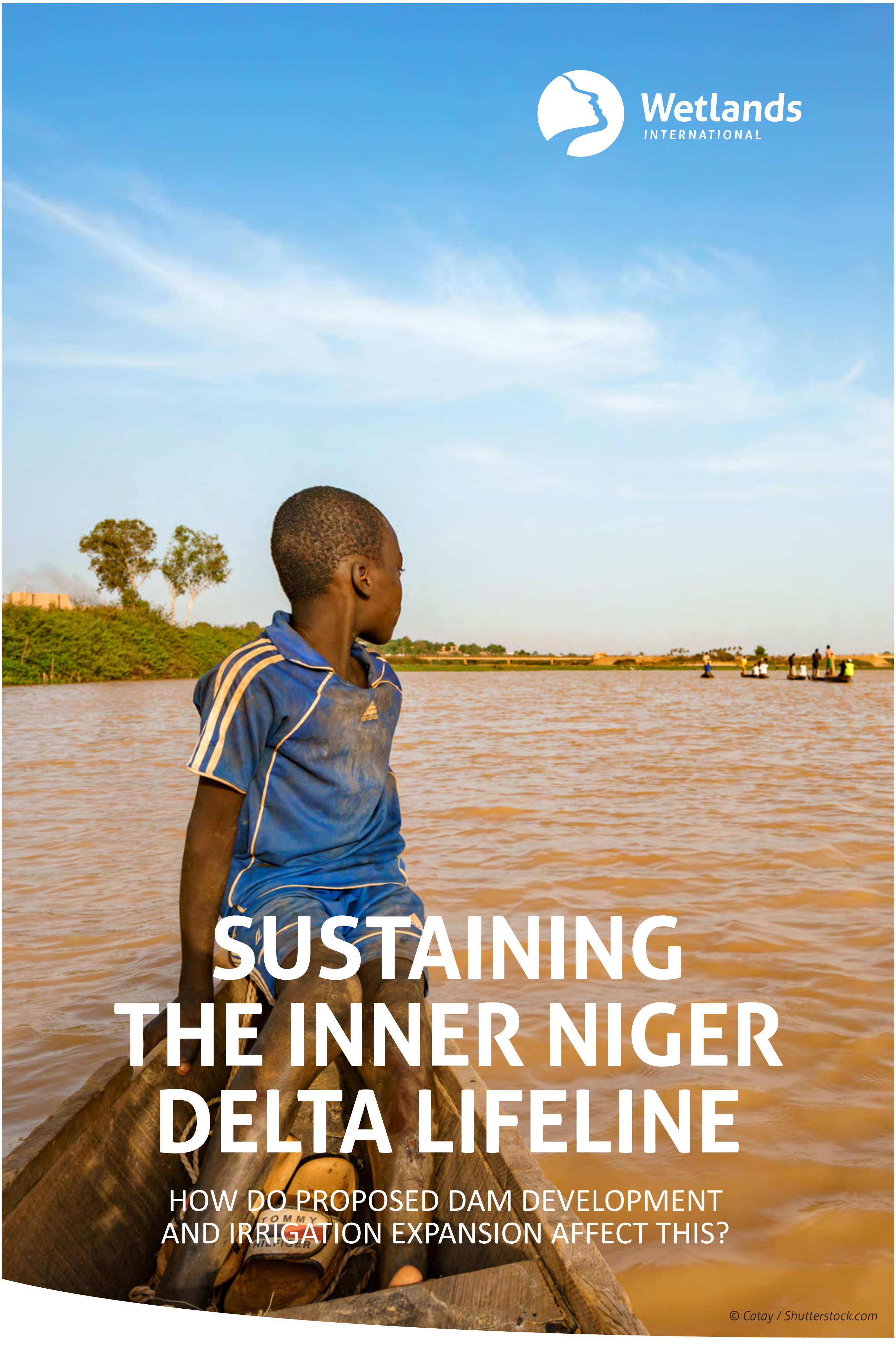

Wetlands
INTERNATIONAL

SUSTAINING THE INNER NIGER DELTA LIFELINE

HOW DO PROPOSED DAM DEVELOPMENT AND IRRIGATION EXPANSION AFFECT THIS?

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Contents

Glossary

Basin – the land area that is drained by a river and its network of tributaries

Biodiversity – the variety and variability of life on Earth

Bourgou – a species of grass widespread in tropical Africa and Asia, and common in the Inner Niger Delta. It is used as food for human consumption but more commonly as fodder for livestock.

Climate change – the change of climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and that occurs in addition to natural climate variability observed over comparable time periods

Drylands – arid, semi-arid and dry sub-humid areas, characterised by limited soil moisture and resulting from low rainfall and high evaporation

Ecosystem – a community of living organisms in conjunction with the non-living components of their environment, interacting as a system. These biotic and abiotic components are linked through nutrient cycles and energy flows.

Ecosystem services – the many, varied benefits that humans freely gain from the natural environment and functioning ecosystems

FCFA – the West African (CFA Franc) currency used in Benin, Burkina Faso, Guinée-Bissau, the Ivory Coast, Mali, Niger, Senegal and Togo

Firm hydropower yield – the maximum quantity of electricity generation that can be guaranteed with some specified degree of confidence during a critical period. This is the low flow season in the context of this study.

Floodplain – an area of land adjacent to a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls, and which experiences flooding during periods of high discharge

Global Climate Model or general circulation model – a description of climate behaviour through the integration of a variety of fluid-dynamical, chemical or even biological equations that are either derived directly from physical laws or constructed by more empirical means

Human Development Index (HDI) – a summary measure of average achievement in key dimensions of human development, including life expectancy and quality of life

Irrigation – the artificial application of water to land for the purpose of agricultural production

IUCN Red List (of Threatened Species) – the world's most comprehensive inventory of the global conservation status of biological species. It uses a set of criteria to evaluate the extinction risk of species and subspecies.

Livelihoods – the ways in which people make a living. A livelihood comprises the assets (natural, physical, human, financial and social), activities and access to these (mediated by institutions and social relations) that together determine the living gained by the individual, household or extended family.

Natural flow discharges – river discharges (level and timing) that occur in the absence of artificial upstream water storage or diversion

Representative Concentration Pathway (RCP) – time-dependent projections of atmospheric greenhouse gas (GHG) concentrations adopted by the Intergovernmental Panel on Climate Change of the United Nations

Resilience – the ability of a community or (eco-)system to absorb shocks

Seasonal floods – the floods that occur yearly due to increased rainfall and runoff in the wet season (in this case the West African monsoon)

Sustainable development – development that reaches economic, social and environmental goals without impacting negatively on future societies

Vulnerability – the propensity to be affected by shocks, related to socio-economic, demographic, political, cultural and environmental conditions

Water allocation/management – the process of distributing water for various uses and different groups of users

Wetlands – a wide variety of seasonally or permanently inundated areas, such as marshes, floodplains, rivers and lakes, and coastal areas. They may be natural ecosystems (rivers and lakes) or human-made ecosystems (reservoirs).

Acronyms

FCFA	West African CFA Franc
CGM	Global Climate Model
GRDC	Global Runoff Data Centre
IHLNUS	UNESCO's Intangible Heritage List in Need of Urgent Safeguarding
IND	Inner Niger Delta
MW	Megawatt
NBA	Niger Basin Authority
ON	Office du Niger
ORM	Opération Riz Mopti
ORS	Opération Riz Ségou
PAHA	Plan d'Aménagement Hydro-Agricole; Hydro-Agricultural Development Plan of the Office du Niger
RCP	Representative Concentration Pathway
RILH	UNESCO's Representative List of the Intangible Cultural Heritage of Humanity
SWIM	Soil and Water Integrated Model
UNB	Upper Niger Basin

UN Photo / Harandane Dicko

Introduction

Water is one of the key natural resources in the Upper Niger Basin (UNB) and is essential to the development of the region. Mali and Guinea are among the world's poorest countries, with persistent water, food and energy insecurity. As in the wider Sahel belt of Africa, population growth is outpacing food production. Demand for energy is rising. At the same time, the basin is characterised by high natural variability, with extended periods of wet and dry years. Climate change and increasing temperatures are adding uncertainty to the amount of water that will be available in the future. Solutions to many of the critical challenges facing Mali, in particular, a landlocked country on the edge of the Sahara Desert, depend on the sustainable and equitable management of the Niger River's water and natural resources. Sustainable use of water and related ecosystems is central to prospects for increased food and energy security, and additionally for alleviating poverty, reducing conflict and instability, building resilience to climate change and reducing disaster risks.

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To increase water, food and energy security, Guinea and Mali have been using a classical hydraulic engineering approach previously utilised in the Niger River for the construction of water infrastructure to take advantage of hydropower potential and to store and divert water for agricultural irrigation. Planning is currently underway for a new Fomi dam project on the Niger River in Guinea, and the large-scale expansion of irrigation by the Office du Niger (ON) in Mali.

What is at stake

Downstream of the water infrastructure, millions of people and animals currently depend on the goods and services produced by seasonal floodplain wetlands, as in the Malian Inner Niger Delta (IND). These are people who live there permanently or seasonally migrate there from dryland areas. The annual cycle of flooding and de-flooding is integral to the IND's regional economy, which is based on farming, fishing and pastoralism and supports significant biodiversity. Changes in the timing and amount of water reaching the delta are a defining issue for the future survival of ecosystems like the IND. Decisions on building new water infrastructure in the UNB will have a lasting impact that will be almost impossible to reverse, with consequences not only for the people who depend on it, but potentially also for central Mali's stability and migration patterns.

Lake Chad

There are grave dangers from water infrastructure projects in the Sahel, which create distinct groups of winners and losers. Lake Chad is a cautionary example of the ecological collapse of Sahelian wetlands (Coe and Foley 2001). Upstream water impoundments for dams and diversions for irrigation have delivered economic benefits to some but have reduced lake size by 95% over the last few decades. For the people downstream who formerly depended on the lake's ecosystem services, this has resulted in water shortages, crop failures, livestock deaths and the collapse of fisheries. Lake Chad is now synonymous with instability, conflict and the migration of millions of people.

Purpose of this report

Wetlands International has worked in Mali for more than 20 years. We seek to sustain the freshwater ecosystems that form a sustainable foundation for equitable and climate resilient development, improved food and water security, and biodiversity. We see that too often in the Sahel, when water infrastructure projects are considered, sectoral and vested interests obstruct an integral and objective analysis and the exploration of alternative solutions. In such considerations, the value of wetlands in providing goods and services is often overlooked. The real costs in terms of loss and degradation of these ecosystems are not systematically assessed nor adequately factored into decision making.

In order to sustain the flood pulse of the IND, all direct and indirect, and immediate and future costs and benefits of proposed changes to the current water allocation in the UNB must be fully considered. This goes beyond just discussing financial costs and benefits and even economic ones. This is about societal costs and benefits. This would allow everyone, including stakeholders in the IND, the Government of Mali, and institutions and non-governmental organisations supporting development and governance, to understand what is at stake.

In 2005, we published The Niger, a lifeline to assess the role of water infrastructure in the overall economy and ecology of the IND and the upstream basin. This report brought the foreseeable impacts of development choices in the IND into focus and played an important role in informing related dialogue between governments and investors. Since then, the Governments of Mali and Guinea have continued to search for solutions to their food and energy security challenges, leading to new agreements on infrastructure development being struck at the level of the Niger Basin Authority – bilaterally, between the Governments of Mali and Guinea, and within the Malian government itself.

These new agreements, based on the same hydraulic engineering approach, imply a new and dramatically different use of water resources in the coming decades, the implications of which, for the IND, had not been sufficiently evaluated. Furthermore, the science surrounding hydrological modelling and evaluation of ecosystem services has developed since, challenging some of the results and assumptions made by the earlier report. Therefore, together with partner organisations and supported by the Dutch Embassy and the Malian government, new expert-led studies have been conducted that assess the value of ecosystem services in the IND in order to understand the potential impacts of proposed infrastructure, in particular the Fomi dam project and plans for major irrigation expansion in the UNB.

This report synthesises recent information based on the commissioned studies and other work. It is assumed that it will inform discussions between relevant development partners such as the Malian and Guinean governments and international investors, influencing decision making on sustainable and inclusive development in the UNB.

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A dynamic Inner Niger Delta

The Niger River Basin

The Niger River Basin covers a total area of more than two million km^2 and runs through nine countries. It is the main river artery of West Africa, flowing from the highlands of Guinea to its most northern point in Mali and back south to its delta outlet in Nigeria (Figure 1). It is the principal freshwater source in this semi-arid to arid Sahel region, making it crucial for the provisioning of a wide range of ecosystem goods and services along its route to many different beneficiaries.

This report focuses on the Upper Niger Basin (UNB), which includes the headwaters in Guinea downstream to Tombouctou in Mali. Within the Malian part of the basin, the Inner Niger Delta (IND) is an inland delta covering an area of more than 40,000 km^2. The IND is the second largest floodplain wetland in Africa and a designated Wetland of International Importance under the Ramsar Convention.

Inner Niger Delta flood dynamics

The delta's functioning is integrally linked to the river flow arriving from the upstream river basin. It is mainly characterised as a so-called flood pulse-driven system. The seasonal expansion and contraction of lakes and wetlands in the IND depends on the river inflow at the entrance of the delta, Ké-Macina for the Niger River and Sofara for the Bani River. The Niger River receives most of its runoff from rainfall in its headwaters in Guinea, located more than 600 km upstream. The Bani River contributes approximately 21% of the total inflow into the delta and is fed by precipitation in southern Mali and Cote d'Ivoire. Local precipitation in the IND is relatively low and contributes only a limited amount to the annual flooding cycle, meaning that the flood extent of the IND is largely dependent on precipitation in the upstream areas.

In the wet season, from June to November, the IND transforms from an arid environment into a vast wetland landscape with few dry places at the height of the floods, before de-flooding again over several months. Relatively small changes in the amount of water entering the delta during the flood period can have a large effect on the size of the overall flooded area and water availability throughout the delta. This flood pulse results in major seasonal variation in water levels in the delta of up to four to six metres.

Together with seasonal variability, the significant interannual and decadal variability of West African rainfall determines the total amount of annual inflow into the delta. In the period 1961–2000 this total inflow was 1,430 m^3/s (cubic metres per second) on average and ranged between 720 m^3/s and 2,100 m^3/s. The maximal size of the flooded area varies from year to year and appears to correspond strongly to the maximum flood height measured in Akka, north of Mopti (Figures 1 and 2). Whereas the total flooded area in a very dry year (less than 400 cm maximum water level at Akka) is estimated to be around 10,000 km^2, the total flooded area is roughly 20,000 km^2 in a wet year (above about 500 cm on the Akka scale). The IND ecosystem and society are adapted to this annual and decadal variability within a certain range.

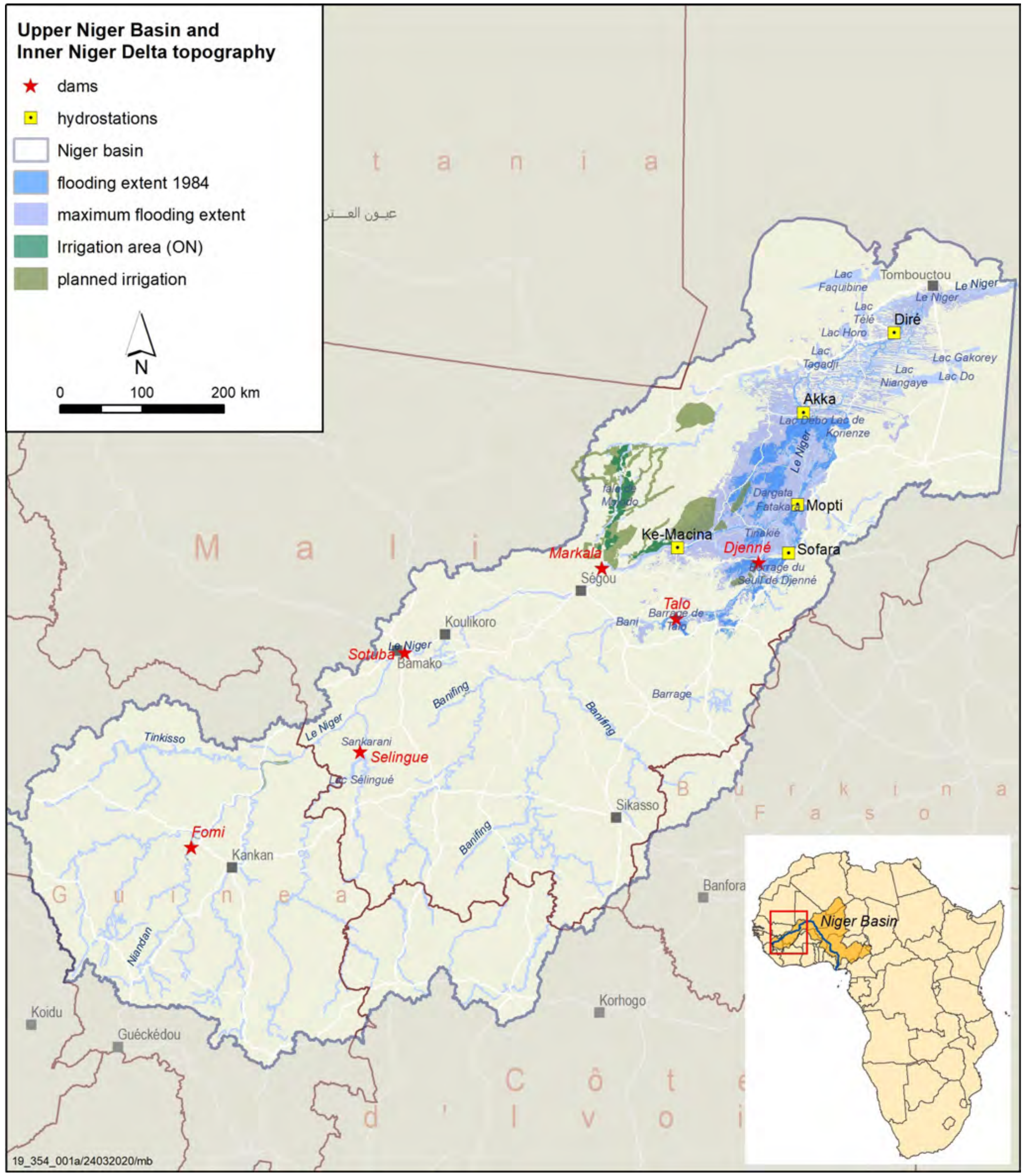

Figure 1. Overview of the Upper Niger Basin and Inner Niger Delta and location of key water infrastructure

Note: Dams on this map include hydropower dams like Fomi and Sélingué and weirs and barrages like that at Markala, used to divert water to large-scale irrigation schemes

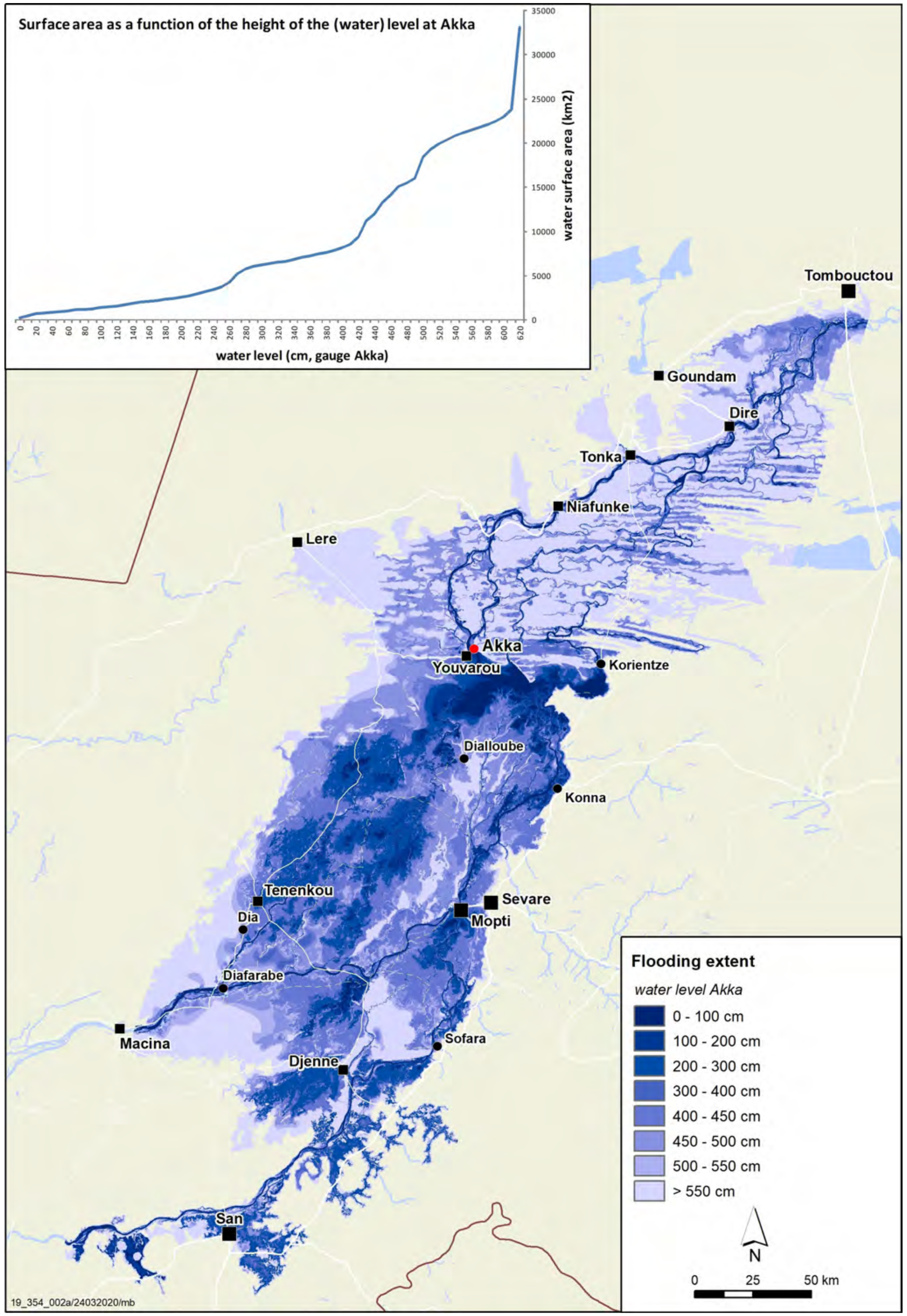

Figure 2. Inundated surface area (km²) as a function of the height of maximal water level (cm) at Akka

Livelihoods in the delta

The IND is known to be a key area for agricultural production in Mali. Throughout history, its floodplains have been cropped by various groups of skilled farmers (Marka, Bambara, Sonrai, etc.). For more than 90% of the farmers, agricultural production is important for subsistence. Key crops are rice and millet. Various irrigation techniques are used for rice production, ranging from rain-fed, flood recession ('submersion libre' or 'culture de crue') where crops are planted on the moist floodplains after the flood recedes, to water levels being controlled in simple polders along the river ('submersion contrôlée'), to small-scale pump irrigation schemes.

