is given, as well as the date and water level at which the flood reached its peak level.

date	water level (cm)			maximum water level (date)			maximum water level (cm)		
	Mopti	Akka	Diré	Mopti	Akka	Diré	Mopti	Akka	Diré
28-nov-1999	583	511	498	26-oct	23-nov	27-dec	662	511	515
16-nov-1986	358	369	417	8-oct	29-oct	2-nov	534	388	424
10-nov-1984	326	327	375	19-oct	30-oct	9-nov	440	336	375
26-nov-1984	236	287	346	19-oct	30-oct	9-nov	440	336	375
2-feb-2001	176	245	328	23-oct	22-nov	27-nov	608	465	486
3-jan-1987	178	202	281	8-oct	29-oct	2-nov	534	388	424
16-jan-1986	138	160	244	13-oct	3-nov	12-nov	571	433	460
19-jan-1987	133	122	206	8-oct	29-oct	2-nov	534	388	424
13-jan-1985	146	90	167	19-oct	30-oct	9-nov	440	336	375
19-mar-00	128	86	170	26-oct	23-nov	27-dec	662	511	515
8-feb-2003	126	86	166	8-oct	1-nov	15-nov	445	411	445
14-feb-1985	99	23	104	8-oct	29-oct	2-nov	534	388	424
20-feb-1987	78	14	89	19-oct	30-oct	9-nov	440	336	375

A comparison of the 24 images clearly shows that the flooded area, during the crue as well as during the décrue, is closely related to the water level. The only exceptions are the lakes in the north where dams were built between 1987 and 1994 in order to control the water (see chapter 2.3 and Fig. 3.1 for the location of the lakes). These dam-supported lakes include Lac Tanda (1987), Lac Kabara (1987), Lac Faguibine (1989), Lac Fati (1991), Lac Takadji (1991) and Lac Horo (1994).

A comparison of the images of northern lakes shows that Lac Horo was and still is a permanent lake, even in very dry years. Also Lac Fati was (nearly) always filled with water. Lac Télé was only dry on

been higher than during the crue of 1985 and 1986 (Table 3.2), when the SE part was covered by water. Apparently the water level must be higher than in the past to fill Lac Faguibine.

The lakes on the west side (Lac Tagadji, Mare de Soumpi, Lac Kabara, Lac Tanda and Gatié Loumo) are visible on all images from 1999 – 2003. They even contained water in June and July. Therefore, the lakes on the west side can be considered as small but permanent lakes. In the extremely dry years 1984 –1987, they were all fully dry, however.

Four lakes on the east side (Lac Haribongo, Lac Garou, Lac Do, Lac Niangaye) are not covered by the selected image, but two (Lac Aougoundou and Lac

Korarou) were fully visible on the northern image. During normal rains, Lac Korarou is a temporary lake from July till October. Yet, after an extremely wet year (1999) there was still water in March. Lac Aougoundou is a permanent lake, but it fell dry during the crue of 1984 and 1987.

Can a single map be constructed where the flooded area for different water levels are indicated? Table 3.3 shows that two maps are required: one for incoming and one for receding water. Both conditions reveal distinctly different outcomes. Table 3.3 shows the difference in water level at Mopti, Akka and Diré. To make this comparison, all measurements have been converted to water levels relative to sea level. The absolute difference between the water level at Mopti and Diré appears to be almost 5 metres during incoming water and just over 3 metres during receding water.

The importance of making a distinction between incoming and receding water is illustrated by comparing the flooded zone at 16-10-01 (429 cm in Akka) with those at 28-11-99 (511 cm in Akka) (Fig. 3.5). With a level of 511 cm, the crue reached its peak in Akka. Yet, the water level in Mopti had already fallen during four weeks, from 662 cm on 26-10-99 to 583 cm on 28-11-99. In contrast, the water level was at its peak in Mopti in 2001 with 621 cm while the water level was still rising in Akka, reaching a water level of 429 cm on 16-10-01. Therefore, although the water level in Akka on 28-11-99 was 82 cm higher than on 16-10-01, the situation was exactly the opposite for the water level at Mopti, which turned out to be 38 cm lower on 28-11-99 compared to 16-10-01. As a consequence, the décrue had started already in the southern Delta on 28-11-99 while the crue was still going on in the northern Delta.

Table 3.3. The absolute difference in water level between Mopti and Akka, between Akka and Diré and between Mopti and Diré during incoming water (left) and receding water (right). The difference has been calculated using the water level measurements (Table 3.1 and Table 3.2), taking into account that a water level of 0 cm at Mopti, Akka and Diré corresponds to 260.62, 258.38 and 256.85 m IGN.

crue Date	difference in water level (cm)			décrue date	difference in water level (cm)		
	Mopti-Akka	Akka-Diré	Mopti-Diré		Mopti-Akka	Akka-Diré	Mopti-Diré
08/07/1985	363	131	494	28/11/1999	296	166	462
10/06/2001	316	107	423	16/11/1986	213	105	318
06/08/1984	353	123	476	10/11/1984	223	105	328
28/07/2001	397	128	525	26/11/1984	173	94	267
13/09/1986	426	124	550	02/02/2001	155	70	225
26/08/2000	408	125	533	03/01/1987	200	74	274
02/10/1987	351	113	464	16/01/1986	202	69	271
25/10/1984	328	117	445	19/01/1987	235	69	304
18/10/1987	362	118	480	13/01/1985	280	76	356
27/09/2000	421	121	542	19/03/2000	266	72	338
16/10/2001	412	127	539	08/02/2003	264	73	337
				14/02/1985	300	72	372
				20/02/1987	288	78	366

Combining water maps for incoming water

The construction of a common map with different water levels for incoming water is straightforward in a situation where land is turned into water during high water while the opposite process, water turning into land, does not occur simultaneously.

By comparing the available water maps in detail, Zwartz et al. (2003) concluded that isolated lakes are (partly) filled by rainwater during the crue and that this complicates combining satellite images during the rainy season since the rainfall differed between years. That is why Table 3.1 also provides information about rainfall preceding the dates of the satellite images.

The effect of rainfall can even be seen on the small scale at which the water maps are printed in Fig. 3.5. For instance, due to local rainfall significantly more depressions were still filled by rainwater on 8-7-1985 (Akka: -2 cm) than on 10-6-2001 (Akka: 40 cm), despite the higher water discharge in 2001. The importance of rainwater is also illustrated by comparing maps with water levels of 294 cm (26-8-2000) and 317 cm (2-10-1987). There was no rain in the weeks before 2-10-87, but abundant rain in the fortnight of 26-8-2000. As a consequence, large areas along the periphery of the Inner Niger Delta had been covered by rainwater. There was no rainfall preceding 2-10-1987 (Akka: 317 cm), 25-10-1984 (331 cm) and 18-10-1987 (343 cm). In contrast, there was a lot of rain preceding 27-9-2000 (381 cm), leading to numerous small blue dots on the maps, indicating areas covered by water.

Combining water maps for receding water

Due to the absence of rain during receding water, modelling of the flooding during the décrue was more straightforward. However, another problem occurred in the modelling of the décrue: the maximum water level. The river water fills isolated lakes if the crue exceeds a certain level. That is why one might expect that the higher the maximal water levels, the more lakes and depressions are being filled. This implies that the flooded surface during the décrue not only depends on the water level itself, but



also on the maximal water level reached in the preceding months. To facilitate the comparison between the images during the décrue, the highest water levels for the different years have been included in Table 3.2.

The expected problem related to the maximal water level did not show in the comparison of the images at a high water level (511 vs. 369 vs. 327 vs. 287 cm), since the maximal crue was about the same for those four images. However, when the images of 287 vs. 247 cm and 247 vs. 202 cm were compared, the image of 247 appeared to deviate from the 287 and 202 cm. The 247 cm image was from 2-2-2001, when the preceding maximal water level had been relatively high at 465 cm. This explains why many areas – in the north as well as in the south – were covered with water at 247 cm but not at 287 cm. In the latter case the maximal crue had been 149 cm lower than in the 247 cm-image (maximal crue: 336 vs. 465 cm).

