A & W ECOLOGISCH ONDERZOEK

Will the Inner Niger Delta shrivel up due to climate change and water use upstream?

A&W-report 1537

commissioned by

Wetlands International

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L.Zwarts

Photograph Front
The Inner Niger Delta during a high flood, November 2009, Leo Zwarts

L.Zwarts 2010
Will the Inner Niger Delta shrivel up due to climate change and water use upstream? A&W rapport 1537
Altenburg & Wymenga ecologisch onderzoek, Feanwâlden

The study was done in the framework of the Wetland & Livelihoods Project: GIRE (Gestion integrée de Resources naturelles) dans le basin du Niger en amont de Taoussa)

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Contents

1 Introduction

The Inner Niger Delta in Mali is huge. On topographical maps from the 1960s, a total surface of 36,000 km^2 is designated as floodplain. When the water level starts to rise in the southwestern part of the Delta in July, the plains in the northeast are still dry. By the time that the northern plains become flooded two months later, the water level is already receding in the south. The area covered by water at any one time amounts to 25,000 km^2. Such a large flood extent is only possible when the combined inflow of Niger and Bani, the major tributaries, exceeds 55 km^3 in the rainy season. In most years, the inflow is smaller. During the disastrous drought in 1984, the inflow was only 15 km^3, and the flood extent did not exceed 5500 km^2.

The Inner Niger Delta not only stands out because of its size, but also because of its hydrological dynamics. Between July and December the water rises by more than 6 m in wet years, and declines by the same amount in the following months. In extremely dry years, however, the flood level rises by only 3m.

This large annual variation in flooding has a direct and governing impact on the natural resources in the Inner Niger Delta. The lower the flood, the lower the production of fish, rice and *bourgou* grass. The impact of a reduced river inflow on the ecological and economic functions of the Inner Niger Delta may be quantified, since the production of these natural resources is strongly related to the flooding, and the flooding is dependent on the inflow of the rivers. Zwarts *et al.* (2005) used this approach to evaluate the net present value (NPV) of the dams and irrigation in the Upper Niger Basin, taking into account these negative downstream impacts.

When the climate will change in the Sahel, this will have an impact on the flooding of the Inner Niger Delta and, therefore, also on its ecological and economic functions. It would be misleading, however, to take the present hydrological circumstances as starting point for an extrapolation of the impact of the climate change on the flood extent. It would be misleading, since even without any change in the climate, the Inner Niger Delta will show a declining flood extent, due to new dams and extended irrigation schemes upstream in the Upper Niger Basin. That means that before a sketch can be given of the impact of a climate change on the flood extent of the Inner Niger Delta, it is necessary to start with a description of the expected decline in the flood extent of the Inner Niger Delta due to new dams and irrigation schemes upstream.

This report evaluates the human-driven changes in the hydrology of the Upper Niger and the possible additional impact of a climate change. The data sets used by Zwarts *et al.* (2005) are re-analysed and updated (as far as possible) for recent years:

- annual rainfall in the Upper Niger Basin,
- annual river discharge of Bani and Niger upstream of the Inner Niger Delta,
- water use (dams and irrigation schemes upstream of the Inner Niger Delta),
- maximal annual flood extent of the Inner Niger Delta

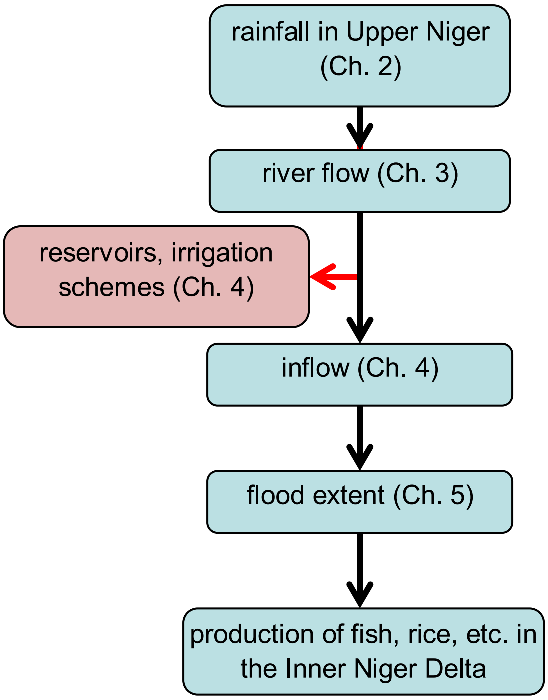

Figure 1-1 - If due to a climate change the rainfall will decline (Chapter 2), it will cause a reduction of the river discharge (Chapter 3), of which anyway an increasing part is taken for irrigation and filling reservoirs (Chapter 4). As a consequence, the flow of the rivers at the entrance of the Inner Niger Delta will decline, by which there will be less inundation (Chapter 5) and, consequently, a loss of economic and ecological functions.

To answer the question whether a climate change will modify the livelihood for the 1.5 million people living in the Inner Niger Delta, it is necessary to analyse a chain of factors (Fig. 1.1):

- impact of rainfall in the catchment area on the discharge of the Niger and Bani Rivers.
- additional impact of existing and planned human infrastructures in the Bani and the Niger upstream of the Inner Niger Delta on the inflow of both rivers into the Inner Niger Delta.
- relationship between the discharge of rivers and the flood extent of the Inner Niger Delta,
- impact of the declining flood extent on the natural resources and the ecological values of the Inner Niger Delta.

This report starts with a description of the Sahelian climate, how it has changed already and how it possibly will change (Chapter 2). Chapter 3 describes the relationship between rainfall in the catchment area and the river flow, and Chapter 4 the impact of dams and irrigation schemes upstream of the Inner Niger Delta on the river flow. Chapter 5 shows how the flood extent of the Inner Niger Delta has declined already due to long-term decline of the rainfall in the catchment area and also due to all human infrastructures. The same Chapter also shows how the Inner Niger Delta will further decline due to new dams and enhanced irrigation schemes. Finally, Chapter 6 takes all information together to arrive at some conclusions regarding the future loss of ecological and economic functions of the Inner Niger Delta.

This study was commissioned by Wetlands International and performed in the framework of the project ―GIRE (Gestion integrée de resources naturelles) dans le basin du Niger en amont de Taoussa‖, - a part of the ―Wetland & Livelihoods‖ programme

2 The climate in the Sahel

Within the Sahel zone, there is a steep increase in rainfall over a latitudinal range of only 500 km, from less than 100 mm annually in the north to more than 2000 mm in the south (Fig. 2.1). This is due to the Intertropical Convergence Zone (ITCZ), a belt of low pressure hugging the equator. Ascending warm and moist air immediately north and south of the equator is sucked into the ITCZ and transported at altitudes of 10-15 km further north and south of the equator. To compensate for the rising air in the convergence zone, the northern flow descends in the desert zone, normally centered between 20° and 30°N. Descending air heats up as the pressure increases, becoming undersaturated with water vapour and leading to the typical clear skies and general aridity of the Sahara. This air circulation system, known as the Hadley cell, is affected by the rotation of the earth, which ensures that the prevailing wind over the Sahara, the Harmattan, always blows from the northeast and not from the north. The Harmattan, a well-known phenomenon in West Africa, brings dry, dusty air to the Sahel and further south. When, during the northern summer, the sun is overhead in the Sahara, a low pressure belt forms over the Sahel, bringing clouds, rain, frequent thunderstorms and a monsoon from the SE.

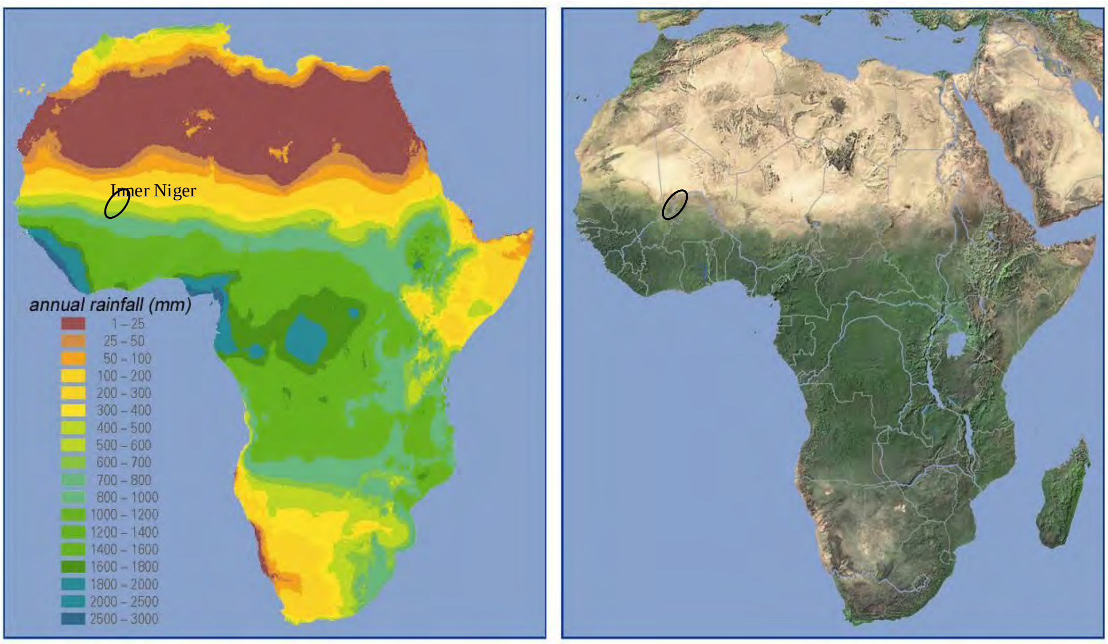

Figure 2-1 - The north of Africa is extremely dry and this holds –to a lesser degree– for the east and southwest. Central Africa, on the contrary, is extremely wet. South of the Sahara the transition from dry to wet south is amazing in its rapidity, with a doubling rainfall for every 160 km southward.

The ITCZ moves seasonally, according to the position of the sun, between the Tropic of Cancer (21 June) and the Tropic of Capricorn (21 December). The northern limit of expected regular rainfall in the Sahel is defined by the position of the ITCZ (with rain-bearing clouds usually lying 150-200 km south of it). The ITCZ, being the dominant rain-making mechanism over Africa, explains why northern and southern Africa are dry, and why central Africa is wet (Fig. 2.1). It also explains why rain occurs in the Sahel during the northern summer and in southern Africa six months later.

Although the tropical rain belt movement annually cycles across the equator and back again, there are year-on-year differences. These differences cause large variations in local rainfall. The Sahel not only experiences unparallelled rapid transitions from dry to wet, but also has suffered a historically unprecedented decline in rainfall since about 1960. According to Hulme (1996) and Dai *et al.* (2004), it is the most dramatic example of climate variability ever measured. Much research has been done to understand what lies at the heart of this decline.

2.1 Historical data

The longest series of daily measurements of rainfall in the Sahel is available from Senegal for Saint Louis, whose annual rainfall, registered since 1848, fluctuated more recently between 937 mm in 1921 and 59 mm in 1992 (Fig. 2.2). This huge variation nevertheless is consistent with a downward trend over the last 150 years. In the 19th century, there were but a few operational rainfall stations, initially only along the Atlantic coast (e.g. Lungi, Sierra Leone, since 1875, Banjul, The Gambia, since 1884 and Dakar, Senegal, since 1898), but later also inland (e.g. Timbuktu, Mali, since 1897 and Kaynes, Mali, since 1896).

There are, beside some meteorological stations along the Guinean Gulf, seven stations in West Africa whose measurements started before 1900 (Table 2.1). All showed a decline during the 20th century, varying between 20.1% in Timbuktu and 37.4% in Saint Louis. Not only in the Sahel, but also further south, the rainfall showed a remarkable decline: the annual rainfall in Lungi declined within 100 years by 34.8%, - from, on average, 4022 to 2621 mm (see also Fig. 2.2). Lungi was also the station showing a more or less continuous decline. The other stations show more pronounced fluctuations, being wet in the 1950s, and dry in the 1970s and especially in the 1980s.

