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Water resources planning in the Upper Niger River basin: Are there gaps between water demand and supply?

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ABSTRACT

Study region: The Upper Niger and Bani River basins in West Africa.

Study focus: The growing demand for food, water, and energy led Mali and Guinea to develop ambitious hydropower and irrigation plans, including the construction of a new dam and the extension of irrigation schemes. These two developments will take place upstream of sensible ecosystem hotspots while the feasibility of development plans in terms of water availability and sustainability is questionable. Where agricultural development in past decades focused mainly on intensifying dry-season crops cultivation, future plans include extension in both the dry and wet seasons.

New hydrological insights for the region: Today's irrigation demand corresponds to 7% of the average annual Niger discharge and could account to one third in 2045. An extension of irrigated agriculture is possible in the wet season, while extending dry-season cropping would be largely compromised with the one major existing Sélingué dam. An additional large Fomi or Moussako dam would not completely satisfy dry-season irrigation demands in the 2045 scenario but would reduce the estimated supply gap from 36% to 14%. However, discharge peaks may decrease by 40% reducing the inundated area in the Inner Niger Delta by 21%, while average annual discharge decreases by 30%. Sustainable development should therefore consider investments in water-saving irrigation and management practices to enhance the feasibility of the envisaged irrigation plans instead of completely relying on the construction of a flow regime altering dam.

1. Introduction

The fast growing population and socio-economic development in the case study area of the Upper Niger and Bani River basins (UNBB) in West Africa add more and more pressure on natural resources (Ogilvie et al., 2010). The UNBB is no exception but rather represents various cases of water-stressed river systems in semi-arid and arid regions worldwide. Sudan, for instance, uses the Blue

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and White Nile Rivers to irrigate one of the largest irrigation schemes worldwide with almost 900,000 ha (Abdelhadi et al., 2000). In Pakistan about 73% of the average Indus flows are abstracted to a vast irrigation scheme (Archer et al., 2010). In the São Francisco River basin in Brazil, the agricultural water demand in the year 2010 corresponded to 77% of the total water demand (Koch et al., 2018c). Worldwide, the agricultural sector is by far the largest water user, consuming on average about 70% of freshwater resources (FAO, 2011). In the African context, irrigation does not play a significant role, where only 6% of the total cultivated area is irrigated, which is lower than in other world regions, like 14% in Latin America and 37% in Asia (You et al., 2010). Possible reasons for this low share of irrigated agriculture are the undeveloped state of institutions for irrigation and the prevalence of subsistence farming (You et al., 2010).

However, in the case study area of the UNBB, irrigation plays a role to meet the growing food demands. Plans to utilise the available land and water resources that have been developed (BRL (Ingéniérie BRL), 2007a; MEME, 2007; RH et al., 2007) are continuously revised to account for development pathways not considered in previous plans (BRL and GEF, 2012; Coyne and Bellier, 2009). But the current expansion plans have not adequately included possible implications in terms of water availability, distribution, and allocation (Hertzog et al., 2012). The Office du Niger (OdN), a semi-autonomous government agency in Mali, is one of the key actors with regard to food production, responsible for the administration and development of a number of irrigation schemes (Hertzog et al., 2012) that are by far the largest in the UNBB. The major OdN irrigation scheme is located just upstream of the Inner Niger Delta (IND) and is supplied with water from the Niger River via a system of canals diverting water from the Markala dam. The Markala dam is operational since 1947 and was actually supposed to supply an irrigated area of 960,000 ha (Zwarts et al., 2005). However, in the year 2005 “only” 113,303 ha were cultivated (BRL and Betico, 2016). According to recent development plans, it is envisaged to expand the area to 460,000 ha until the year 2045 and to intensify agricultural production particularly in the dry season (BRL and Betico, 2016). Up to now it is not clear how realistic this endeavour is with regard to availability of water resources and sustainable development.

As a consequence of the unimodal rainfall regime in the UNBB, the discharge regime of the Niger and Bani Rivers entering the IND is characterised by a low flow season between December and May and a high flow season from June to November. The natural water availability in the dry season puts a clear limit to agricultural water supply already today. An extension of irrigation schemes would therefore either require improved water use efficiency or the construction of new dams to satisfy the required water demands. Dams and reservoirs have always played and will play an important role for the implementation of agricultural development and hydropower production in the UNBB. Generally, reservoir operations alter the natural flow regime by increasing flows during the dry season and reducing the flows and flood peaks during the rainy (wet) season (Liersch et al., 2013).

Beside numerous small dams, a total of five medium to large dams are currently in operation in the UNBB. The Sotuba dam was the first dam in the Upper Niger River. It was built in 1929 and produces a small amount of hydroelectric power and continuously diverts 8 m^3/s to irrigation schemes, but its impact on the water balance and the Niger flow regime is negligible (Zwarts et al., 2005). 35 years after the construction of the Markala dam in 1947, the Sélingué dam was built in 1982 to impound the Sankarani River, a tributary to the Niger River in Mali with a storage volume of 2.35 billion m^3 (Bm^3). It serves the purpose to generate hydroelectric power and to supply agricultural areas nearby with water for irrigation (Kuper et al., 2002). In the Bani River basin, two comparably small dams were recently built, the Talo dam (operational since 2007, 0.18 Bm^3) and the Djenné dam (2014 under rehabilitation, 0.36 Bm^3) (Zwarts, 2010; Zwarts et al., 2005). Their main purpose is to supply adjacent irrigation schemes more reliably with required water volumes. The effect of the existing dams and irrigation schemes in the UNBB is already observable downstream, at the inlets to the IND (Marie et al., 2007). Water volumes are reduced by withdrawals for irrigation and evaporation and seepage from reservoirs. A noticeable share of 55–70% of water withdrawals can be attributed to low water use efficiency, including high transmission losses in the irrigation canal network (Hertzog et al., 2012; Schüttrumpf and Bökkers, 2008; Keita et al., 2002).

However, the combined effect of existing dam infrastructure is relatively small compared to the impacts on downstream discharge expected to be caused by the planned dam in the Niandan River in the Niger headwaters in Guinea. Since decades it is planned to construct the so called Fomi dam with an envisaged storage volume of 5.3 Bm^3. This is more than twice as large as the currently existing storages in the UNBB together and the dam is expected to amplify the already observed impacts on the flow regime. Recently, it is considered to build the dam approximately 20 km upstream, where it would be called Moussako dam with comparable storage properties and therefore comparable expected impacts (Tractebel, 2017a,b). For convenience, the dam is henceforth called Fomi dam in this study although it might be constructed at the Moussako location. With its large storage capacity, the Fomi dam has the potential to substantially alter the flow regime by further increasing the flows during the dry season and decreasing the high flows and flood peaks during the reservoir refilling period. Indirectly, the Fomi dam may also lead to long-term reduced discharge entering the IND by enabling or supporting higher water withdrawals for agricultural consumption in the OdN irrigation scheme in the dry season.

The increasing demand for food and energy in Mali and Guinea may justify such plans but, depending on the level of implementation, they are expected to affect downstream ecosystems and associated livelihoods of local communities. The IND is an important, seasonally inundated wetland, providing natural resources and livelihoods for more than 10% of Mali's population inhabiting the delta. About 40% of Malian cattle depend on the fodder production and grazing grounds in the IND while 80% of Malian fish production comes from the IND (RH et al., 2010). Livestock and fisheries contribute respectively with 10% and 4% to Malian GDP (RH et al., 2010; Dolo et al., 2005) and form an essential component of Malian food consumption, not only quantitatively, but also qualitatively as it increases nutritional diversity and gastronomic variety. The Upper Niger and Bani Rivers constitute the inflows into the IND. Altering their flow regime towards generally lower average annual inflows and a changed annual cycle is expected to challenge the integrity of the IND ecosystem. This ecosystem has evolved in and has adapted to the natural variability of the hydroclimatic conditions prevalent in the last centuries, including extremely wet (e.g. 1950s and 1960s) and dry (e.g. 1970s and 1980s) decades. In very wet periods, like in the 1950s, the inundated area can expand up to 36,000 km^2 in the flooding season (Zwarts et al., 2005). Over the period 2000 to 2011, Ogilvie et al. (2015) estimate the variation of the annual maximum flooded surface area between 10,300 km^2 and 20,000 km^2, receding progressively to a magnitude of 3800 km^2 on average in the dry season. In extraordinary dry years, the inundated area can be much smaller. The seasonal flood dynamics are vitally important for its integrity. The inundated area directly relates to ecosystem services that are provided by the IND. For example, fish rejuvenation is dependent on the availability of various habitats suitable for spawning and nursing of the young fish that will only form under particular flood dynamics. Similarly, the large amounts of submerged grasses like bourgou, used as cattle fodder, will only develop when favorable habitats exist during germination and early plant growth stages. As a rule of thumb one can say that the larger the inundated area the higher the productivity of the IND (Zwarts et al., 2005). The altered flow regime and the general reduction of inflows and flood peaks entering the IND, caused by intensified activities in the UNBB upstream the IND, like agricultural and hydropower production, constitute clear trade-offs with the IND's ecosystem integrity and the services it provides.

The first objective of this study is to investigate the feasibility of the plans to expand irrigated agriculture in the scheme operated by OdN considering different reservoir operation scenarios. The gap between the estimated irrigation water demand and supply in the years 2025, 2035, and 2045 determines the feasibility. Three reservoir settings are analysed, where the first scenario represents the current state with only the Sélingué dam operational in the Sankarani River. In the other two scenarios it is assumed that the Fomi dam is operational in the Niandan River in the Niger headwaters, and either operated to largely preserve the natural flow regime or to optimise hydropower production. The second objective is to assess the combined impacts of increasing agricultural water demands and reservoir operations on the discharges of the Niger and Bani Rivers and the average maximal inundated area in the IND. However, the impacts on the IND's ecosystem services are not covered in this study.