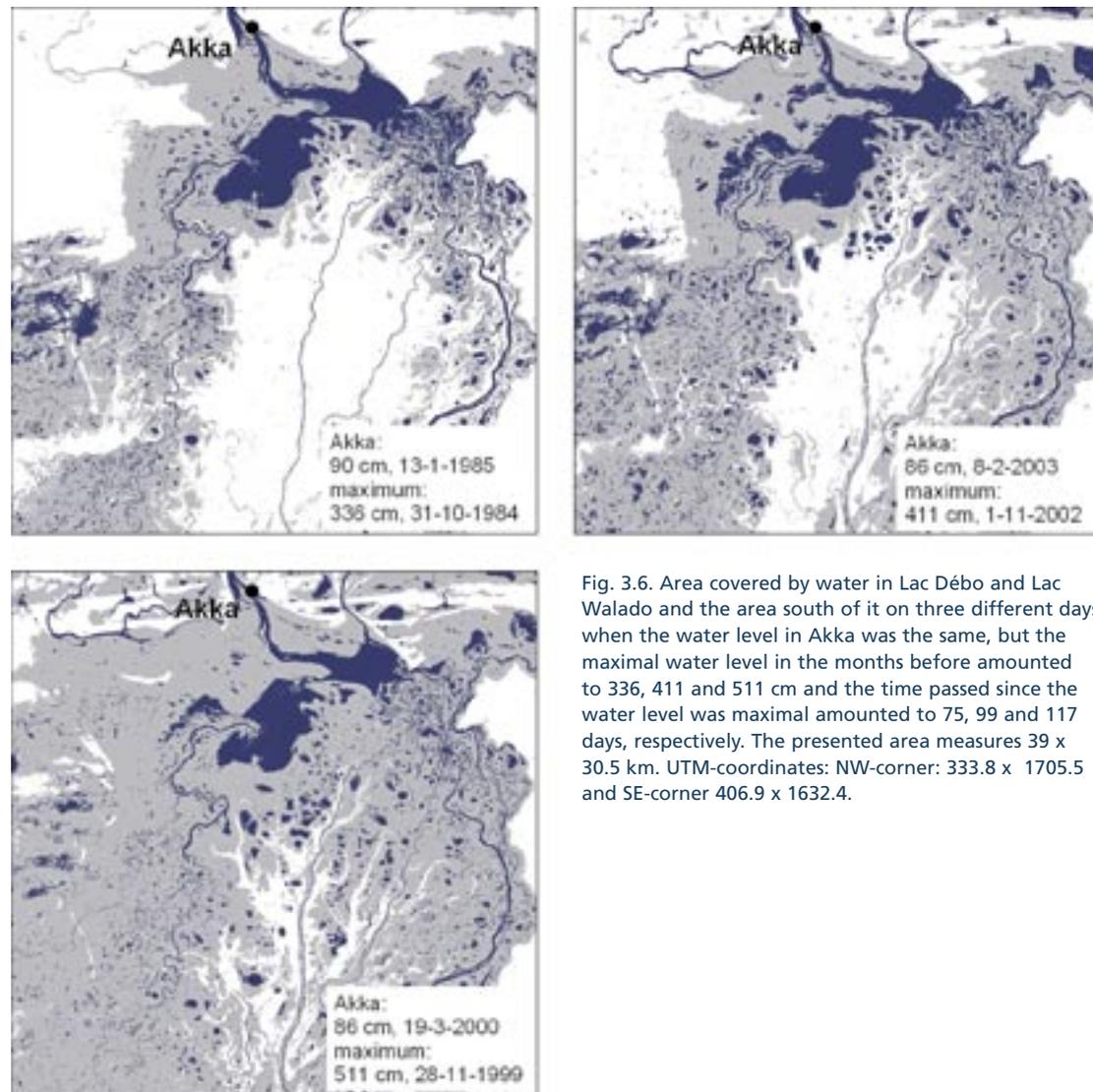


Fig. 3.6. Area covered by water in Lac Débo and Lac Walado and the area south of it on three different days when the water level in Akka was the same, but the maximal water level in the months before amounted to 336, 411 and 511 cm and the time passed since the water level was maximal amounted to 75, 99 and 117 days, respectively. The presented area measures 39 x 30.5 km. UTM-coordinates: NW-corner: 333.8 x 1705.5 and SE-corner 406.9 x 1632.4.

Another complication in modelling the decrue is caused by the shallow lakes and depressions which are no longer connected to the flood system. In other words, the model needs to account for the period between the moment that the lake lost connection with the hydrological system and its disappearance due to evaporation. Evaporation amounts to 7 mm per day.

The combined effect of maximal water level and time of evaporation can adequately be illustrated with three images during receding water with nearly the same water level at Akka (i.e. two of 86 cm and one from 90 cm). Fig. 3.6 provides the same information as Fig. 3.5. but at a much larger scale for Lac Débo and surroundings.

Fig. 3.6 shows that the higher the flood, the more isolated lakes come into existence. This can for example be observed for the area south of Lac Débo and Walodo. As shown in Fig. 3.5, this area only floods at high water levels. However, the inundated area in the Plaine de Séri, west of the Diaka and southwest of Lac Walado, was already nearly dry on the 2000 image (after the water level had been high) and was still covered by water on the 1984 image (when the maximal water level had been very low). The explanation for this phenomenon is that the Plaine de Séri is found low in the inundation zone and is also covered by water in the dry year. However, the time passed since the water level had reached its peak level was 75 days in 1984 compared to 117 days in 2000. Therefore, from the moment the low-lying lakes were isolated, more water evaporated in March 2000 than in January 1985.

Combining all the above information, the flooding during the décrue can be confidently described with the 13 available images. However, when the water level at retreating water is lower than 300 cm, it becomes more difficult to compare images from different years. In such conditions, the maximal water level as well as the time passed since the water level has reached its peak, determine where isolated and temporary lakes with water can be found.

3.5 Digital flooding model

The inclusive and exclusive model

To produce a composite water map, on the basis of the water maps shown in Fig. 3.5, the complications explained in the previous sections need to be solved. The problem of rainfall during the crue and the problem of the maximal water level and evaporation time during the décrue boil down to the same issue: how to deal with areas being covered with water while at a higher water level they remain dry? Or to put it the other way around, how to deal with areas being dry while they were covered with water at a lower water level? In this study, two different algorithms (i.e. the inclusive and the exclusive) are used to deal with isolated lakes and other problems related to maximal water level and evaporation.

In the “inclusive algorithm”, an area is considered water if it is covered by water at this water level AND at a lower level. The “exclusive algorithm” is less strict: an area is considered water if it is covered by water at this water level OR at a lower water level. The effect of the applied rule on the composite map is shown in Fig. 3.7 for the central part of the Inner Niger Delta for incoming water and receding water. On average, the exclusive algorithm clearly underestimates the flooded area while the inclusive algorithm evidently overestimates the level of flooding. The same is illustrated in Fig. 3.8, which plots the flooded areas against the water level in Akka according to both models, and also shows the measured inundation areas (see Fig. 3.5) as yellow triangles.