Tabel 2-1 - The average decline of the rainfall in seven meteorological stations calculated for the long-term series shown in Fig. 2.2 (except for Gambaga in The Gambia). —since‖ = the year at which the measurements started; —n‖= the available number of years (until 2004) without lacking data; —R^2‖ = explained variance in a linear regression of rain against year; —mm/year‖ = the average decline over the years as derived from the linear regression; —1900‖ and —2000‖ rainfall in 1900 and 2000 as derived from the linear regression; —% decline‖ relative difference between rainfall in 2000 and 1900.

site	since	n	R^2	mm/year	1900	2000	% decline
Saint Louis, Senegal	1848	152	0.184	-1.53	409.3	256.3	37.4
Lungi. Sierra Leone	1875	120	0.494	-14.02	4022.9	2621.0	34.8
Banjul, The Gambia	1884	106	0.108	-3.29	1270.4	941.6	25.9
Kayes, Mali	1896	97	0.087	-1.57	765.4	608.2	20.5
Tombouctou, Mali	1897	99	0.047	-0.43	217.5	173.8	20.1
Dakar, Senegal	1898	107	0.134	-2.19	593.7	374.3	37.0
Gambaga, The Gambia	1899	71	0.106	-3.31	1229.2	898.0	26.9

The rainy period in the northern Sahel is limited to a few months, typically punctuated by local downpours and tropical thunderstorms causing considerable local variation in daily rainfall to such an extent that the tallies of adjacent rainfall stations can show remarkable differences over the entire rainy season. The existence of such large variations requires many rainfall stations to describe adequately the annual variation of rainfall over the entire Sahel. From about 1920, rainfall was measured over the entire Sahel, the number of rainfall stations reaching a peak between about 1950 and 1990, but decreasing since then.

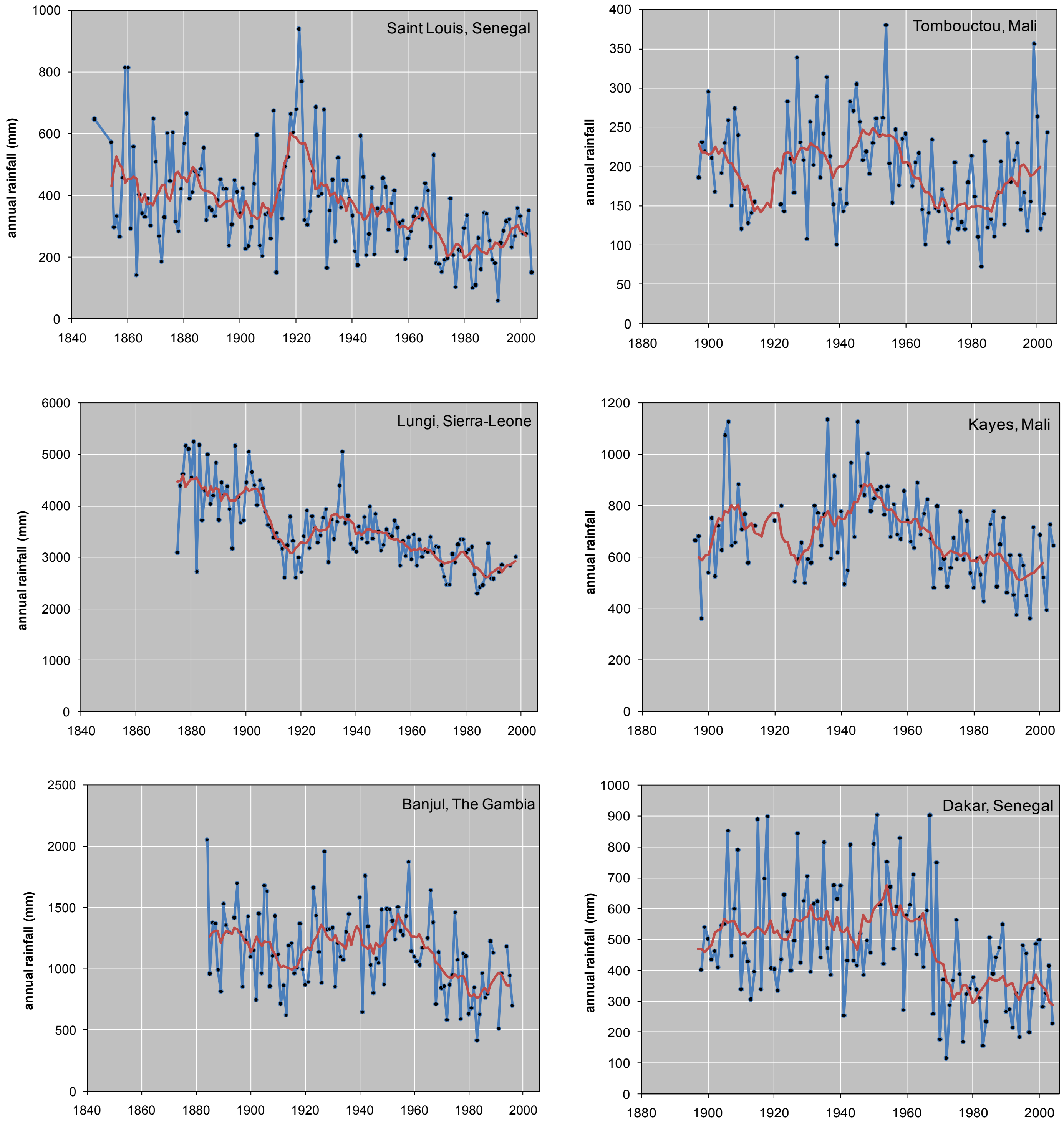

Figure 2-2- The annual rainfall in six meteorological stations in West Africa, having the longest series of measurements (all started before 1900). The red line gives the running mean over an interval of 9 years (4 year before – 4 years after the year concerned)

An analysis of all these data show that, although there are subtle differences (see also Nicholson 1986, 2005, Nicholson & Palao 1993, Balas *et al.* 2007), the year-to-year variations in rainfall in the actual Sahel zone (12-18°N), for the different latitudes are quite alike. Hence rainfall in the Sahel zone proper can be fitted adequately into a single index (Fig. 2.3).

During the 20th century, three periods of drought can be discerned: the first two, in 1900-15 and 1940-49 respectively, were followed by periods of improved rainfall. Again 30 years later, another drought occurred, but instead of the expected recovery in rainfall, there was a further decline in rainfall until 1984. This last period is called the Great Drought in Africa – *La Grande Sécheresse* (1972-1993). Since then, rainfall has gradually improved somewhat.

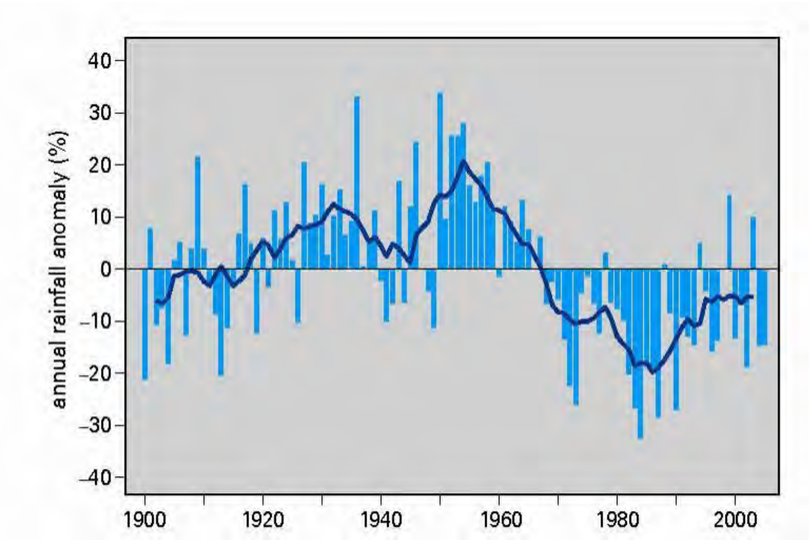

Figure 2-3 - The average rainfall in the Sahel since 1900 (bars), given as percent deviation from the average in the 20th century. The line shows the running mean calculated over an interval of 9 years (4 year before – 4 years after the year concerned).

The recent Great Drought is not unique. The dip in the 1980s looks prominent because the peak in the late 1950s was exceptionally high. The reconstructed climate history of Africa, based upon meteorological, hydrological and historical sources (Nicholson 1981b, 1982, 2001) and paleohydrological research (Gasse 1998), showed several such climate epochs over the last centuries. The Sahelian kingdoms of Ghana, Mali and Songhay developed, thrived and declined in conjunction with prolonged periods of abundant rainfall or drought (McCann 1999). The period from 800 to 1300 is thought to have been relatively wet, to be followed by a drier period from 1300-1450, a wetter period until 1800 and a gradual decline since then.

2.2 What determines the variation in the annual rainfall?

The most obvious hypothesis postulated that a reduced rainfall in the Sahel was due to a southward shift of the entire ITCZ. Indeed, the ITCZ remained further to the south in 1972, the first extremely dry Sahel year of the Great Drought between 1972 and 1992 (Fontaine & Janicot 1996). However, when long series of dry and wet years are compared, a southward shift of the ITCZ could not explain the ongoing decline of rainfall in the Sahel – there was no commensurate increase in rainfall south of the equator. Instead, it appeared that the action of the Hadley cell had become less intense (Nicholson 1981b). Further research confirmed that the atmospheric circulation in the Sahel simply had varied between dry and wet years

(Nicholson & Grist 2003). This meant that a new hypothesis was needed to explain the changing atmospheric circulation. Since 1977 it has been understood that rainfall in Africa largely depends on the sea surface temperature (*SST*) of the oceans, although the relationship is complex (Hastenrath & Lamb 1977) and remains so 30 years later (Balas *et al.* 2007). Drought in the Sahel occurs during years of relatively warm equatorial oceans and relatively low temperatures in the subtropical oceans. Given this complexity, it is not surprising that it took more than 30 years of intensive research to begin to understand the relationship between Sahel rainfall and the temperature sequences in oceans on both sides of the continent.

The first studies on the relationship between seawater temperature and Sahelian rainfall could only partly explain the recent drought in West Africa. Alternative explanations for changes in rainfall patterns were the rapid changes in land usage and vegetation cover in the Sahel and adjacent vegetation zones and that climate change had apparently caused an advance of the Sahara desert into the Sahel (Nicholson *et al.* 1998). The United Nations Convention for Combat Desertification (*UNCCD*) suggested this process had been accelerated by ‗desertification', i.e. ‗land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities'. Charney (1975) hypothesised that this loss of vegetation caused a change in the energy flux between surface and atmosphere. Later research showed that the change of climate was unlikely to be triggered by desertification itself (Nicholson 2000). This does not imply, however, that surface processes do not play a role in maintaining the drought. Wang *et al.* (2004) and Giannini *et al.* (2005) actually concluded that vegetation dynamics have enhanced the severity of the drought. The regional climate may also have been affected by dust in the atmosphere (Tegen & Fung 1995). During the drought in the 1970s and 1980s, the number of dust storms in the Sahel increased sharply (Prospero *et al.* 2002).

In conclusion, recent climate models are better equipped to capture the variation in the Sahel rainfall in conjunction with ocean temperatures, but this does not rule out the significance attributed to regional effects.

2.3 Climate change in the Sahel

What, then, determines the variation in surface temperature of the ocean? If sea temperature is so important, what has changed in the oceans to explain enduring droughts in the Sahel? Furthermore, if the Sahel drought has a bearing on greenhouse gases and global warming, what will the future bring?

Warming is – usually – a global phenomenon, and the northern half of Africa does not escape this trend. The six warmest years in northern Africa since 1860 were registered after 1998. The rise in temperature since 1970 has been even faster in the Sahara-Sahel zone than worldwide, with a 0.2°C rise per decade in the 1980s. This rate increased to 0.6°C per decade at the end of the 20th century (Fig. 2.4).

Global Circulation Models predict a further warming of Africa in the 21st century, varying between 0.2 and 0.5°C per decade (Hulme *et al.* 2001; Caminade *et al.* 2006). The warming is expected to be even greater in the Sahel. Consequently, the temperature may therefore rise another 2-7°C the next 80 years – a daunting prospect!