More than one third of the people in the delta are to some degree dependent on the fish resources for their livelihood: 4% depend exclusively on fisheries, while more than 30% practice a combination of fishing, pastoralism and/or agriculture. For fisheries, the Mopti region is most important (Schep et al. 2019). Historically, fisheries data has been collected by the Opération Pêche de Mopti (OPM) and, more recently, by the Direction Nationale de Pêche (DNP). These data sources show fresh fish to be mostly auto-consumed, while processed fish mostly reaches the Mopti market.

Livestock farming is a particularly important livelihood in the IND, with a deep cultural history and significance. Cattle and other livestock are herded seasonally, grazing across the delta during the flood recession, through a practice known as 'transhumance' (see 'Transhumance in changing times' on page 48). Twenty percent of the 20 million goats and sheep and 60% of the 5 million cows in Mali are concentrated in the IND and its surroundings during the dry period.

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The Great Drought

The UNB has historically experienced large annual and decadal variation in rainfall and resulting fluctuation in river discharge. The period 1961–2000 exemplifies this characteristic. The 1960s are considered wet years characterised by high precipitation and river discharge. From 1969 to 1992, the Sahel suffered the Great Drought (known locally as La Grande Sécheresse), which was a catastrophe for people in the Sahel and the IND. During this prolonged drought, a time of regular 'disaster', the flooded area of the IND averaged only 11,000 km². These years fell outside society's adaptative range. The cumulative effects included severe famine in the Sahel and increased desertification.

The lowest flood level ever recorded was in 1984, when the IND only reached an inundation of 8,000 km², one third of its maximal range. While the IND was a relative haven during the drought compared to the rest of the Sahel, the carrying capacity of the ecosystem and its services collapsed under the pressure of too many people and livestock and too few resources. The maximal flood level decreased to 336 cm and bourgou lost most of its optimal habitat. Intensified human pressures caused pastures to be stripped bare and trees to be torn out. Most of the delta's flood forests, habitat for nesting birds and nurseries for fish, suffered overexploitation and some were entirely destroyed. Many cows died and herders lost more than half their cattle due to reduced food resources and the reduction of the inundated area.

Climate change is likely to result in increased temperatures for the region and changes in precipitation (see Annex). Simultaneously, the number of people competing for ecosystem goods and services in the UNB is rapidly increasing due to a rapidly growing population and internal migration to access the delta's resources. Hence a situation like that of 1984 might occur more frequently in future and affect a larger population.

Biodiversity

The delta has exceptional ecological value. It is a globally important biodiversity hotspot and one of the largest designated Ramsar sites, i.e. Wetlands of International Importance, in Africa. Seasonal flood patterns are crucial in maintaining the biodiversity of the area (Klop et al. 2019; Wymenga et al. 2017a and 2017b).

Vegetated with plant and tree species that are adapted to fluctuations in water level, the IND ranges from nutritious temporary grasslands around the delta in the wet season to pastures, marshes and flood forests of Acacia kirkii in the delta. Important vegetation types include wild rice, didere (hippo grass) and bourgou, all of which are governed by the depth of water during the flooding season. This set of vegetation is manifested as an immense green plain that is intensively grazed during the retreat of the water. The floating bourgou fields are essential to the fish populations in the delta as a spawning area and nursery.

The IND is one of the major floodplains in Africa and as such of paramount importance to both resident and migratory bird species. The enormous ornithological importance of the area has been documented many times (Zwarts et al. 2006). At least 27 species of migratory water birds are seasonally present in very high numbers. For more than 11 species, a high proportion of the non-breeding Eurasian population congregates here (>10%, for seven species even >25%). The numbers of colonial breeding water birds in the central lakes are amongst the highest for wetlands in Africa. The IND's Acacia kirkii flood forests and the Acacia seyal forests at the fringes of the delta are home to high densities of migratory land birds, hosting many European species from the Red List of the International Union for Conservation of Nature (IUCN). The survival of wintering birds and reproduction of resident birds is also closely linked to flood extents. This means that the population size of many Eurasian and African species is (partly) determined by flood performance in the IND.

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Sustaining livelihoods, society and the economy through ecosystem services

Ecosystem services

While covering only 1.6% of Mali's land area, the Inner Niger Delta (IND) provides about 15% of national cereal production (Ministère du Développement Rural 2015/2016) and makes it possible for farmers to grow crops farther north than anywhere else in the West African Sahel. During the dry season, 60% of the national livestock herd is found in the delta (Wetlands International 2019). The delta also produces 80% of Mali's fish and pasture, 30% of its national rice production (considered separately from cereals) and delivers 8% of Mali's Gross Domestic Product, sustaining more than two million people, 10% of the national population (Pearce 2017). The economic benefits extend well beyond the delta and serve as a driver of the rural economy and food security across the entire region. How does the delta sustain all these livelihoods, the regional society and economy and reach even beyond? It does so through its ecosystem services and goods.

Provisioning of these ecosystem services is directly related to the flood pulse as expressed by the extent of the flooded area and the depth of the water. Primary and secondary production in the delta depends on the flooding and hence changes to the timing and extent have a significant impact on production. Biodiversity also plays an important role in the delta's sustaining ecosystems and in ecosystem service delivery, e.g. some species act as food for humans, bacteria support nutrient recycling and water purification, and insects support pest control and pollination.

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Ecosystem Services

Ecosystem services in the delta (and elsewhere) are the many, varied benefits that humans gain from the natural environment and functioning ecosystems (Millennium Ecosystem Assessment 2005). They are grouped into four broad categories:

- Provisioning ecosystem services – production of food and water, and natural products for energy, construction materials and medicines;
- Regulating – carbon sequestration and climate regulation, waste decomposition, water and air purification, pest and disease control, and flood regulation;
- Supporting – nutrient cycling, primary production, soil formation, habitat provision and pollination;
- Cultural – spiritual and historical value, recreational and therapeutic benefits, and importance for science and education.

Key to this all is the connection between systems, where climate and the changes occurring to it determine variable rain patterns in West Africa, which in turn affect the Niger flood pulse feeding into the delta. This determines the availability of ecosystem services on which livelihoods and the regional economy depend (Figure 3). Storing and diverting water resources with water infrastructure significantly affects this connectivity. This report notes that low flooding levels, especially during consecutive years, have detrimental impacts on the amount of ecosystem goods and services that can be produced.

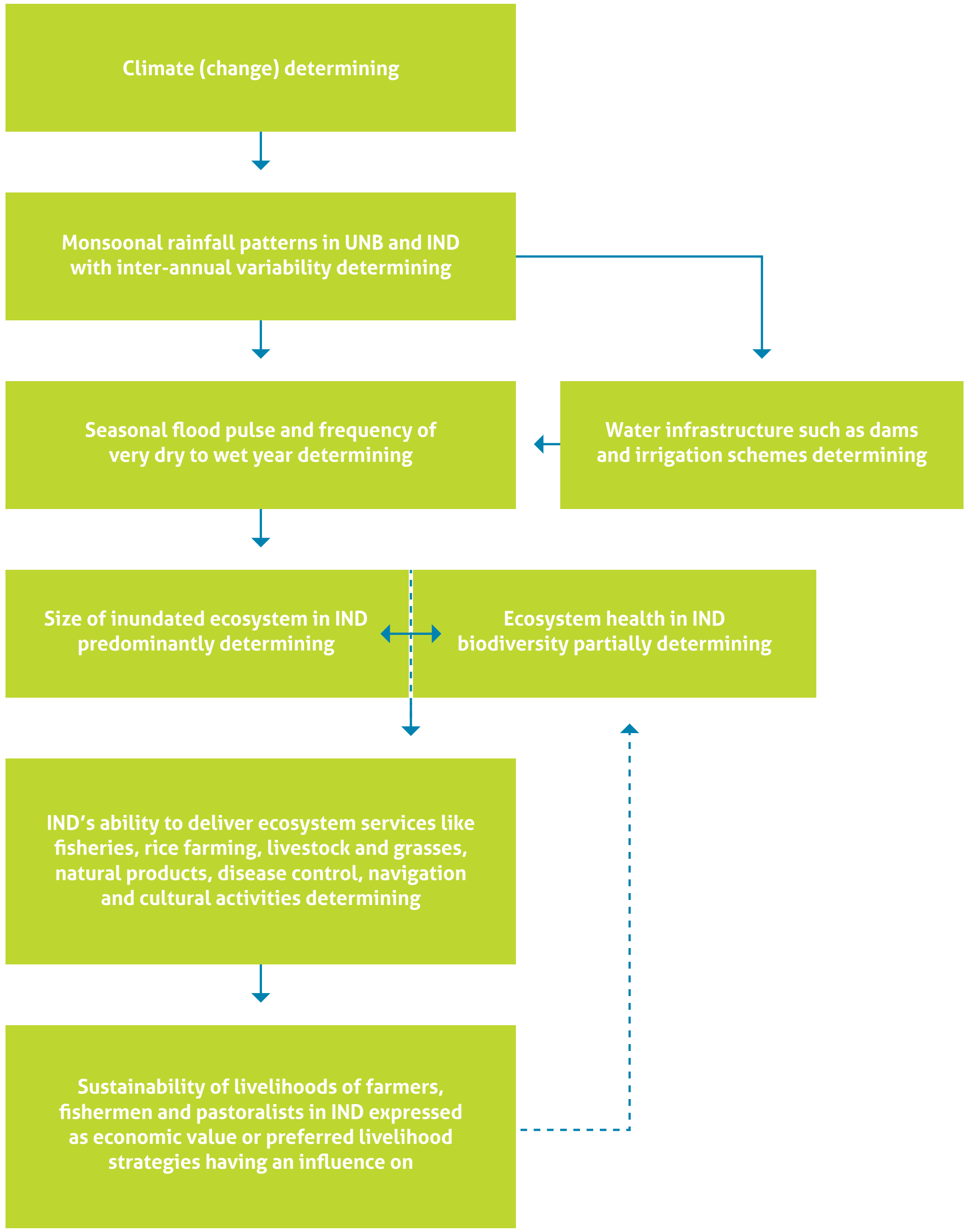


Figure 3. Connections: climate and rainfall patterns determining the IND's ecosystem size

Note: The IND's ecosystem size defines the level of ecosystem services that it can provide. Water infrastructure is an anthropogenic factor determining the flood pulse and hence ecosystem service delivery in the delta.

The following sections will examine the connections between key ecosystem services considered and the flood pulse in the delta's floodplain wetlands (Table 1).

Provisioning services	Fisheries Rice farming Livestock and grasses Natural products
Regulating services	Disease control
Cultural services	Transportation/navigation Cultural activities

Table 1. Overview of studied ecosystem services in the IND region

Fisheries

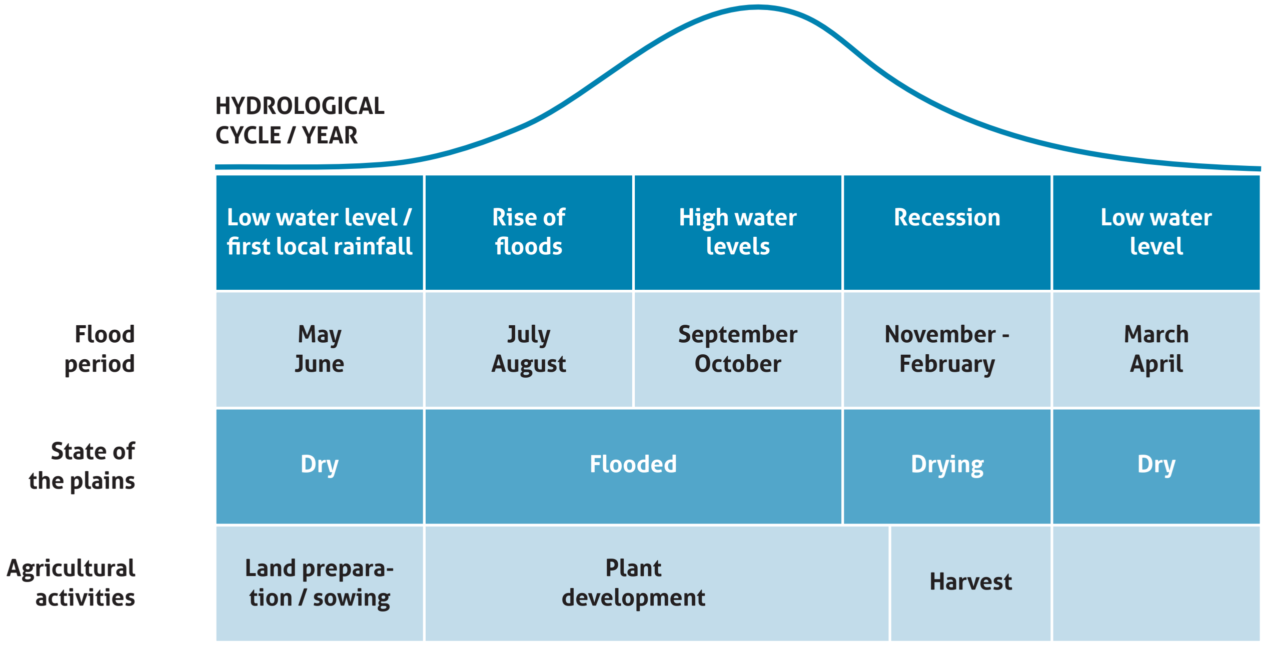
As mentioned, about a third of the population in the IND catches fish for either subsistence purposes or to sell on the market. Fish from the IND are exported across West Africa. Total fish trade in the IND is estimated to be between 10,000 and 50,000 tonnes and is also related to the flooding of the IND (Zwarts et al. 2005). The total value of fisheries (traded and auto-consumption) in the entire delta is valued at between 50 and 95 Billion West African CFA Franc (FCFA) per year (Schep et al. 2019).

The fishing season typically takes place after peak flooding, generally in the last quarter of any given year. During the de-flooding period, fish become concentrated in temporary enclosed water bodies like lakes or riverbeds with low water flow. The duration of the flooding period, and in turn, the maximum water levels at Akka during the flooding season, are critical for fish growth and biological reproduction each year (Zwarts et al. 2005). Longer flooding periods provide sufficient time for fish species to complete their lifecycle and maintain their populations.

A steady reduction in fish catch due to the increase in fishing pressure, water scarcity and shorter flooding periods has been observed over the last 20 years. In recent surveys, local Mopti fishers indicate that in the last five years, at least, catches have been lower and competition for fish is increasing.

Rice farming

Farming in the delta is highly dependent on the combined effects of the rainy season and flooding period. Cropping types, distribution and yields are greatly defined by the date on which rainfall and flooding starts, the duration of the flooding period, the maximum water level and the speed at which de-flooding occurs (Thom and Wells 1987). Agriculture in the delta is mostly focused on rice and millet production. While rice is highly dependent on flooding and irrigation, millet and other important cereals such as fonio, maize and sorghum are more dependent on rainwater availability.



HYDROLOGICAL CYCLE / YEAR	Low water level / first local rainfall	Rise of floods	High water levels	Recession	Low water level
Flood period	May June	July August	September October	November - February	March April
State of the plains	Dry	Flooded		Drying	Dry
Agricultural activities	Land preparation / sowing	Plant development		Harvest	

Figure 4. Flood pulse-driven agricultural cycle in the delta (adapted from Zare et al. 2017)

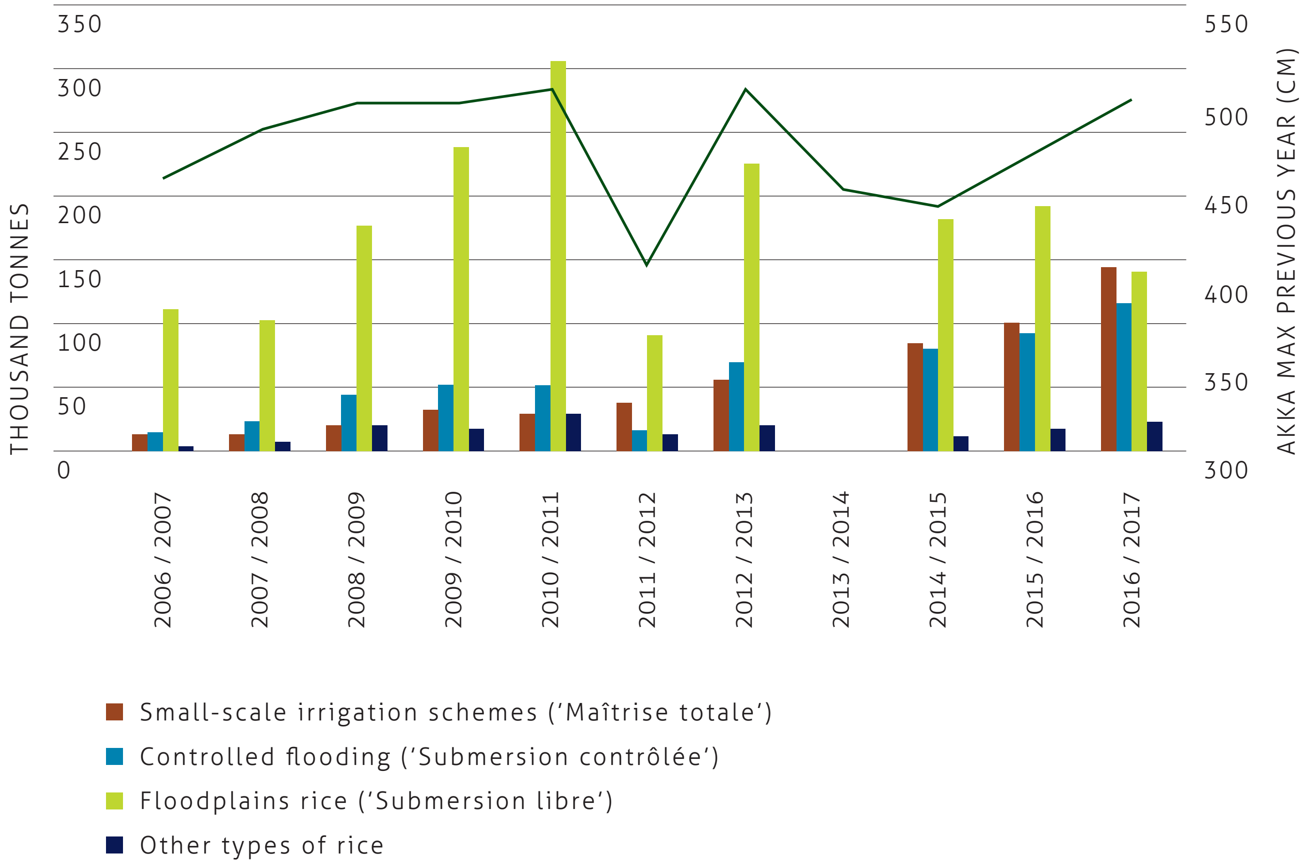


Figure 5. Small-scale rice production in the Mopti region

The largest share of the rice produced at small scale in the IND corresponds to traditionally grown rice (natural flood irrigation) in the Mopti floodplains, followed by that produced through controlled flooding irrigation, as in ORM (Opération Riz Mopti) and ORS (Opération Riz Ségou) (Figure 5). Small-scale irrigation schemes are experiencing an increase in recent years, matching rice grown in the floodplains in the last year studied.