The inundated surface for which we had no northern image is shown as open triangles: this surface is of course always underestimated. The composite model also predicts the entire inundated area without the northern image. This is done using a

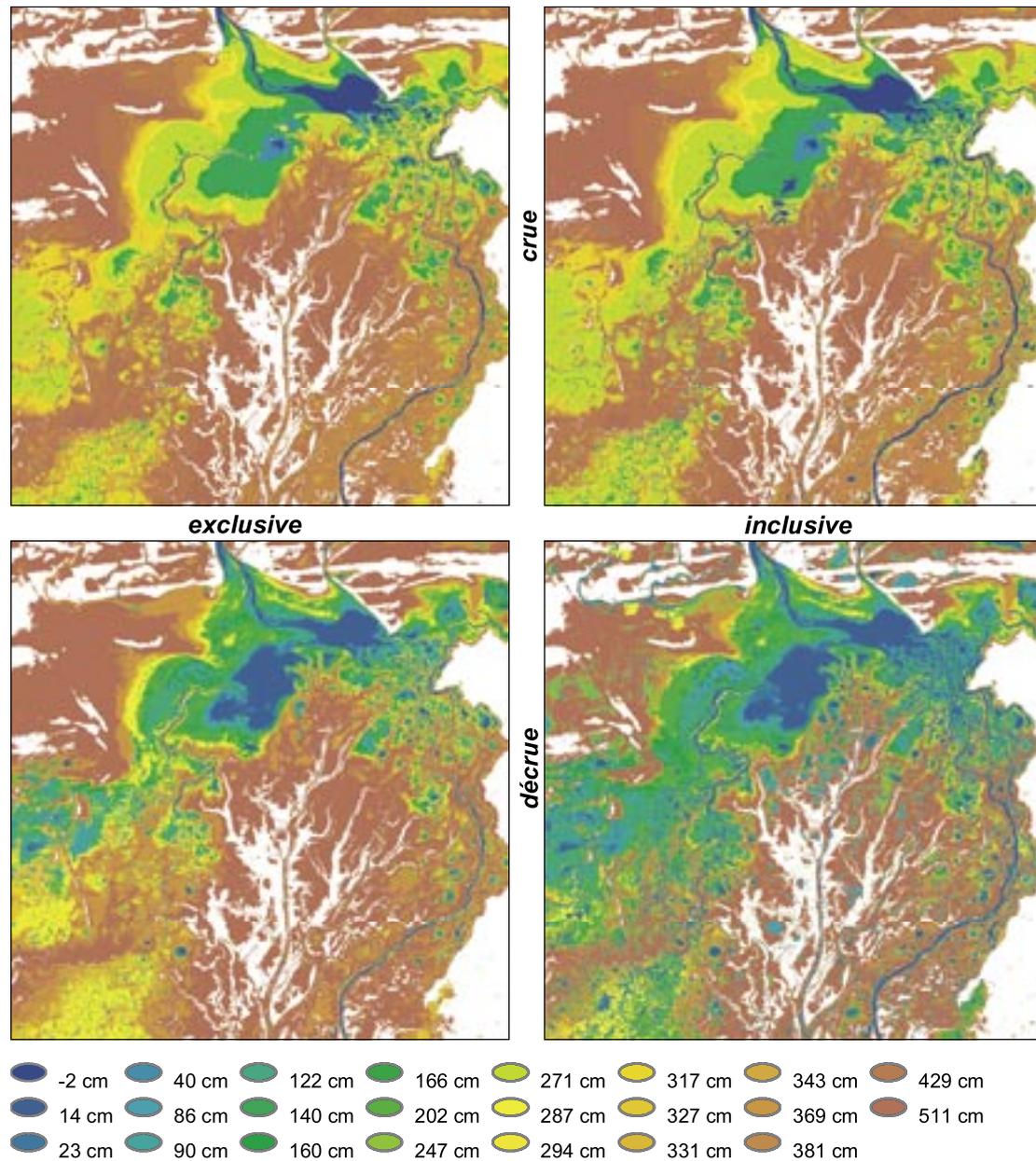


Fig. 3.7. Composite water maps of Lac Débo and Lac Walado and the area south of it (same area as shown in Fig. 3. 6), based on the water maps (Fig. 3.5), given separately for incoming water (up) and receding water (down) and according to the exclusive model (left) and inclusive model (right).

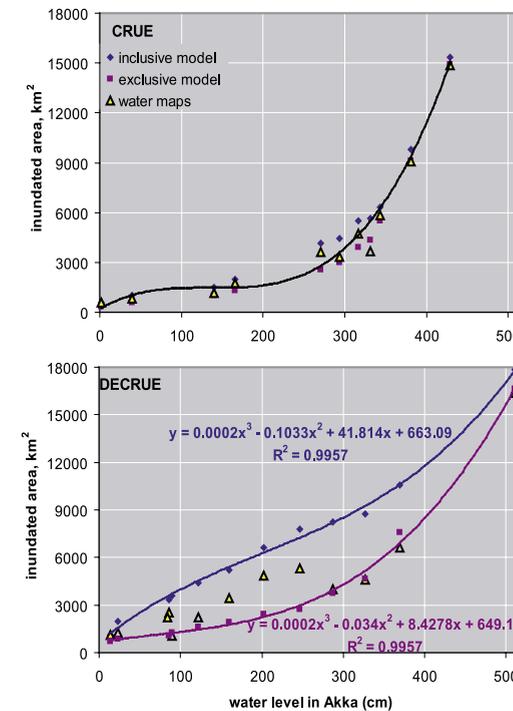


Fig. 3.8. Inundated area (km²) as a function of the water level during incoming water (up) and receding water (down). The inundated area, such as derived from the satellite images (Fig. 3.5), is shown with yellow triangles (full coverage) and open triangles (only southern part of the Delta). The surface areas according to the inclusive and exclusive mode are given. The deviation between the two models is small during incoming water, but large during receding water. The regression line is based on the average of both models. The exclusive model for incoming water describes the situation with little local rain. If there has been a lot of rainfall in the Inner Delta, the inclusive model is more appropriate. The exclusive model for receding water refers to years with a very low peak level of the flood, during which many isolated lakes have not been filled by water. The inclusive model refers to a year with a high flood, but will always be an overestimation of the flooded surface. The regression equations of both models are shown.

separate algorithm, in which images with a comparable water level are used to estimate the area being covered by water in the northern Delta.

Fig. 3.8 shows that the surface area being flooded is about the same for incoming and receding water, at least according to the exclusive model. This model shows the flooded area connected to the river and considers nearly all area not connected to the river as dry. The difference between inclusive and exclusive is small for the cruce. This suggests that the effect of rainfall is, generally speaking, limited. A common equation based on the average values of both models results in:

Incoming <511 cm:

$$km^2 = 0.0005cm^3 - 0.215cm^2 + 28.807cm + 194.36$$

(R² = 0.995)

where:

$$km^2 = \text{total inundated area in the Inner Niger Delta}$$

$$cm = \text{water level in Akka.}$$

In contrast, the difference between the inclusive and exclusive model is large for the décrue. This shows that many more areas remained covered by water if the water level was high in the months before. Zwartz et al. (2003) determined the surface area being connected and disconnected to the river system for each satellite image. Their analysis shows that during the décrue about 50% of the inundated area is disconnected to the river by the time the water declined to a level between 100 and 300 cm at Akka. In a dry year, with a low maximum water level, such as in 1984, most of these areas remained dry all year round. Fig. 3.9 shows that the actual surface measurements of 1984 coincide with the surface area according to the exclusive model. For all recent images, however, the actual surface measurements are in between the inclusive and exclusive model estimates. In other words, the surface area is always overestimated in the inclusive model, even when the water level has been very high. Hence the best average prediction of the flooded surface at receding water would be to take the mean of both models:

Receding <511 cm:

$$\text{km}^2 = 0.0002 \text{ cm}^3 - 0.0687 \text{ cm}^2 + 25.121 \text{ cm} + 656.14$$

$$(R^2 = 0.995)$$

where:

km² = total inundated area in the Inner Niger Delta

cm = water level in Akka.

3.3

For our selection of satellite images the maximal water level in Akka is 511 cm, but it has been as high as 625 cm. Therefore, we assume that at such a high water, the inundation area is as extensive as indicated on the topographical maps, i.e. 31,000 km² (Fig. 3.1). Still, the area being inundated at a certain moment must have been smaller because a part of the inundation area in the southeast will already be dry while the flood is still covering the areas in the northeast. Possibly, the inundation area never exceeded 25,000 km² at a level of 625 cm in Akka.