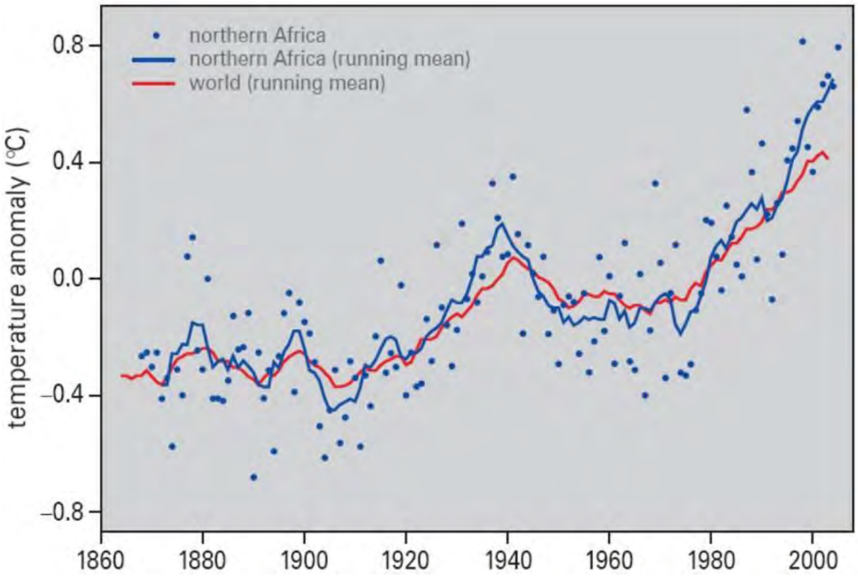

Figure 2-4 - The average temperature given as departures from the 1961-1990 average in northern Africa (0-40°N, 20°W-60°E) and worldwide (source: www.met-office.gov.uk/research/hadleycentre/CR_data/Monthly/HadCRUG.txt). The trends show the running mean calculated o over an interval of 9 years (4 year before – 4 years after the year concerned).

Global Circulation Models also provide predictions about rainfall. Given the important role that ocean surface seawater temperatures exert on rainfall in Africa, it is to be expected that a continuing warming of the tropical oceans would lead to a further reduction of rainfall. However, global warming may also impact the temperature gradient in tropical and subtropical oceans, which would complicate predictions of African rainfall.

Also more recent studies still struggle with the processes leading to more or less rainfall in the Sahel (as reviewed by Giannini *et al.* 2008, Caminade & Terray 2010). There are three mechanisms leading to *less* rain:

1. A cooling of the southern hemisphere oceans and a warming of the northern hemisphere oceans leads to more rainfall in the Sahel, while a warming of the southern hemisphere oceans and a cooling of the northern hemisphere oceans will have the opposite effect. The latter appears to be the case, so this would lead to less rain in the Sahel.
2. There will also be less rain in the Sahel if the Indo-Pacific Ocean gets warmer (causing a more stable troposphere). This appears to be the case too.
3. Also a desertification of the Sahel will lead to less rain.

In contrast to these three mechanisms leading to less rain, there are two reasons to assume that there might be be *more* rain in the Sahel, one worldwide, and one specific for the Sahel.

1. At a higher temperature, the warmer atmosphere is expected to hold more water, thus moister and hence wetter.
2. Due to the higher temperature, for two reasons the Hadley cell will become more intense, leading to more rain. There is hardly any doubt that the Sahara will become warmer, causing more rain in the Sahel, whereas for the same reason the difference in temperature above the African continent and the Atlantic Ocean will become larger.

Since there are several competing mechanisms leading to more or to less rain in the Sahel, it is extremely difficult to predict whether there will be more or less rainfall in the Sahel. After comparing four climate change scenarios and seven global climate models, Hulme *et al.* (2001) concluded that annual rainfall in the western Sahel would possibly remain at the same level, but that a decrease of 10-20%, or even 40%, is more likely.

One of the problems with Global Circulation Models is that, when applied to the Sahel, they are not able to capture the Great Drought in the 1980s. Recently, however, Held *et al.* (2005) presented a model that appears to simulate 20th century rainfall reliably for the Sahel. They predict that rainfall until 2020-2040 will remain at about the same low level as the last twenty years of the 20th century, but will then gradually decrease by about 20% in the next 50-100 years.

Biasutti & Giannini (2006) showed that 16 of the 19 models being used in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 4AR), do reproduce a drier Sahel at the end of the 20th century. They conclude that aerosol emissions from industrialization, causing global dimming, and thus cooling, in the northern hemisphere, may have played a role in causing the Sahel drought. At least 30% of the observed negative rainfall trend over the 1930–2000 period was estimated to be externally—and most likely anthropogenically—forced.

Caminade & Terray (2010) compared 21 different climate scenarios and concluded from this ..‖ our results converge with those highlighted in Held *et al.* (2005), namely that the prediction of twenty-first century drying over sub-Saharan Africa could be considered as a plausible but not certain scenario‖. The reports made by ACMAD (Centre Africain pour les Applications de la Météorologie au Développement 2009a & 2009b) for the *Autorité du Bassin du Niger* (ABN) gives more details about the statistical power of the different climate models and the predicted increase of the temperature and likely decline of the local rainfall until 2025.

Agrhymet (2009) used the predicted climate change in the basin of the Niger to forecast the river flow of the Niger between 2011 and 2040. Since five of the six climate models being analysed show a decline of the rainfall in the Upper Niger, this study concludes it has to be taken into account there will be a decline of the river flow (but see the next chapter for an analysis of the relationship between rainfall and river flow).

In conclusion, still much is uncertain, but a decline of the rainfall in the Sahel seems to be likely. Since human influences are assumed to be substantial, this gives reasons to worry about the future.

2.4 Evaporation in the Inner Niger Delta and the climate in the western Sahel

Evidently, evaporation has an immediate impact on the local climate by regulation the temperature. In the hot, dry season, the surface temperature above and close to the floodplains is by day more than 10° C lower than in the dry surroundings.

The evaporation in the flooded areas in the Inner Niger Delta is usually described as ‗water loss'. Indeed a comparison between the inflow of the Niger and the Bani into the Inner Niger Delta and the outflow shows a large difference, which may be attributed to water loss due to evaporation (Mahé *et al.* 2009). The water loss between Ké-Macina and Douna at the entrance and Diré at the other side varies from year to year. This variation can be attributed to the total amount of the water brought by the rivers. The total annual river discharge entering the Inner Delta varies between 22 and 81 km^3. If the flood is poor, 15 km^3 leaves the Inner Delta. Therefore, 7 km^3 or 32% of the river discharge at the entrance of the Inner Delta is lost to evaporation in a dry year. In contrast, when the flood extent is very large, 40 km^3 (i.e. 50%) of the total river discharge is lost to evaporation. In other words, the water loss increases more than proportional with the amount of water entering the delta. The main reason for the disproportional relationship between the inflow and the water loss is the fact that in years with a high flood a larger area is covered by water, subsequently leading to more evaporation. Evaporation varies between 160 and 240 mm per month, depending on temperature and sunshine, with an average of 200 mm per month. Another factor to be taken into account is the duration of the transport of Niger water from the entrance to the exit of the Inner Delta. This duration varies between 5 and 7 weeks, depending whether the flood is low or high, respectively.

Evaporation is ‗water loss' in a strict hydrological sense but, as argued by Mohamed *et al.* (2005), atmospheric processes should not be ignored in an appropriate water resource planning and management at a river basin level. Mohamed *et al.* (2005) showed that 11% of the total rainfall in the Nile Basin is locally generated (thus due to evaporation within the Nile Basin).

Highly relevant for our study is the paper of Taylor (2010), who compared over a span of 24 years the flood extent of the Inner Niger Delta with cloud cover. He found indeed there are more clouds in a year with more inundation. His main conclusion is worth to be fully cited:

―This study implies a link between rainfall in the upper Niger catchment and storms many hundreds of kilometres downstream occurring weeks or even months later. The efficiency of such a land-rainfall feedback will depend on the management of the river upstream of the wetlands. Using a hydraulic model, Zwarts *et al.* (2005) estimated that irrigation and hydro-electric schemes to date may have reduced flow entering the wetland in September by 10–15%. However, they suggest that the construction of a major hydroelectric dam proposed in Guinea would produce an additional decrease of 33%, resulting in a 48% reduction in flooded area during September. Such a change would significantly reduce the window in the seasonal cycle when the wetland can influence rainfall. This raises the possibility that major upstream hydroelectric schemes on the Niger could reduce rainfall at the regional scale, a suggestion which would benefit from further examination with an atmospheric model.‖

In conclusion, more rain leads to more flooding, but the inverse relation does exist too: ―the larger the flood extent of the Inner Niger Delta, the more rainfall in the Western Sahel‖.

3 Rainfall and river flow

The rivers in West Africa demonstrate huge between-season variations in discharge. For instance, the average discharge of the Niger at Koulikoro in September is eighty times larger than in April. This is caused by the short but intense rainy season, reaching a peak in August. It takes some time before all this surface water finds its way via shallow gradients into the Upper Niger, which normally reaches its maximum height in September or October. Without this large seasonal variation in rainfall there would be no seasonal floodplains and thus also no Inner Niger Delta.

The flooding of the Inner Niger Delta is determined by the inflow from the Niger and Bani Rivers, which in turn relate to the rainfall experienced 600-900 km SW of the area (Fig. 3.1). Local rainfall is too limited to have an effect on the flood height, although temporary lakes may be filled with rain water. The average annual rainfall varies within the Inner Niger Delta between 700 mm in the southwest and 200 mm in the northeast. Most rains fall in August. The raining season in the northern Delta is limited to July-September, but longer in the southern Delta (June-October) (Fig. 3.2). In the Guinean Highland (with more than 1500 mm rainfall per year; Fig. 6.1), it starts to rain in April to reach a peak in July and August (Fig. 3.2).

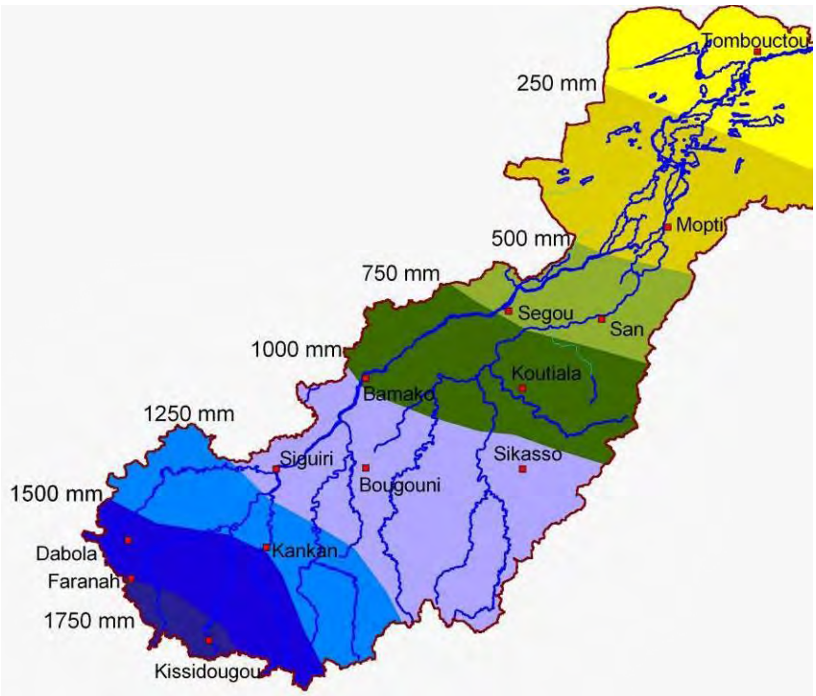

Figure 3-1 - The annual rainfall (mm/year) in the basin of the Upper Niger shown as eight different zones. Thirteen major meteorological stations are indicated with red dots. From: Zwarts *et al.* (2005).

The Niger and its Niandan, Milo and Sankarani tributaries rise in the Guinean Highlands (Fig. 3.3). The most northerly branch, the Tinkisso, originates in the Fouta-Djalon. The main tributary to the Niger is the Bani, which drains southernmost Mali and the northeastern corner of Ivory Coast. After the Bani flows into the Niger near Mopti, at the southern edge of the Inner Niger Delta, there is no further run-off from eastern Mali and Niger. Consequently, evaporation gradually diminishes the river flow.

The total catchment area of the Bani (129,000 km^2) is nearly as large as the rest of the Upper Niger Basin (147,000 km^2). Yet the discharge of the Bani is less than half of the Niger, because the Bani sub-basin receives less rainfall than the other sub-basins of the Upper Niger. We investigate separately the relationship between rainfall in the Upper Niger and the river discharge, and that for the Bani and the rest of the Upper Niger. We relate the data from the 28 long-term rainfall stations (red diamonds Fig. 3.3) in the Upper Bani to discharge at Douna (blue diamond in Fig. 3.3). The relation is shown in Fig. 3.4.