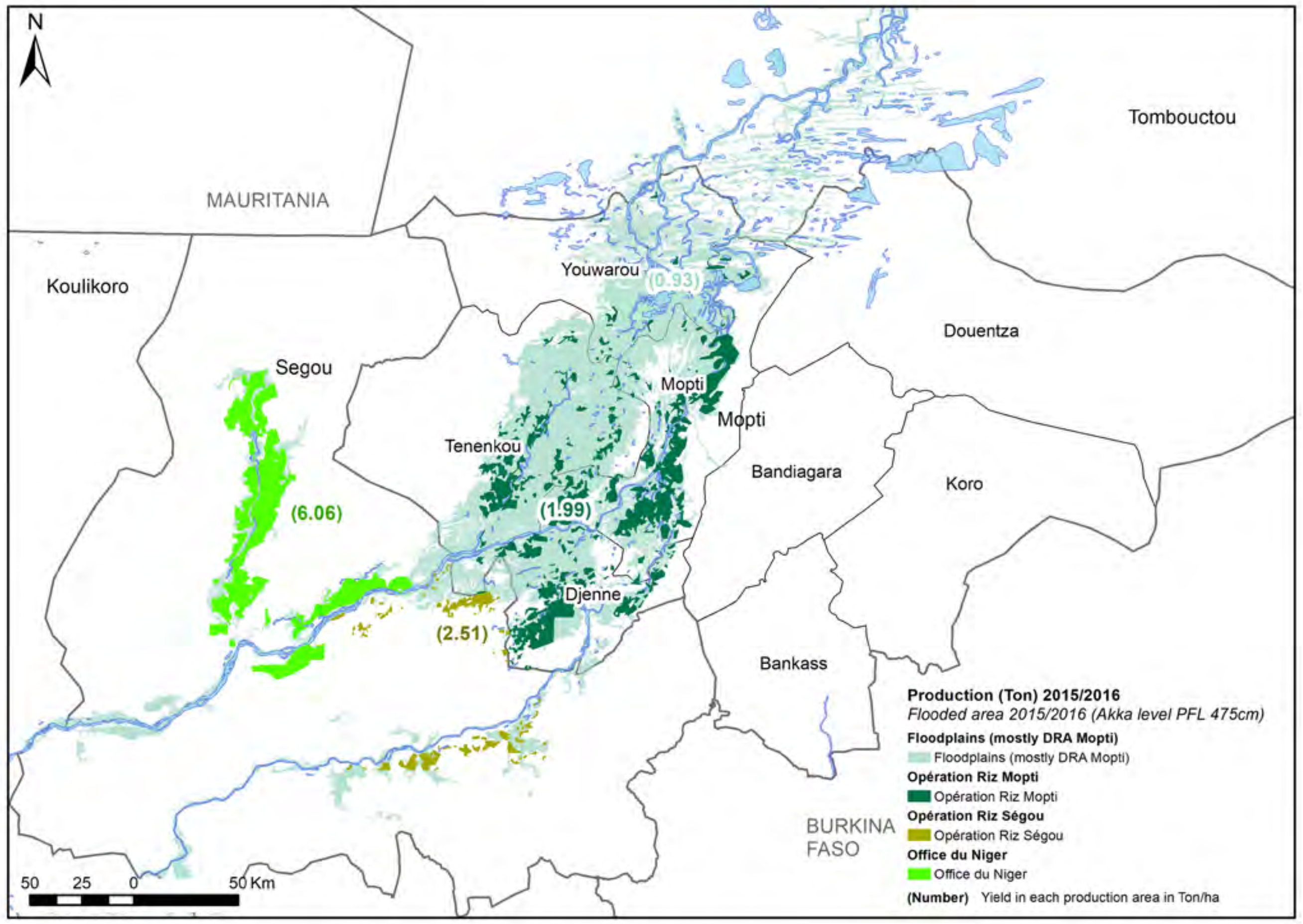


Figure 6. Small-scale rice production areas in the Inner Niger Delta (floodplains, ORM and ORS), and Office du Niger (ON)

Traditional floodplain rice production (yields) can vary greatly between years as it strongly depends on water availability and depends on the inundation zone and water depth (optimal depth 1–2 m). The suitable area for traditional rice growing is not a linear function of the water depth, due to the shape of the delta (see Figure 2). For instance, at a peak flood of 400 cm in Akka, the potential rice zone amounts to 4,000 km², but halves to just 2,000 km² at a peak flood level of 350 cm, only a 50 cm reduction. This non-linearity explains that rice production in the Mopti region can easily decline from about 400,000 tonnes in a wet year like 2010/2011 to about 100,000 tonnes in a dry year like 2007/2008 (Figure 5).

Compared to natural floodplain rice production (0.93 t/ha productivity in the Mopti floodplains), crop yields can be doubled when water is slightly managed, as with flood-controlled irrigation (1.99 t/ha by ORM or 2.51 t/ha by ORS). In comparison, when land is fully irrigated the yield may be boosted up to six times (6.06 t/ha by the ON, see Figure 6). Normally, such a yield improvement requires higher agricultural inputs (e.g. fertiliser, labour, mechanisation) and hence may also happen in the IND with the right sort of investment. However, at the same time it must be said that the water productivity (defined as the amount of yield produced per unit of consumed water) of the ON is under debate, with huge irrigation losses due to canal seepage and non-beneficial evaporation.

In 2011, small-scale rice production in Ségou and Mopti (orange and green) was worth approximately 130 billion FCFA, and 50 billion FCFA in 2012. Comparatively, for the same time period, the value of rice produced by the ON ranged between 114 and 180 billion FCFA (Figure 7).

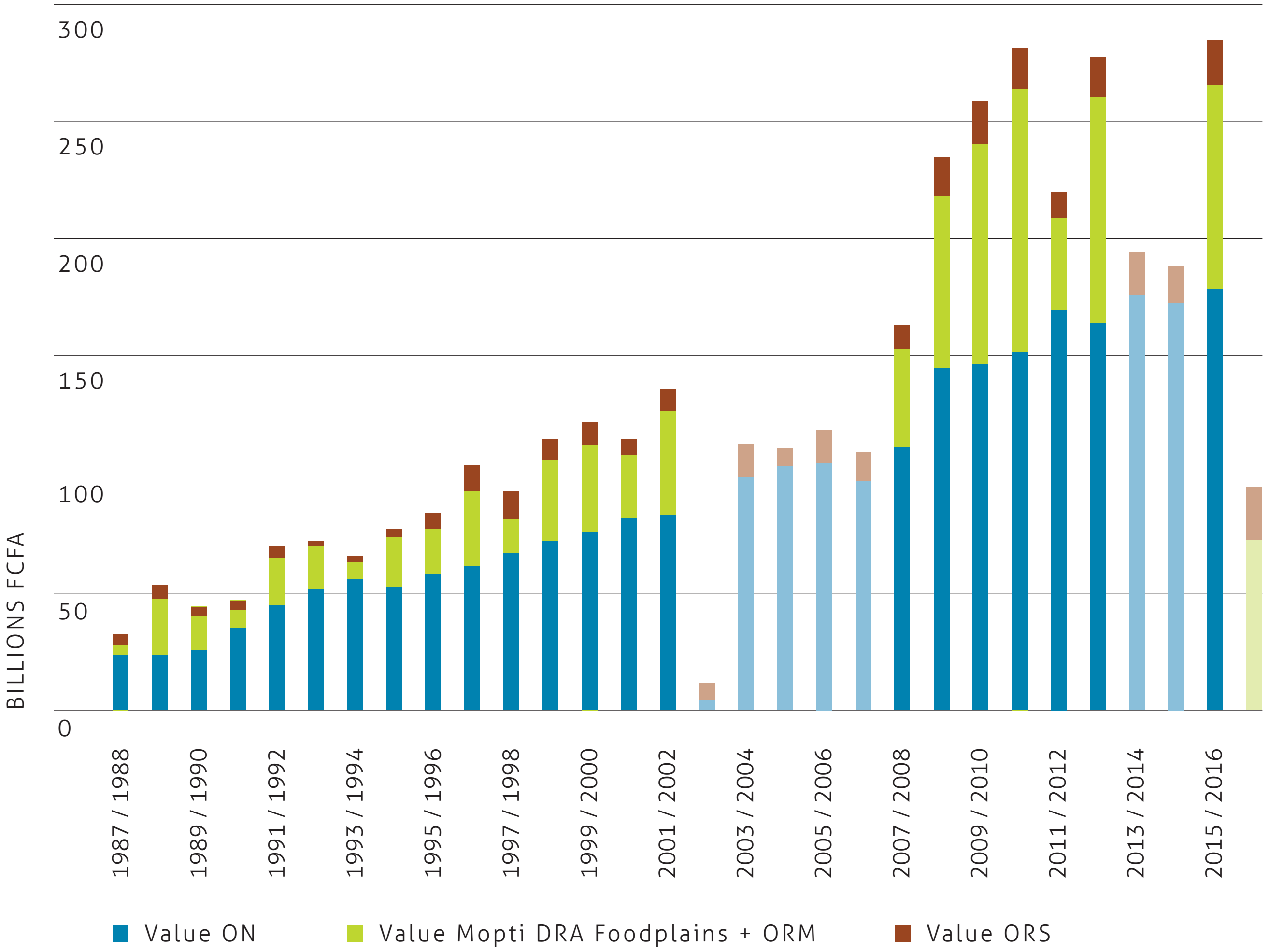


Figure 7. Value of rice production in different zones (2014 FCFA value)

Note: The years with lighter bars are those with production data gaps or with less detailed data

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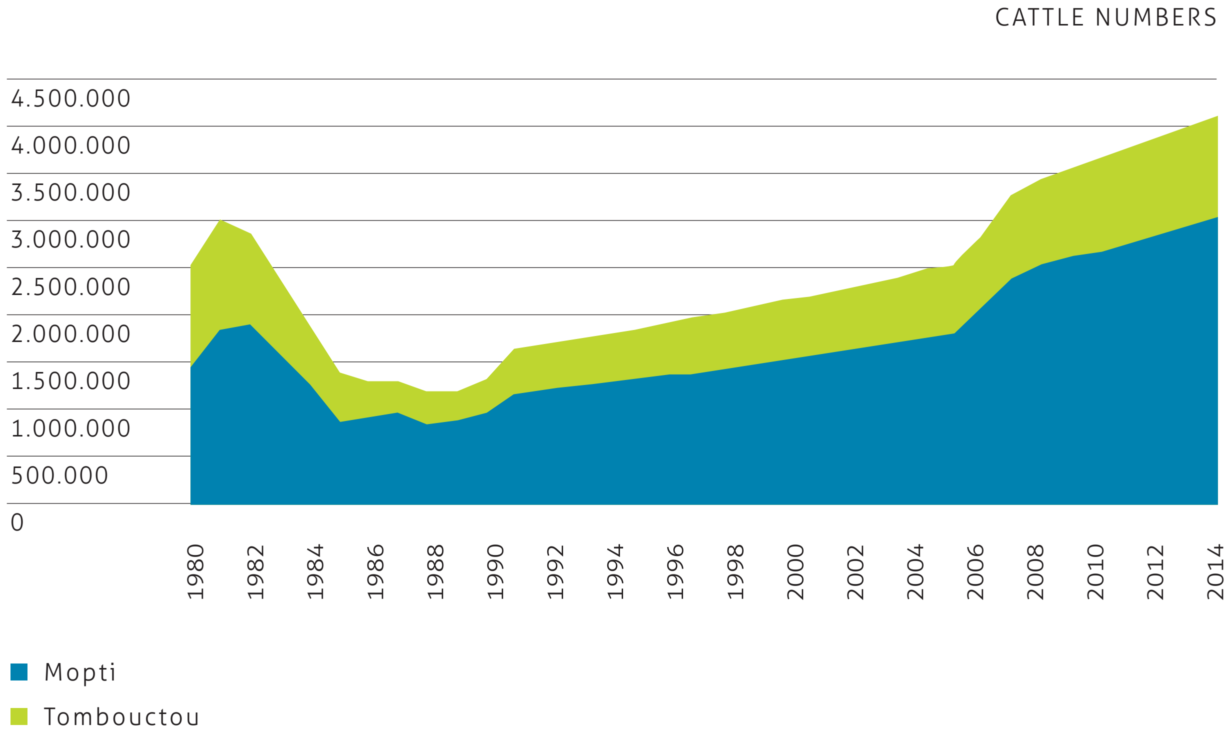
Livestock

The IND supports millions of cattle, sheep, goats, horses and camels. It is highly productive for livestock, not only because of its size, but also because of its flood dynamics. About 40–60% of the estimated 10 million cows in Mali are concentrated in the delta and its surroundings.

The IND represents an essential dry season resource for pastoralists. When the floodplains are submerged in the wet season from July to September, the herders gradually retreat to higher ground, travelling up to several hundred kilometres to reach good pasture. During the de-flooding in the dry season months from December to June, the herds gradually return to graze in the IND. Floodplain areas such as the IND are critical for livestock in the Sahel because they offer excellent grazing grounds (see text box on bourgou) during the dry season when the drylands cannot sustain fodder.

Historically, the quantity of cattle, sheep and goats has been highly correlated to human population. Periods of drought significantly reduce the number of cattle in the region (see section 2.34 on the Great Drought). Since the Great Drought, the number of cattle, sheep and goats in the Mopti and Tombouctou area has steadily increased.



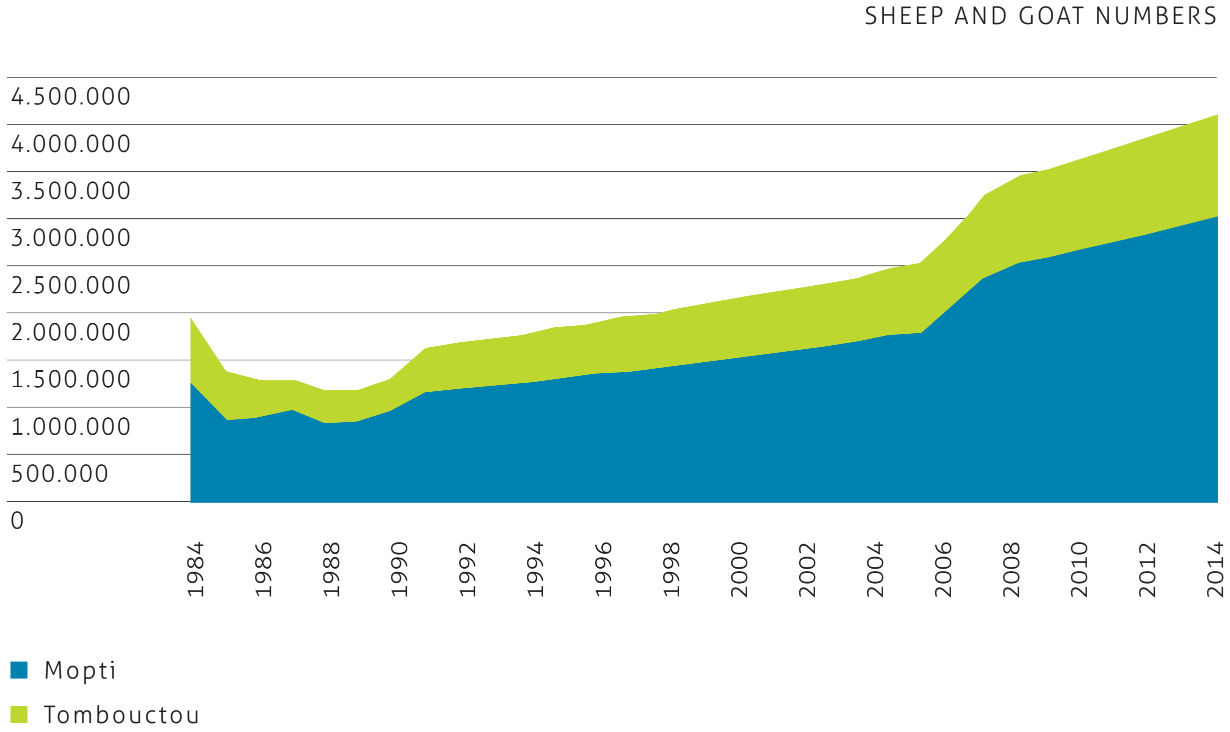


Figure 8. Chart showing livestock numbers between 1980 and 2015

The current economic value of livestock raising including meat and milk production, animal sales and leather, calculated for the regions of Mopti, Tombouctou and Ségou, represent an annual total of about 250 Million FCFA.

Value (millions FCFA)	Meat	Dairy	Animal sales	Skins	Total
Mopti (2015)	64,408	10,766	59,295	825	135,294
Tombouctou (2015)	30,838	7,476	28,361	387	67,063
Ségou (2011)	20,242	4,041	24,898	323	49,504

Table 2 Overview of economic valuation of livestock products by IND region

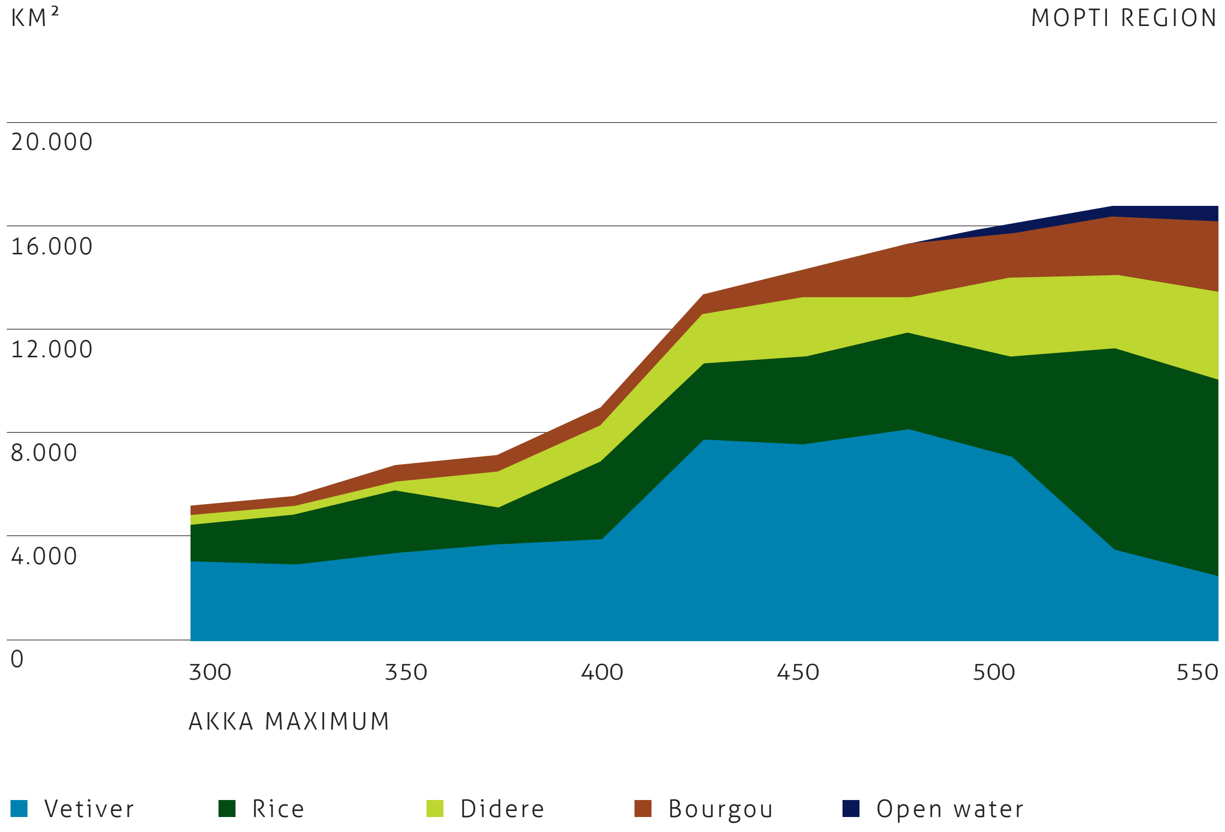


Figure 9. Change in flooded area (km²) and vegetation cover in Mopti region related to maximum water level at Akka

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Grasses

Grasses are mostly utilised for livestock grazing while wild rice is used for human consumption. Cattle in particular benefit from bourgou, as the most nutritious and last available grass to graze before the next flood. Each type of grass has its own optimal habitat, strongly correlated to water depth:

- Wild and cultivated rice, best grown in water depth 1–2 m during the peak flood;
- Floating grass locally known as didere, water depth 2–3 m;
- Larger floating grass locally known as bourgou, water depth 3–5 m.