When equation (3.3) of incoming water is extrapolated to a water level of 625 cm in Akka, the predicted water level is 56,300 km², thus 2.25 times higher than the expected 25,000 km². The exponent is less steep for receding water (equation 3.4), but even here the extrapolated surface at 625 cm, would be 38,300 km², thus 1.53 times too high. When a flooded area of 25,000 km² at a water level of 625 cm is added to the data of the incoming water, it is clear that the relationship have to be described with a S-curve. When the same is done for receding water, equation (3.3) change not much into:

Receding <625 cm:

$$\text{km}^2 = 0.00007 \text{ cm}^3 - 0.0032 \text{ cm}^2 + 13.408 \text{ cm} + 1044.2$$

$$(R^2=0.997)$$

3.4

Equation (3.4) was used to derive the surface of the surface of the inundation zone for the peak water level in Akka since the start of the measurements in 1956. Fig. 3.9 shows the variation in the peak water level and the corresponding surface of the inundation zone. Since the relationship between flood level and inundated surface is not linear, the variation in surface is larger than in water level. The maximal water level since 1956 was measured in 1957 (i.e. 625 cm) and the lowest peak level occurring in 1984

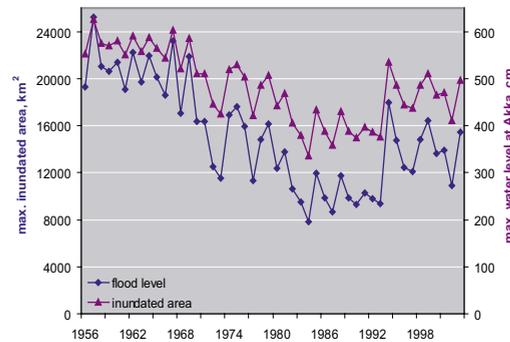


Fig. 3.9. Year-to year variation in peak flood level (Akka, cm; right scale) and maximal inundated surface (km², left scale)

was nearly twice as low (i.e. 336 cm). The inundated surface in 1957 amounted to 25,000 km² and was more than three times lower in 1984 (i.e. 7,800 km²).

The digital elevation model per 10 cm

The disadvantage of the given composite water maps as presented in Fig. 3.7 is that the intervals between the different water levels are unequal. To make a water map with equal intervals, the water line is interpolated at a water level of each additional 10 cm (i.e. 10, 20, 30 cm, etc.), using a pycnophylactic interpolation technique (Tobler 1992). The script can be downloaded from the website of ESRI (<http://arcscrips.esri.com>). A nice image of how the algorithm is working can be found on: <http://www.ncgia.ucsb.edu/pubs/gdp/pop/pycno.html>. Some other applications can be seen on: <http://mywebpages.comcast.net/ldecola/baltwash/autocarto/>. We ran the interpolation with 60 iterations and generated composite water maps per 10 cm. Fig. 3.10 shows the water map per 50 cm for incoming water. Fig. 3.11 and Fig. 3.12 present the same type of water map for receding water according to the inclusive and exclusive model, respectively.

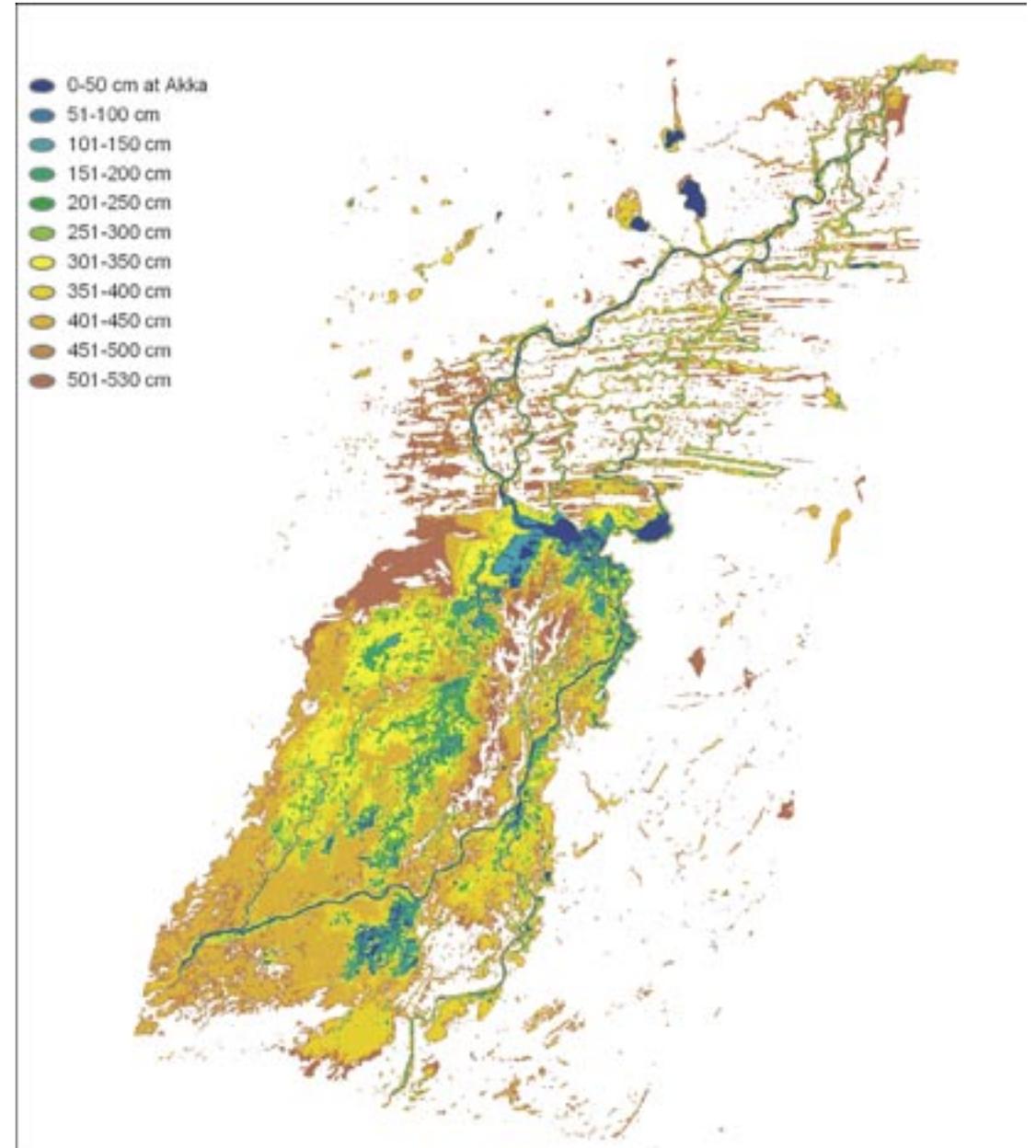


Fig. 3.10. Flooded area in the Inner Delta during incoming water as a function of the water level in Akka, based on the water maps given in Fig. 3.5, using the inclusive model to combine the maps and an interpolation technique to construct the flooded area per 10 cm. The map shows the change in flooded area per 50 cm.