Only 15 long-term stations (red dots in Fig. 3.3) are available for the Upper Niger. To increase sample size, two stations just across the border of the basin were included in the calculation of the average annual rainfall. These data are compared with the discharge at Koulikoro (blue dot in Fig. 3.3). The relation is shown in Fig. 3.5.

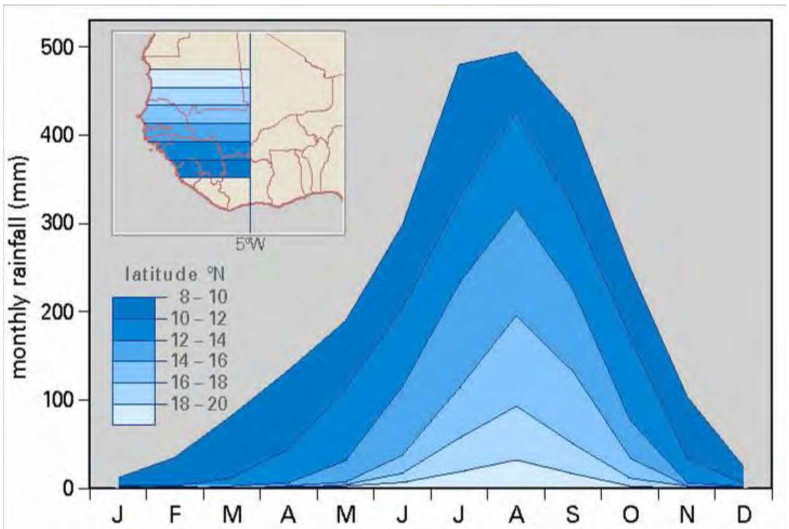

Figure 3-2 - The average monthly rainfall in West Africa (west of 5° given per latitude; the countries are indicated. The rainfall given for 14-16°N and 12-14°N refers to the northern and southern Inner Niger Delta, respectively. There is more rain in the southern Delta (as already shown in Fig. 3.1), but the raining season also extends over a longer period as in the northern Delta. The raining season starts still earlier in the headwaters of the Niger (8-12°N). From: Zwarts *et al.* (2009).

The annual rainfall in the Bani catchment area usually varies between 1000 and 1200 mm (Fig. 3.4). The Bani's flow in September fell back from 3000 m^3/s to only 250 m^3/s during the drought in the early 1980s, but subsequently gradually increased again. The long-term effect of a series of dry years on the flow of the Bani is evident. The Bani was a river with a fully natural flow until 2006 when the Talo dam became operational.

Since 1922, the average annual rainfall in the Upper Niger has varied between 1300 and 1600 mm (Fig. 3.5). The trend resembles those shown for the Bani (Fig. 3.4). But where the Bani lost 80% of their flow during the Great Drought in the 1980s, the decrease in the Niger was slightly less than 50%.

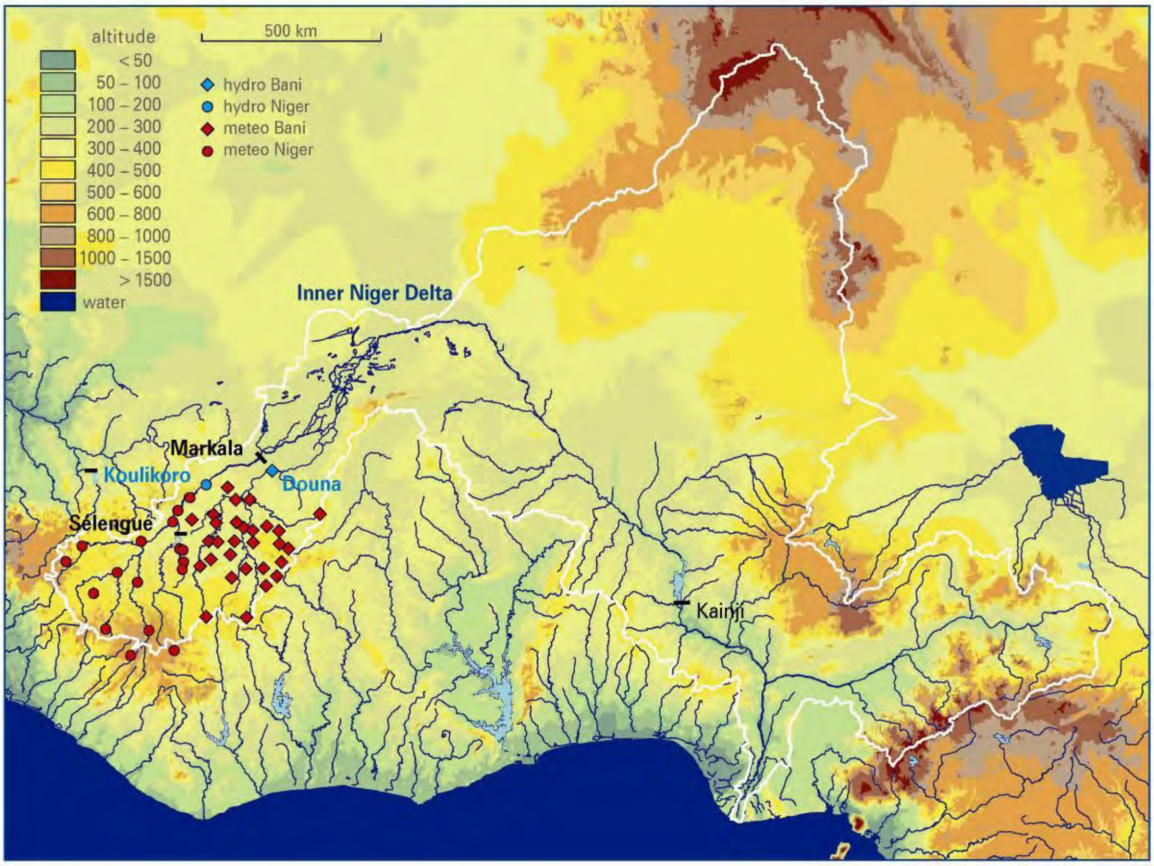

Figure 3-3 - The Niger Basin, showing three dams (Sélingué and Markala in the Upper Niger and Kainji in the Lower Niger), the hydrological stations (Koulikoro and Douna) and 45 long-term meteorological stations in the Upper Niger. From: Zwarts *et al.* (2009).

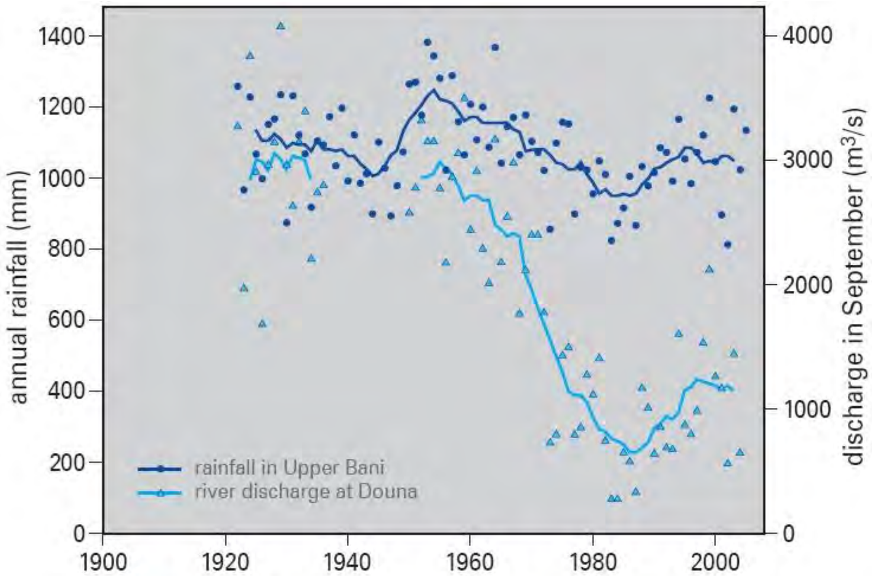

Figure 3-4- Annual rainfall of the Upper Bani averaged for 28 rainfall stations in the catchment area (dark blue symbols, left y-axis) and the river discharge in September at Douna (light blue symbols, right y-axis). The trends show 9-year running means. See Fig. 3.3 for the location of Douna and the rainfall stations. From: Zwarts *et al.* (2009).

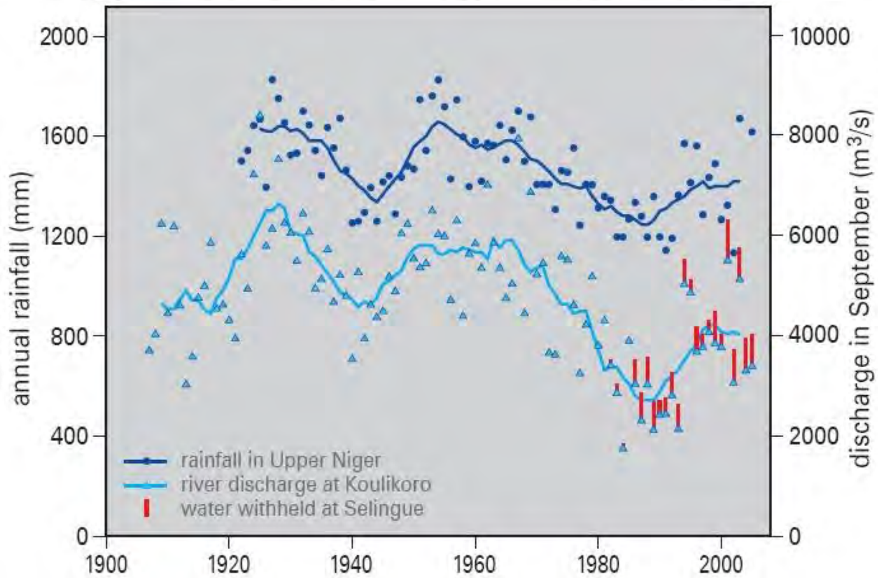

Figure 3-5- Annual rainfall of the Upper Niger (dark blue symbols, left y-axis) averaged for 17 rainfall stations in the catchment area, and the river discharge in September in Koulikoro (light blue symbols, right y-axis). The trends show 9-year running means. The red bars show the effect of the Sélingué reservoir on the river discharge in September. See Fig. 3.3 for the location of Sélingué, Koulikoro and the rainfall stations. From: Zwarts *et al.* (2009).

In conclusion, the comparison between rainfall and the discharge in the various basins reveals a large variation in river flow and a much smaller variation in rainfall. The explanation hinges on the cumulative effect of rainfall on river discharges: dry years lower the discharge, but it takes a number of wet years to attain subsequently a high discharge. In other words: river discharges not only relate to rainfall in the preceding wet season, but to a large extent also to earlier wet seasons. Hence a decrease in discharge after a series of dry years, during which the discharge is insufficient to keep the groundwater table at a certain level; in turn a low groundwater table increased seepage of surface water. In the catchment area of the Bani, Mahé *et al.* (2000) indeed found that a low discharge goes with a low groundwater level.

4 Human impact on river flow

The river flow of the Niger and the Bani depends on the rainfall, but also on human structures, such as the Sélingué dam lowering the peak river discharge of the Niger River. The Sélingué reservoir is one of the three existing, large hydro infrastructures in the basin of the Upper Niger; three others are currently considered for construction (Fig. 4.1). The existing and planned reservoirs have an impact on the river flow and, consequently, on the flooding of the Inner Niger Delta. Since the amount of water consumed hardly differ for dry and wet years, the relative impact of these infrastructures on the river flow becomes more pronounced in years with a poor flooding.