Occasionally, where the water is too deep for bourgou to grow, open water remains. Figure 9 shows the various potential growing areas for these grasses as a function of the measured maximal water level in Akka.

Bourgou

Bourgou is a type of grass commonly used as feed for cattle by the nomadic herders that come to the IND (Zwarts et al. 2005; Zwarts et al. 2009). Due to its qualities as fodder, it is cultivated across the delta and is usually grazed once the flood begins to recede and farmers have harvested their crops. Bourgou grows in deeper waters than other grasses such as didere and vetiver. Most floodplain areas in Africa are flooded by 0.5–2 m of water, but the depth of maximal flooding is exceptionally high in the IND, varying between 4–6 m. That is the reason why bourgou grass, which grows where the water depth reaches at least three metres, is common in the IND but not in other African floodplains. People in the IND plant bourgou where possible in deep water because they know it is extremely productive and has a high nutritional value.

Many bourgou pastures have been lost over the last four decades, affecting the livelihoods of herders and fishers. Survey results indicate that almost all respondents have observed a decrease in the amount of bourgou available in the last five years. Given the strong dependence of bourgou on flooding, this observation may be related to the decrease in water availability, as observed by respondents practicing agricultural activities.

Natural products

In addition, the IND provides many natural products that are important to the sustenance of its inhabitants:

- Raw materials for construction – clay, wood, straw;
- Raw materials for energy – firewood, charcoal, straw;
- Natural products for traditional medicine – herbs and tree-related products.

The vast majority of the local population collects clay for construction purposes (94%). About 85% of delta inhabitants collect firewood materials as a source of energy, for their own consumption, and many have observed a decrease in its availability in the last five years. Collection of herbs and tree-related products, natural products used in traditional medicine, is carried out by almost half of the respondents. A decrease in their availability has been observed over the past five years (69% in the case of trees, and 87% for herbs).

Disease control

Public health in the delta is inextricably linked with the combined functional characteristics of wetlands and rivers. For example, stagnant water bodies, often abundant near wetlands or within irrigation systems, provide an ideal habitat for many of the vector species related to key waterborne diseases. Also, such stagnant water bodies accumulate pollutants from untreated wastewater and chemical-loaded irrigation return flows. In a healthy flood pulse-driven system such stagnant water bodies get flushed during the wet season. This diminishes the suitable habitat for vectors and flushes out pollutants. Obviously, public health is also directly linked to additional factors such as food security, water, sanitation and hygiene (WASH), and the availability of medical services.

Transport/Navigation

Transport by boat is important for both commercial and leisure purposes in the delta. Passengers and freight are primarily transported by two different types of boat, the ferry and the pinasse (a traditional wooden boat). Ferries only operate during the wet season as they require a minimum of 3–4 m of water depth for navigation. The pinasses run through into the dry season until the water level becomes too low even for these smaller boats, which require around a metre of water. Based on the day rates and the average number of navigable days per route, the total value for fluvial transportation can be estimated to have a total annual value of 2.1 billion FCFA for the Koulikoro–Mopti route and 1.6 billion FCFA for the Mopti–Gao route.

Cultural activities

Since gaining independence in 1961, Mali has worked to preserve and promote elements of its national heritage. These efforts resulted in the inscription of four elements in UNESCO's Representative List of the Intangible Cultural Heritage of Humanity (three on the Representative List of Intangible Heritage, RLIH, and one on the Intangible Heritage List in Need of Urgent Safeguarding, IHLNUS). Two of these elements are in the IND: the cultural space of the Yaaral and Degal (inscribed on the RLIH), and the so-called Sanké Mon, a collective fishing rite of the Sanké (inscribed on the IHLNUS).

Residents of the delta were surveyed on their participation in the following types of cultural activities: animal crossing events (transhumance festivals), collective fishing events and pirogue racing events. The results showed that 44% participated in these activities.

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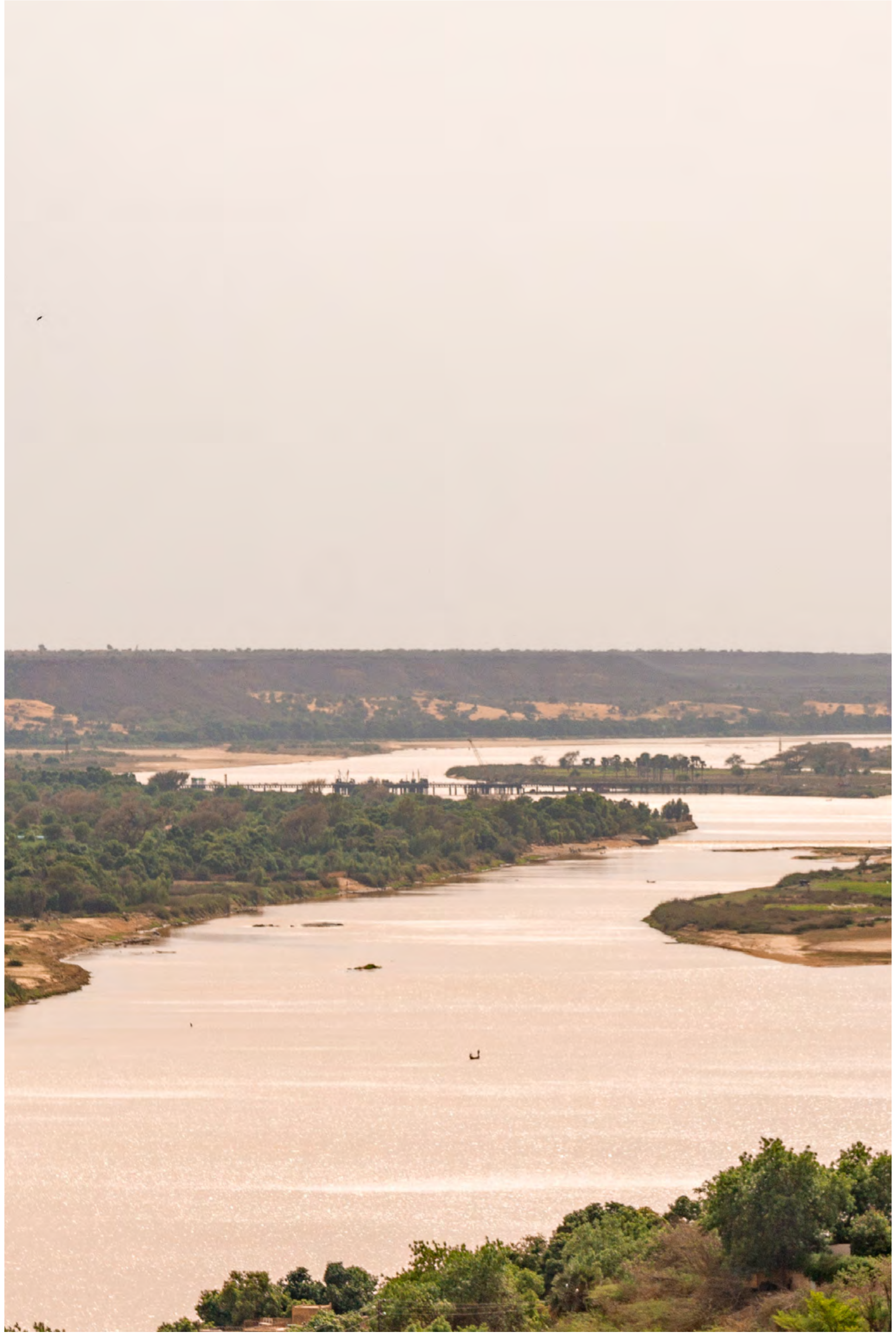

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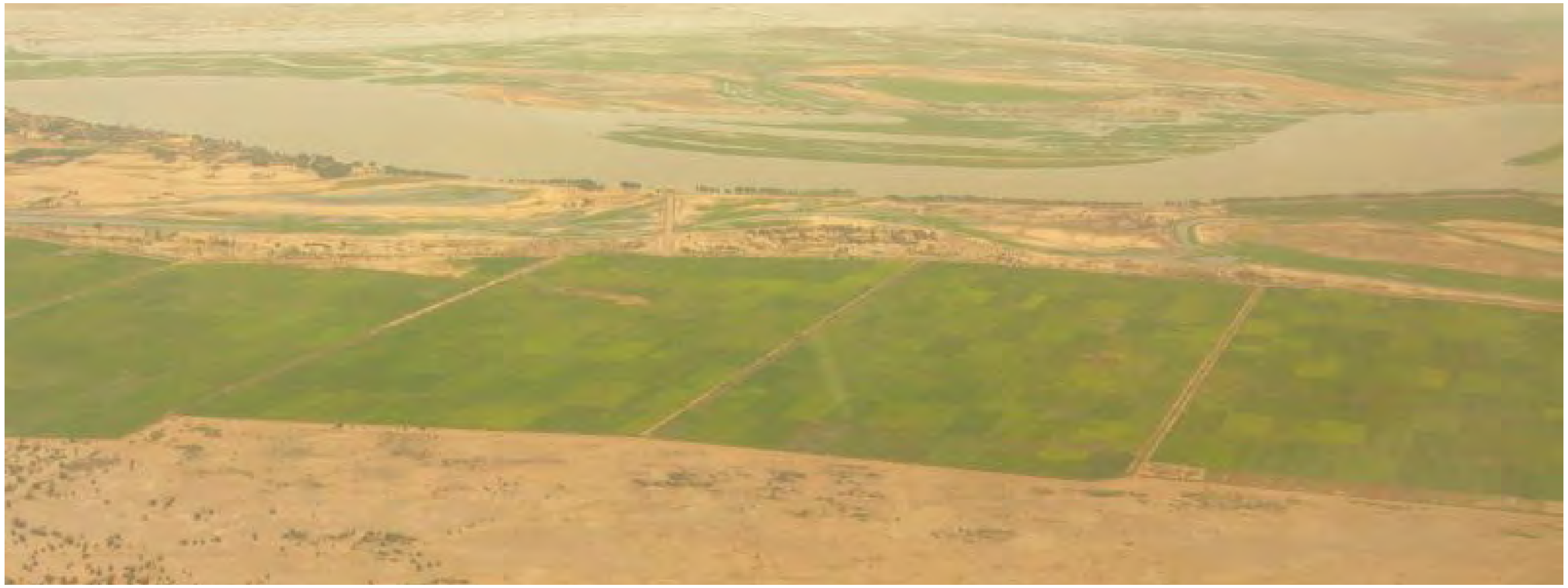
Need and feasibility of water infrastructure for food and energy security

As a response to the severe droughts in past decades, Guinea and Mali have undertaken several food and energy security strategies (Zwarts et al. 2005; Zwarts et al. 2006). These governmental objectives have been pursued through the construction of water infrastructure to take advantage of Malian and Guinean hydroelectric potential and to store and divert water to agricultural irrigation systems to improve food security.

Current dams, barrages and reservoirs

In Mali, the water infrastructure that has been constructed in the Upper Niger Basin (UNB) for energy and irrigation purposes include the:

- Markala barrage downstream of Ségou. This was built in 1945 and supports the Office du Niger (ON) and is currently using about 2.6 km^3 of water per year. In wet years, this water diversion represents 3% of the annual flow of the Niger River, while in dry years it can be up to 14%. During the dry season this diversion may use most of the Niger River's water resources;
- Sélingué dam, built in 1980 on the Sankarani River, a Niger River tributary. It produces electricity for the capital of Bamako, and 1,400 ha of rice irrigation and fishery activities are supported as well. The reservoir has a total volume of 2.2 km^3. Current dry season water demands of the ON would not be sufficiently supplied without Sélingué, which increases the discharge between January and June;
- Sotuba dam, in operation since 1929, is a very small hydropower plant located directly downstream from Bamako. It does not have a significant hydrological impact;
- Talo dam, on the Bani River, takes 0.18 km^3 of water to irrigate upstream rice and pasture. The expectation is that due to Talo, the flow of the Bani River at Mopti between July and October will be reduced by 0.39 km^3;
- Djenné dam was recently constructed. About 0.3 km^3 of water will be used annually to irrigate rice and pasture.



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Fomi dam project in Guinea

While Guinea has long desired to build the Fomi reservoir for electricity to support both its growing population and the energy needs of its mining industry, its most recent proposed design makes it multifunctional. A key secondary goal is to guarantee water for downstream irrigation expansion for the same reason the Sélingué reservoir is important. Water released from the Fomi reservoir for hydropower generation during the dry season and then diverted at the Markala barrage would enable the ON to irrigate more land. Fomi is therefore a key element in the Sustainable Development Action Plan of the Niger Basin Authority (NBA 2007), and the construction of Fomi is supported by the Ministry of Agriculture in Mali as a prerequisite to extend the irrigated area of the ON.

For the purposes of studying the potential impacts, three different dam sizes and reservoir dimensions proposed by the Fomi dam project are considered here:

- Small: dam height 388.5 m above sea level, storage volume 1.17 km³, reservoir surface area 159.6 km²;
- Medium: dam height 396 m above sea level, storage volume 2.8 km³, reservoir surface area 287.0 km²;
- Large: dam height 402 m above sea level, storage volume 4.9 km³, reservoir surface area 416.4 km².

Downstream of the IND, two new dams are planned: the Taoussa dam between Tombouctou and Gao in Mali and the Kandadji dam in Niger. Both dams are expected not to influence IND flood pulse dynamics.

When this research was conducted, multiple sizes were being considered for the Fomi dam. Hence the research shows impacts of various water development scenarios based on different dam options together with multiple irrigation ambitions for the Office du Niger. Meanwhile the dam size of 396 m height has been selected by the relevant authorities for further development. The dam was originally scheduled to be built near the village of Fomi. From there, its proposed location moved to Moussako, 20 km upstream, and from there again it moved to the current location of Folon 30 km upstream of Fomi. Whilst changing the Fomi project location has considerable hydrological effects in the direct surrounding environment, the research showed no significant effects on the hydrological discharges reaching the IND.

Office du Niger

Over the last century, various irrigation schemes have been developed in Mali and Guinea by government, often in close cooperation with international development partners. These irrigation schemes contribute to food security in the region and allow for the export of agricultural products. Mali's largest irrigation scheme, located just upstream of the IND, is managed by the ON, the Malian authority charged with contributing to food security. The goal of the ON is to be the rice granary for West Africa, and the current production of 740,000 tonnes across an irrigated area of about 1,300 km² generates 52% of national rice production.

There are two main harvest periods in the area irrigated by the ON, one during the wet season ('hivernage') and one during the dry season ('contra-saison'). Currently, during the wet season there is normally enough water for the ON to irrigate the entire area. During the dry season, the ON takes an average of 100 m³/s of water from the Niger River at the inlet of the Markala weir in May and June, which is made possible by discharges from the Sélingué reservoir. Without this additional water, dry season irrigation would currently not be realistic.

To meet increasing demand for food, the Malian government proposed an expansion of the ON in the Study of the Agricultural Development Programme of the Office Zone du Niger, 2014–16 (PAHA IV). In total, about 3,300 km² will be added to the 1,200 km² already being irrigated. The goal is to expand the total irrigated agricultural area to about 2,000 km² by 2025, 3,100 km² by 2035 and almost 4,600 km² by 2045. This corresponds to an annual extension rate of 90 km². By comparison, over the last 10 years expansion has averaged 40 km² per year. Adding 3,300 km² will result in a significant increase in potential cereal production, projected at two million tonnes, including 1.2 million tonnes of rice, an increase of 58%. The total annual irrigated area will be even more as some areas will be cropped more than once a year. Based on these ambitions, the total irrigated area in 2045 will be about 5,400 km².

The ON has received a lot of attention from international private investors and agrobusinesses including those interested in biofuel production. This is supported by various policies from African economic entities like the Economic Community of West African States (ECOWAS) and Mali itself, and by institutes like the World Bank and the Food and Agriculture Organization, who promote the development of so-called agropoles in Africa to achieve food security (Brondeau 2018). Clear figures are missing on how much of the ON's produce is contributing to achieving food security in Mali or in other countries.

Feasibility of ON expansion

The available water in the Niger River would technically allow the ON's expansion plans to be realised during the wet season. However, the plans also propose an intensification of crops such as off-season rice and perennial sugarcane in the dry season, from January to June. A further extension of the ON's area in the dry season is not possible under current conditions and can only be achieved by either increasing irrigation efficiency or by supplying more water from the Niger River. Supplying more water by diverting the Niger River at Markala is not possible without the construction of a large new dam like Fomi for water storage upstream.

Thus, the question is, would the current plans for new water infrastructure enable the anticipated irrigation and production goals? A completely unmanaged Niger River (without any dams upstream of Markala but with irrigation at 2015 levels) would currently provide enough irrigation supply for dry season cropping by the ON in extraordinarily wet years, comparable to conditions at the end of the 1960s. Looking at the average water availability over the period 1961–2000, only 67% of the current irrigation water demand of the ON would have been met, leaving a gap of 23% (represented by the blue bar in the top part of Figure 10). Looking at the dry and wet seasons separately reveals that the deficits in the dry season are up to 43% and therefore on average quite substantial, whereas wet season irrigation supply deficits amount to only about 3%.

Current water discharges released from the Sélingué dam upstream reduce the average supply gap for irrigation from 23% to 4% in average years and 8% in the dry season, while eliminating the irrigation supply gap entirely in the wet season.

While Sélingué dam releases are adequate to meet current irrigation demands in the wet season, expansion of dry season irrigation by the ON would not be feasible due to average projected water deficits of 18% in 2025, 32% in 2035 and 42% in 2045 in the dry season (Figure 10, middle part, Sélingué scenario).

ON expansion feasibility by means of a new upstream dam depends primarily on its storage volume and operation rules for impoundment and release. Plans to intensify dry season cropping irrigation by the ON as envisaged in the year 2045 are unreasonable in all dam scenarios, except if a large Fomi dam is operated. A small Fomi dam would reduce the dry season water supply gap versus that achieved by Sélingué, but only by a small amount (Figure 10, middle part, Sélingué only and Small Fomi scenarios). Average supply gaps would be 14% in 2025, 28% in 2035 and 39% in 2045. A large Fomi dam would significantly reduce this average dry season supply gap to 0% in 2025, 6% in 2025 and 17% in 2045 (Figure 10, middle part, Large Fomi scenario).