2. Materials and methods

2.1. Study area

The Upper Niger and Bani River basins (UNBB) in West Africa are defined in this study as the catchments upstream the IND at the gauges Ké-Macina (Niger) and Sofara (Bani), see Fig. 1. The UNBB covers an area of 273,700 km^2. The following countries have a decreasing share in the basin area: Mali, Guinea, Ivory Coast, and Burkina Faso. According to CIESIN (2016), the basin was populated by 9.8 million people in 2005 and increased by 42% to 13.9 million inhabitants in 2015 and thus belongs to a region with one of the fastest growing population worldwide, corresponding to an annual growth rate of about 4%.

Following the Köppen-Geiger climate classification, the UNBB is located in a climatic transition zone (Fig. 1). About three quarters of the area are characterised by the tropical savanna climate and the northern quarter is dominated by a warm semi-arid climate. In the very north, the basin is influenced by the warm desert climate and in the south by the monsoon climate.

2.2. Data

Following data sources were used to set up the hydrological model described in Section 2.3. The SRTM Digital Elevation Model in 90 m horizontal resolution (Jarvis et al., 2008) was used to delineate the UNBB and its sub-basins. Soil properties were derived from the Harmonized World Soil Database (HWSD) (FAO, 2009) and information on land use/cover was taken from GLC2000 (Bartholomé and Belward, 2005). The source of daily weather variables in the period 1960–2000, such as daily precipitation, minimum, mean, and maximum temperatures are the gridded Watch Forcing Data (WFD) with a spatial resolution of 0.5 ° (Weedon et al., 2011). WFD are based on ECMWF Re-Analysis ERA40 (Uppala et al., 2005) assimilating surface observations. It was found that WFD radiation data are consistently lower than observations in the UNBB and radiation was therefore calculated based on minimum and maximum temperature and the respective sub-basin's latitude according to Hargreaves et al. (1985). Simulated radiation data were adjusted to fit values estimated by solargis.info. Discharge data of 10 gauges provided by the Global Runoff Data Centre (GRDC) were used to calibrate and validate discharge simulations.

Data and information from various reports (BRL and Betico, 2016; BRL (Ingéniérie BRL, 2007a; BRL (Ingéniérie BRL, 2007b; BRL and DHI, 2007; Zwarts et al., 2005) were used to parameterise the reservoirs and to develop land and water management scenarios. The rating curves relating reservoir water level, volume, and area for the Fomi dam were derived from the SRTM DEM using the GRASS GIS module r.lake, which computes the water volume and flooded surface area at given water levels. Values in between the given water levels are linearly interpolated. Corresponding values and other relevant reservoir data are shown in Tables S1 and S2 in the Supplement.

2.2.1. Climate projection uncertainties

Hulme (2001) states that: "There is no such thing as 'normal' rainfall in the Sahel." Instead, rainfall fluctuates erratically and the "normal" is rather the variability of rainfall in space as well as from year to year, and from decade to decade (Hulme, 2001). An adequate spatio-temporal representation of weather variables in such climatic transition zones governed by the West African monsoon system is challenging for climate models (Turner et al., 2011; Cook and Vizy, 2006). Moreover, rainfall projections of Global Circulation Models (GCMs) diverge in future scenarios, where some models project a wetter and others a drier future in the UNBB (Monerie et al., 2017; Rowell et al., 2015, Aich et al., 2014; Biasutti, 2013; Giannini, 2010; Cook and Vizy, 2006; see also Figs. S1 and S2 in the Supplement). According to Giannini (2010) there is no way to discern whether the future climate in the Sahel will be different from that experienced over the 20th century. According to Rowell et al. (2015), the projection uncertainties of climate

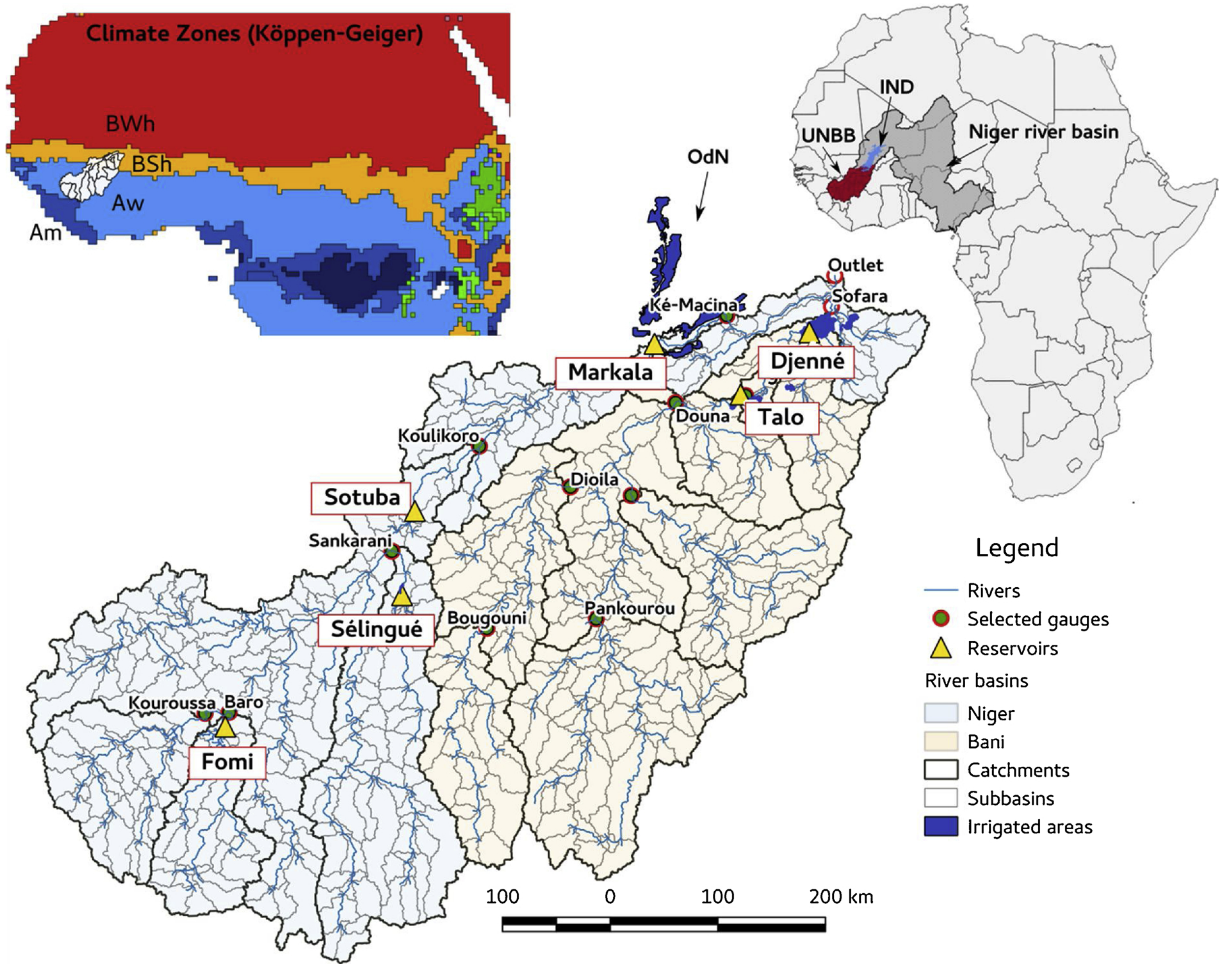


Fig. 1. Map of the case study area of the Upper Niger and Bani River basins (UNBB) with catchments, sub-basins, discharge gauges, reservoirs, irrigated areas, and climate zones. OdN = Office du Niger; IND = Inner Niger Delta; Am = monsoon climate; Aw = tropical savanna climate; BSh = warm semi-arid climate; BWh = warm desert climate.

models in the Sahel are not reduced if only the best performing models are selected. Vetter et al. (2015) and Hattermann et al. (2018) found that GCMs are the main source of uncertainty in climate impact assessment in the UNBB, while hydrological models contribute only a small part to uncertainty. Vetter et al. (2017) confirms this finding for the entire Niger basin.

2.2.2. *Dealing with climate projection uncertainties*

As discussed in Liersch et al. (2018), the value of climate projection data for quantitative, application-oriented studies, where a certain degree of accuracy in input data is required, is still rather limited. Even bias-corrected climate simulations do not always provide input that is of adequate quality for regional impact studies (Liersch et al., 2018). Therefore, we use a historical gridded weather dataset (Weedon et al., 2011) representing the variable hydro-climatic conditions observed in the period 1960–2000 to investigate the feasibility of irrigation extension in OdN and to assess the impacts of combined irrigation and reservoir operation scenarios on river discharges and the inundated area in the IND.

Fig. 2 shows that the years 1960–2000 represent a large range of natural rainfall variability and consist of a wet period, the 1960s with rainfall anomalies above the 20th century average, and an extremely dry period in the 1980s where all years are below the 20th century average. It is also the period with the highest density of meteorological stations in the UNBB (Schneider et al., 2015) and therefore, the uncertainties are expected to be the lowest. Decision makers may have experienced these extreme conditions themselves and will remember what consequences consecutive wet or dry years have had on, e.g., high and low flows in the Niger and Bani Rivers, agricultural and fishery production or the extent of the inundated area in the IND. Climate simulations for the 21st century show that the cyclic behaviour with consecutive wet and dry years that was observed and is simulated by GCMs in the past, will continue in future, independently if a GCM projects a dryer, wetter or no trend in annual rainfall at all (Figs. S3 and S4 in the Supplement).