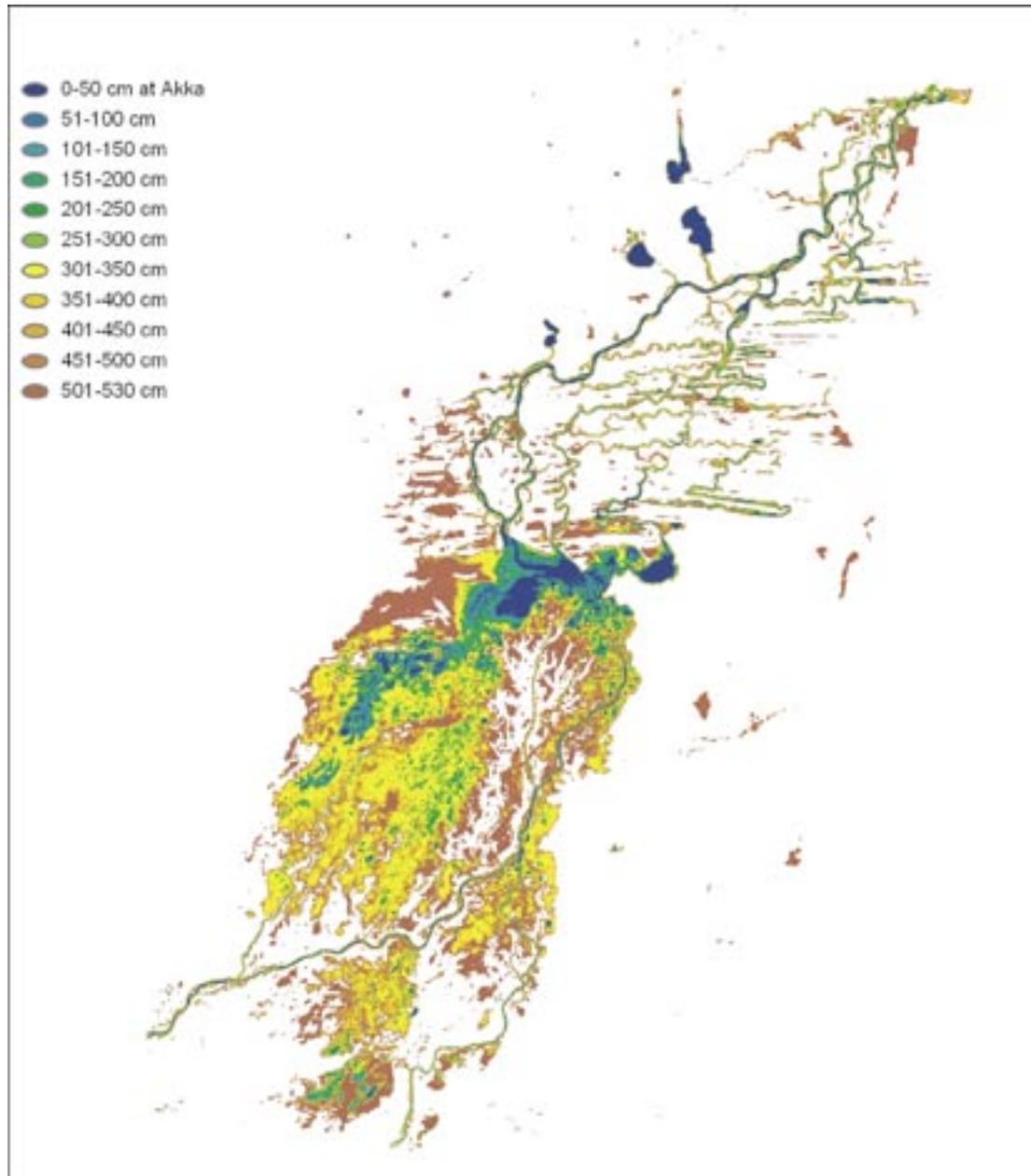


Fig. 3.11. Same map type as Fig. 3.10, but for receding water, using again the exclusive model to combine the water maps. This is the situation when the maximal water level has been very low.

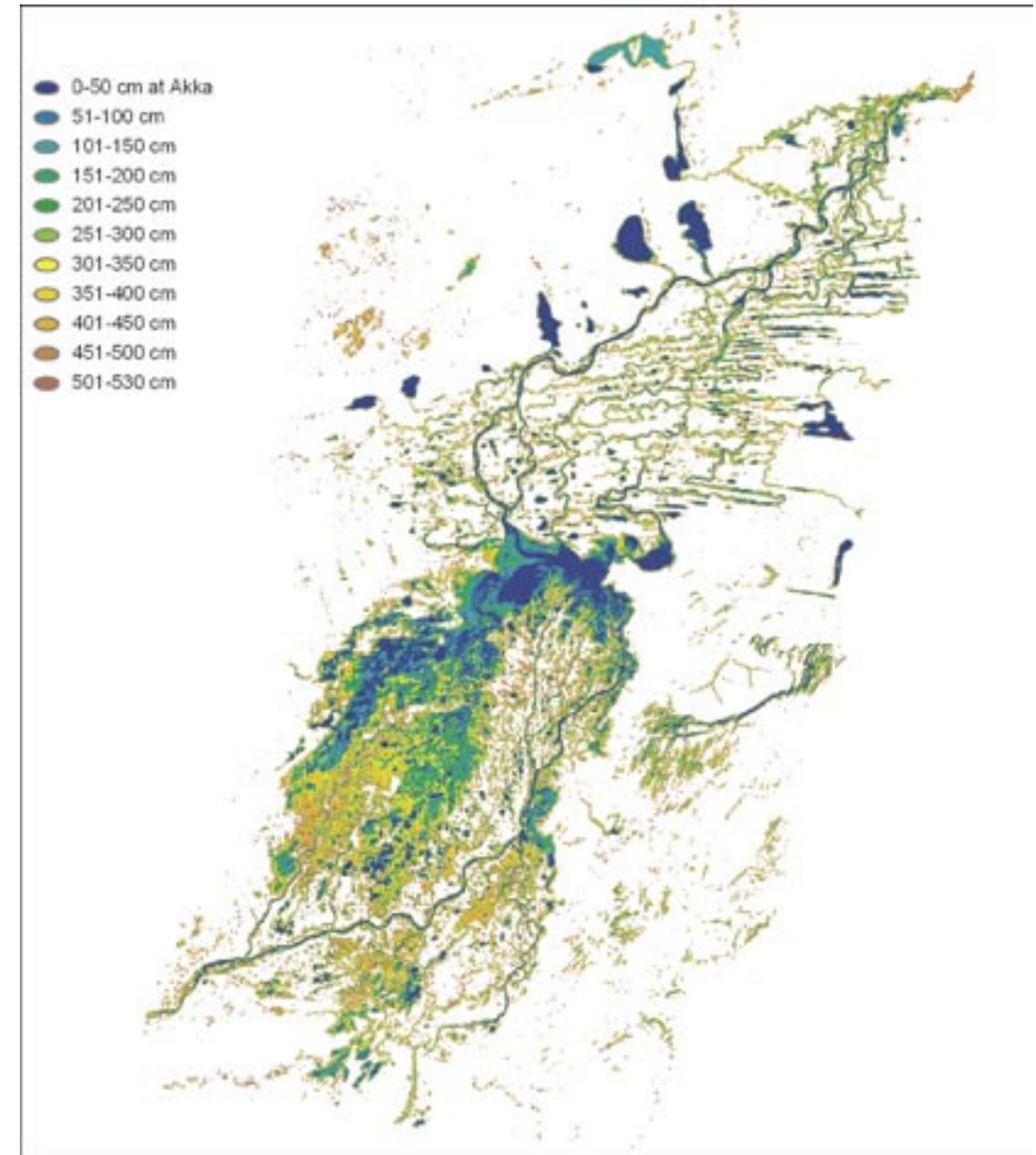


Fig. 3.12 Same map type as Fig. 3.10 and Fig. 3.11 for receding water, but using the inclusive model to combine the water maps. This is the situation when the maximal water level has been very high.

3.6 Impact of irrigation and reservoirs

Similar to chapter 2, the study followed two approaches to determine the impact of the above-mentioned human activities on the river discharge. The first method is based on the water balance approach of the RIBASIM model. The second approach consists of a statistical analysis of the interaction between dams, reservoirs and the river flow in the Inner Niger Delta. Both models can be used in a complementary manner.

Water balance approach

As explained in chapter 2, irrigation and storage reservoir affect the river flow into the Inner Delta. Irrigation by Office du Niger reduces the river discharge. The effect of the Sélingué dam is seasonal and therefore less straightforward. The river flow is reduced during the crue while river discharge is larger during the dry period (see Figures 2.17 to 2.19). Figure 2.22 indicates that the future Fomi dam is expected to have a much larger impact on the river flow than the Sélingué dam.