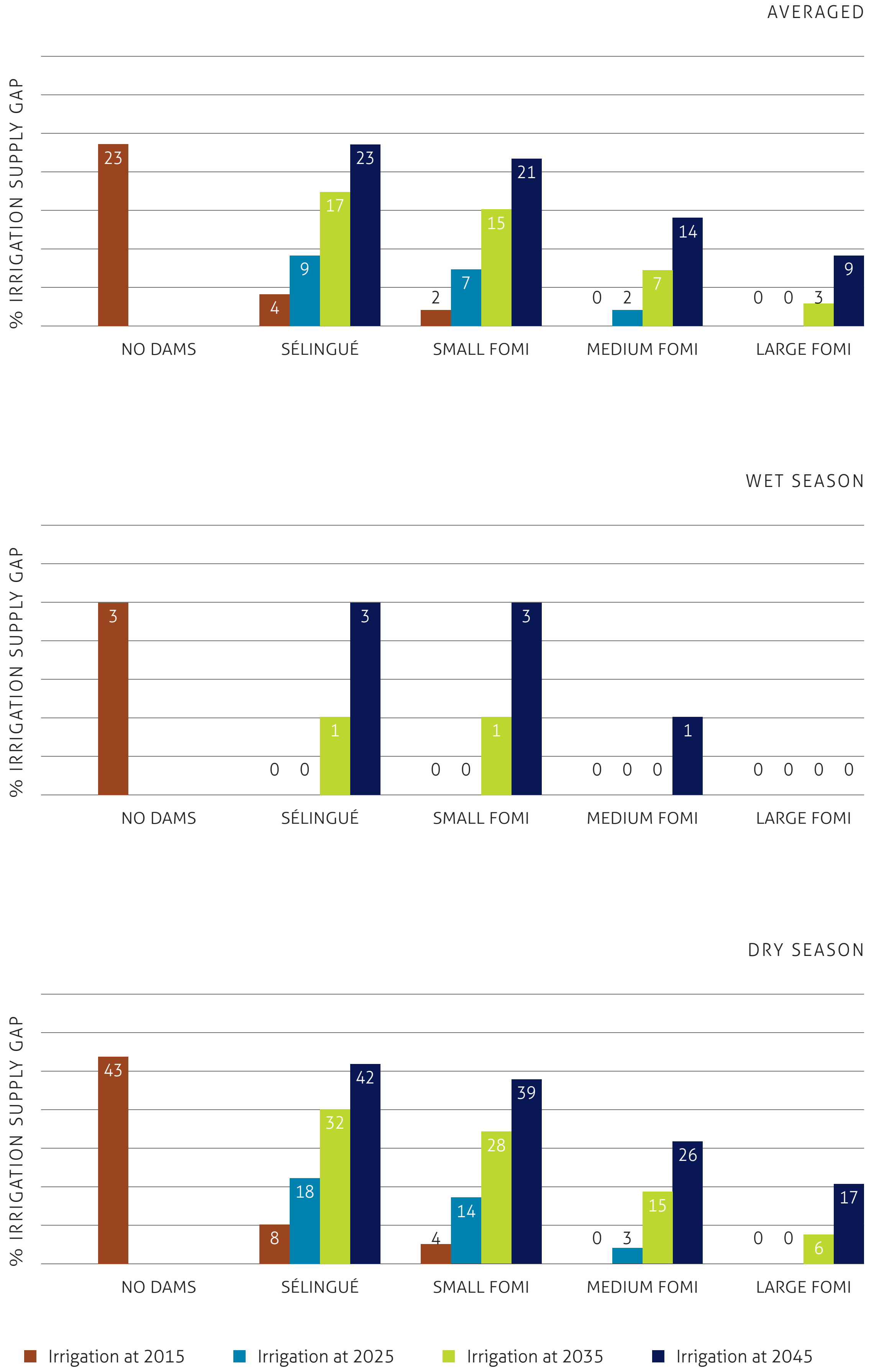

Figure 10. Irrigation supply gaps (%) for wet and dry seasons for various scenarios of ON expansion under different dam scenarios, averaged over the period 1961–2000

The irrigation supply gap numbers mentioned in Figure 10 differentiate between wet and dry seasons. However, these are averaged numbers over the entire simulation period of 1961–2000 and hence they do not show the particular effects during dry or disaster years. In order to show such extreme conditions, the maximal three-month consecutive irrigation supply gap of the disaster year 1984 was calculated under the (then actual) situation of having the Sélingué dam and the Markala diversion. This gap was about 50%. Hence only 50% of the required irrigation demand could be fulfilled at that time. It was then calculated how often such three-month irrigation supply gaps (or worse) would occur under different dam and irrigation scenarios. With only the Sélingué and Markala infrastructure in place, a 1984-like irrigation supply gap would occur in 10% of the years (see Figure 11). But when these dams are meant to meet irrigation demands as planned in 2025, 2035 and 2045, irrigation supply gaps as experienced in 1984 would happen 29%, 59% and 78% of the years. An additional small Fomi dam would reduce these occurrences to 0%, 17%, 56% and 78% of years for ON irrigation targets in the years 2015, 2025, 2035 and 2045. A medium and large Fomi dam would reduce these occurrences significantly, but not fully. If the ON’s 2045 irrigation plans are to be realised, a supply gap like that experienced in 1984 will occur with a medium dam 39 out of every 100 years. With a large Fomi dam this would still occur every 17 out of 100 years.

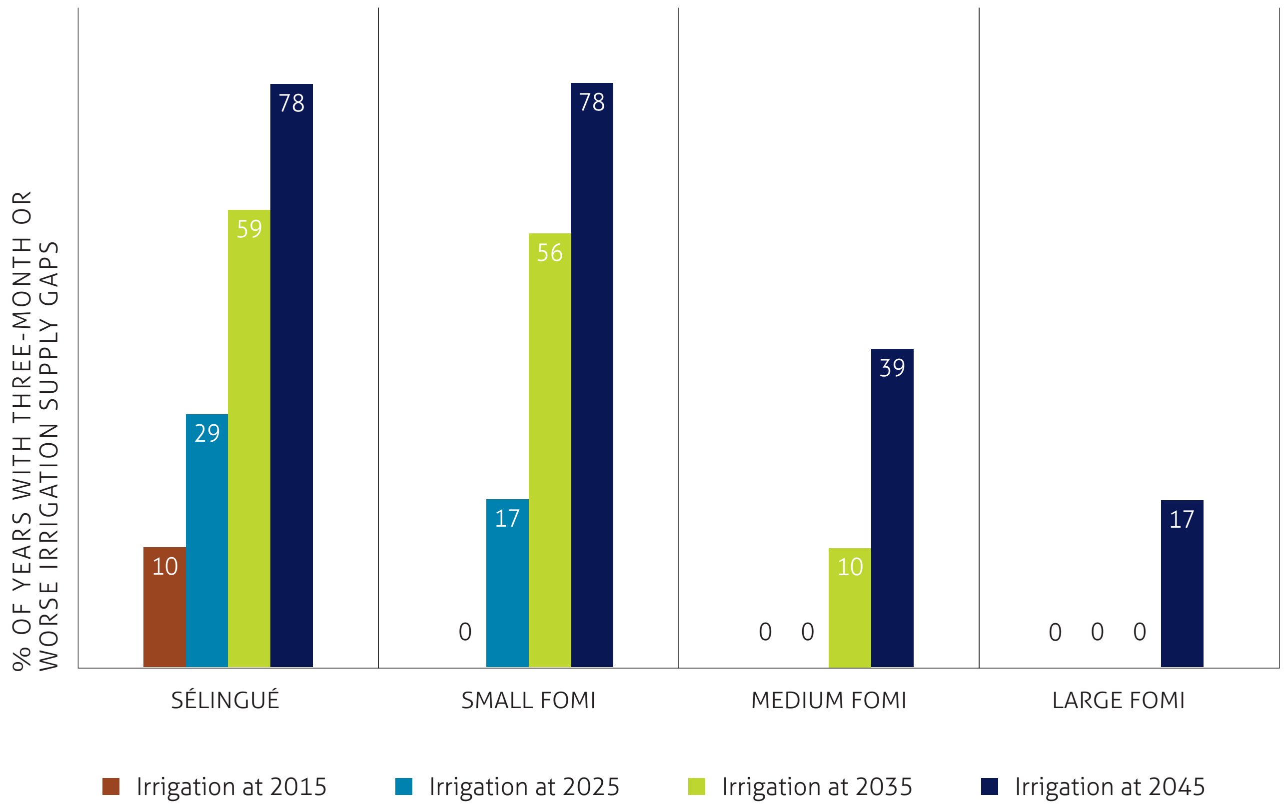

Figure 11. Occurrence of a three-month (consecutive) irrigation supply gap or worse under different dam and irrigation scenarios (% of years)

Hydropower from Fomi

The utility of a Fomi dam for energy production depends on various factors, such as seasonal and diurnal electricity demand profiles, and plans to develop and implement other alternative and complementary renewable electricity sources at the Fomi location. From the perspective of hydropower production, the large or medium-sized version of the Fomi dams are more advantageous than a smaller dam to meet energy security. Long-term average annual energy production would be 36.6 MW for the larger dam but only 21.1 MW for the smaller version (Sélingué average production is 17.4 MW). However, these options would also have the largest adverse impacts on the inflows into the IND, mainly due to the fact that they would enable much higher irrigation withdrawals during the dry season while withholding the peak discharges required to inundate the IND.

From an economic perspective, it is often more important to look at the ‘firm’ or ‘safe’ hydropower yield, which is the maximum quantity of electricity generation that can be guaranteed with some specified degree of confidence during a critical period, i.e. the low flow season in the context of this study. In regions characterised by high seasonality of river discharges, the hydropower generation potential is naturally much higher in the rainy season and the firm yield is limited by the generation potential in the dry season. The firm yield in the dry season depends basically on the storage capacity of the reservoir. The firm yield of a smaller version of the Fomi dam that can be guaranteed 99% of the time would be 1 MW, while the biggest version would generate a guaranteed 20 MW. For comparison, the Sélingué dam generates a guaranteed yield of 6.6 MW 99% of the time.

Scenario	**Long-term average annual hydopower genenration (MW)**	**Firm yield guaranteed 90% of time (MW)**	**Firm yield guaranteed 99% of time (MW)**
Sélingué	17.4	8.6	6.6
Small Fomi	21.1	2.3	1.0
Medium Fomi	31.0	12.7	10.6
Large Fomi	36.6	25.2	20.0

Table 3. Calculated hydropower generation (MW) under the conditions of the 1961–2000 period

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Impacts of new water infrastructure on the Inner Niger Delta

Impacts on discharges into the delta

Additional water infrastructure as currently planned in the Niger Basin will store and divert large volumes of water and hence have impacts on river discharges into the IND. While irrigation withdrawals from the Niger River normally tend to reduce discharges entering the IND, the management of a hydropower dam changes the flow regime by increasing discharges during the dry season and decreasing discharges during the wet season. The extent to which the flow regime is altered depends on the reservoir's operations. Additionally, some volume of water will be lost to the atmosphere via evapotranspiration from the reservoir's surface area and seepage into the groundwater aquifer.

Considerable changes are to be expected to the low flow Niger discharge into the IND under different development scenarios. Operating Fomi purely for hydropower generation (and hence not diverting the extra volume of released water from the Fomi reservoir to supply dry season irrigation across the Office du Niger's area) would increase the dry season discharge into the delta. Compared to natural flow conditions these would go up by 12% and 156% with a small and large Fomi dam respectively (Figure 12). Potential benefits of increased low flows would be the corresponding increase in flow velocities in the main river channels in the delta, reducing some water quality risks resulting from stagnant water.

However, when this extra water released during the dry season from Fomi is diverted to expand dry season irrigation, the low flows entering the delta at Ké-Macina will be reduced below the level of natural flows. With the existing Sélingué dam, diverting water to meet the projected irrigation demands of the Office du Niger (ON) would reduce low flows by 58% in 2025, 91% in 2035 and 98% in 2045. In the case of a large Fomi dam, the low flow would change from a 156% increase under 2015 irrigation conditions to a 78% reduction under 2045 irrigation projections compared to natural conditions. This reduction in low flows increases the risk from stagnant water bodies in the IND and could dry up the delta significantly.

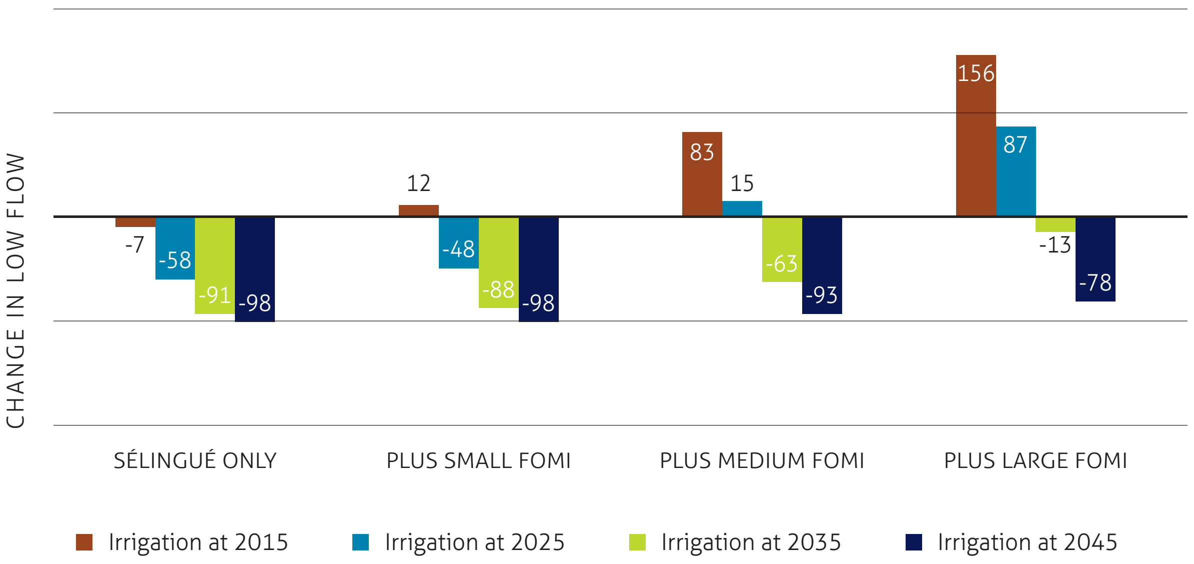

Figure 12. Impacts of upstream dams and irrigation expansion on average low flow discharges into the IND at Ké-Macina (% change to natural flow discharges, averaged over 1961–2000)

Note: Natural flows occur when no artificial water storage or diversions take place upstream

The flood peak in the Niger River at the entrance of the delta at Ké-Macina in September is the most important indicator for maximal inundation in the IND. Peak flows in the Niger River are already lower than under a natural flow regime, which are the combined result of irrigation withdrawals and reservoir storage during the high flow season (Zwarts et al. 2005).

According to recent research, current irrigation and reservoir operations reduce the September flood peak into the delta by 20% compared to natural flow conditions (Figure 13). A small Fomi dam would reduce this flood peak by an additional 6% compared to the existing Sélingué dam, provided that irrigation withdrawals are at 2015 levels. A large Fomi dam would reduce peak discharge by 32% due to storage effects only (without increased irrigation demand). In the 2045 irrigation scenario, median September flood peaks would be reduced by 28% with a Sélingué dam only. With a large Fomi dam, the average discharge peak could decrease by as much as 39% under the 2045 irrigation scenario.

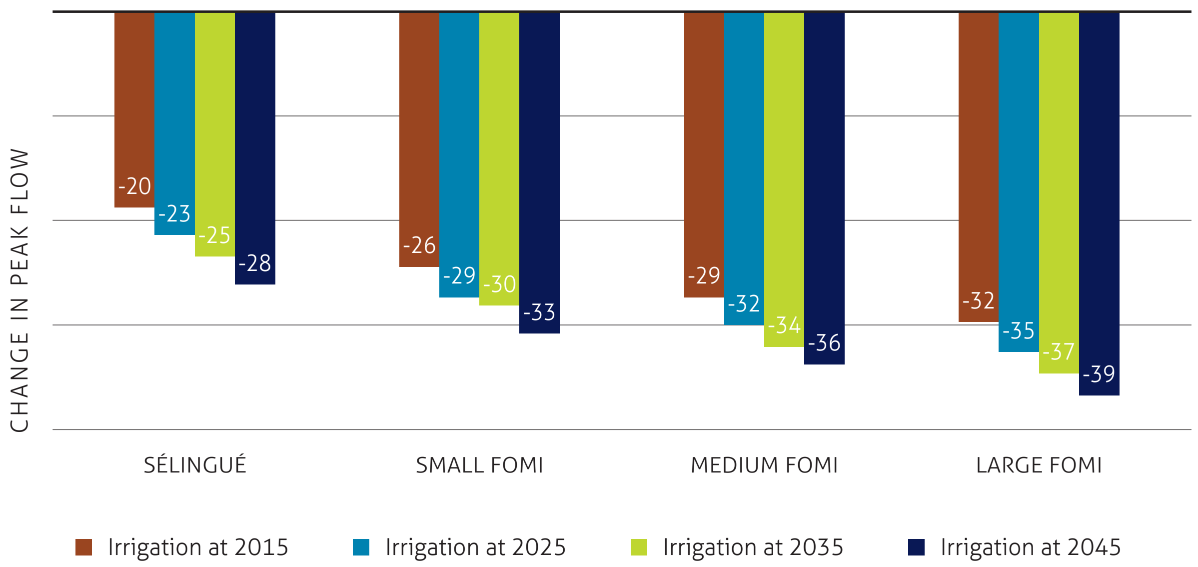

Figure 13. Impacts of upstream dams and irrigation expansion on average peak flows into the IND (% change to natural flow discharges, averaged over 1961–2000)

Note: Peak flows are the flows that reach the delta during September

In the scenario of a large Fomi dam and ON irrigation projected at the 2045 level, the median peak flow would be reduced to the level of the second-lowest September discharge simulated in the period 1961–2000, which in 1987 resulted in an flood extent of 10,000 km² in the IND and compromised the productivity of the ecosystem for the population. In an even worse scenario, a dry year could reduce peak charges below levels ever seen and completely dry up the IND, leading to a complete collapse of the ecosystem and food production.

In addition to the reduction of Niger River discharges, the recently built Talo and Djenné dams and adjacent irrigation schemes in the Bani River basin are reducing water flows into the IND by another 4%.

In conclusion, the biggest future impacts on both dry and wet season discharges into the delta are attributable to planned irrigation expansion, predominantly withdrawals by the ON. As discussed, meeting those irrigation demands would only be feasible (in average and wet years but not dry years) with an additional large upstream dam like Fomi and/or with increased irrigation efficiency.

Impact on flooding level and extent

The Niger River's discharges into the delta determine its inundation dynamics, such as flooding level and flooded area. As mentioned earlier, local rainfall within the delta's perimeter only has a limited effect on this. Annual flooding level is often denoted by the maximal water level measured at Akka.

IND's inundation dynamics

To understand how the IND's inundation dynamics change as a result of differential amounts of discharge, various inundation levels are defined:

Inundation level	Akka max. water level (cm)	Flooded area (km²)
Wet year	> 500	> 20,000
Average year	450 - 500	15,000 - 20,000
Dry year	400 - 450	9,000 - 15,000
Very dry year	300 - 400	8,000 - 9,000
Disaster year like 1984	< 350	< 8,000

In a scenario with the current (2015) state of irrigation and upstream water diversions, about one out of every four years is considered to have inundation dynamics similar to that in very dry years or worse (Figure 14). If a large Fomi dam is operated for hydropower generation, this frequency increases to 30%, a little less than once every three years. If a large Fomi dam is complemented with an expansion of irrigation according to the ON's 2045 projections, the frequency of very dry years or worse in the IND is expected to increase to 42%, almost one every two years. Inundation dynamics similar to so-called disaster years like 1984 change from 2% under current conditions (once every 50 years) to 10%, or once every 10 years.

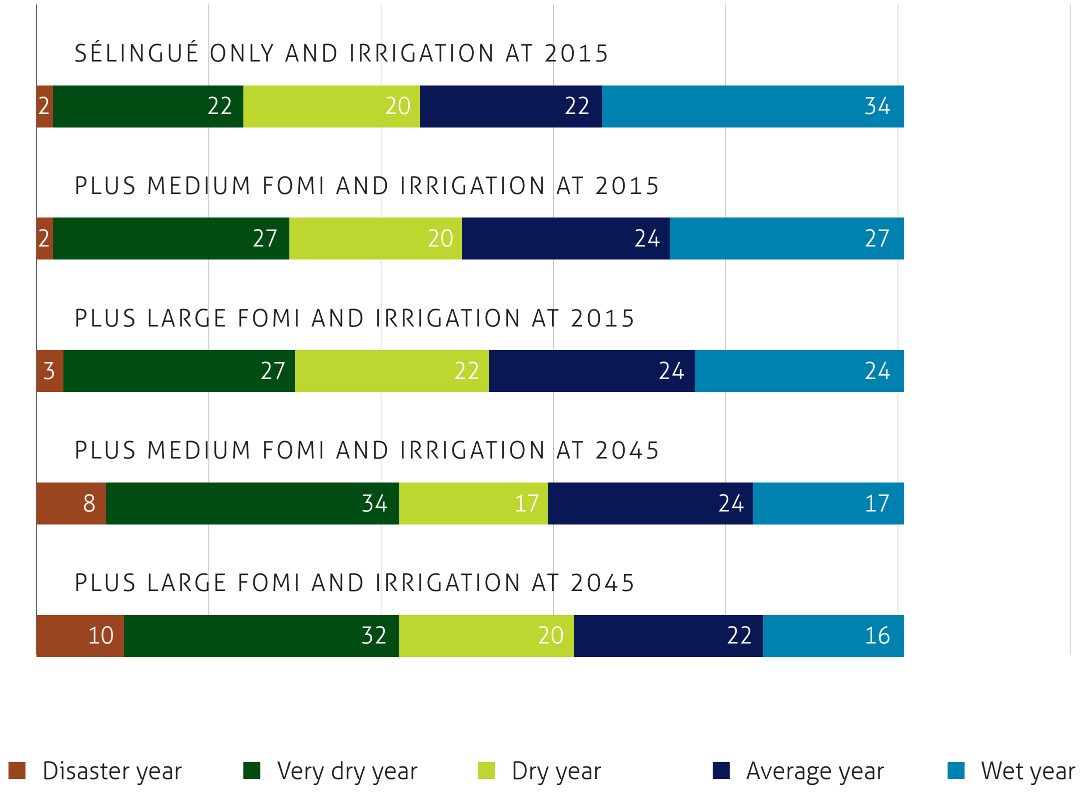

Figure 14. Frequency of various inundation levels categorised as disaster years (like 1984) under different irrigation and dam scenarios

Impacts on rice and bourgou and other grasses

Changes in flooding level change the relative abundance of grasses in the delta. The higher the flood, the more abundant the bourgou and hippo grass, whereas vetiver is a dominant vegetation type in drier years. Bourgou grows optimally at water depths greater than three metres. In wet years, with maximal water levels at Akka starting from 550 cm, the habitat suitable for bourgou is approximately 2,827 km². For dry and disaster years (maximum water levels of 450 cm and 350 cm) these areas reach a maximum of 2,035 and 494 km² respectively (Figure 15). For floodplain rice, wet years provide more suitable habitat area as well, with 6,185 km² available in a wet year of 550 cm maximum water depth versus only 1,213 km² in a disaster year.