Communicating the uncertainties related to climate change projections and their consequences for future water availability is difficult and does usually not satisfy stakeholders and decision makers, because they do not know or understand how to prepare or

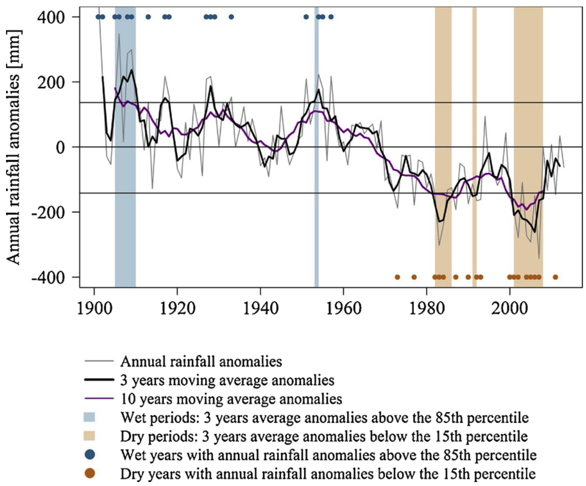


Fig. 2. Observed rainfall anomalies in the Upper Niger and Bani River basins from 1901 to 2013 based on Schneider et al. (2015). Horizontal black lines refer to the 15th percentile (lower), the 50th percentile (middle, zero line) and the 85th percentile (upper) of annual rainfall anomalies.

adapt to these diverging trends and may thus be reluctant to trust in the presented results. In addition to this, following arguments justify the application of historical meteorological data in this study instead of applying climate scenarios are: a) water resources management studies require a certain degree of meteorological input data accuracy which is, particular with regard to rainfall patterns and volumes in the UNBB, not provided by climate models and b) the 40 years observational meteorological data show a high variability, allowing the analysis of current and future water management activities under a range from extremely dry to wet hydro-climatic conditions. A deficiency with this approach is that the projected temperature increase of 1.5–1.7 °C between 2030–2049 and 1986–2005 is neglected (Fig. S2b), which would result in higher potential evapotranspiration rates of approximately 2% reducing water availability.

2.3. Hydrological modelling

The Soil and Water Integrated Model (SWIM) is an eco-hydrological model, developed by Krysanova et al. (2005). It operates at the daily time step and is a semi-distributed and process-based catchment model, which is continuously developed and adapted to meet new or specific challenges and requirements (Krysanova et al., 2015). SWIM was already 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., 2012). The model was used in this study, because it contains sophisticated features to account for various reservoir operation options and irrigation management, which are required to address the research questions at hand.

In this study SWIM was calibrated and validated to observed discharges provided by the Global Runoff Data Centre (GRDC) at 10 selected gauges in the UNBB (Fig. 1) available during the period 1960–2000, where the first year is omitted in the analysis. In a first step, a manual sensitivity analysis was conducted to understand the model behaviour and to define reasonable parameter ranges. Based on these parameter ranges, the sub-catchments were finally calibrated using a multi-objective evolutionary automatic algorithm.

The performance of the simulations of the annual cycle is exemplarily shown for the most important gauges used in this study (Baro, Sankarani, and Ké-Macina). Corresponding figures at the daily time step are presented in the Supplement in Fig. S5. The model results show a very good fit for the gauge Baro, the closest downstream gauge from the location where the Fomi dam may be built, see Fig. 3a and b. A rather large volumetric error (PBIAS) is simulated in the calibration period at gauge Sankarani (before the Sélingué dam was built), see Fig. 3c. However, in the period where the Sélingué dam was operational, the results can be judged as very good in terms of volumetric error and seasonality (R^2), see Fig. 3d. R^2 values of 1 are achieved in both the calibration and validation periods at gauge Ké-Macina (downstream the Markala dam), where average discharge is underestimated by 8.4% in the calibration period and overestimated by 17.4% in the validation period, see Fig. 3e and f. Following model performance in terms of Nash Sutcliffe efficiencies (NSE) were achieved at the daily time step in the calibration and validation periods: Baro 0.77 and 0.77; Sankarani 0.78 and 0.26; Ké-Macina 0.93 and 0.86. However, the results are reasonable enough at all 10 gauges to answer the questions addressed in this study.

2.3.1. Reservoir module

A reservoir module, developed by Koch et al. (2013), was implemented in SWIM to account for the effects of dam infrastructures in river basins that may, depending on their capacities and operation rules, substantially alter the natural flow regime and reduce downstream water availability by evaporation and seepage. The actual reservoir area, volume and water levels are changing on a daily time step depending on inflows, reservoir release and losses due to evapotranspiration, seepage and withdrawals. Actual evapotranspiration from the reservoir area (ET_{Res}) is determined by the area-weighted sums of the lake's open water surface

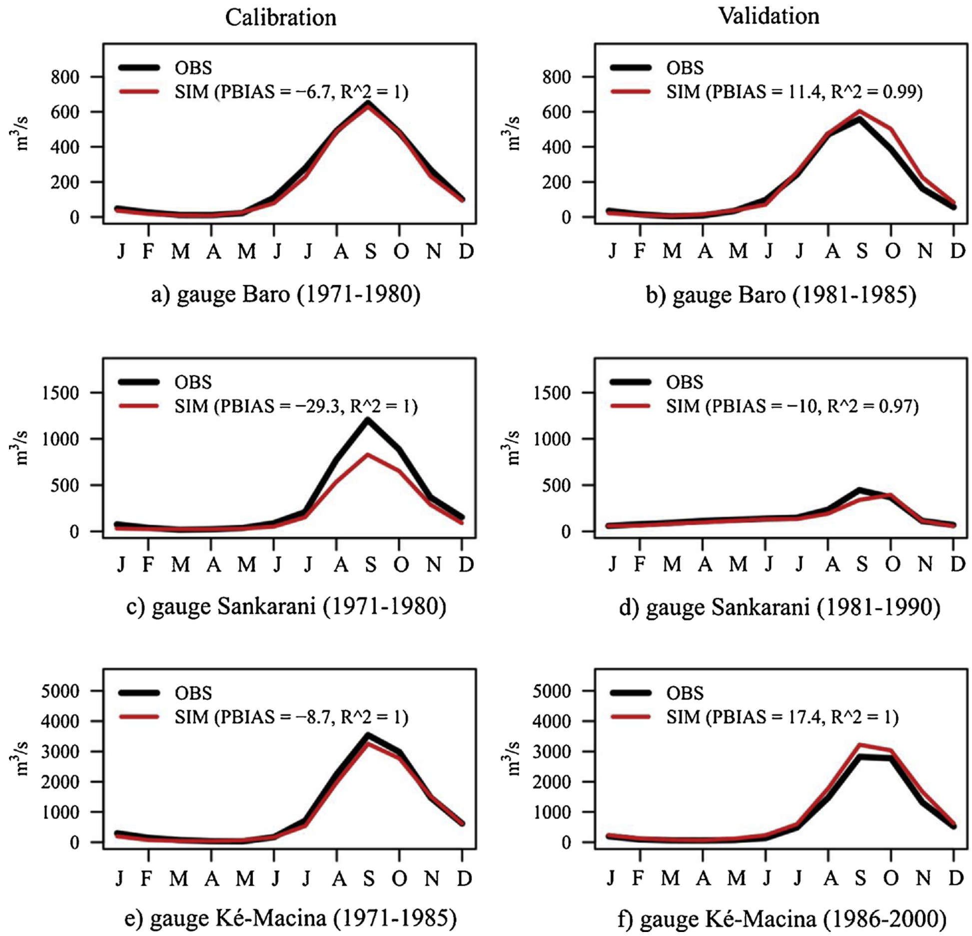


Fig. 3. Observed (OBS) and simulated (SIM) discharges of the annual cycle at gauge Baro (Fomi), Sankarani (downstream Sélingué), and Ké-Macina (downstream Markala dam).

evaporation (ET_p) and actual evapotranspiration (ET_a) from the land area, i.e. the reservoir area not inundated at the respective day. Both ET_p and ET_a rates depend on the actual volume of the reservoir. The daily seepage rate is computed as a user-defined fraction of the actual total storage volume. The module was already applied to investigate reservoir filling strategies and their downstream impacts, which is especially relevant for dam projects in the planning phase (Liersch et al., 2017), to analyse the impacts of various operation rules on downstream discharges (Koch et al., 2018a; Liersch et al., 2017; Lobanova et al., 2017; Lobanova et al., 2016; Aich et al., 2016), to account for storage effects of natural lakes (Liersch et al., 2018), and to simulate hydropower production (Koch et al., 2018b; Liersch et al., 2017; Lobanova et al., 2016; Koch et al., 2013).

2.3.2. Water allocation module

The water allocation module in SWIM allows the withdrawal of water volumes from river sections or reservoirs. Water demand data can be included at the daily, monthly, or average monthly time step. Abstracted volumes can either be allocated to water users, such as irrigation schemes or cities, outside the system (river basin) or to water users inside the system. In this study, the module was used to account for reported water uptakes in the past during the calibration and validation periods and to investigate scenarios of planned developments of several irrigation schemes in the UNBB. Since the main irrigation scheme (OdN) is located outside the UNBB, groundwater return flows are neglected here.

2.4. Scenarios

The coupled irrigation and reservoir operation scenarios developed in this study consider different assumptions of reservoir settings and withdrawals for irrigation schemes at several locations in the UNBB. Details are described in the following sections.

To analyse the reservoir operation impacts on irrigation water supply, river discharge, and inundated area under past hydro-climatic conditions, the scenario settings are constant over the entire simulation period, even if dams were built during (Sélingué in 1982) or after (Talo 2007, Djenné 2014, Fomi planned) the scenario period. Land use was also not considered to change over the scenario period.