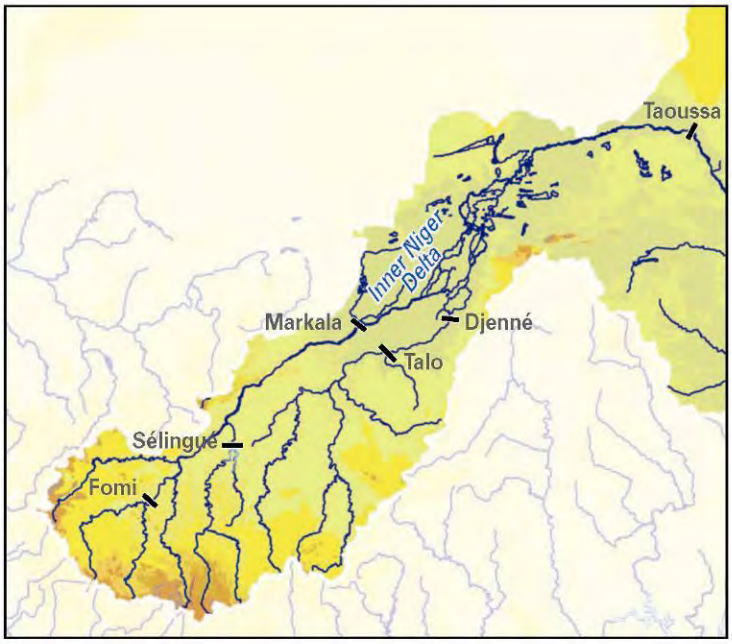

Figure 4-1- The Upper Niger with the Niger River and its branches. The dams are indicated, either existing (Sélingué, Markala, Talo) or still in study (Fomi, Djenné, Taoussa).

4.1 Sélingué

Since 1982, the flow of the Upper Niger has not been fully natural due to the construction of the Sélingué reservoir in the Sankarani. The Sélingué reservoir covers 450 km^2 when full (2.1 km^3). The monthly inflow and outflow have been registered since its inception. The annual loss amounts to 0.83 km^3, of which 0.57 km^3 is lost to evaporation; the rest becomes groundwater (Zwarts *et al.* 2005a). More important than water loss is the change in seasonal water flow. A comparison of the flow into the reservoir (representing natural flow) and the outflow reveals that due to the filling of the reservoir the flow is reduced by, on average, 61% in August and by 36% in September. In contrast, when water is released from the dam in the dry season, the outflow between February and April is about three times the amount of the natural flow. During the first years of its existence, the effect of the Sélingué dam was limited (red bars in Fig. 3.5), because the lake was only partly emptied in the course of the year and not fully refilled. After these first years, 1.8 km^3 of the annual flow is withheld by Sélingué in August and September, of which 0.5 km^3 is lost due to evaporation and 0.2 km^3 per month is released in the dry season. The water stored annually in the reservoir amounts to 10-20% of the peak flow in wet years, but to 20-30% in dry years.

Table 4.1 The average difference (m^3/s) between the monthly inflow into, and monthly outflow from, the Sélingué reservoir in the period 1989-2008 (―mean‖), during five years with the lowest river flow (1989-1993; ―dry‖) and five years with the highest flow (1994, 1995, 2001, 2003; ―wet‖).

month	J	F	M	A	M	J	J	A	S	O	N	D	mean
mean	-50,3	-62,3	-97,3	-124,8	-116,6	-92,7	7,8	344,4	348,1	98,4	15,7	-30,1	20,0
dry	-40,5	-51,9	-81,9	-121,0	-101,5	-93,1	-2,5	363,7	367,9	70,8	15,2	-46,3	23,2
wet	-30,9	-50,6	-76,3	-124,6	-126,0	-144,4	-5,9	409,4	270,1	89,8	10,1	-28,4	16,0

Table 4.1 shows for dry and wet years the water stored in the reservoir (inflow larger than outflow) or released from the reservoir (inflow smaller than outflow). In a year with a large inflow the reservoir is already filled for a large part in August, but in a dry year relatively more water is withheld in September. Furthermore, the annual variation in river flow has hardly any impact on the seasonal pattern of storing and releasing the water.

4.2 Small irrigation schemes in the Upper Niger

The rice fields immediately downstream the Sélingué dam measure 1400 ha. The area consumes 1.1 m^3/s (Table 4.2). 40 km downstream of the Sélingué dam the irrigation scheme of Maninkoura measures 850 ha. According to the Enquête Agricole de Conjoncture, Office Haute Vallée Niger (OHVN) plans to make seven other irrigation schemes further downstream along the Sankarani; total surface 3700 ha (Schüttrumpf & Bökkers 2008). The low Kourouba dam (to be constructed between 2010 and 2015) in the Sankarani, just downstream of the Sélingué dam, would enable to irrigate the rice fields near Maninkourou (5000 ha).

Along the Upper Niger, OHVN manages another 12,000 ha of rice fields (Schüttrumpf & Bökkers 2008; Enquête Agricole de Conjoncture).

The irrigated area of Baguinéda near the Sotuba dam has a surface of 2400 ha. Hassane (1999) mentioned an annual water consumption of 6.8 m^3/s for Baguinéda, Schüttrumpf & Bökkers (2008) gives a separate estimate for the dry season (3 m^3/s) and the wet season (9.5 m^3/s) (Table 4.2).

The total annual water intake to irrigate the 17,776 ha of irrigated rice fields along the Upper Niger in 2008-2009 may be roughly estimated at 18 m^3/s. This will increase to 20-25 m^3/s if the Kourouba dam is functional.

Table 4.2. The average amount of water taken per month (m^3/s), for irrigation by ODRS near the Sélingué dam and by OPIB near the Sotuba dam (Baguinéda). The data of Sélingué refer to the years 1982-2003 and are taken from Zwarts *et al.* (2005; their Annexe 2, based on data from ODRS and EDM). The data for Baguinéda, collected by OPIB, were taken from Schüttrumpf & Bökkers (2008).

site	J	F	M	A	M	J	J	A	S	O	N	D	mean
Sélingué	0,8	1,6	1,8	1,9	1,2	0,3	0,3	0,7	1,2	1,5	1,3	0,7	1,1
Baguinéda	3,0	3,0	3,0	3,0	3,0	9,5	9,5	9,5	9,5	9,5	9,5	3,0	6,8

4.3 Office du Niger

The irrigation zone managed by Office du Niger is possible thanks to the Markala dam, a weir across the river used to raise the water level 5.5 m above the lowest water level of the river. This enables irrigation under gravitation. The irrigation zone of Office du Niger is located in the *Delta mort*, an ancient branch of the Niger. The Markala dam has been operational since 1947, but it took many years before the irrigation scheme was developed.

The water intake, as registered by Office du Niger, amounts to 2.69 km^3 per year, equivalent to 86.5 m^3/s. Despite the gradual extension of the irrigated zone, the total water extraction remained at the same level between 1988 and 2009. Over the same period, the annual river discharge at Markala varied between 539 and 1229 m^3/s. As a consequence, water use by Office du Niger is not more than 7% of a high river flow (1995), but this increases to 16% when the flow is low (1989). The annual water use does not differ for dry and wet years (Table 4.2).

The monthly water use by Office du Niger varies seasonally and is 60 m^3/s in January, gradually increasing to 130 m^3/s in October, decreasing to 90 m^3/s in November and 50 m^3/s in December. The available water supply varies between 100 m^3/s in March and 3200 m^3/s in September. Hence 60% of the flow is tapped in March against only a few percent in September.

Table 4.3. The amount of water taken per month, on average (m^3/s), for irrigation by Office du Niger near Markala between 1989 and 2009 (―mean‖) and during five years with the lowest river flow (1989-1993; "dry‖) and five years with the highest flow (1994, 1995, 2001, 2003, 2008; ―wet‖).

month	J	F	M	A	M	J	J	A	S	O	N	D	mean
mean	58,3	62,5	71,1	74,5	87,0	95,8	95,7	97,1	121,4	131,4	88,7	54,6	86,5
dry	62,2	62,3	63,6	64,5	87,1	84,6	76,8	90,0	129,4	136,6	105,6	67,7	85,9
wet	55,8	65,1	68,3	73,1	87,6	85,1	90,8	91,1	120,0	130,2	86,2	50,4	83,6

The water consumption in September and October amounts to 120-130 m^3/s (Table 4.3) and has never been above 146 m^3/s during a month. This limit is determined by the dimensions of the hydrological system. The water from the river just upstream of the weir is directed through a large canal with a maximum capacity of 200 m^3/s to Point A, from where it is divided between three large canals:

- Canal du Sahel (max. 100 m^3/s) discharging northwards into Fala de Molodo leading to the irrigated areas north of Niono.
- Canal Costes-Ongoïba (max. 13 m^3/s) supplying the sugar cane plantation of Siribala.
- Canal du Macina (max. 45 m^3/s) leading into Fala de Boky-Wéré, running in an easterly direction towards the polders of Macina.

The first priority of Office du Niger is to enlarge the capacity of the Canal du Sahel (from 100 to 190 m^3/s) and of the Canal du Costes-Ongoïba (from 13 to 45 m^3/s) and not to increase the flow along the Canal du Macina (45 m^3/s). This means that the total maximal water extraction would increase from 130 m^3/s in September-October to 280 m^3/s.

However, since a concession of 100,000 ha has been given to Malibya in the eastern irrigation zone, fed by the Canal du Macina, more water is needed. This extension is only possible if the Canal du Macina is enlarged as well as the main canal to point A. To extend Office du Niger to a 280,000 ha, the total water consumption will further increase to nearly 500 m^3/s, compared to 130 m^3/s at present.

4.4 Fomi

The Fomi dam is still under consideration. The reservoir is planned to be constructed in the Niandan tributary in Guinea-Conakry. The reservoir is meant for hydropower in combination with irrigation and flood control. The Fomi reservoir will have about the same surface area as Lac Sélingué (500 km^2), but it will be much deeper (up to 12 m). That is why it will contain three times as much water as the Sélingué reservoir.

The impact of the Fomi reservoir has been simulated by Zwarts & Grigoras (2005). They assumed that if the water management of the Fomi dams would be similar to the management of the Sélingué reservoir, one may expect that the impact on the flow during the wet and dry period is similar to Sélingué, yet its magnitude will be around 2.9 times larger. However, is has to be taken into account that the dead storage differs for both reservoirs, being 0.24 km^3 or 11% of lake Sélingué if full, but 2.46 km^3 or 40% of the Fomi lake if full. The ratio of the effective volume is 3.7 : 1.93, thus the expected impact of Fomi might be 1.9 as large as Sélingué.

Another difference between Sélingué and Fomi is that the annual inflow into the Fomi reservoir would be nearly twice as low as the average inflow of the Sankarani (12 km^3) into the Sélingué reservoir. Assuming that the Fomi reservoir will be managed in the same way as Sélingué, given the limitation of expected monthly inflow and effective volume, we may assume that to fill the Fomi reservoir 1.0 km^3 will be withheld in August, 1.6 km^3 in September and 1.2 km^3 in October (being equivalent to 373, 617 and 448 m^3/s, respectively).

4.5 Reduced flow of the Niger

The existing and planned reservoirs have an impact on the river flow (Table 4.1-4.3) and, consequently, on the flooding of the Inner Niger Delta. Since the amount of water consumed hardly differ for dry and wet years, the relative impact of these infrastructures on the river flow becomes more pronounced in years with a poor river discharge. Table 4.4 gives a reconstruction of the natural monthly flow of the Niger at Markala in relatively dry years. A selection was made for the period 1989-1993 when the average flow in September was 2050 m^3/s, representing a flow being in 20% of the years 1989-2008 below this level and 80% of the years above this level.

The natural flow was estimated by adding to the present flow the water withheld, or subtracting the water released in Sélingué (Table 4.1; Zwarts *et al.* 2005b: p. 273-275) and by adding the water taken from the Upper Niger for irrigation (Table 4.2; Zwarts *et al.* 2005b: p. 278). The expected change in the river flow at a further extension of Office du Niger and an enlarged water inlet is unknown; most likely the water consumption between July and December will be twice as high, although it may become four times as high at an enlarged water inlet along the Canal du Macina.

Table 4.4. The monthly flow of the Niger at Markala without human infrastructures (‗natural‘), with existing infrastructures (‗actual‘) and with a double water consumption by Office du Niger (―2020‖) and if the Fomi dam would be constructed (―2030?‖). The water use is taken from Table 4.1 (Sélingué reservoir– dry years), Table 4.2 (irrigation at Sélingué and Banguinéda) and Table 4.3 (irrigation Office du Niger, dry year). The existing water use by OHVN in the Upper Niger is ignored, but assumed to be at least as large as the existing water use of Sélingué and Baguinéda combined. The expected water consumption by Office du Niger may be enhanced to 280 m^3/s at an enlarged inlet system; hence an assumed consumption in July to December being twice as large as at present. The estimation of the water withheld in Fomi is explained in the text. All data refer to a relatively dry year (taking 1989-1993 as an average).