The effect of the reduced river flow into the Inner Niger Delta can be analysed in two ways. Since the water level and river flow are measured at different hydrological stations, it is possible to do a statistical analysis to predict the downstream water level and river flow from upstream data. This analysis will be described in the section 3.7. The second approach is to use the water balance model RIBASIM. This approach is described in this section.

The SW part of the Inner Delta is inundated 1 to 2 months earlier than the NE part. This seriously complicates a water balance study for the entire area. That is why Passchier et al. (2004) split up the Inner Delta into eight zones (Fig. 3.13). In this stage, the areas

west and north of basin called “South of Diré” have been ignored. Passchier et al. (2004) used the water maps derived from the satellite images shown in Fig 3.5 to calculate the relationship between water level and water surface during incoming and receding water for each of the eight zones (Appendix 4). Subsequently, this information is used to derive the relationship between water level and water volume.

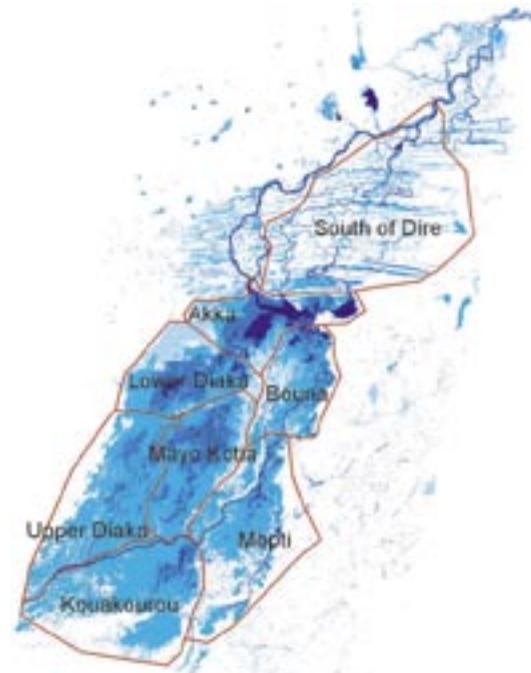


Fig. 3.13. Flood plains of the Inner Niger Delta, split up in eight regions. The different blue tints show the flooded area during incoming water at 23, 140, 317, 429, 511 cm (see Fig. 3.5).

The most difficult part of the water balance study is to estimate the actual flow between the eight zones. The delay of the high water wave through the Delta depends on the flood level. If the flood is low the delay is 1 to 2 months, but it may be a month longer if the flood is high (Quensière et al 1994a, Orange et

al. 2002a, Picouet et al. 2002, Zwarts & Diallo 2002). The model calculates the discharge by multiplying a fixed cross section with varying average flow velocities. Finally an average flow velocity of 0.08 m/s results in a delay of ca 1.5 month.

The next step involves the estimation of how the water flow through the different zones is divided. The final bifurcation ratios were: 25% of the water flows through the Diaka, 30% through the Moya Kotia and the rest through the Niger. Moreover it is assumed that 20% of the Bani flow bifurcated into the inundation area between the Bani and the Niger, near Kouakourou.

On the basis of the above estimates (see also Appendix 4), the inundation process can be simulated. Among others, the simulation allows for the approximation of the effect of a reduced river flow into the Niger. The reservoirs upstream of the Inner Delta are also taken into account in the RIBASIM model.

As described in chapter 2.5, two runs of the RIBASIM model have been included in this study. Run ‘1’ describes an unrealistic situation in which no management of the water level in the reservoir will take place. Therefore, this chapter only evaluates run ‘2’, which describes the effect of the dams during

firm production of electricity and thus full management of the reservoir.

Fig. 3.14 shows the effect of the Office du Niger and the combined effect of Office du Niger and Sélingué on the flood level. The flood level is reduced by 5 – 25 cm due to the irrigation by Office du Niger. The impact of Office du Niger is most distinct in January and February. Due to the releases of Sélingué, the water level is raised more than 50 cm between January and April. Therefore, the combined effect of irrigation and the Sélingué is that the water level is 30 cm higher in these months. Sélingué lowers the flood level in the period of August to October with an additional 10–20 cm. As shown more explicitly in Fig. 3.15, the impact of both structures varies across the year. Without the presence of Sélingué and Office du Niger, the flood level would be 20 cm higher in August and September and 30 cm lower in the period January to March.

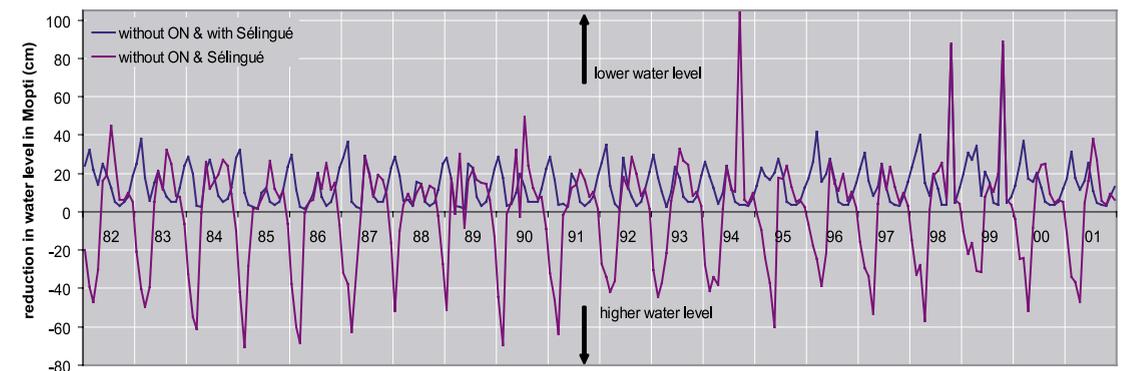


Fig.3.14. Reduction of the flood level at Mopti (cm) due to irrigation by Office du Niger and the combined effect of this irrigation and the Sélingué reservoir. Note that a decrease of the water level is positive and an increase negative. Source: WLIDelft Hydraulics.

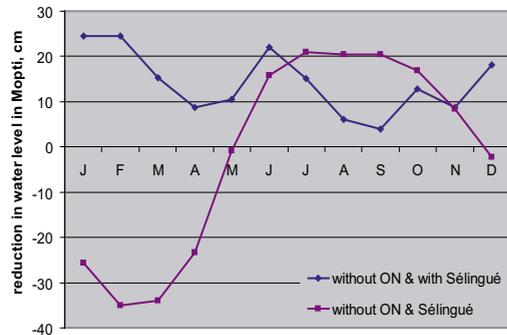


Fig. 3.15. Seasonal variation in impact of Office du Niger and Office du Niger + Sélingué on the flood level at Mopti; same data as Fig. 3.14.

Statistical approach

The flood level in the Inner Delta can accurately be predicted from the flow of the Niger and Bani into the Inner Delta using statistical analysis. These predictions are based upon a comparison of different time series of river flow and water level. This information will be used to check the water balance model described above.

River flow and flood level

To indicate the effect of irrigation and reservoirs on the Inner Delta, it is crucial to capture the relationship between river flow into the Inner Delta and water level in the Inner Delta itself. Since Akka is situated in the middle of the Delta, this hydrological station is selected to describe the fluctuation in water level.



It takes approximately one month before the water entering the Inner Delta reaches Akka. Therefore, we compare the average water level per month in Akka with the average monthly flow of the river entering the Inner Delta. The flow is determined by the sum of the river discharge at Ké-Macina along the Niger at the entrance in the Inner Delta and at Douna along the Bani.

When the monthly water level in Akka is plotted against the river flow of Niger+Bani the month before, a cloud of dots appears which reveals no relationship whatsoever. By splitting the data by month, however, the relationship between water level and river flow becomes distinct. Yet, the relationship differs by month (Fig. 3.16). Because the power function for August, September and October is the same, these three months are joined together. The regression shows a very close fit. Therefore, the water level during the crue can be predicted accurately from the river flow.