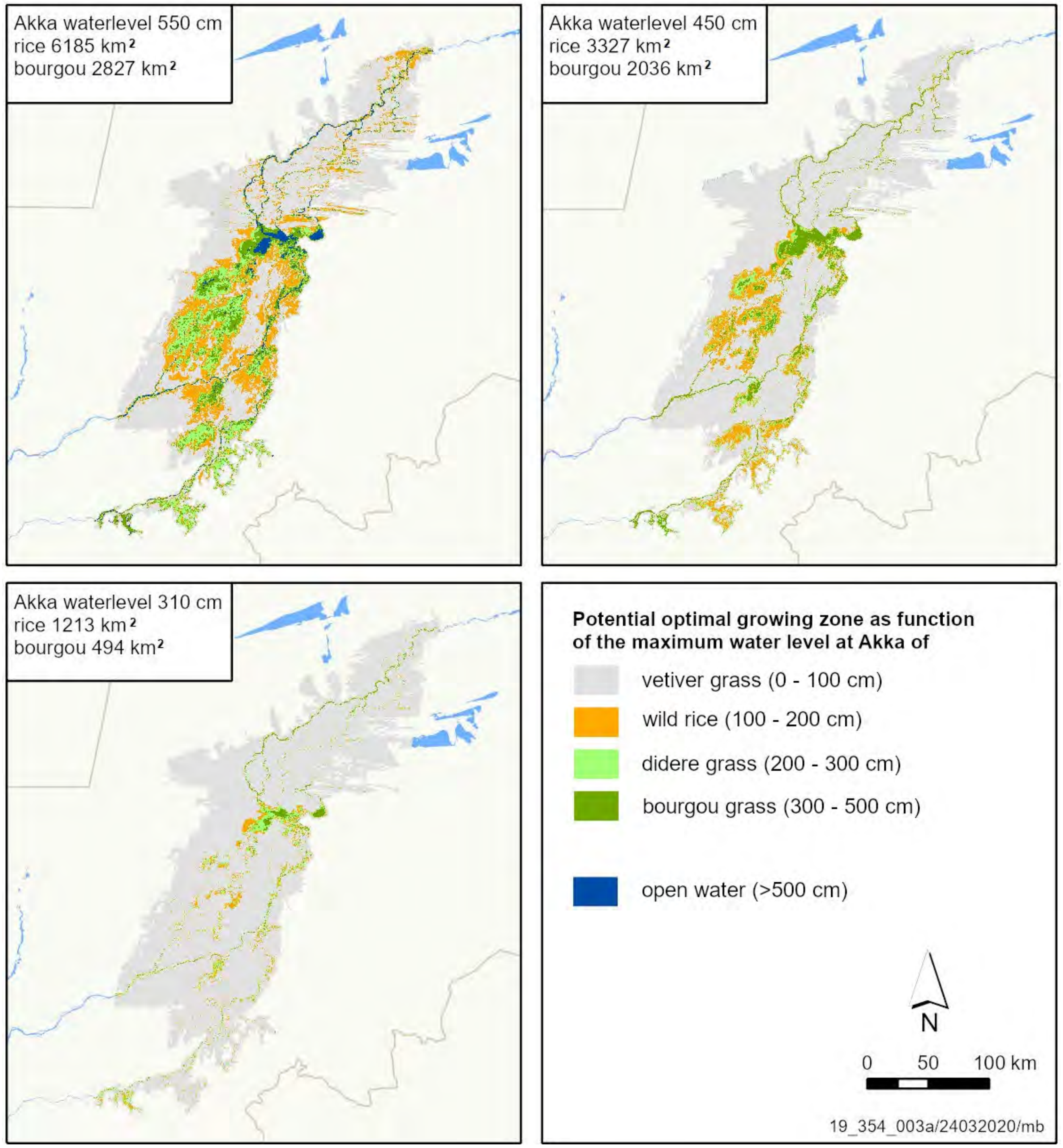

Figure 15. Flooded area suitable for various plants at different water levels

Note: 550 cm: wet year, 450 cm: dry year, 300 cm: disaster year)

With the frequency of wet, average, dry and disaster years changing under different development scenarios (Figure 14), the area suitable for bourgou would be reduced 4% on average with a small Fomi dam (Figure 16). This reduction would go up to 17% in the case of a large Fomi dam being combined with projected irrigation levels in 2045. Hippo grass would be most affected by changes in flood levels, with up to a 31% decrease in total area in the case of a large Fomi dam at 2045 irrigation levels in an average year. Rice habitat extent will also be significantly reduced. Once again, these are average reductions in habitat suitability. Particularly in very dry years, the storage effect of even a small Fomi dam may tip the balance of the ecosystem and lead to a collapse of bourgou and rice production and significant subsistence challenges in the IND.

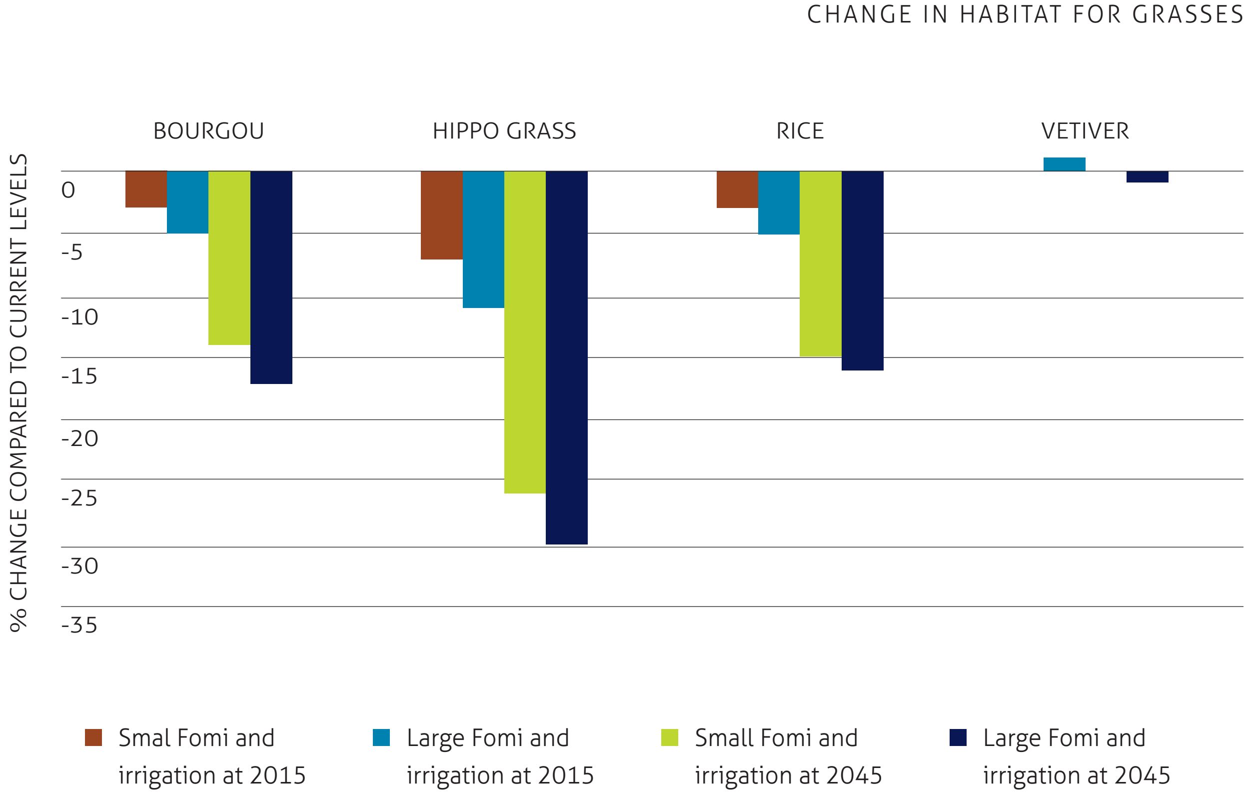

Figure 16. Percentage decrease in vegetation type in the IND under different dam and irrigation scenarios compared to the current situation (Sélingué dam and irrigation at 2015 level) over the period 1961–2000

Pastoralists will likely suffer from decreased fodder production in the IND. Additionally, the planned extension of the ON (as defined in PAHA IV) will result in a direct exclusion of transhumance herds from some current grazing grounds. The extension will lead to a direct loss of 3,300 km² of grazing areas, of which 300 km² are in the IND and 3,000 km² in ON areas. In practice, this will mean more competition for the remaining grazing grounds.

Impacts on fisheries, rice farming, livestock and navigation

Under a scenario with a large Fomi dam and full irrigation expansion in 2045, average rice production in a period like 1961–2000 is estimated to decrease by 13%, the traded fish catch in Mopti is estimated to decrease by 24%, and the cattle population is expected to decrease by 8% in Mopti and 12% in Tombouctou. Sheep and goat populations are expected to decrease by respectively 5% and 13%.

Ecosystem service	**Sélingué + 2015 irrigation**		**Medium Fomi + 2015 irrigation**		**Large Fomi + 2015 irrigation**		**Medium Fomi + 2045 irrigation**		**Large Fomi + 2045 irrigation**	
Rice, IND (tonnes)	220,330	0%	214,720	-3%	210,962	-4%	195,215	-11%	191,255	-13%
Fish traded, Mopti (tonnes)	17,612	0%	16,800	-5%	16,256	-8%	14,021	-20%	13,445	-24%
Cattle, Tombouctou	845,151	0%	825,109	-2%	811,777	-4%	755,482	-11%	741,476	-12%
Cattle, Mopti	2,234,092	0%	2,200,344	-2%	2,177,895	-3%	2,083,101	-7%	2,059,517	-8%
Sheep and goats, Tombouctou	4,092,841	0%	3,987,182	-3%	3,916,899	-4%	3,620,116	-12%	3,546,278	-13%
Sheep and goats, Mopti	5,142,499	0%	5,088,086	-1%	5,051,890	-2%	4,899,050	-5%	4,861,024	-5%
Navigable days, Koulikoro - Mopti	111	0%	107	-4%	105	-5%	95	-14%	92	-17%
Navigable days, Mopti - Gao	78	0%	73	-6%	69	-12%	56	-28%	52	-33%

Table 4. Overview of key flood-dependent IND ecosystem services and % changes in production compared to current levels

The combined economic value of recorded rice and livestock production, fishing (Mopti only) and fluvial transportation is estimated at about 238 billion FCFA per year in the current situation, in which only Sélingué is operational and irrigation corresponds to 2015 levels (Table 5). This is the economic value of those ecosystem services for which sufficient data exists such that they could be included in the analysis. The construction of the Fomi dam is estimated to result in a decrease of the total economic value of these ecosystem services of 2%–4%, a loss of 5.4–8.9 billion FCFA per year, depending on the dam dimensions. If the dam is combined with an expansion of ON irrigation, the overall value is estimated to decrease by 10–12%, equivalent to 23.7–27.4 billion FCFA per year.

Ecosystem service	**Sélingué + 2015 irrigation**	**Medium Fomi + 2015 irrigation**	**Large Fomi + 2015 irrigation**	**Medium Fomi + 2045 irrigation**	**Large Fomi + 2045 irrigation**
Rice, IND (tonnes)	70.1	68.3	67.1	62.1	60.8
Fish traded, Mopti (tonnes)	20.6	19.7	19	16.4	15.7
Cattle, Tombouctou	20.7	20.3	19.9	18.6	18.2
Cattle, Mopti	68.6	67.5	66.8	63.9	63.2
Sheep and goats, Tombouctou	19.6	19.1	18.8	17.3	17
Sheep and goats, Mopti	34.9	34.5	34.3	33.3	33
Fluvial transportation Koulikoro - Mopti	2.1	2	2	1.8	1.8
Fluvial transportation Mopti Gao	1.6	1.4	1.4	1.1	1.1
Total	**238.2**	**232.8**	**229.3**	**214.5**	**210.8**
% change versus current scenario	0%	-2%	-4%	-10%	-12%

Table 5. Economic value of selected ecosystem services in the IND per year (in billion FCFA) and average changes under different dam configuration and irrigation scenarios

It should be stressed that the numbers shown in Tables 4 and 5 cover only a subset of the ecosystem services provided by the IND floodplains, based on available data averaged over the entire simulation period of 1961–2000.

The IND provides many products that are important to the sustenance of inhabitants, from building materials to traditional medicines, and only a limited set of ecosystem services has been quantified in this study.

Transhumance in changing times

Livestock grazing and the related production of milk and meat form the pillars of the national rural economy in Mali. In numbers, Malian livestock amounts to more than 10 million cattle, 20 million goats and nearly 14 million sheep (FAOSTAT, 2019). An analysis of data up to 2001 showed that especially in drier years, 60% of the cattle in Mali are concentrated in the Mopti and Tombouctou regions (data from Cellule de Planification et de Statistique du Ministère du Développement, Mali, in Zwarts et al. 2005), underpinning the importance of these regions to the national rural economy.

Three main systems of livestock raising have existed in the Sahel since time immemorial. The sedentary and the pure nomadic (northern grazing grounds) systems are of little importance compared to the semi-nomadic system, which involves the large-scale movements of cattle, called the transhumance (Breman et al. 1978). In the dry season, from November to July, the herds feed in the perennial pastures of the IND. First, the pastures around the villages are exploited and when the flood recedes the common pastures in the centre of the delta are exploited. Bourgou fields are very important to survive the dry period. When the rainy season starts, the herds move to the north to exploit the protein-rich annual pastures in the northern rangelands to the west, north and east of the delta.

Transhumance is an effective way to profit from the temporarily available rich grazing grounds in the north; during this phase in the grazing cycle, the reproduction and growth of the cattle is realised (Breman and de Wit 1983). The rangelands north and west of the delta are essential to the system of the transhumance (www.sigsahel.info). Recently, the process and system of the transhumance has undergone significant changes due to insecurity and conflicts in the rangelands east, west and north of the delta (Bagayoko et al. 2017). This has led to overexploitation, in particular east and west of the delta (e.g. in the Niono region), even leading to livestock movements to the south, for example the savannas north of Cote d'Ivoire.

Future developments in the long run (2045) involve an extension of 3,300 km² of ON irrigation to areas that are now exploited as grazing grounds. The transition of these rangelands to irrigated cultures will lead to a substantial loss of grazing grounds. In addition, the grazing pressure in neighbouring areas (that are already overexploited) will increase even further, leading to soil degradation and unsustainably high densities of cattle. This means that the loss of grazing grounds has consequences far beyond the IND itself.

This loss cannot easily be mitigated or compensated. Sedentarisation is associated with several social and ecological risks, such as increased pressure on land, risk of conflict and a high risk of soil degradation. In addition, sedentary systems are vulnerable to fluctuations in grass availability, both in quantity and quality (e.g. the adequacy of protein levels, needed for the growth of individual animals, and reproduction). Additional bourgou planting in the IND to provide fodder is hardly feasible, as delta water depths in the future would be below the growing potential of bourgou.

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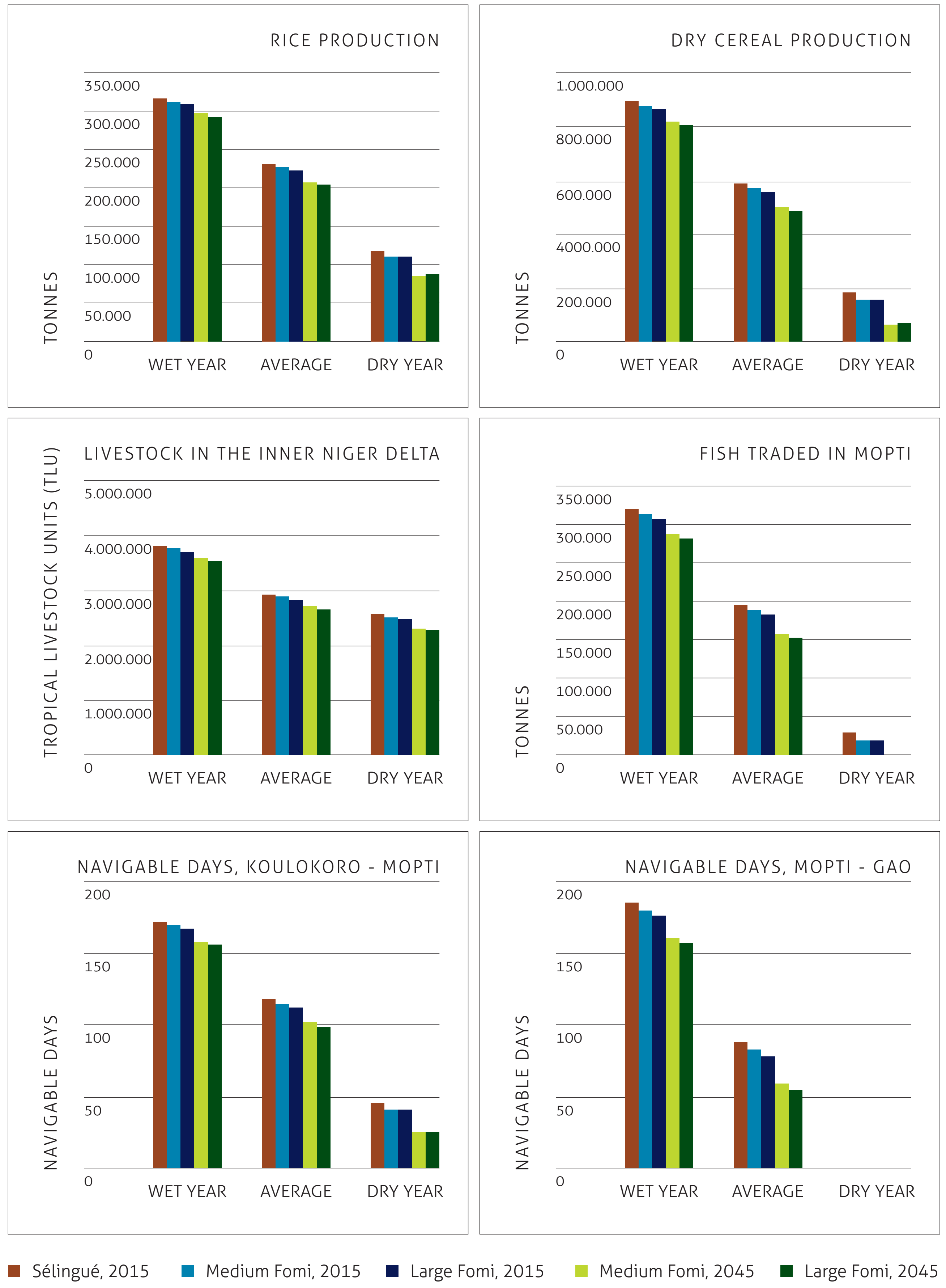

Figure 17. Several ecosystem services for a typical wet year (1968), average year (1996) and dry year 1984) for various water infrastructure scenarios

Figure 17 shows IND ecosystem services for a typical wet year (1968), average year (1996) and dry year (1984, a disaster year) for various water infrastructure scenarios. More ecosystem services are produced in the IND during wet years than in dry years. Dry year ecosystem services can be between 60% to 0% of wet year production, even under current circumstances. Overall, new infrastructure, such as a new dam, reduces ecosystem service production in the delta. Reductions due to additional irrigation scheme diversions are even higher. Impacts of new infrastructure on IND ecosystem services delivery are higher in dry years like 1984 than in wet years. In particular, dry cereal production, fish traded (in Mopti) and navigable days decrease significantly during dry years. In trying to meet the ON's irrigation demands for 2045 using Fomi dam water releases, fish trade and fluvial navigation between Mopti and Gao are even likely to experience a total collapse.