NIGER at Markala (m^3/s)	J	F	M	A	M	J	J	A	S	O	N	D	mean
Natural	161.5	106.8	74.5	40.4	126.9	172.7	524.1	1628.7	2557.6	2039.8	928.8	353.1	726.3
Sélingué reservoir	-40.5	-51.9	-81.9	-121.0	-101.5	-93.1	-2.5	363.7	367.9	70.8	15.2	-46.3	23.2
Sélingué irrigation	0.8	1.6	1.8	1.9	1.2	0.3	0.3	0.7	1.2	1.5	1.3	0.7	1.1
Banguinéda irrigation	3.0	3.0	3.0	3.0	3.0	9.5	9.5	9.5	9.5	9.5	9.5	3.0	6.2
Office de Niger irrigation	62.2	62.3	63.6	64.5	87.1	84.6	76.8	90.0	129.4	136.6	105.6	67.7	85.8
Actual	136.0	91.8	88.0	92.0	137.2	171.4	440.0	1164.8	2049.6	1821.4	797.2	328.0	609.8
Haute Niger irrigation	3.8	4.6	4.8	4.9	4.2	9.8	9.8	10.2	10.7	11.0	10.8	3.7	7.3
Office du Niger extension							76.8	90.0	129.4	136.6	105.6	67.7	37.7
2020	132.2	87.2	83.2	87.1	133.0	161.6	353.4	1064.6	1909.5	1673.8	680.8	256.6	564.9
Fomi reservoir								373.0	617.0	448.0			
2030?								691.6	1292.5	1225.8			

Table 4.4 gives no estimate for the expected change in the river flow downstream of Markala during the dry months. It is to be expected that, if the Fomi would be constructed, the water released at Fomi between December and July will be used for the larger part by Office du Niger. At present, the additional water released by Sélingué in the dry months is also fully consumed by Office du Niger (Table 4.4) and possibly the same will be the case with the water from the Fomi reservoir. Hence, Sélingué, and possibly also Fomi, reduce the inflow into the Inner Niger Delta during the flood but due to the water consumption by Office du Niger, the flow is not enlarged during the dry months.

4.6 Talo

The Talo dam, built in 2005 in the Bani River, is meant to facilitate irrigation. The planning was to develop 20,320 ha, of which 16,030 irrigated rice fields; the rest will be converted into bourgou (water meadows) and fish ponds (African Development Fund 1997). The expectation is that due to the Talo dam, the flow of the Bani at Mopti between July and October will be reduced by 0.39 km^3 (BCROM *et al.* 2006a, 2006b, Lamagat 2006). Lamagat (2006) gives the expected impact on the flow in Mopti per 10 days between early July and late October; these are summarised per month in Table 4.5.

Table 4.5. The predicted monthly loss in discharge of the Bani (m^3/s) due to the Talo dam during a dry year. Source: Lamagat (2005), who defined a dry year as the river flow being in 90% of the years higher.

Talo	J	F	M	A	M	J	J	A	S	O	N	D	mean
Dry							3,0	49,7	15,3	29,7	59,7		31,5

4.7 Djenné

The Djenne dam is intended to counteract the water losses in the lower Bani caused by the Talo dam. Due to the dam a reservoir of 150 km^2 and 0.357 km^3 will come into existence, 245 km^2 will be flooded and assumed to be covered by a vegetation of bourgou.

Lamagat (2006; see also BCEOM *et al.* (2006a) studied the change in the river flow due to the water withheld at the Djenné dam and due to the irrigation. In a year with an average flow, the water level in Sofara will be 30-55 cm lower in September, but in a dry year 64-90 cm. Further downstream, the impact will be less but in Mopti, where the Bani flows into the Niger, the water level is yet reduced by 5-15 cm in a year with an average flow and by 17-27 cm in a dry year. The monthly reduction in the discharge at Mopti due to the Djenné dam is given in Table 4.7 for a dry and for an average year.

Table 4.6. The predicted monthly loss in discharge of the Bani at Sofara (m^3/s) due to the Djenné dam during a dry year and an average year. Source: BCEOM *et al.* (2006a).

Djenné	J	F	M	A	M	J	J	A	S	O	N	D	mean
dry							16	60	91	112	84		72.6
mean							15	46	82	162	99		80.8

4.8 Reduced flow of the Bani

Table 4.7 gives the natural, actual and expected monthly discharge of the Bani, taking into account the impact of the Talo (Table 4.5) and the Djenné dam (Table 4.6). No impact is indicated for December-July, but possibly the amount of water being withheld or released in these months will be relatively small.

Table 4.7 The monthly flow of the Bani at Sofara (m^3/s),. without the Talo (‗natural‘), with Talo (‗actual‘) and with Talo and Djenné (‗2020‖). The water use is taken from Table 4.5 (Talo) and Table 4.6 (Djenné). All data refer to a relatively dry year (taking 1989-1993 as an average).

BANI at Sofara (m^3/s)	J	F	M	A	M	J	J	A	S	O	N	D	mean
Natural	41.6	21.8	9.5	4.0	1.7	7.3	51.6	303.5	605.8	504.8	202.4	81.0	152.9
Talo							3.0	49.7	15.3	29.7	59.7		31.5
Actual							48.6	253.8	590.5	475.1	142.7		
Djenné							16.0	60.0	91.0	112.0	84.0		72.6
2020							32.6	193.8	499.5	363.1	58.7		

4.9 The inflow of the Niger and Bani River into the Inner Niger Delta

The combined impact of the existing and planned infrastructures of the inflow into the Inner Niger Delta is shown in Fig. 4.2. At present, 20% of the peak flow in September is lost, but this will increased to 25% in 2020 (at a water inlet by Office du Niger being twice as large as at present) and to 50% if the Fomi dam would become operational. The green line (extension ON) and the purple line (extension ON+ Fomi) will be 240 m^3/s lower if the water use by Office du Niger will become four times as large as at present. The flow of the Bani in September has been reduced by 2.5% and this will increase to 17.5%. What this means for the Inner Niger Delta is shown in the next Chapter.

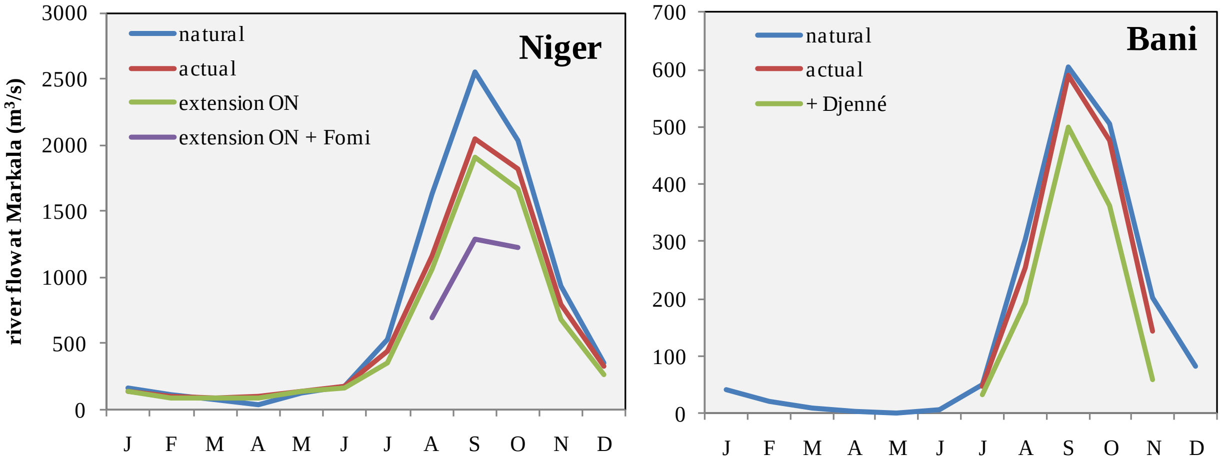

Figure 4-2- The natural, actual and future monthly flow of the Niger River at Markala (downstream of the dam) (left) and of the Bani River at Sofara (right). All data from Table 4.4 for the Niger and from Table 4.7 for the Bani.

5 Flood extent, inflow and rainfall

The inundation of the Inner Niger Delta depends on the combined inflow of the Niger and the Bani during the flooding. The peak flow in September showed a huge variation for the Bani, measured at Douna since 1922. The minimal peak flow, measured in 1984 (254 m^3/s), is 7.3% relative to the maximal peak flow, measured in 1929 (3470 m^3/s) (Fig. 3.4). The variation is less extreme for the Niger at Koulikoro, known since 1906: the September flow was at a minimum in 1984 (1649 m^3/s) and reached its maximum in 1928 (7586 m^3/s) (Fig. 3.5). As a consequence, there is also a large annual variation in the flood extent of the Inner Niger Delta.

5.1 Flood extent and inflow

The topographical maps of the Institut Géographique National (IGN) reveal that the inundation area of the Inner Niger Delta measures 36,470 km^2, including 5340 km^2 of levees, dunes and other islands within that area. They also show that water coverage declines from 31,130 km2 in wet periods to 3840 km^2 in the dry period (Fig. 5.1). The entire floodplain area is included in the 41,195 km^2 designated as a Ramsar Wetland Site of International Importance in January 2004.

Topographical maps show the floodplain as if it were flooded at a maximum level (Fig. 5.1). The area actually inundated, however, varies considerably between years. Zwarts & Grigoras (2005) used satellite images to produce a continuum of 24 water maps of the Inner Niger Delta covering the range of water levels between -2 and +511 cm, as measured on the gauge at Akka in the central lakes.

The digital maps allow the determination of the relationship between water level and the area inundated. Water maps were combined to construct a digital flooding model. This was done separately for rising and receding water. For receding water, they made two flooding models: one for years when the peak flood level had been high (inundating a large area) and one for years of low flood (when only the lowest-lying floodplains connected to the river became inundated). In a dry year (as 1984), just one third of the Delta became inundated; the northern Delta was not even reached by the flood. In a wet year (such as 1999) though, the southern Delta was fully flooded, as well as a large part of the northern Delta including several of the lakes just north of the Delta (Fig. 5.2).