Fig. 3.6 also shows the relationship between river

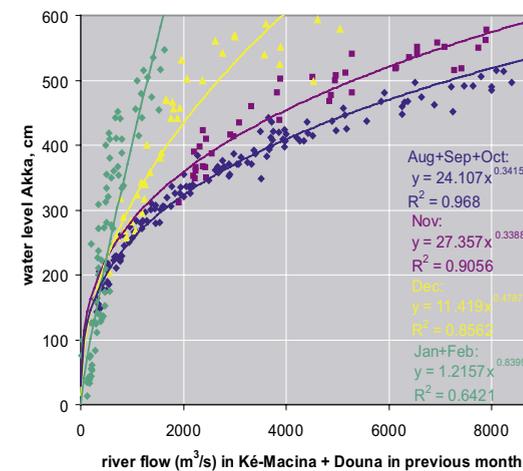


Fig.3.16. Water level in Akka as a function of the river flow in Ke-Macina and Douna in the preceding month. All data are based on daily measurements, but are averaged per month. The figure shows the relationship separately for four periods. The regression equations of the power functions are also given, as well the explained variance (R²).

discharge and water level for other months. The fit is not as good as for the period August-October. The graph seems to indicate that later in the year, the same river flow goes with a higher water level than earlier in the season. The explanation is that the flow in the preceding months has already flooded the Inner Delta and that the river flow in a later month only adds little extra water to the large existing water body. In other words, the water level in Akka depends on the flow entering the Inner Delta one, two, three, four, or more months ago. A multiple regression revealed that the water level in October can perfectly be predicted from the flow in September. The flow in July and August has no effect on the water level in October. In contrast, the water level in November depends on the river flow in August, September and October. The same holds for the water level in December, which depends on the water flow in September, October and November. The equations that represent the relationship between the water level in Akka in November or December (cm) and the river flow of Bani+Niger (m³/s) in three foregoing months, are given below. Note that the very high R² shows that the fit is very good.

November
 $cm = \exp(2.775 + 0.164 \cdot \ln(O) + 0.173 \cdot \ln(S) + 0.066 \cdot \ln(A))$
 (R² = 0.969), 3.5

December
 $cm = \exp(0.793 + 0.216 \cdot \ln(N) + 0.122 \cdot \ln(O) + 0.306 \cdot \ln(S))$
 (R² = 0.970) 3.6

where:
 cm = The water level in Akka in November or December
 A, S, O or N = The river flow of Bani+Niger (m³/s) in August, September, October or November.

Impact of irrigation and reservoirs on flood level

The power function of August to October as shown in Fig. 3.16 and the two separate functions of November and December presented in equations (3.5) and (3.6) can now be used to calculate the water level from the river flow in the preceding month. The calculation is carried out for the actual

monthly river flow data as well as for the reconstructed river flows representing the different scenarios introduced in chapter 2. These scenarios include the river flows in the absence of irrigation, without the dam at Sélingué and with the presence of the Fomi dam. Subsequently, the three reconstructed series of monthly water levels are plotted against the actual monthly water levels. The results are shown in the first few columns of Table 3.4. The fit of the regression analysis is extremely good.

The regression equations can now be used to indicate the effect of the irrigation and the Sélingué and the future Fomi reservoir on the water level in Akka. The impact of the three structures, which have been depicted on the right hand columns of Table 3.4, depends on the water level, but also varies between the months:

- Office du Niger: Office du Niger reduces the water level in Akka by about 10 cm if the water level is

250 cm and this gradually decreases to 5 cm if the water level is as high as 550 cm. The water balance study described in the previous section showed that Office du Niger lowered the water level by 5–10 cm, thus in full agreement with the statistical prediction.

- Sélingué: Sélingué reduces the flood level in September–December by another 15–20 cm, again exactly the same outcome as the water balance study (Fig. 3.15). The months do not differ for moderate and high flood level, but if the water level is low, the impact of the Sélingué is twice as large in September as in December. Such a difference is to be expected since the amount of water withheld by the reservoir is large at the start of the flood wave and gradually decreases in later months (Fig. 2.18).
- Fomi: The effect of the Fomi reservoir has been simulated by assuming that the flow reduction

Table 3.4 The water level in Akka (cm) with no irrigation by Office du Niger and no Sélingué reservoir ('without ON & Sél'), with no irrigation by Office du Niger but Sélingué still present ('without ON & with Sél'), and with irrigation by ON, and two dams Sélingué and Fomi dam ('present + Fomi') as a function of the present water level in Akka (cm). The linear function is given for four months (a = constant, b = slope); R^2 = explained variance. The deviation between the predicted water and the present water level, according the regression equation, is shown in the right columns; no values are a given if the water level is out of reach of the actual measurements

Scenario	Month	a	b	R ²	Water level Akka (cm) present situation			
					250	350	450	550
Without ON & Sél	Sept	43.5	+0.939	0.938	28.3	22.2		
	Oct	43.2	+0.937	0.981	27.5	21.2	14.9	
	Nov	43.5	+0.942	0.999	29.0	23.2	17.4	11.6
	Dec	32.1	+0.974	0.998	25.6	23.0	20.4	17.8
With ON & without Sél	Sept	13.4	+0.974	0.999	6.9	4.3		
	Oct	14.7	+0.975	0.999	8.4	5.9	3.4	
	Nov	16.9	+0.975	0.999	10.7	8.1	5.6	3.1
	Dec	19.8	+0.975	0.999	13.6	11.1	8.6	6.0
Present + Fomi	Sept	-155.6	+1.231	0.938	-97.9	-74.8		
	Oct	-119.2	+1.178	0.839	-74.7	-56.9	-39.1	
	Nov	-106.4	+1.130	0.974	-73.9	-60.9	-47.9	-34.9
	Dec	-48.4	+1.020	0.974	-43.4	-41.4	-39.4	-37.4



would be in agreement with Sélingué, but than 2.9 times larger. Note that 2.9 is the ratio between the water volume of Fomi and Sélingué. The impact of Fomi on the flooding of the Inner Delta is significant. Even at a flood level of 450 cm and higher, the water would be reduced by 35–40 cm. The reduction would increase to 50–100 cm at a lower flood level and earlier in the season.

3.7 Annual flooding statistics

There is a large year-to-year variation in the flooding of the Inner Delta. The next chapters will investigate to what degree the ecological and economical values of the Inner Delta depend on the degree of flooding. By determining this relationship, we can estimate the downstream impacts for the economy and the ecology in the Delta of a decline in river flow caused by upstream irrigation and reservoir management.

To determine the link between flooding and downstream impacts, we first need to find out which measure of flooding can be used. There are at least five ways to describe the annual fluctuation in flooding: (1) maximum flood level, (2) maximum inundated surface, (3) duration of flooding, (4) annual or (5) maximal flow of the river entering the floodplains. Each of these measures can be described in several ways. For instance, the flood level of the Inner Delta has been measured at several hydrological stations. All these variables are highly correlated, since the river flow determines the maximal flood level as well as the surface of the flooded area.

Second, we also need to find out which flooding measure reveals the strongest link with the annual production of fish, livestock or rice. This measure is likely to differ between the various sectors. Fish production, for example, is probably best explained by the surface of the inundated area and the duration of the flooding. Rice production, on the other hand, is expected to depend mostly on the maximal flood level and the time of year at which the rice fields are flooded. Finally, the production of cattle may depend mainly on the production of a species of floating grass (i.e. 'bourgou'), which in turn depends on the maximal flood level and the duration of flooding.

This section provides a short overview of the inter-relationships between the different flooding statistics. In the next section, the effect of Sélingué, Office du Niger and the planned Fomi dam on the different series of data will be indicated. An overview of all measurements and derived values is provided in Appendix 5.