Impacts on disease control

There are significant problems in water and sanitation provision, practices and awareness in the IND. About 80% of diseases in the area are linked to drinking water supply and sanitation conditions. The severity of disease is directly relatable to the IND flooding regime and extent. Human health problems are notably worse during low flood years when dilution is reduced and the circulation of water in the IND is lower, leading to increased exposure to diarrheal disease and schistosomiasis (Wetlands International 2010). Upstream water storage and diversions would further reduce the regular flushing of the water bodies. Also, access to drinking water may become more difficult in case of reduced inundation of the delta as distances to open water bodies may become larger. The effects of a long-term decline in inundation on the groundwater resources in the delta, from which people derive drinking water, are unknown. Possibly, reduced inundations will lead to reduced groundwater replenishment and hence a lower groundwater table in the delta.

Impacts on biodiversity

A reduction in the inundated area of the IND has implications for the conservation of globally significant nature. The shrinkage of floodplains will lead to a large loss of suitable habitats for breeding and foraging. The proposed extension of the ON is partly in the floodplains of the IND, including into two flood forests next to the Diaka in the southwest of the IND, the most natural and undisturbed area near the Plaine de Seri, a hotspot for biodiversity.

Dozens of migratory bird species spend the northern winter in the Sahel zone, much of which is concentrated in the IND. Key habitats and the food resources they contain, such as bourgou fields and flood forests, are expected to decline by one third, which would have a huge impact on international populations of water and land birds, including the partial disappearance of colonial breeding water birds in the delta. Additionally, in situations of low food security, there is increased pressure on biodiversity from hunting on wildlife and birds.

Key areas for biodiversity have been identified (Wymenga et al. 2017a and 2017b) to prioritise and stimulate effective management of the area as a whole. This information could be used to enforce the protection of specific sites or species in the IND, given that the IND, to date, has not been designated a legally protected area. The classification of vulnerable sites and key areas within the IND is based on four main criteria: key habitats in the floodplain ecosystem; water bird concentrations; breeding colonies; and important areas for threatened species.

Impacts on migration as livelihood strategy

The sustainability of livelihoods for fishers, farmers and pastoralists in the IND depends greatly on whether they have access to and control over various types of assets like the water, fish, soil and fodder provided by the wetlands, along with other assets like technologies, information and financial resources.

Access to these assets strongly influences which strategy people choose to either maintain or boost their livelihood. Basically, there are three livelihood strategies: intensification, diversification and migration. Those with more access to financial capital and less uncertainty and risks will be more likely to invest, for example to intensify their current practices. Diversification represents the choice to increase one's effort to obtain income from sources other than the primary income source. For instance, for a fisherman this could mean generating additional income by using his boat for transportation services as well. Seasonal migration within a region to search for the best grazing grounds and fishing spots is part and parcel of the livelihood strategies of the Sahel's pastoralists and fishermen. However, migration could also be a strategy to permanently relocate outside of the delta and start a new livelihood.

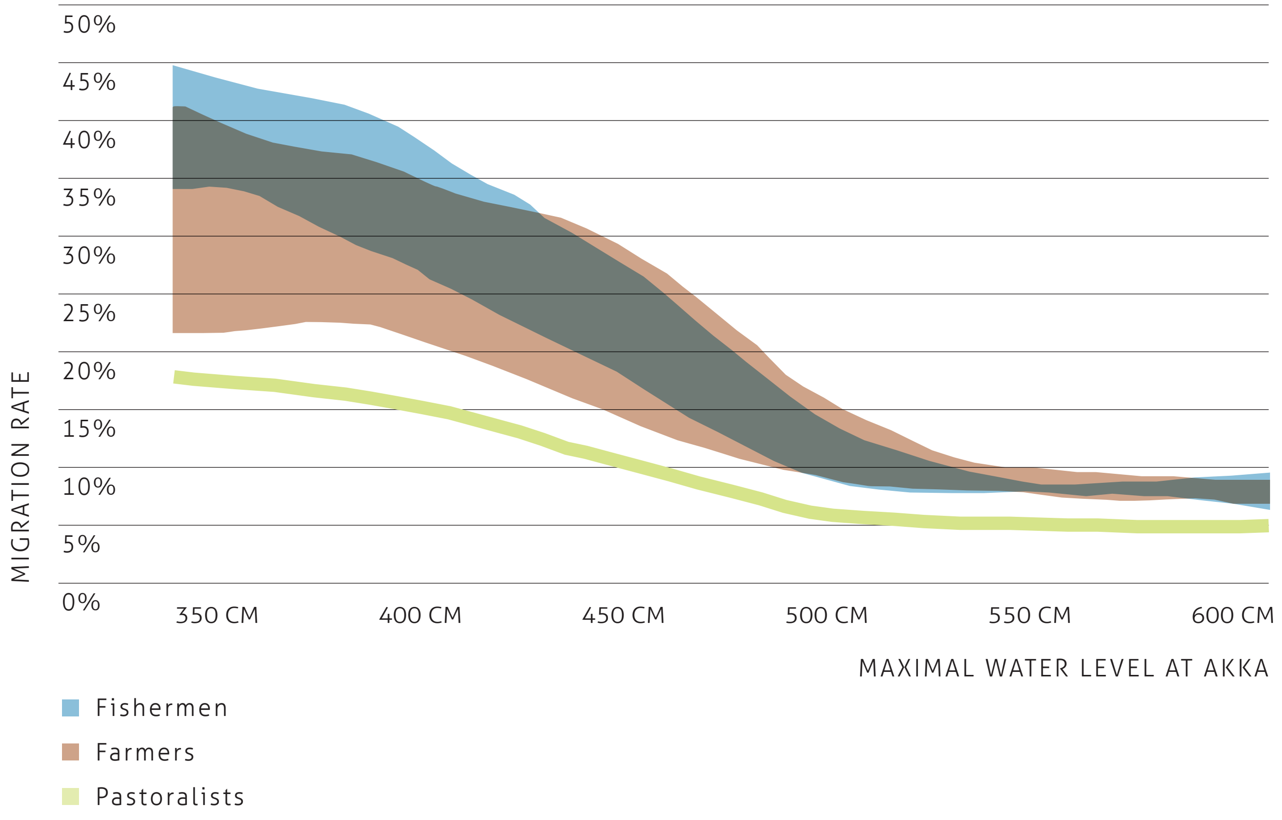

Figure 18. Percentage of IND farmers, fishermen and pastoralists considering migration under different water levels by region

Supported by a probability model, it is shown that for each of these three livelihood strategies, migration increases for every decrease in water level in the delta, and that a considerable share of farmers and fishers would abandon their occupation and permanently migrate to a different region, country or continent if they considered the water level to be too low. In a situation with maximal water levels at Akka above 500 cm (so constantly a wet year), less than 10% of interviewed farmers said that migration would be a likely strategy to sustain their livelihood (Figure 18). With decreasing water levels, more and more farmers consider migration a viable sustainable livelihood strategy, going up to 20%–40% in case of maximal water levels of 350 cm (very dry year). Pastoralists are less influenced by the water level. At the lowest level of 350 cm, 16% of pastoralists expressed a willingness to permanently outmigrate, while more than 40% of the fishers of Tenenkoun and Ké-Macina agreed that permanent outmigration was the most viable strategy under these conditions.

Considering that the frequency of 'disaster years' changes under the different dam and irrigation scenarios, one can determine changes in potential migration over a reference period like 1961–2000. In a hypothetical natural flow situation, fewer than 10% of farmers and fishers around Mopti and fewer than 5% of pastoralists view permanent migration out of the delta as a sustainable livelihood strategy (Figure 19). In scenarios that result in a higher occurrence of dry, very dry and even disaster years, consideration of permanent outmigration as a preferred sustainable livelihood strategy increases. In a scenario with a large Fomi dam and ON irrigation at 2045 projections, 21% of farmers, 24% of fishers and 10% of pastoralists would be willing to outmigrate.

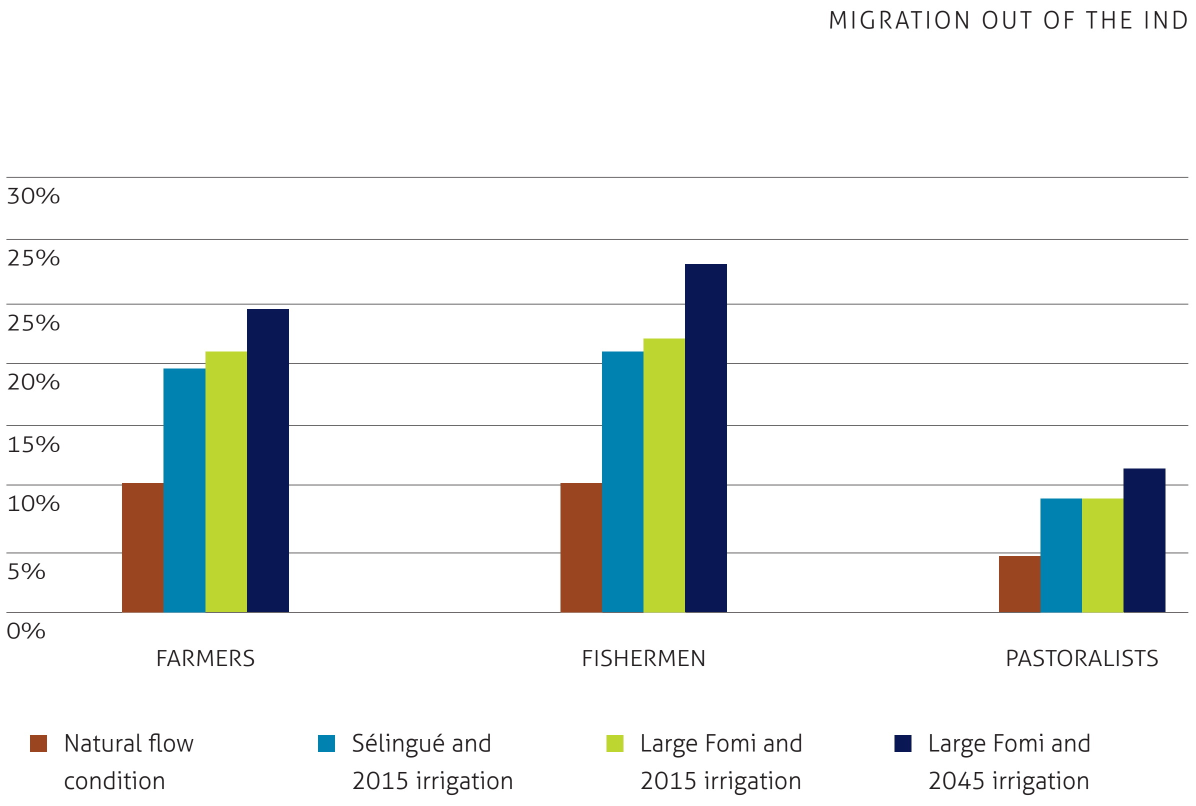

Figure 19. Percentage of farmers, fishers and pastoralists in the Mopti region considering migration under different dam and irrigation scenarios over the reference period

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Conclusions and discussion

This report reiterates the importance of the Inner Niger Delta (IND) for Mali. About two million people call it their home and rely on it for livelihoods based on a combination of mostly farming, fishing and pastoralism. The delta provides food security for these people and beyond. It also produces 80% of Mali's fish and pasture, and 30% of its national rice production. The economic benefits extend well beyond the delta and serve as a driver of the rural economy and food security in the entire region, delivering 8% of Mali's Gross Domestic Product.

This high value is generated by making use of the goods and benefits the delta ecosystem provides to the people and biodiversity. The mosaic of habitats and vegetation biodiversity creates a naturally productive landscape that allows people to farm the land on the floodplains, graze their cattle on the extensive bourgou pastures and fish the river channels or water bodies formed after flooding. They also use other natural products for construction, energy and traditional medicine. The current total value of these ecosystems is estimated to be about 238.2 billion FCFA per year.

The specialty of this inland delta is that its ecosystem has adapted itself to a very dynamic water system. Fed by the Niger and Bani Rivers, which receive most of their runoff in their headwaters from a very variable West African monsoon, this flood pulse-driven system has developed over history with prominent wet and dry seasons and with periods of wetter and drier years. The ecosystem and its linked human society follow the rhythm of this flood pulse with, generally, more ecosystem services being generated when flooding extents and levels are high during the wet season and in wetter years.

In other words, the IND ecosystem and society have inbuilt resilience to deal with the variation in flood pulse. However, this is only within certain limits. In recent history, extreme dry years (like in 1984) have had such low rainfall that it led to historically low flooding levels and a small inundation extent of 8,000 km^2, only one third of its maximal extent. This has resulted in dried-up ecosystems that are unable to provide ecosystem services. Most of the delta's flooded forests, habitats for nesting birds and nurseries for fish, suffered overexploitation and some were destroyed. Many cows died and herders lost more than half their cattle due to reduced food resources and the reduction of the inundated area.

As mentioned, the IND is located in the Upper Niger Basin (UNB) and is part of a bigger landscape where water, food security and energy security need to be met. As a response to the severe droughts in past decades, Guinea and Mali have undertaken several food and energy security strategies. These governmental objectives have been pursued through the construction of water infrastructure to take advantage of Malian and Guinean hydroelectric potential and to store and divert water to agricultural irrigation systems to improve food security. Currently, concrete plans have been developed to construct a new hydropower dam in Guinea (in this report, described as the Fomi dam) with various options with varying dam height and reservoir size (small, medium and large). Also, plans have been made to expand the large-scale irrigation schemes in Guinea and especially the Office du Niger (ON) in Mali, just upstream of the delta. The ON's irrigation scheme is expected to be expanded by about 90 km^2 every year, leading to a total additional 5,400 km^2 of irrigated land by 2045.

It is assumed that ON expansion will lead to increased food production. With an annual rice yield of about 6 t/ha a potentially large amount of food can be produced. However, it is also known that at the ON's current irrigation efficiency, irrigation demands will often not be met. In the current situation, with the Sélingué dam releasing its stored water in the dry season, which is subsequently diverted to the ON using the Markala weir, an average of 4% of the irrigation demand cannot be met. If this constellation needs to supply the irrigation demand in 2045, there will be an average 23% gap. Building a Fomi dam in Guinea would reduce such gaps. Being used predominantly as a hydropower dam, most water would be released during the dry season. When these water releases, together with that of the already existing Sélingué dam, are diverted to the ON at Markala, the overall 2045 irrigation supply gaps will be significantly reduced to 9%.

Zooming into more extreme years like 1984, however, shows that a Fomi dam may still leave the ON with considerable crop yield risk. In 1984, there was a three-month consecutive irrigation supply gap of about 50%, leading to great crop losses and hence financial losses. Currently, such an extreme irrigation supply gap would occur about 1 every 10 years. If the Sélingué dam had to cover the entire irrigation demand in 2045 such an extreme situation would occur 78 out of 100 years. With an additional dam this would be reduced, however it will not be nil. Even if a large Fomi dam is operated, about 17 out of 100 years may lead to high crop losses for the ON, possibly resulting in food insecurity situations.

While new water infrastructure will contribute to wider water, food and energy security in general, it may come at certain costs for some groups and areas. The Niger, a lifeline (2005) has already shown that these upstream water storages and diversions have adverse effects on ecosystem service delivery in the delta. How would the current Fomi dam plan and ambitions for ON expansion affect this?

Based on recent hydrological model simulations it becomes evident that if the Fomi dam project is operated and ON irrigation is expanded as planned, the inundation dynamics in the delta will see a shift towards a higher number of drier years compared to the current situation. If the Fomi dam is built, the frequency of very dry years is estimated to increase from 24% to 29%. Irrigation expansion will have an even larger impact. If more water is diverted for irrigation by the ON, the frequency of very dry years could increase to 42% – almost one out of every two years. The probability of disaster years (comparable to 1984) will also increase substantially. In the current situation, these occur once every 50 years. In the scenario with an operational Fomi dam and expanded ON irrigation, the frequency increases by a factor of five – to once every 10 years. In other words, the median flood peak would be reduced to the level of the year with the second-lowest peak simulated in the period 1961–2000 under natural conditions, which in 1987 resulted in an inundation of 350 cm and flood extent of 10,000 km^2 in the IND and compromised the productivity of the ecosystem for the population.

These changed inundation dynamics determine the total amount of ecosystem services that can be provided in the delta. Areas potentially suitable for the growth of bourgou, hippo grass and wild rice would on average reduce by 17%, 30% and 16% compared to the current situation if a large Fomi dam is operated and 2045's irrigation demand met as far as possible. Fisheries in the Mopti region would decrease by 24%. The amount of cattle, sheep and goats that could be sustained in the region would decrease between 5% and 13%. The number of navigable days with ferries and pinasses in the delta (crucial for access to local markets and medical, financial and agricultural service providers) would on average go down by 17% between Mopti and Koulikoro and even up to 33% between Mopti and Gao.

The new water infrastructure is also assumed to have significant effects on biodiversity. First of all, a smaller delta provides less habitat for flora and fauna. Secondly, with livelihoods providing less food security people resort more to wildlife hunting, leading to huge stress on local populations of birds and mammals and on areas like flooded forest for construction, energy materials and traditional medicines.

If ON irrigation remains at 2015 levels, operating a large Fomi dam is expected to decrease the total economic value of key ecosystem services in the delta by up to 3.7% in an average year. If in addition, irrigation is maximised as planned by 2045, an average reduction of up to 11.5% in the value of these economic activities is expected (up to 24 billion FCFA loss per year).

On top of the average year reductions in productivity, the possibility of another dry period, as experienced in the early 1980s, in combination with the planned infrastructure projects and a growing population, could result in a chronic humanitarian disaster, led by a collapse of rice production, fishing and livestock that increases food insecurity, intensifies conflict and leads to even more widespread migration. The year 1984, the driest year in the simulation period, is often used to illustrate the destructive forces of drought conditions, which led to a mass livestock die-off and famine. In a worst-case scenario, the combination of a Fomi dam and expanded irrigation and a very dry year could reduce peak flows below levels ever seen and completely dry up the IND, leading to a complete collapse of the ecosystem and food production.

For the more than two million people living in the IND, this would mean diminished economic prospects and increased food and water insecurity. Traditionally, people have tried to build sustainable livelihoods using a combination of intensification, diversification and migration. While seasonal migration is part and parcel of the livelihood strategies of some of the IND's pastoralist and fishermen groups, permanent migration out of the delta is increasingly becoming an alternative coping mechanism. Research shows that permanent migration out of the IND increases with every decrease in water level. Under the peak flood level projected for 2045 if the ON's irrigation demands are met, between 20% to more than 40% of fishers and farmers are expected to migrate due to reductions in fish, fodder and rice that would compromise the IND's potential to support livelihoods for many inhabitants.

The information provided in this report has been developed to support decision making on water resource allocation in the UNB that helps to create water, food and energy security. Preferably, such water allocation is Pareto-optimal, meaning that developing new utilities by using the water resources should leave no one who is already dependent on these resources worse off. Here it is shown that the foreseen solution for more water, food and energy security through the development of more infrastructure does actually leave many people, biodiversity and ecosystems in the delta worse off.

This information was generated with robust methodologies using the most up-to-date data (see Annex). However, many new questions arose that cannot yet be answered. To truly create informed decision making these, and likely other questions, should be addressed:

- What are the consequences of the filling of the reservoir of a new Fomi dam before it gets fully operational as a hydropower dam?
- What is the effect of climate change on river dynamics in the Niger Basin and on the feasibility of producing hydropower and irrigation?
- Are there alternative solutions for Guinea and Mali that lead to the same level of water, food and energy security while being less dependent on water storage and diversions, and with fewer consequences for the delta?
- What if one includes more explicitly the nutrition factor in the food security debate in Mali? Would a reduction of protein-rich products coming from the delta be acceptable?
- How much resilience is there in the delta? How would a 1984-like year be absorbed by the IND population, which has become much larger since then?
- Could investing in ecosystem management and restoration combined with the introduction of community-focused technologies and value-adding chains help to improve the food productivity of the delta?
- Research shows there is a relationship between the height and extent of IND inundation and the willingness of people to migrate out of the delta. The IND has also become known recently for increased instability. Is there a relationship? Would a healthier flood pulse-driven IND help to bring back stability to the region?