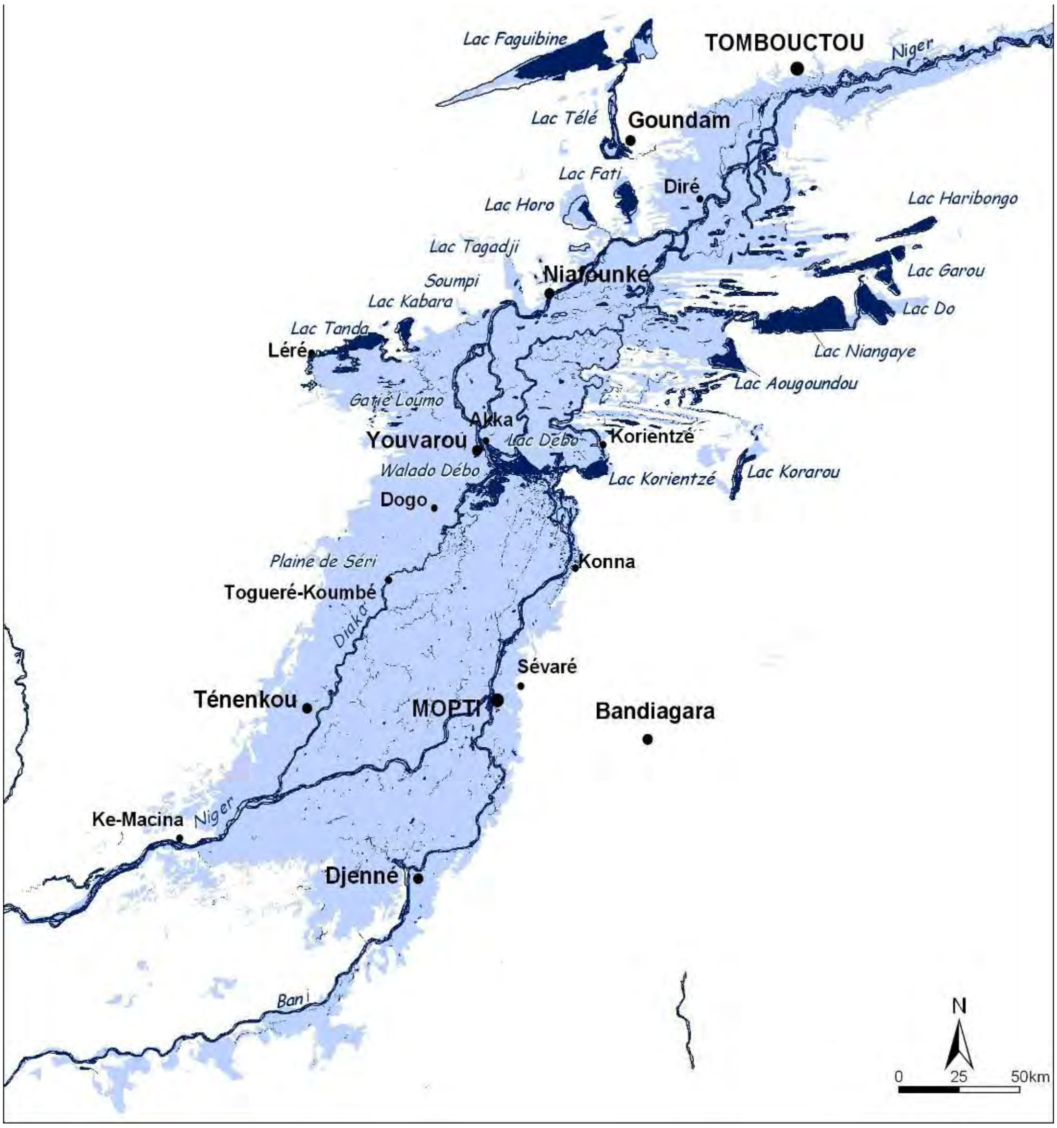

Figure 5-1- The floodplains (light blue) and permanent water bodies (dark blue) of the Inner Niger Delta, as indicated on the topographical maps of the Institut Géographique National (IGN). The maps are from 1956, and based on aerial photographs and field work in the early 1950s, a period with very high floods. Hence the map shows the maximal extent of the inundation zone.

The flood level and flood extent are determined by the inflow of the Bani and Niger Rivers. The maximum water level in Akka, usually reached in November, can be predicted reliably from the average river flow in August, September and October combined for these two rivers (Fig. 5.3, left axis). A high river discharge not only produces a high flood, but also floods a more extensive area (Fig. 5.3; right axis). Since the mid-1950s, the average flow in August-October for Bani and Niger has varied between 1850 and 7200 m^3/s, equivalent to a total seasonal flow of 14.7 and 57.2 km^3 respectively. In 1984, the water level at Akka did not exceed 336 cm and the flooded area was limited to a mere 7800 km^2. In contrast, in 1957 and 1964, the water level at Akka reached the very high level of about 600 cm, leading to a flooded area of 22,000 km^2. It should be noted that this is still substantially smaller than the total floodplain of 31,000 km^2 as shown on the IGN maps (Fig. 5.1). This apparent discrepancy is caused by the shallow northward slope of the floodplain that delays flooding in the north with two-three months; by that time the southern floodplain has already been drained of water. Because our remote sensing analysis is based on actual water coverage, the area flooded at any one time is always less than the total area flooded in the course of a year.

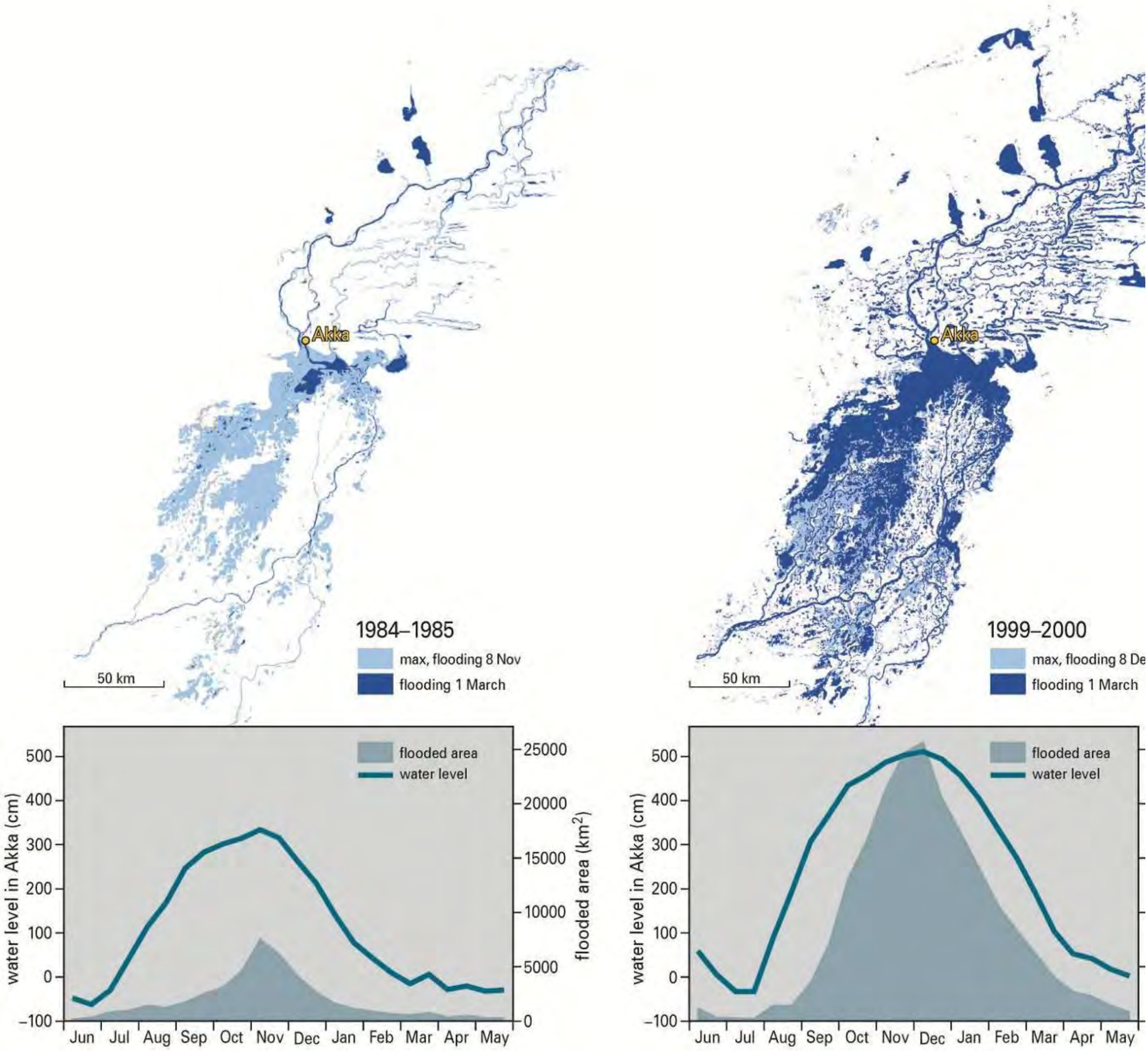

Figure 5-2- The graphs show daily measurements of the water level at Akka (left axis in both graphs) between June and May in 1984/85 (left graph; the lowest flood ever measured) and in 1999/2000 (right graph; one of the highest floods since 1970, but of normal height when compared with pre-1973 floods). The surface areas flooded (right axis in both graphs) in 1984/85 and 1999/2000, shaded in the same graph, are derived from the water level data, using the digital elevation models of Zwarts & Grigoras (2005). The maps show the flooded area when the water level at Akka reached its peak, and for 1 March. Note that the peak flood level in 1999 (511 cm) was 1.5 times higher than in 1984 (336 cm), but that the maximal flood extent was nearly 5 times larger. The difference is even larger some months later. The flood extent on 1 March (shown as dark blue on the map) was in 2000 13 times more than in 1985 (right map). From: Zwarts *et al.* (2009).

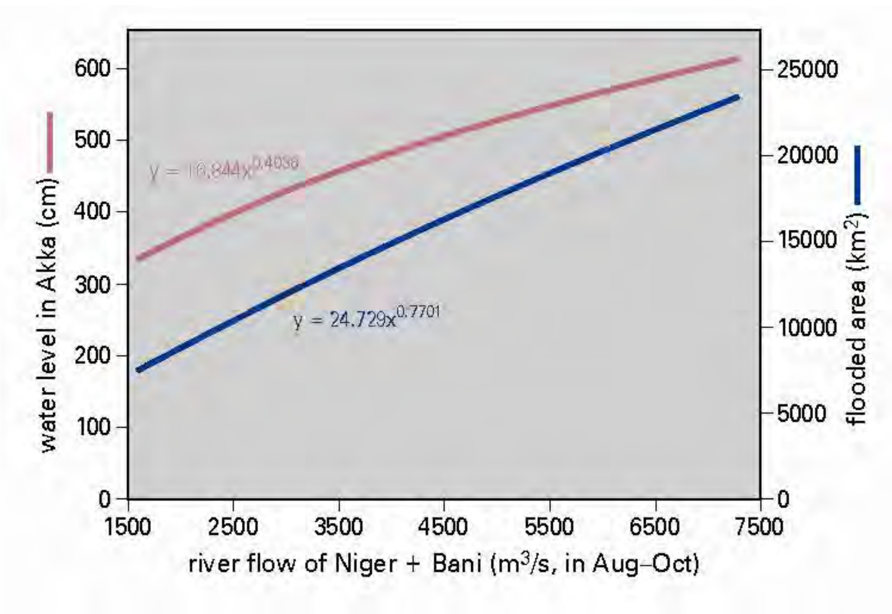

Figure 5-3- The highest water level in Akka (cm; red line, left axis) reached within a year as a function of the combined river discharge of the Niger (downstream of the Markala dam) and the Bani (Douna), averaged for August-October that year. The blue line gives the same relationship for the flooded surface (km2). From: Zwarts & Grigoras (2005).

In the present situation the combined average flow of the Niger and Bani in a dry year amounts to 2191 m^3/s in the period August-October (Tables 4.6 and 4.7), Using the formulas given in Fig. 5.3, we may calculate that in such a year the water level in Akka would reach a maximal level of 375 cm and that 8812 km^2 would be flooded. Without Sélingué and the irrigation in the Upper Niger, the flow would have been 430 m^3/s higher, by which the flood level would have been 28 cm higher and the inundated surface area 1400 km^2 larger (Table 5.1). In the same way we can calculate that the presumed doubled water intake by Office du Niger would lower the water level in the Delta by 15 cm in a dry year, leading to a loss of 700 km^2. At a quadrupled water intake by Office du Niger, this would be not 15 cm, but 33 cm, and not 700 km^2, but 1500 km^2. If also the Fomi and Djenné dams would be constructed the peak flood level will further decline by 80 cm and the flood extent by another 2000 km^2 (Table 5.1).

Table 5.1. The peak water level in Akka (cm) and the maximal flood extent (km^2) of the Inner Niger Delta in a dry year at (1) a natural flow, (2) in the present situation, (3) in 2020 (double water intake of Office du Niger), (4) in 2020 ? (water intake by Office du Niger four times as large as at present and (5) in 2030 ? (assuming the Djenné dam and Fomi dam are operational). The inflow in the five situations refer to the average flow of the Bani and the Niger in August-October (from Table 4.7, but 73 m^3/s was added to correct for the difference in flow between Douna (used in the formula given in Fig. 5.3) and Sofara (data given Table 4.7).

River flow in Augustus -October	Flow at Macina + Douna, m^3/s	max. flood level Akka, cm	Flood extent, km^2
natural	2620	403	10607
actual	2191	375	9244
2020	1974	360	8531
2020 ?	1736	342	7726
2030 ?	905	263	4679

In conclusion, the flood extent of the Inner Niger Delta is determined by the flow of the Bani and the Niger. Due to irrigation and reservoirs, the inflow has been reduced already by 16% in a relatively dry year, causing a reduction of the flood by 28 cm and a reduction of the flood extent by 1400 km2 (13%). At a larger consumption by Office du Niger, the inflow will decline with another 200, or even 400, m^3/s, leading to a reduction of the flood level by 15 to 33 cm and a reduced flooded area (700 - 1500 km^2). The construction of the Djenné and Fomi dam would even be more detrimental, reducing the flood extent by another 2000 km^2.