2.4.1. Reservoir scenarios

Reservoir settings comprise the number of active reservoirs in each scenario as well as their operation rules. Following dams are considered in this study: Fomi (Niandan River, Guinea, planned), Sélingué (Sankarani River, Mali), Talo (Bani River, Mali), and Djenné (Bani River, Mali). The Sotuba dam and the Markala dam in Mali along the Niger River are not implemented as reservoirs in the model, because their storage volume is very small. These dams solely serve the purpose of diverting water to irrigation schemes. However, water withdrawals at the Markala dam are considered by the water allocation module. Withdrawals at the Sotuba dam account for only 0.2% of Niger river discharge and were thus neglected in this study. The Sélingué dam and the Fomi dam (planned) are both impounding tributaries of the Niger River. They are therefore relevant for the assessment of the feasibility of irrigation expansion plans in the OdN irrigation scheme and for the investigation of inflows and inundated area in the IND. The Talo and Djenné dams in the Bani River basin are not relevant for the OdN irrigation scheme but for the inflows and inundated area in the IND. However, due to their small storage capacities they play only a minor role in this study. Operation of the Sélingué dam was parameterised in the model to represent realistic dam management in the period between 1982 and 2000 (Koch et al., 2013).

The planned Fomi dam was parameterised to represent two different operation rules. One rule was developed to assess the impacts of the Fomi dam when operated to optimise hydropower production (HPP scenario) with a dam height of 388 m.a.s.l. The simulated operation is aimed at generating a firm yield of 35 MW, which corresponds to about 80% of the potential mean production of 43 MW (Coyne and Bellier, 2009). These settings represent the state of the planning process in March 2017 (Fomi directorate, 2017), where the total storage would have a volume of 5.279 billion cubic metres (Bm^3) with a dead storage of 1.212 Bm^3 (23% of total storage). However, a recent environmental impact study (AECOM, 2017) suggests a lower dam height and consequently a smaller storage capacity (2.415 Bm^3) to be an alternative. In the latter, the active storage has, due to the large dead storage, an active capacity of only 1.203 Bm^3 (50% of total storage). This latter dam setting is represented by the Fomi ENV scenario, where released discharge largely preserves the natural flow regime downstream the dam. In general the minimum discharge from the dam in the ENV scenario is based on the monthly Q_{95} values, derived from SWIM simulations in the period 1961–2000. The minimum discharge in the low flow season is set to 10 m^3/s. In the high flow season the capacity of the hydropower plant (421 m^3/s) is set as the maximum discharge. In the ENV scenario the release from the reservoir does not change the natural flow regime noticeably during the dry season between January and June. In the wet season, however, discharge is reduced by the reservoir management in the ENV scenario to a certain extent. In both scenarios the dead storage head is assumed to be at an elevation of 370 m.a.s.l. Water level, surface area, and storage volume relationships are shown in the Tables S1 and S2 in the Supplement. The seepage rates in all implemented dams are assumed to be in the order of the rate in the Sélingué dam, where Zwarts et al. (2005) assumes losses of 0.83 Bm^3/a.

2.4.2. Irrigation scenarios

Monthly irrigation water demands (DI_{mon} *in* m^3/s) employed in the irrigation scenarios in OdN were simulated with the model used by the hydro-agricultural improvement programme (BRL and Betico, 2016). The monthly water demand in OdN is estimated based on monthly crop demand (DC_{mon}) in millimetre per day corrected by a monthly irrigation network efficiency coefficient ($Coef_{mon}$) and multiplied with the irrigated area (A) in hectare for a given target year (Eq. (1a)). The irrigated area for eight different crops and the crop calendar is shown in Tables S4 and S5 in the Supplement. The monthly irrigation demand for the other irrigation schemes was estimated based on the annual irrigation scheme water demand (DS_{yr}) corrected by a monthly coefficient ($Coef_{mon}$), see Eq. (1b), as was estimated for the Action Plan for the Sustainable Development of the Niger Basin of the Niger River Basin Authority (BRL (Ingéniérie BRL, 2007a). Changes in water use efficiency, as expressed by $Coef_{mon}$, were not taken into account in the scenarios. Vandersypen et al. (2006) found for instance that the water use efficiency has not improved between 1995 and 2005.

$$DI_{mon}\ \text{OdN scheme} = A * DC_{mon} * \text{Coef}_{\text{mon}} / 8640 \quad (1a)$$

$$DI_{mon}\ \text{Other schemes} = A * DS_{yr} * \text{Coef}_{\text{mon}} / 8640 \quad (1b)$$

The baseline for all sites refers to estimated irrigation demands in the year 2005 (BRL and Betico, 2016; BRL (Ingéniérie BRL, 2007a). Based on these documents, irrigation scenarios were derived for the year 2025 for all sites. Additionally, water demands were estimated for the periods around 2035 and 2045 in the irrigation scheme operated by OdN (BRL and Betico, 2016). Corresponding data used in the simulation is shown in Table 1 and monthly withdrawals are listed in Table S3 in the Supplement.

Based on our simulations, the long-term average natural discharge at the Markala dam was about 1140 m^3/s in the period

Table 1
Irrigation scenario data for the Office du Niger irrigation scheme.

	Year			
	2005	2025	2035	2045
Irrigated area [ha]	113,303	198,561	314,461	459,461
Demand [m^3/s]	79.3	159.9	228.3	306.3
% of Q_m at Markala	7.0 (5-13)	14.0 (10-26)	20.0 (14-37)	26.9 (19-50)

Demand = average daily; Q_m = long-term mean discharge; numbers in brackets indicate the range between wettest and driest year in the period 1961–2000.

1961–2000. The current irrigation demand (79.3 m^3/s, equivalent to 2000 mm/a) corresponds to 7% of long-term average natural Niger discharge and will, according to the development plans, increase to 14% in 2025, to 20% in 2035, and to 27% in 2045 (Table 1). Remarkable is the range of irrigation demands in relation to annual discharges, indicating a high variability of water availability. In the 2045 irrigation scenario, the irrigation water demand would correspond to 50% of discharge in the year with lowest discharges and to 19% in the year with highest discharge in the entire simulation period (Table 1).

Withdrawals for irrigation are considered in the model as water volumes diverted to irrigation schemes from reservoirs at the sites Sélingué, Fomi, Talo, and Djenné or from the river section at the Markala dam (OdN), see Fig. 1. Actual withdrawals (W) are based on the irrigation demand (DI) but can be limited by water availability (Q_{avail}, see Eq. (2)) and/or minimal flow thresholds (TH_{min_flow}) defined at the corresponding reservoir or river section (Eq. (3)), where Q is the discharge and the unit of all variables Eqs. (2) and (3) is m^3/s.

$$Q_{avail} = Q - Th_{min\_flow} \tag{2}$$

$$\begin{aligned} W_{mon} &= DI_{mon} \text{ (if } Q_{avail} >= DI_{mon}) \\ &= Q_{avail} \text{ (if } Q_{avail} < DI_{mon}) \end{aligned} \tag{3}$$

To ensure drinking water supply in the country Niger, it was agreed that the minimal flow to be continuously released at the Markala dam is 50 m^3/s (BRL and DHI, 2007). Hence, water uptake for irrigation can be restricted during the low flow season by that threshold. However, the Sélingué and Markala dams Commission in Mali aim to meet a minimum of only 40 m^3/s. In reality even this agreement is not always respected. OdN mentions that in 2015, 2016 and 2017 the minimum of 40 m^3/s was not met for 105, 100, and 109 days, respectively. While the 50 m^3/s threshold is applied in simulations to analyse the feasibility of irrigation expansion, it is not applied in simulations used to analyse the impacts on IND inflows and the inundated area because of the non-compliance issue.

2.5. Performance criteria and definitions

To analyse the feasibility of the irrigation scenarios in the irrigation scheme operated by OdN, the simulated daily supply gaps (SG) in percent were aggregated to monthly deficits for each year (see Eq. (4)). The relative supply gap or deficit is the share of the actual monthly withdrawals (W) in relation to the irrigation demand (DI).

$$SG_{mon} = 100\text{-}(W_{mon} \;/\; DI_{mon} * 100) \tag{4}$$

The impacts of irrigation and reservoir operation scenarios on the inflows into the IND are analysed by considering changes in average annual discharge and high and low flows compared to natural flows at Baro (just downstream of the Fomi dam) and at Ké-Macina (just before the Niger River enters the IND). The natural flows were simulated by the SWIM model not considering irrigation and reservoir management. High flows are represented by the Q_{10} and low flows by the Q_{90} indicator. The Q_{90} value represents the discharge value that is exceeded in 90% of the time and the Q_{10} value is the discharge value that is exceeded in 10% of the time. The indicators are calculated for each year and are averaged over the entire simulation period.

Zwarts et al. (2005) and Observatoire (2018) found that the sum of water volumes (V in km^3) entering the IND from the Niger and Bani Rivers in the period between 1st of June and 15th November correlates to water levels (WL in cm) at gauge Akka in the IND (Eq. (5)).

$$WL = 0.044 * V^2 + 8.7075 * V + 226.5 \tag{5}$$

The maximal water levels in a year at Akka, in turn, allow an estimation of the maximal inundated area of the IND (A_{IND} in km^2), see Eq. (6). By applying Eqs. (5) and (6), the simulated maximal inundated area achieves an R^2 value of 0.85, see also Fig. S6 in the Supplement.

$$A_{IND} = 2040.148 * \text{EXP}(0.0040674 * WL) \tag{6}$$

The dry or low flow season refers to the months from December to May and the wet or high flow season to the months between June and November. The term “period” is used in the context of a period of years, like the 1980s to indicate a dry period, for instance.