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Annex

Methodology

To assess the impacts of current proposals for different water infrastructure development scenarios on the ecosystem services in the delta, a suite of tools was developed for the UNB and IND. These tools translate the potential impacts of water storage in, and release from, dam reservoirs, and water diversions to irrigation schemes, into changes in river discharges throughout the year. With this information, inundation dynamics and ecosystem provisioning – and the impacts on the livelihoods of people living in the IND – are estimated.

Climate change

The UNB and IND are located in a climatic transition zone that includes the tropical savanna climate in the southwest, the warm semi-arid climate in the middle, and the warm desert climate in the very north of the catchment. Global Climate models (CGMs), which are used to predict climate change effects on temperature and rainfall, are less certain in these sorts of transition zones. Therefore, rainfall projections for the Sahel are less robust than the 20th-century hindcast.

With regard to future rainfall patterns, the climate scenario (RCP) and the period selected both matter for future predictions in the UNB. An increase in average annual rainfall is generally projected in RCP 4.5 in both the near future (2030–2059) and far future (2070–2099). A decrease in annual rainfall is projected under RCP 8.5 conditions in the far future. Most of the CGMs also predict the same sort of seasonal and interannual variability in rainfall patterns as experienced in the 20th century.

The climate models are more certain on temperature change. All climate models agree on a trend of increased air temperature (Figure 20) in West Africa. This has a direct impact on evapotranspiration of water and temperature stress, not only on vegetation, but on people and animals as well. In the last year of the simulation period (2099) for example, the range of the projected temperature increase in RCP 8.5 is between 3.9 °C and 7.2 °C. For RCP 4.5 this is between 1.5 °C and 3.5 °C.

Overall, some studies predict that a 21st-century drying trend should be seriously considered as a possible future scenario for the UNB, while others predict that there is the possibility of an abrupt intensification of rainfall under future climate change.

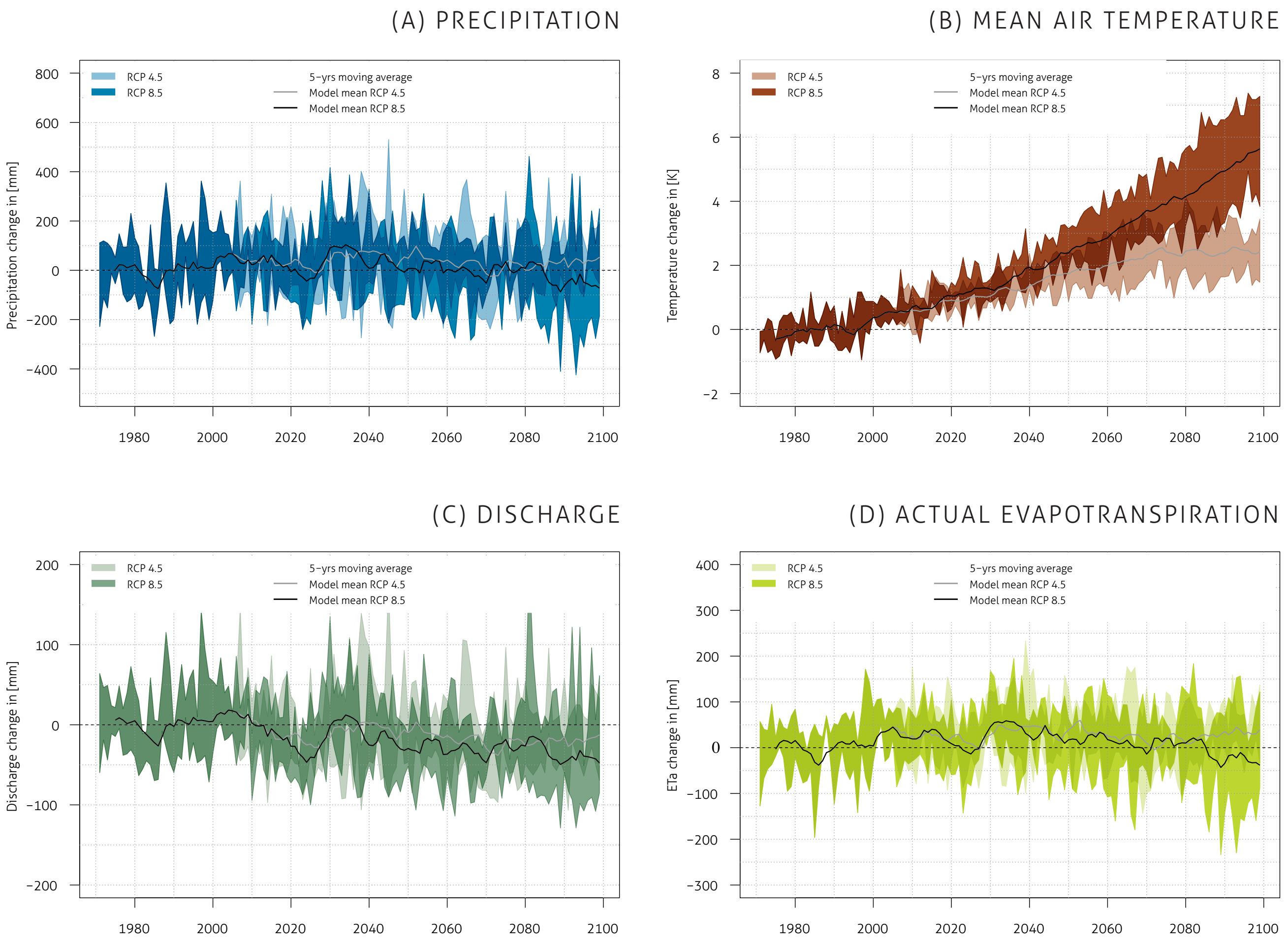

Figure 20. Projected development of annual precipitation, air temperature, discharge and actual evapotranspiration for the Upper Niger Basin

Note: Changes are relative to the period 1971–2000

Climate change versus historical reference

While changes in rainfall patterns and temperature will have an impact on future water availability, the scenario analysis described in this report does not include climate change. The projected annual rainfall changes resulting from climate change are in the range of past natural variability. The studies underlying this synthesis have adopted a method that superimposes the various water development scenarios on the highly variable hydro-climatic conditions observed in the past, in the period 1961–2000. This period represents a large range of natural rainfall variability and consists of a wet period in the 1960s with rainfall anomalies above the 20th-century average, and an extremely dry period in the 1980s. By not including the projected temperature increase of about 1.5°C–1.7°C in 2035 compared to now, the water availability in the development scenarios is underestimated by about 2%. Direct impacts of an increase in temperature on various ecosystem services, including the yields of crops (Barnabás et al. 2008; van Oort and Zwart 2017) and livelihoods are not assessed in the described studies.

Scenario building

There are two major scenario components that determine water availability in the delta:

- The amount of water that can be stored, as a result of the number, location and size of the dams and reservoirs: no dams, current dams, and the proposed Fomi dam project with small, medium and large dimensions;
- The amount of water diverted to irrigation, determined by the size, crops produced and irrigation efficiency: no irrigation, 2015 (current) irrigation, proposed extension of irrigation in 2025, 2035 and 2045.

Irrigation water demands are estimated based on crop demand, corrected by irrigation efficiency coefficients and multiplied by the irrigated area, as was estimated for the Action Plan for the Sustainable Development of the Niger Basin of the Niger River Basin Authority (BRLi and Betico 2016; BRLi 2007). Purported improvements in water use efficiency were not considered in the scenarios. Vandersypen et al. (2006) found for instance that the water use efficiency has not improved between 1995 and 2005. Dam dimensions and locations are derived from various feasibility study and environmental impact assessments (Tractebel 2017; AECOM 2017).

For the sake of simplicity and comparability, a dynamic development of land and water management, as may have occurred in real time, is not considered in the scenarios. This means that a scenario component is either switched on or off from the beginning of the simulation period (1961–2000), detached from real-time events. This approach allows for examination of the impact of single scenario components on water availability in the study area in dry, normal and wet years. In practice this means that the Sélingué dam, although not operational before 1982, is continuously operational in the simulations from 1961, in all scenarios except in the natural flow scenario. In this analysis the minimal flow threshold of 50 m³/s at Markala dam is not used as it is mostly not respected.

Results of scenarios are compared by using averaged values of scenario characteristics over the entire historical period, or differentiated for disaster, very dry, dry, average and wet years or differentiated for the wet season (high flow) or dry season (low flow) of a year.

Calculating river discharge and flood dynamics

To calculate the impacts of different water development scenarios on river discharges, the eco-hydrological Soil and Water Integrated Model (SWIM), a semi-distributed and process-based catchment model, was operated. SWIM was selected for this study in part because it contains sophisticated features to account for various reservoir operations. SWIM has been applied to the Upper and entire Niger River basin in several studies (Aich et al. 2016; Aich et al. 2015; Aich et al. 2014; Liersch et al. 2013; Liersch et al. 2019, Koch et al. 2013). SWIM was calibrated and validated to observed discharges provided by the Global Runoff Data Centre (GRDC) at 10 selected gauges in the UNB. As groundwater recharge and depletion could not be incorporated in the SWIM model, the model cannot account for the 'hydrological memory' of the system. This means that water availability in dry years is overestimated, while water availability in wet years is underestimated (less water simulated than observed).

For low floods the difference between the simulated water levels and observed water levels at Akka (based on the current situation) may be in the order of +20 cm or more. This corresponds with a too-optimistic inundation surface area of 2,000 km² or more (in that range 10 cm is 1,000 km² on average). For high floods the opposite is true, and the difference between the simulated water levels and observed water levels at Akka is -40 to -60 cm. This corresponds with a too-pessimistic inundation surface area of 4,000–6,000 km² or more. For wet years, and thus high floods, the model results are always on the safe side. However, for dry years, with low floods, we must emphasise that model results may have a deviation in the order of 20%, thus the inundation surface area may be 20% less than projected. Other models have comparable problems and cannot account for the hydrological memory, as for the IND no groundwater data are available. This does not account for the flooding model used (Davids et al. 2019; Zwarts et al. 2005), as this is based on a large set of satellite images and observed water levels.

To correct for the bias mentioned, the relative change in water availability between the modelled scenarios is calculated in percentages. This difference is then projected on the observed historical time series for the maximum water level at Akka, thereby giving a more accurate representation of the water availability in the delta in both dry and wet years. Calibration results are reasonable enough at all 10 gauges to answer the questions addressed in this study.

Long-term records of river discharges and water levels allow for the development of statistically significant hydraulic relationships between water levels at various positions in the basin, and river discharges and water levels in the Niger River. This forms the basis of the flood forecasting tool OPIDIN (www.opidin.org). OPIDIN combines the information of 56 satellite images that distinguish inundated and non-inundated parts of the IND at different observed water levels. It provides a proxy for inundation depths and duration, and whether the inundation is caused by local runoff or the overflow of the main river channels.

Household survey

To understand the (perceived) state of various ecosystem services in the delta and how livelihoods are affected by that state, an elaborate household survey was carried out. This survey was conducted in about 95 communities across the delta in 2018. About 1,000 individuals from various livelihood groups, ethnicities, age and gender were interviewed with a pre-structured questionnaire. The majority of the local population sampled have diversified livelihoods, and are largely dependent on pastoralism, agriculture or fisheries, or combinations thereof for subsistence and income. Each of these three livelihoods relies heavily on the IND's ecosystem services from the annual flood pulse.

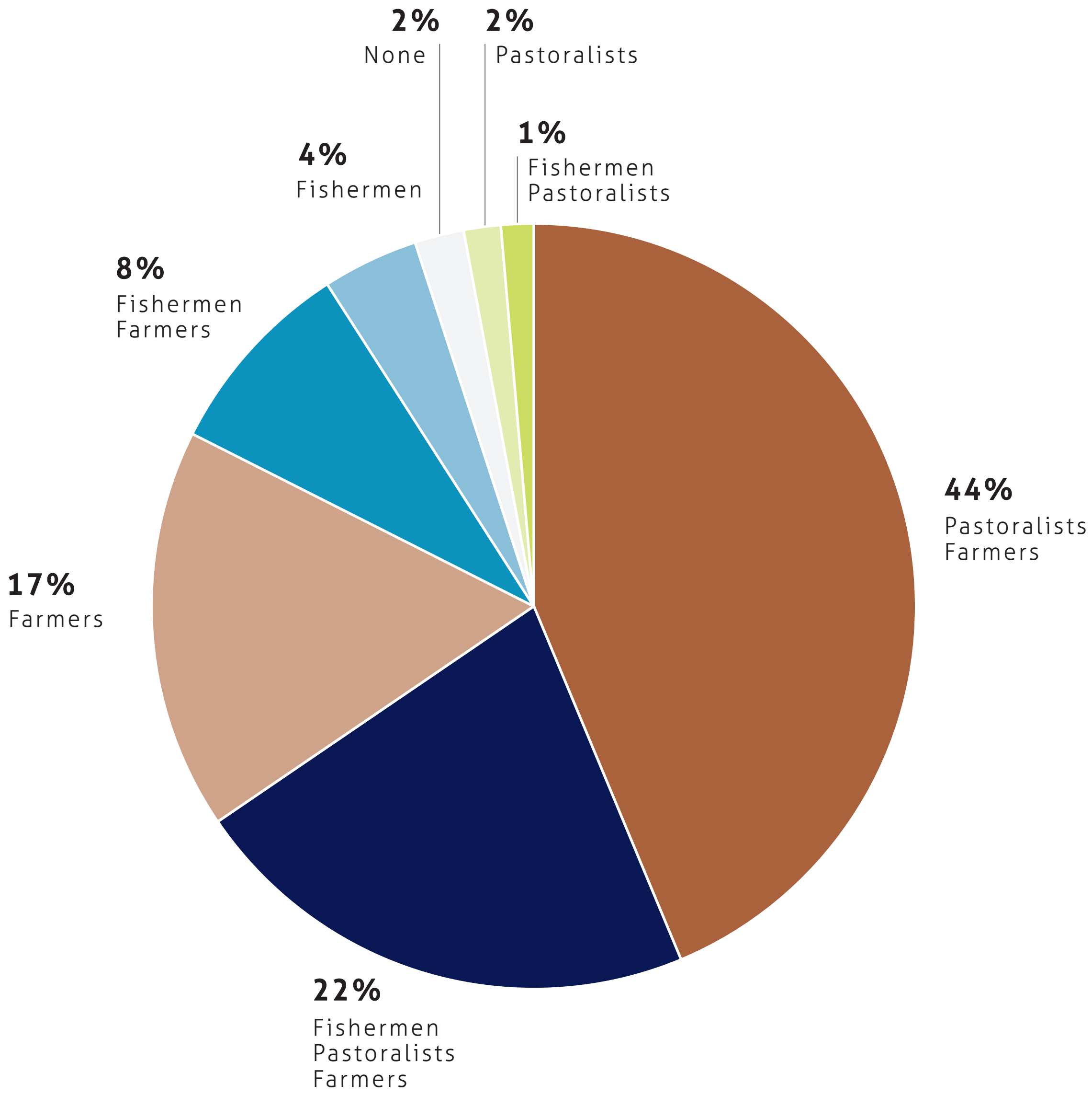

Figure 21. Distribution of IND livelihoods

Calculating changes in ecosystem service provisioning

Ecosystem services in the IND were identified and ranked in importance during workshops with stakeholders in Bamako.

To calculate the impacts of upstream infrastructure development on ecosystem services provisioning in the IND, it is necessary to establish relationships between those services and the hydrological and inundation characteristics of the delta. The flooding model informs the value of some ecosystem services at various inundation levels. For various grasses such as bourgou and wild rice, production and optimal growth can be determined by flood extent and water depth. The feasibility of navigation with different types of boats that require a minimal water depth can also be calculated.

For other ecosystem services, it is possible to create so-called dose-response functions explaining the statistical relationship between hydrological and flooding characteristics of the delta in a certain year, and the observed availability of a certain ecosystem service and that year. While data is not complete, such dose-response functions are possible for some goods in some years, in certain parts of the delta, as various government institutions in Mali record the amounts of traded fish, cows, sheep and goats.

As some of the dose-response functions use population size as an explanatory variable, different settings for population will have an effect on the outcome of the scenario analysis. Unfortunately, population statistics are not available for recent years. The latest census was held in 2009. In addition, there is insufficient information to make any assumptions about the carrying capacity of the ecosystems within the delta in relation to increased pressures as a result of population growth. Therefore, information from the 2009 census is used throughout the scenario analysis and the model does not account for population growth in the IND. For other ecosystem services like public health and cultural services, a more qualitative approach was used. These services are not linked to water availability in the scenario analysis.

Calculating the economic value of ecosystem services

The market price valuation technique is applied to the three main types of provisioning ecosystem services calculated (fish, rice and livestock). The application of economic valuation techniques was not feasible with the remaining ecosystem services due to the nature of the service or the lack of sufficient data. In these cases, a qualitative assessment was conducted to gain further insights into the importance of the service for the people living in the delta.

For the economic valuation of ecosystem services in the delta, the 2015 price level was applied, as this is the most recent year in which all prices are available. Future values have not been corrected for inflation, which implies that all values reported are 2015 price levels. However, aggregating economic values for the entire period of the analysis would not be valid. Therefore, only annual values of ecosystem services are provided and compared between the different scenarios. These annual values are based on the average water availability under each scenario, regardless of the year.

Dose-response functions for agricultural production are only defined for rice grown in the delta, as the production of dry cereals is mainly explained by changes in local rainfall. Production is estimated for the areas that rely on flood recession irrigation or semi-controlled flood irrigation. Functions could be defined for the regions of Ségou and Mopti. Production in Tombouctou is not incorporated in the model.

Calculating changes in livelihood strategies

To capture the impact of flood pulse alterations on livelihood strategies in the delta, a Bayesian Network Model was constructed that explores the effects of these changes on local ecosystem services, and how the livelihoods of the farmers, pastoralists and fishers are affected. The model is based on a series of expert interviews, extensive literature reviews and a survey with more than 1,000 inhabitants of the IND identifying the degree of access that households (i.e. farmers, fishers and pastoralists) have to the five types of capital (i.e. human, physical, natural, financial and social), estimating their annual household production, and identifying their attitude towards different livelihood strategies. The main outcomes provide an insight into how many people would be unable to continue their current livelihood strategy and consider permanent migration a solution.

Limitations

Although the scenario analysis provides an insightful overview of the change in ecosystem service values under the different water allocation scenarios, there are certain limitations to consider. First of all, we must stress that the modelling of the water levels at Akka has significant limitations for the lower and higher floods, as explained above. This means that the projected ecosystem services based on maximum water levels at Akka have the same biases. Secondly, it is important to stress that the set of ecosystem services assessed is not an exhaustive list, and therefore the values reported underestimate the total economic value of the ecosystems in the IND. Although a wider set of ecosystem services was discussed, only those with strong linkages to inundation dynamics in the delta and for which dose-response functions could be derived were included. Cultural services, regulation of waterborne diseases and provisioning services on a household level were qualitatively assessed but were not included in the scenario analysis. Ecosystems services related to the conservation of biodiversity and global commons, for example gene pools, are not considered.

For fisheries, the dose-response function for subsistence fisheries and fish traded outside of Mopti could not be defined. This narrow definition means that all the fish catch consumed directly or traded elsewhere in the delta is not considered.

The study area does not cover the full range of economic production in the IND. Due to the difficulty of collecting both primary and secondary data in the region of Tombouctou, the area could not be incorporated in the analysis for all the ecosystem services produced in this region, despite covering a relevant part of the delta. Furthermore, ecosystem services in the rest of the UNB were not considered, despite the fact that the water regime will be affected by the construction of the Fomi dam project. The results presented therefore underestimate the downstream effects of the dam and irrigation scenarios.

The ecosystem services are included in the economic valuation model using linear regression functions. Often, however, the provisioning of these services is not likely to have a linear relationship with water availability in the delta. Instead, it is more likely that there are tipping points at which the ecosystems and services provided collapse. The dose-response functions used in this study are therefore only effective in predicting relatively small changes in the provisioning levels.

Finally, the economic valuation should not be interpreted as a conclusive assessment of the planned infrastructure projects. The values presented only represent downstream effects in the IND. In order to conduct a conclusive cost-benefit analysis on the desirability of the dam, investments, operating costs and benefits of the infrastructure projects should also be considered, as well as externalities elsewhere in the delta. These results should primarily be seen as an effort to generate insight into the impacts of water management decisions on the ecosystem services and related livelihoods of people in the IND.

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