River flow and flooding

Fig. 3.16 already showed how the flood level in September and October was determined by the amount of water entering the Delta one month earlier. Later in the season, the flood level is highly dependent on the river discharge in the three foregoing months (Table 3.4). The maximal flood level is also closely related to the water flow in the preceding months. When the maximal water in Akka is plotted against the river discharge of Niger and Bani combined, the best fit is generated by taking the flood level as a function of the river flow in September (see Equation 3.7):

$$\text{cm} = 17.762 * \text{flow}^{0.3872} \quad 3.7$$

($R^2 = 0.8902$)

where:

cm = maximal water level in Akka

flow = river discharge (m^3/s) for Ké-Macina + Douna in September.

The fit improves even further if the flood level is plotted against the average river discharge in August, September and October:

$$\text{cm} = 16.801 * \text{flow}^{0.4038} \quad 3.8$$

($R^2 = 0.9313$)

where:

cm = maximal water level in Akka

flow = average river discharge (m^3/s) for Ké-Macina + Douna in August-October.

The flooded surface is closely related to the flood level (section 3.4). When the inundated maximal surface for the different years is plotted against the river flow, the function becomes:

$$\text{km}^2 = 24.497 \text{flow}^{0.7651} \quad 3.9$$

($R^2 = 0.9245$)

where:

km^2 = inundated surface on the area indicated in Fig. 3.9-3.11;

flow = average river discharge (m^3/s) for Ké-Macina + Douna in August-October.

The annual peak river discharge, flood level and flooded surface are highly correlated. In a statistical sense, the three variables describe the same process.

Flood level and flood duration

The flood level is closely related to the duration of the flooding period. In a year with a high peak flood level in the Inner Delta, the flood lasts four months longer than in a year with a low flood. As shown in Fig. 3.17, the wave comes one month earlier and continues for an additional three months. To construct this figure, all daily measurements since 1944

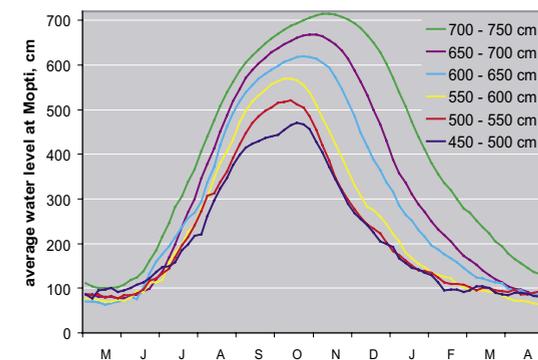


Fig. 3.17. Average daily water level in Mopti during the hydrological year (1 May - 31 April) for six different flood levels

were subdivided into six categories on the basis of the highest water level in each year. There are three years with a maximum flood between 450 and 500 cm (1984/5, 1987/8, 1993/4). For these three years the average water level per date is calculated. The same is done for the other categories: 500 – 550 cm ($n = 6$), 550 – 600 cm ($n = 9$), 600 – 650 cm ($n = 7$), 600 – 650 cm ($n = 20$) and 650 – 700 cm ($n = 12$). Besides the fact that the flood wave lasts longer with a higher flood, Fig. 3.17 shows that the peak level is reached more than a month later if the flood is high. Note that Appendix 5 provides the maximum water level per year for two stations (i.e. Akka and Mopti) as well as the specific date of this peak level. Details about of the annual variation in the dates of inundation are presented by Zwarts & Diallo (2002).

A surface area in the central Inner Delta at a level of 300 cm, relative to the gauge of Akka, is covered by water for 41% of the year. Due to variations in flood level, however, the coverage by water varies between 15% and 65% of the year (Zwarts & Diallo 2002). Fig. 3.18 shows the relationship between

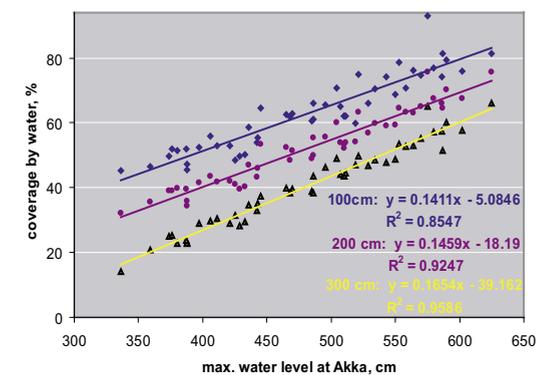


Fig 3.18. Relationship between maximal water level and flooding period of the floodplain at three different levels, 100, 200 and 300 cm, relative to the gauge of Akka (% of the hydrological year: 1 May – 30 April the next year). Data is based on all daily measurements in 1956-2004; each dot represents a year.



flood duration and maximum water level for areas at a level of 100, 200 and 300 cm, respectively. The data are calculated for Akka in the central Delta, using the daily measurements of the water level. The positive slope of the three curves indicates a strong relationship between the maximum water level and the flood duration. In years with an extremely high flood, a part of the Inner Delta is still flooded at the beginning of the next hydrological year, which starts on May 1st. Therefore, the water level in the previous year partly explains the variation along the regression lines shown in Fig. 3.18. This variation is small, however. Hence, the conclusion remains that the maximal flood level and the flood duration are statistical interchangeable.

3.8 Scenario analysis on inundation area

Section 3.5 described the effect of irrigation and reservoirs on the flood level. The outcome of water balance calculations coincides with the statistical analyses regarding the effect of the irrigation and the Sélingué reservoir on the flood level in the Inner Delta. Because the two approaches do not differ, only the statistical analysis will be applied in the forthcoming chapters.

Besides the original data on the flood level, the river flow and the water use, Appendix 5 also provides an overview of the equations used to predict the monthly water levels and the maximum water level. When the monthly water use by Office du Niger and the Sélingué reservoir is added to the current river discharge, the reconstructed discharge can be entered into the equation of flood level against river flow to derive the flood level. In this way the average water level in October and November for the four scenarios is calculated. Although these details are not provided in Appendix 5, flood levels can be calculated with the described equations. The same Appendix also describes how the maximum water level in the four scenarios is derived from the predicted water levels in November.

The relationship between the water level in Akka and the flooded surface in the Inner Niger Delta has been estimated in section 3.5 (see equation 3.4). This equation is now used to calculate the surface of the inundated area for the four scenarios. Fig. 3.19 shows the impact of irrigation and reservoirs on the maximum water level at Akka and the maximally inundated area. Without Office du Niger the inundated area would be 300 km² larger and without Sélingué another 600 km². The absolute reduction in surface is about the same in September, October and

December. The Fomi dam has a much larger impact. Compared to the present situation, the inundated surface declines by 2,000 to 2,300 km², implying a reduction of the flooded area of 48% in September and 25% in following months.

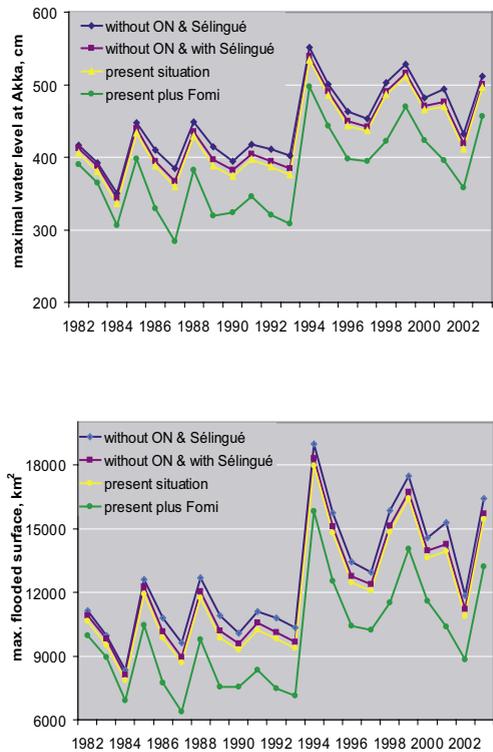


Fig. 3.19. Year-to-year variation in the maximum water level in Akka (top) and the surface of the maximum inundated area in the Inner Delta (bottom). The effect of the irrigation by Office du Niger and the Sélingué and future Fomi reservoir are indicated