3. Results

3.1. Fomi operation scenarios

In this section, the two scenarios to operate the planned Fomi dam are analysed considering reservoir release, hydropower production, water levels in the reservoir, and water losses from the storage. Under the HPP scenario, reservoir operation changes the natural flow regime at Baro considerably, where average dry-season discharge increases by 316% or 102 m^3/s on average, where the range is between 280% in January and 1215% in April. The average wet-season discharge decreases by -46% or -185 m^3/s and the highest reduction occurs in September with -67% or -440 m^3/s (Fig. 4a). The impact of the ENV scenario on the natural flow regime is much lower, where the average dry-season discharge experiences a reduction of -35% or -11 m^3/s, where the values are between + 33% or 3.7 m^3/s in April and -52% or -50 m^3/s in December. Average wet-season discharge decreases by -12% or -47 m^3/s, where the lowest impact is in August with only + 0.4 m^3/s, the highest increase in September with 5% or 32 m^3/s, and the maximal impact in November is a decrease of -39% or -120 m^3/s (Fig. 4a).

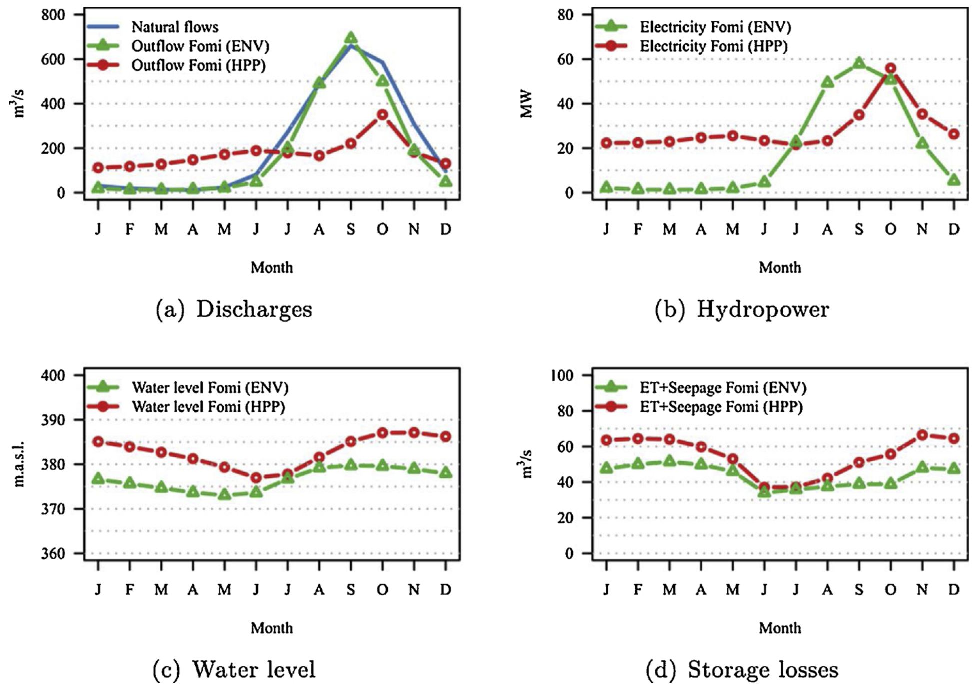


Fig. 4. Comparison of Fomi dam operation strategies and their impacts on selected processes at gauge Baro downstream Fomi (monthly mean values 1961–2000).

From an economic perspective, reliable hydropower production with a high firm yield is probably the most important feature of the Fomi dam. Such a scenario would also be optimal from an irrigation perspective in OdN, because it supports dry-season cropping by increasing the discharge in the low flow season. Under the HPP scenario, the Fomi dam can generate 28 MW on average and the firm yield with an exceedance probability of 90% (EP_{90}) corresponds to 16 MW and the EP_{95}*-value* is 13 MW. The firm yields have been calculated based on the daily production time series. The average production under the ENV scenario is 18.4 MW and the firm yield EP_{90} is only 1 MW. The lower average production in the ENV scenario may not be a major issue, but the fact that either no or only very little electricity could be produced between January and June is a clear limitation (Fig. 4b). The reason for the low production in the dry season in the ENV scenario is that the water level in the daily time series frequently drops below the head of the dead storage at 370 m.a.s.l., where electricity generation becomes impossible (Fig. 4c). It should be noted that the firm yield of 35 MW, which represents 80% of the average production of 43 MW, as assumed by Coyne and Bellier (2009), are not achieved in both scenarios. The reason is that the estimation of Coyne and Bellier (2009) were based on a larger Fomi dam with a dam height of 390 m.a.s.l. and a storage capacity of 6.1 Bm^3, instead of 388 m.a.s.l. and 5.3 Bm^3 as assumed in the study at hand.

Compared to the HPP scenario, the losses via evaporation and seepage are about 20% lower in the ENV scenario (Fig. 4d). In total, the long-term average discharge released in the ENV scenario is 6% higher than in the HPP scenario.

3.2. Feasibility of irrigation management in Office du Niger

3.2.1. The role of the Sélingué dam

In this section it is demonstrated how the Sélingué dam contributes to the realisation of dry-season irrigation referring to the year 2005 in the area operated by OdN.

Fig. 5 shows simulated withdrawals supplied to the OdN irrigation scheme as percentage of the demand. White patches represent months without deficits and coloured areas indicate supply gaps. In the scenario without any dam (Fig. 5a) current irrigation practices would suffer deficits based on the natural availability of the Niger River in the low flow season in most of the years, except in extraordinary wet years comparable to conditions at the end of the 1960s. Averaged over the entire period, 83% of the demand would be supplied, leaving a gap of 17%. Looking at the low and high flow seasons separately reveals that the deficits are negligible from June to November but are with 33.5% considerable in the low flow season, see Table 2. Particularly between February and May, the gap between demand and supply would amount to 80% in many years, making current agricultural practices in the dry season impossible.

In Fig. 5b, the Sélingué dam is operational during the entire simulation period. Due to increased discharge in the dry season, the deficits are reduced to a minimum and occur only in extremely dry years. The dam reduces the average supply gap from 17% to 1%.

3.2.2. The effects of an additional Fomi dam

If the Fomi dam would be operational in addition to the Sélingué dam and assuming the same simulation settings as depicted in the previous section, there would be no visible change for dry-season irrigation supply, if the Fomi dam is operated to preserve a

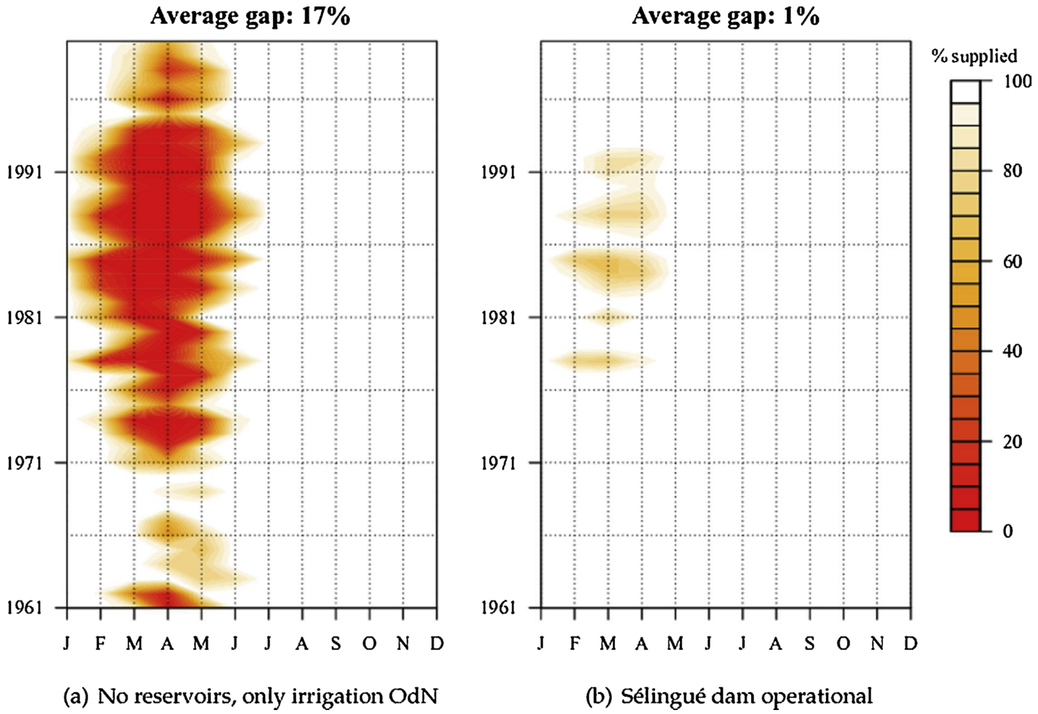


Fig. 5. Monthly irrigation supply in the Office du Niger irrigation scheme, referring to the state of development in 2005. Numbers in title denote the percentage of the supply gaps averaged over the entire simulation period.

Table 2
Mean supply gaps of irrigation scenarios in Office du Niger (in % of demand), for hydro-climatic conditions in 1961–2000.

Scenario	2005			2025			2035			2045		
	ave	dry	wet	ave	dry	wet	ave	dry	wet	ave	dry	wet
No dams	17.0	33.5	1.4	26.4	48.8	4.1	–	–	–	–	–	–
Sélingué only	1.0	1.9	0.0	6.8	13.5	0.1	13.1	25.7	0.6	19.2	36.5	2.0
Sélingué & Fomi (HPP)	0.0	0.0	0.0	0.2	0.4	0.0	2.5	4.9	0.0	7.2	14.2	0.1

ave = average; dry = dry season; wet = wet season.

natural flow regime downstream (ENV scenario). This is due to the fact that discharge in the low flow season is not substantially affected by the ENV reservoir management, as is shown in Fig. 4a. Hence, a corresponding figure showing irrigation deficits would be very similar to Fig. 5b, where only the Sélingué dam is operational. Therefore, the ENV scenario simulations are omitted in the analysis of irrigation feasibility.