5.2 Flood extent and rainfall

To check whether the existing infrastructures in the Upper Niger have indeed the large impact on the flood extent of the Inner Niger Delta, as shown in Table 5.1, we may also compare directly the yearly maximal flood extent with the average, annual rainfall in the Upper Basin of the Niger. The average rainfall is based on the meteorological stations indicated in Fig. 3.3 and the flood extent of the Inner Niger Delta, such as may be derived from the combined inflow of Bani and Niger. The average rainfall in the Upper Niger varied since 1922 between 1200 and 1800 mm, but the maximal inundation showed a larger variation, between 8000 and 25,000 km^2 (Fig. 5.4).

When the maximal inundation is plotted against the rainfall, it becomes evident that when years with a similar rainfall are compared, the flood extent of the Inner Niger Delta during the last decades is about 5000 km^2 smaller than in the past (Fig. 5.5). This difference is more than three times larger than the calculated water loss due to the Sélingué reservoir and the irrigation schemes in the Upper Niger (Table 5.1). The actual loss is indeed larger than indicated in Table 4.6 and 4.7, since the water intake by Bamako and Ségou has been ignored, as well as all small irrigation schemes. These amounts are, however, negligible. As already discussed before, the river flow, and thus also the flooding of the Inner Niger Delta, not only depends on the rainfall in the foregoing months, but also on the groundwater level which is determined by the rainfall in the foregoing years. A part of the groundwater deficits, however, may be attributed to reservoirs and irrigation schemes further upstream.

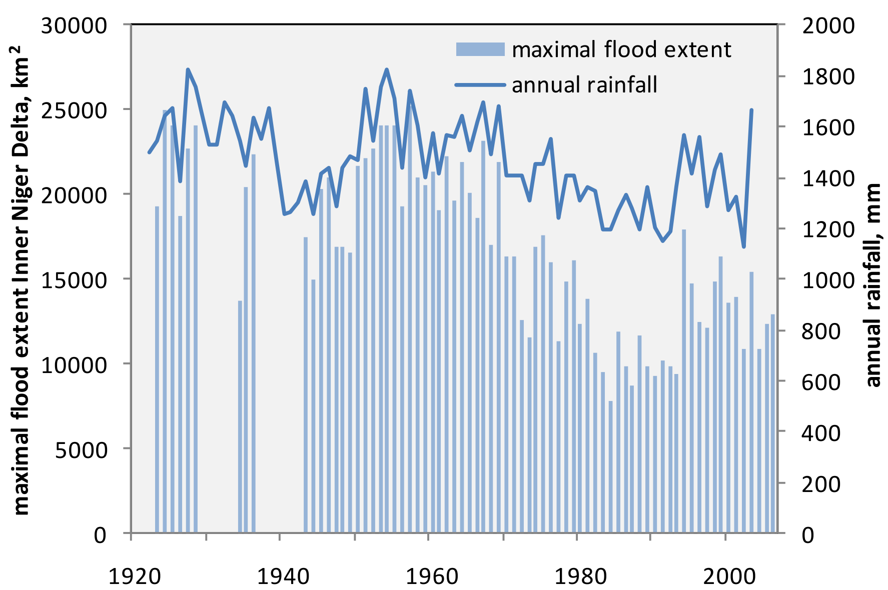

Figure 5-4- The flood extent of the Inner Niger Delta (columns; left-handed axis) and annual rainfall in the Upper Basin of the Niger (based on data given in Figs. 9 and 10) (line; right-hand axis).

Fig.5.4 shows that a small reduction in rainfall has a large impact on the flood extent. Several recent studies found exactly the opposite trend: an enhanced runoff of Sahelian rivers at a same, or even declined, rainfall (Séguis *et al.* 2004, Descroix *et al.* 2009, Mahé & Paturel 2009), with the paradoxal outcome that at a declining rainfall the ground water table becomes higher and (temporary) lakes larger (Gardelle *et al.* 2010). The explanation is that more and more land in the Sahel is cleared and cultivated, resulting in a crusting of the soil surface and, consequently, an enhanced surface runoff. Apparently, this process of declining infiltrating and increasing surface runoff is limited to the Sahel, since the increase of runoff relative to rainfall was only observed in the Sahel and not in the Sudan (Descroix *et al.* 2009) and also not in the Upper Niger (Fig. 5.4).

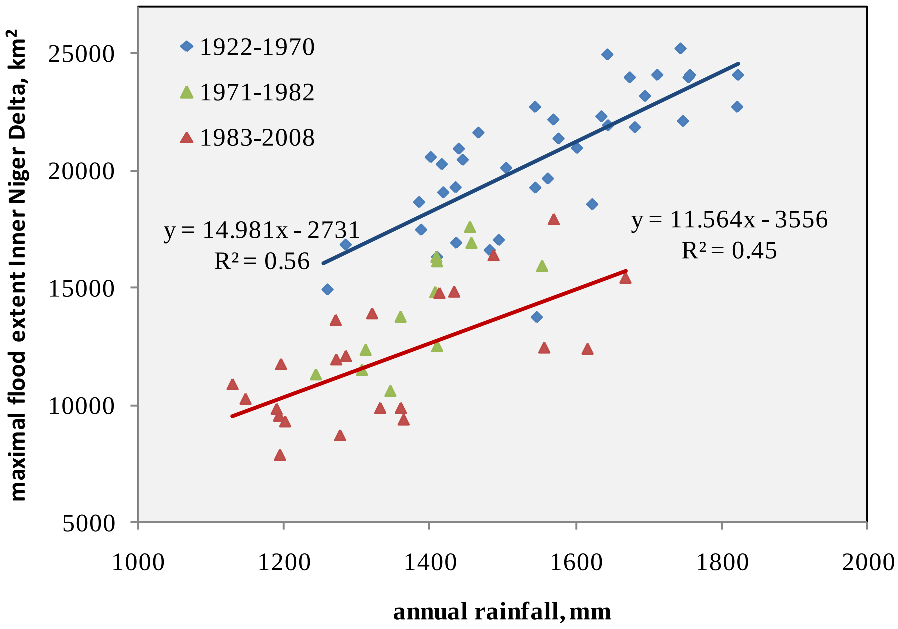

Figure 5-5- The relationship between the flood extent of the Inner Niger Delta and the annual rainfall in the Upper Basin of the Niger; same data as Fig. 5.4. Subdivision into three temporal categories (before 1971 and after 1983 and a between-category) well illustrates how the flood extent has declined due to dams and irrigation schemes, but also due to the increased seepage of surface water (see text and Figs. 9 and 10).

In conclusion, over the past century, rainfall in the Sahel and the flooding of Inner Niger Delta alternate between extended periods of drought and abundance. The annual rainfall and the flooding fluctuate in accordance, but apparently the floods are irreversibly smaller than in the past, independent of the rainfall in the same year. This may be partly attributed to the lower ground water level in the last decades causing an increased seepage of surface water before reaching the Inner Niger Delta, but also by the water loss due to the construction of the Sélingué reservoir in 1982 and the water taken from the river for irrigation.

6 Conclusion

What will the global climate change mean for the Inner Niger Delta? During the Great Drought, the decline of the rainfall was about 20%, but the decline in the flood extent was about 60% (Fig. 5.4), due to the decline in river flow of the Niger (50%; Fig. 3.5) and the Bani (80%; Fig. 3.4). Hence a small reduction in rainfall causes a substantial drop in the river flow, being most evident in an arid land river such as the Bani. This effect was confirmed by De Wit & Stankiewicz (2006) who compared rainfall with drainage of African rivers. They found that with a 10% decrease in rainfall, drainage would drop by 17% in regions where annual rainfall was 1000 mm, but the impact was much greater (50%) in regions with only 500 mm of rainfall. Hence, if due to the global climate change, the rainfall in the headwaters of the Niger and Bani Rivers will show a further decline of, on average, 10-20%, we may assume that the diminution of the Inner Niger Delta will be much larger, possibly showing shrinkage of 20-40%.

The flood extent of the Inner Niger Delta has already been reduced by 13% in a dry year due to the Sélingué dam and irrigation by Office du Niger. Since the irrigated area of Office du Niger will be expanded in the future, this loss will increase to 20% or even 27% at a maximal extension. If also the Djenné and Fomi dams would be constructed, 56% of the flooded area would be lost in total (Table 5.1).

Irrigation schemes and reservoir are constructed such that, even if in years with a low river flow, the same amount of water can be taken (as shown in Table 4.1, 4.3 and 4.6 for Sélingué, Office du Niger and Djenné, respectively). Consequently, the lower the river flow in a year, the larger the relative impact of these infrastructures. Hence, if the river flow will decline by 20-40% due to the global climate change, the combined effect of climate change and all infrastructures would be that more than 70% of the floodplains will be lost, an average.

An average loss of 70% of the flood extent would be dramatic, but there will remain a large year-to-year variation and also longer periods with more or less rain. What really matters is the risk of disaster years and how far this risk will increase due to climate changes and changes in the Upper Niger. Fig. 6.1 shows an example (taken from Zwarts *et al.* 2005): the Fomi dam will have a relatively small impact on the peak flood level in years with a high flood, but the impact will be large in a dry year. Hence, if Fomi would already have been present in 1982, a low flood such as in the disaster year 1984, would have occurred not once, but eight times between 1982 and 2003.

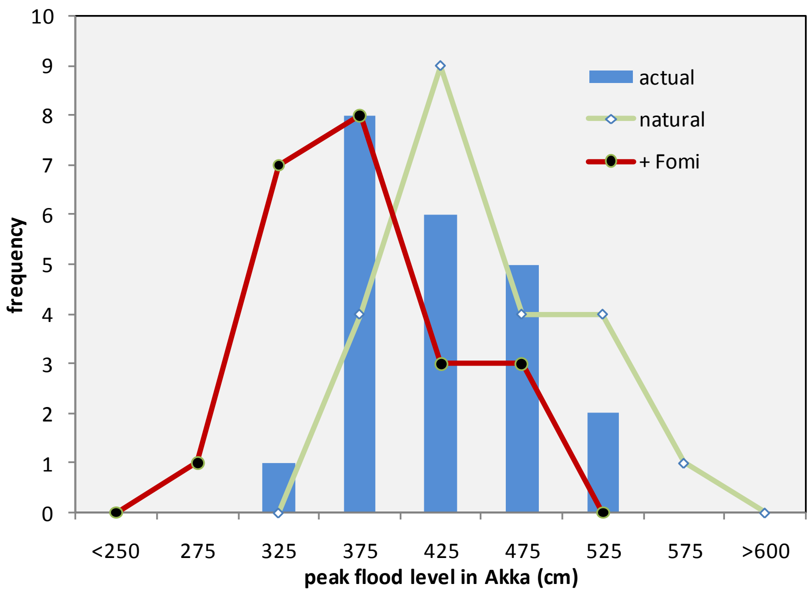

Figure 6-1- The number of years during which the peak flood in Akka reached a certain level (less than 250 cm on the local scale, 250-299 cm, 300-349, 350-399 cm, and so on) between 1982 and 2003. The blue bars show the frequency distribution of the actually observed peak floods; the green line the peak floods if there would be no Sélingué and no Office du Niger and the red line if the Fomi dam would already have been constructed before 1982.

The impact of the climate change on the rainfall in West Africa is still uncertain, so possibly it will be better than anticipated now. However, most climate scenarios indicate less rain in the Sahel, so it would be wise to take that into account. Moreover, all recent climate research indicates an increase of the temperature in the Sahel. Thus, a reduced river flow is to be expected given the increased evaporation rate in conjunction with the rise in temperature.

The irrigation schemes and dams in the Upper Niger Basin are meant to enhance the prosperity in Mali or, more specific, to achieve food security. However, for the people living downstream the only consequence is that the food security will not increase but decline. Is the Fomi still worthwhile when all negative impacts downstream are seriously considered? What may be gained if the water management of the existing upstream infrastructures takes into account the interest of the people living downstream? All these, and other, arguments should be well thought-out within an integrated, effective water management plan for the entire Basin, certainly taking into account the climate change.

The shrinkage of the Inner Niger Delta will lead to a larger competition for the still available natural resources. Farmers growing rice and farmers raising cattle are already in competition with each other and this competition will certainly further increase with a reduction of the flood level. An integrated resource management system may hopefully help the people in the Inner Niger Delta to share the burden.

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