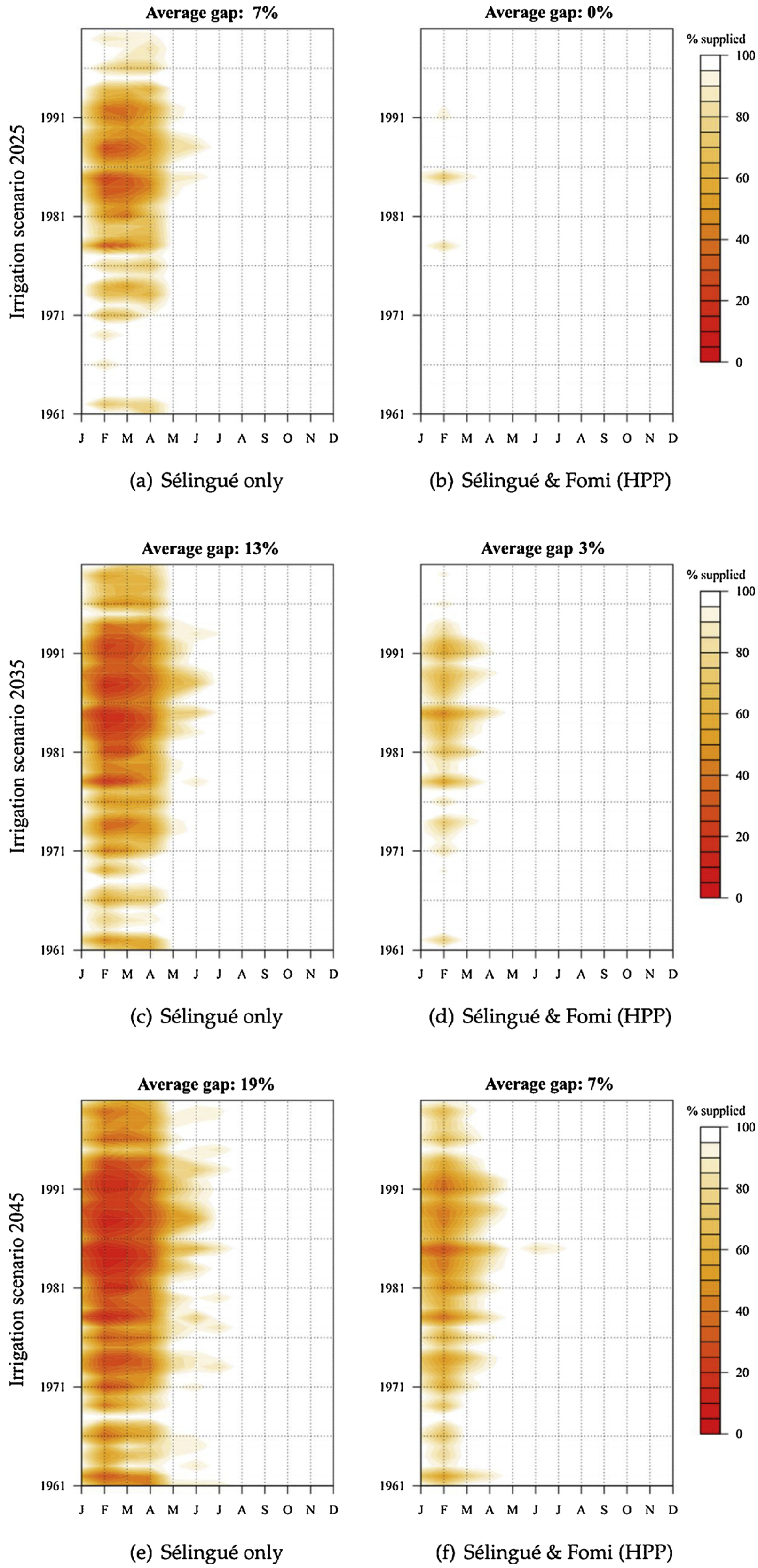
In case the Fomi dam is operated to prioritise hydropower production (HPP scenario), discharge in the low flow season would be much higher than in the ENV scenario (Fig. 4a). The supply gaps in the OdN irrigation scheme would be nullified, even in extraordinary dry years while respecting minimal flows of 50 m^3/s released at Markala. A corresponding figure for recent irrigation practices (like Fig. 5b) would show no coloured patches at all.

3.3. Feasibility of envisaged irrigation scenarios in Office du Niger

This section analyses the feasibility of the development plans to increase the irrigated area considering two reservoir scenarios. In one scenario it is assumed that only the Sélingué dam is operational (left column in Fig. 6) and in the other scenario the Fomi dam (HPP scenario) is operational in addition to the Sélingué dam (right column in Fig. 6). Table 2 shows average supply gaps for dry-season and wet-season irrigation.

In dry periods comparable to conditions prevailing in the late 1970s and 1980s, only 40% of the water demand could be supplied in February and March in the 2025 irrigation scenario (Fig. 6a). The Fomi dam would almost eradicate those gaps, see Fig. 6b. Only in extraordinary dry years, irrigation deficits of about 20% can be expected in February while the supply gaps averaged over the entire simulation period are < 1%.

Irrigation practices would be compromised in the 2035 irrigation scenario between January and April if only the Sélingué dam is operational (Fig. 6c). Only in wet periods comparable to some years in the 1960s, the demand may be fully met in the dry season. In very



(caption on next page)

Fig. 6. Monthly irrigation supply (gaps) in the Office du Niger irrigation scheme for expansion and intensification scenarios for the periods 2025 (top), 2035 (middle), and 2045 (bottom).

dry periods, comparable to the 1980s, only 20% of the irrigation demand would be supplied. If the Fomi dam (HPP scenario) is operational in addition, dry-season irrigation would be feasible in wet and average years with an average supply gap of 5% over the entire period.

In the 2045 irrigation scenario, average deficits in the low flow season were simulated to be 36.5% and in almost half of the years only 20% of the demand would be supplied if only the Sélingué dam is operational (Fig. 6e). Noticeable is also that in the wet 1960s, an average supply gap of about 40% would occur between January and March. Even with an additional Fomi dam, the increased dry-season discharge would not satisfy the high irrigation demands in most of the years (Fig. 6f). However, the Fomi dam would reduce the supply gap averaged over the entire simulation period from 19% (Sélingué only) to 7%. Irrigation demands in the high flow season could theoretically be satisfied in all scenarios.

3.4. Impacts of management scenarios on inflows into the Inner Niger Delta

3.4.1. Niger River (gauge Ké-Macina)

Fig. 7 shows the individual impact of single management components (irrigation only, Sélingué only, and Fomi HPP only) on discharge at Ké-Macina. Figs. 8 and 9 illustrate their combined impacts. Note that the changes in Figs. 7 and 8 are expressed in relative terms and the values are therefore higher in the low flow season although absolute changes would be smaller than in the high flow season. Fig. 9 shows absolute changes. All scenarios show that reservoir operations reduce annual inflows and peak discharge into the IND and alter the natural flow regime. Depending on the water demand of the irrigation scenario, average annual discharge at Ké-Macina is reduced substantially.

On a long-term annual average, the irrigation withdrawals in OdN in 2005 reduces the discharge at Ké-Macina by 7% (Fig. 7a). The highest relative changes are simulated between January and June where discharge is reduced by at least 50% in most of the years. In the high flow season, discharge is reduced by 5–10% on average, where in very dry years the irrigation demand can correspond to about 20%.

Both dams show a similar impact by decreasing discharge in the high flow season up to 10% and increasing discharge in the low flow season on average by 10% and more than 200% as maximum values (Figs. 7b and c). Only in the low flow season, the larger storage capacity of Fomi is visible by releasing larger volumes than the Sélingué dam and therefore increasing low flows to a greater extent. Due to evaporative and seepage losses from the reservoirs, average annual discharge at Ké-Macina decreases by 3% (Sélingué) and 4% (Fomi). Table S7 shows the simulated water balance variables of the reservoirs.

Assuming irrigation withdrawals corresponding to the year 2005, the managed discharge is higher than natural flows in the low flow season between February and June and lower in the rest of the year (Fig. 8a and e). Both dams compensate the current irrigation withdrawals, which is not the case in the 2025 irrigation scenario with only the Sélingué dam operating (Fig. 8b). In the 2035 and 2045 irrigation scenarios, there is not a single month where discharge is higher than under natural flow conditions (Figs. 8c and d). The scenarios including the Fomi dam show basically a similar behaviour, except there is always a short period around May where the discharge is relatively higher compared to natural flows (Fig. 8g and h).

As is shown in Fig. 9a, land and water management has a large impact on peak discharge in September. Under current management practices (irrigation scenario 2005 and Sélingué only), the average discharge at Ké-Macina in September is reduced by 540 m^3/s, which corresponds to a reduction of 14%. An additional Fomi dam (HPP) would reduce September discharge by another

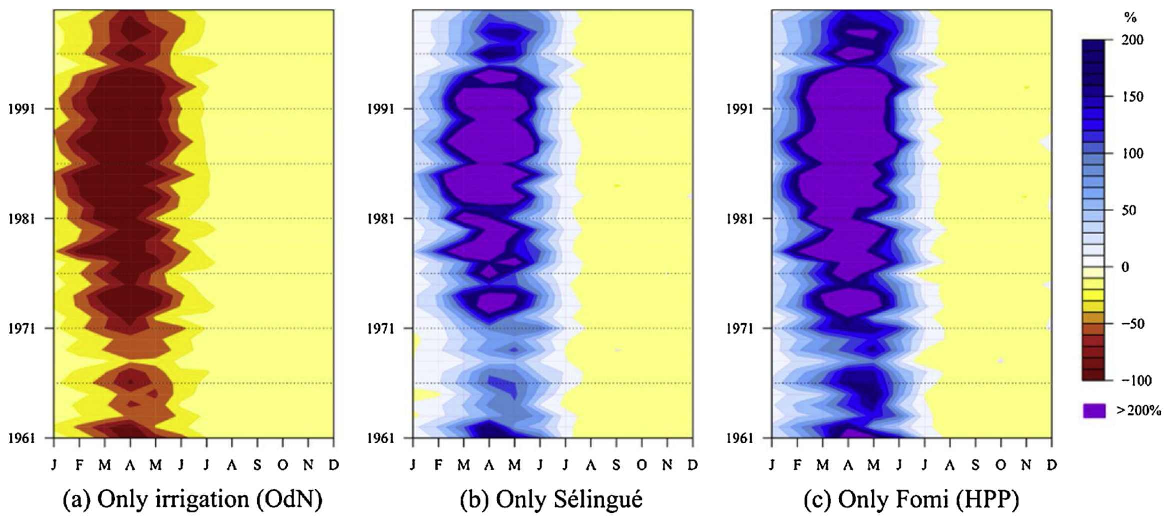


Fig. 7. Relative changes of monthly discharge of single management components at Ké-Macina compared to natural flow simulation.

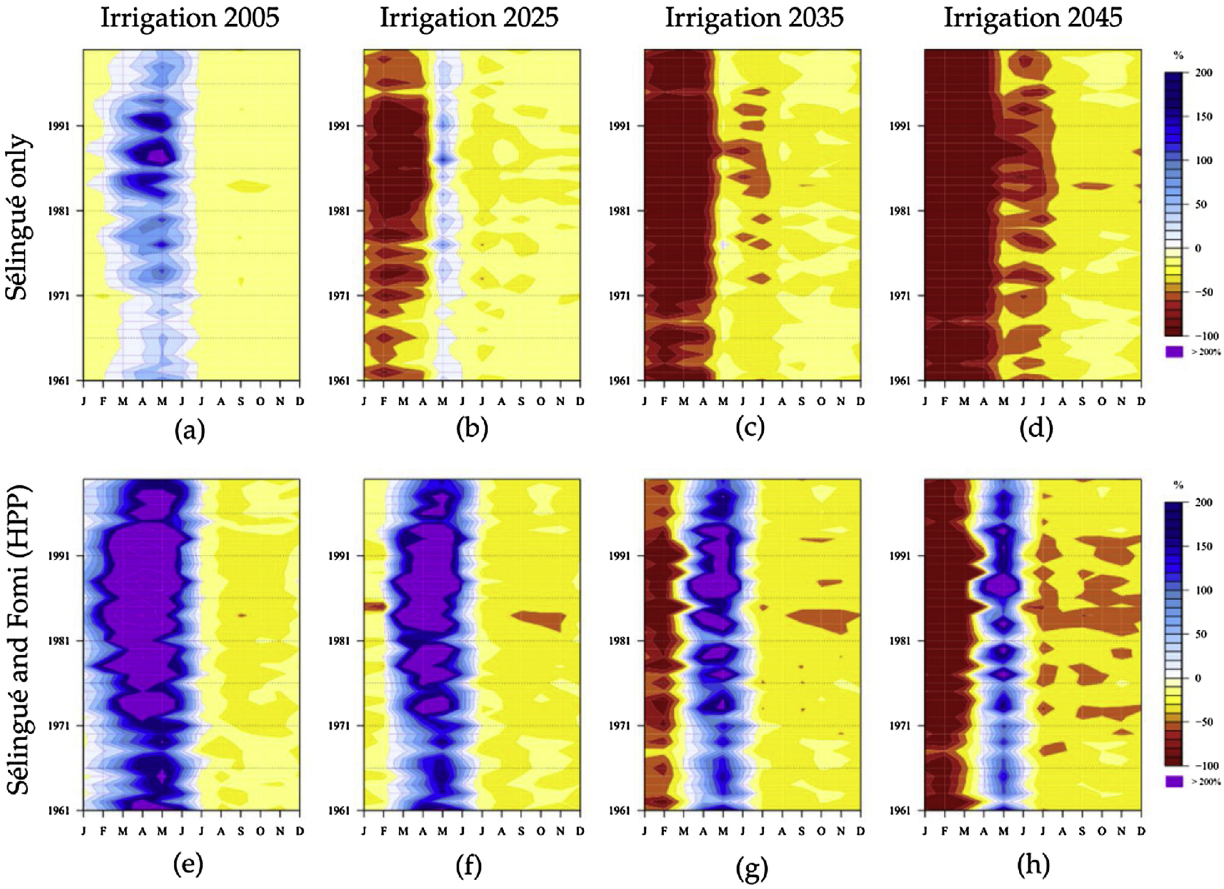


Fig. 8. Relative changes of monthly discharge at Ké-Macina compared to natural flow. In top row (a–d) only the Sélingué dam is operational. In bottom row (e–h) both Sélingué and Fomi (HPP) dams are operational. From left to right are the four irrigation scenarios.

390 m^3/s leading to a total reduction of 24%. The latter is comparable to a situation where irrigation demands correspond to the 2045 irrigation scenario with the Sélingué dam in operation (Fig. 9b). With an additional Fomi dam (HPP), the September discharge would be reduced by 1300 m^3/s or by 34% on average. If one subtracts the 1300 m^3/s from average September discharge, the flood peaks would be reduced to a level of the second driest year in the period 1961–2000.

Compared to simulated natural flows, the current water management (irrigation scenario 2005 and Sélingué dam) reduces the long-term annual average discharge at Ké-Macina by 10%. An additional Fomi dam would lead to a total reduction of 14% (Table S6, which also shows the impacts on high flow (Q_{10}) and low flow (Q_{90}) indicators.

3.4.2. Bani River (downstream Djenné)

The long-term average annual discharge of the Bani River (˜300 m^3/s) contributes approximately 21% to the total inflows into the IND. Compared to the Sélingué and Fomi dams in the Niger River, the storage capacities of the Talo and Djenné dams are with 0.1 Bm^3 and 0.36 Bm^3 relatively small. Their simulated evaporative and seepage losses are also rather small and amount to 1.8% (Talo) and 5.2% (Djenné) of their total inflows (Table S7). The Talo dam is not far upstream of the Djenné dam and since both dams are either switched on or off in the simulations, the Talo dam is slightly impacting the results of the Djenné dam. The relative total losses of 5.2% of the Djenné dam represent therefore the combined losses of both dams. Land and water management impacts in the Bani River basin may, although reducing peak discharge, play a subordinate role regarding the IND inflows.

In contrast to the OdN irrigation scheme, where irrigated agriculture is practised throughout the year, irrigation schemes at the Talo and Djenné dams are only supplied from the reservoirs in the high flow season between August and November. However, this period is relevant for the flooding in the IND, since peak flows determine the size of the inundated area.

The irrigation demand estimated for 2025 in the Talo and Djenné irrigation schemes, would account for a reduction of 13% of the Bani River discharge on the long-term annual average. Where the low flows are not impacted at all, high flows (Q_{10}) would be reduced by about 15%. The combined impact of irrigation withdrawals in 2025 and the losses from the Talo and Djenné dams would reduce the long-term average annual inflows from the Bani River into the IND by 18%, reducing the total inflows into the IND by another 4%. The major impact by a decreased discharge from the Bani River occurs in the high flow season between September and November where a reduction of 23% is simulated.

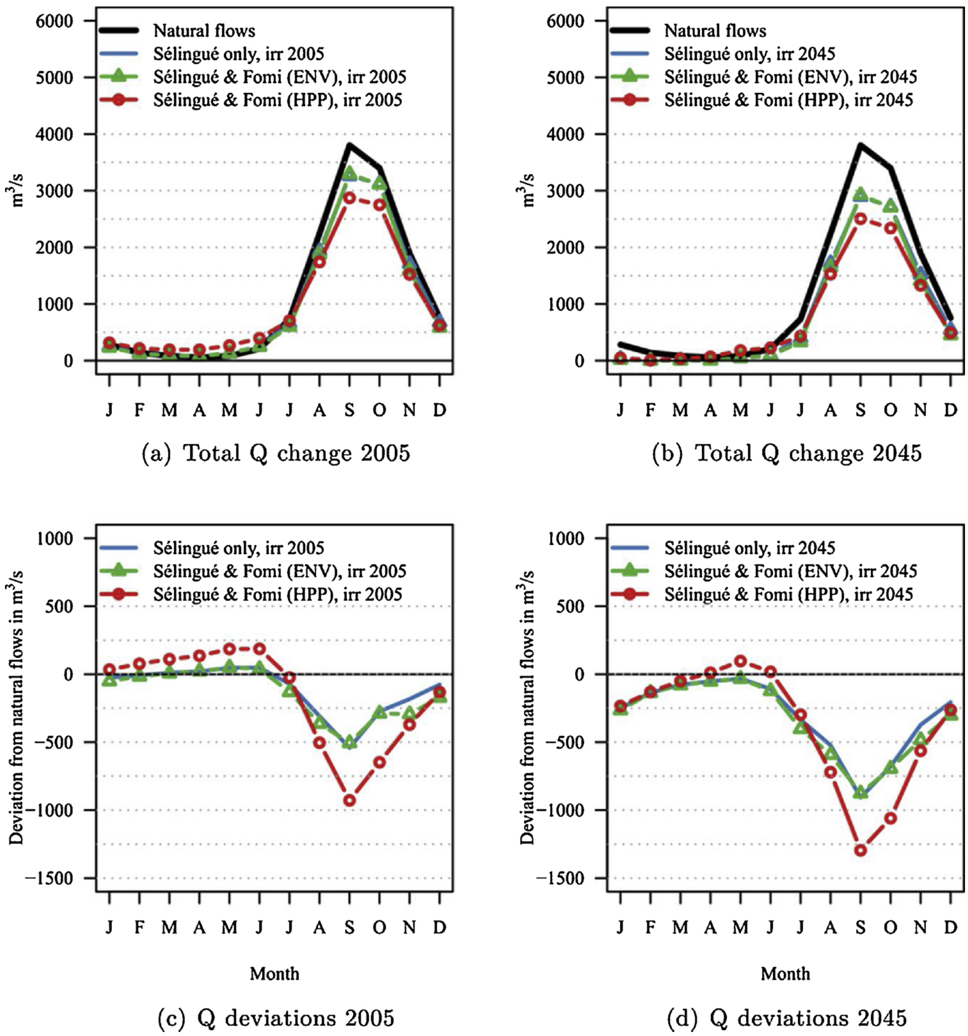


Fig. 9. Total changes of mean monthly discharge and deviations from simulated natural flows at Ké-Macina in the period 1961–2000. Left panel with irrigation withdrawals corresponding to the year 2005 and right panel with irrigation withdrawals corresponding to the year 2045.

3.5. Trade-offs and win-win

Fig. 10 summarises the win-win situation between hydropower production of the two Fomi operation scenarios (including the Sélingué dam) and the irrigation scenarios in OdN, while considering the trade-offs with the inundated area in the IND.

As was discussed in Section 3.2, about 99% of the irrigation demands, referring to the year 2005, are supplied with only the Sélingué dam operational. An additional Fomi dam operated to preserve the natural flows (ENV scenario) would not change this situation, but the supply gaps are nullified with a Fomi dam operated to optimise hydropower production (HPP scenario), as is shown in Fig. 10a. Apart from additional hydropower production, there is therefore no real win-win with irrigation supply. A clear win-win situation can be observed in the future irrigation scenarios (Fig. 10b–d) and the Fomi HPP scenario. In the 2045 irrigation scenario, the average annual irrigation supply increases from about 80% in the ENV scenario to 93% in the HPP scenario while the average hydropower production is with 240 GW h/a (151–357 GW h/a) also much higher and more reliable than in the ENV scenario with an average production of 157 GW h/a (113–218 GW h/a). This win-win situation would be even more pronounced, if hydropower production would be plotted against dry-season irrigation supply instead of average annual supply. The corresponding irrigation supply gap values are shown in Table 2.

Even though the win-win between irrigation supply and hydropower production in the HPP scenario is obvious and would be a clear benefit in the context of the UNBB, the impact on downstream ecosystem services and water users has to be considered. According to the simulations under natural flow conditions, the IND's average maximal inundated area in the period 1961–2000 would be about 15,200 km^2. Both irrigation withdrawals referring to the year 2005 and reservoir storage by the Sélingué dam have decreased the average maximal inundated area by about 7% (14,144 km^2). An additional Fomi dam (HPP scenario) would shrink the inundated area by another 5% to a total reduction of 12% (13,434 km^2). The irrigation scenarios would contribute to a total reduction of 16% in 2025, 18% in 2035, and 21% in 2045 (see Table 3). The level of reduction of the maximal inundated area per year is

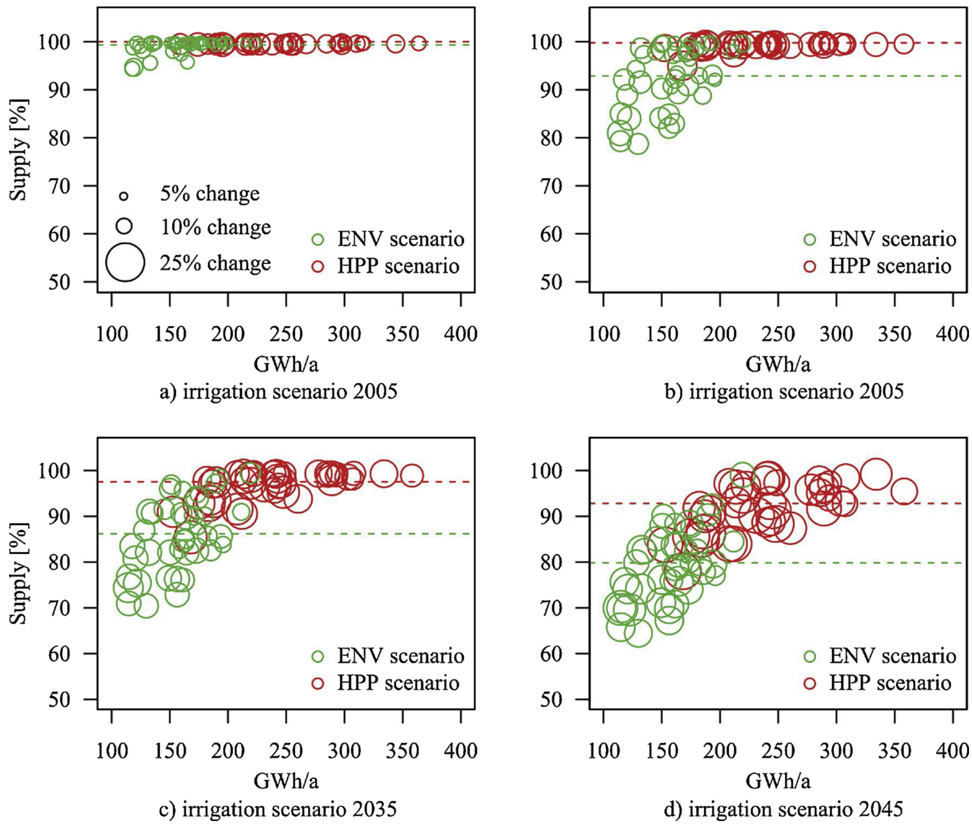


Fig. 10. Trade-offs and win-win between irrigation supply, hydropower production at Fomi, and reduction of September inflows into the Inner Niger Delta. Each circle represents one year (1961–2000) and the circle sizes denote the reduction of September inflows, the larger the circle the larger the reduction. Dashed lines indicate the average irrigation supply as percentage of demand.

qualitatively indicated by the circle sizes in Fig. 10, where the larger the circles the higher the reduction and therefore the higher the trade-off between management scenario and inundated area in the IND. The circles in the HPP scenario are generally larger than in the ENV scenario, denoting a larger impact on the inundated area and thus on ecosystem services provided by the IND. The impacts in dry years are relatively higher than in wet years. It is important to mention that the IND's ecosystem integrity does not only rely on discharge peaks, which are important for the maximal flood extent. It also depends on the general dynamics of the flow regime like the timing of the discharge peak as well as on a distinctive low flow season.

4. Discussion and conclusions

Countries in the UNBB rank very low on the worldwide scale in terms of the human development index (UNDP, 2016) and food

Table 3
Scenario impact on the inundated area in the IND in km^2 and relative change (Fomi scenarios).

Scenario	min	max	average
Natural flows	9518 km^2	20,103 km^2	15,195 km^2
BAU	8586 km^2 (-10%)	19,103 km^2 (-5%)	14,144 km^2 (-7%)
Fomi ENV			
2005	8418 km^2 (-12%)	19,163 km^2 (-5%)	14,032 km^2 (-8%)
2025	7964 km^2 (-16%)	18,545 km^2 (-8%)	13,455 km^2 (-12%)
2035	7686 km^2 (-19%)	18,154 km^2 (-10%)	13,100 km^2 (-14%)
2045	7386 km^2 (-22%)	17,715 km^2 (-12%)	12,713 km^2 (-17%)
Fomi HPP			
2005	8281 km^2 (-15%)	18,462 km^2 (-8%)	13,434 km^2 (-12%)
2025	7840 km^2 (-20%)	17,850 km^2 (-11%)	12,875 km^2 (-16%)
2035	7564 km^2 (-22%)	17,458 km^2 (-13%)	12,520 km^2 (-18%)
2045	7255 km^2 (-25%)	17,009 km^2 (-15%)	12,120 km^2 (-21%)

BAU = Business as usual (Sélingué dam and irrigation scenario 2005).

security (GFSI, 2017), while the population is projected to double by mid-century (UN-DESA, 2017). Hence, socio-economic development is crucial and requires the utilisation of natural resources. The management of natural resources aiming at sustainable intensification in the UNBB needs to consider various aspects related to transboundary as well as upstream-downstream issues or the cross-sectoral trade-offs along the climate-water-food-energy nexus. Therefore, trade-offs between developments in the UNBB and food production and ecosystem service-based livelihoods in the IND deserve special attention. Ecosystem integrity of the IND relies on the seasonal flood pulse with certain thresholds for discharge in the dry season and flood peaks and flood duration in the wet season. Both are jeopardised by current and planned upstream land and water management activities as well as by the drying trend in the Sahel observed since the late 1960s.

4.1. Uncertainties

Dai et al. (2004) state that the decreased rainfall in the last three decades of the 20th century represents the largest recent observed climate change of any region. According to Biasutti (2013), CMIP5 GCMs do not reproduce the amplitude of observed oscillations at multidecadal timescales and rainfall projections for the Sahel are less robust than the 20th century hindcast. Thus, rainfall change signals projected by global and regional climate models in the Sahel are highly uncertain, which is underlined by the Figs. S2, S3, and S4 in the Supplement. Where Held et al. (2005) states that a dramatic 21st century drying trend should be considered seriously as a possible future scenario, Schewe and Levermann (2017) argue that there is a possibility of an abrupt intensification of rainfall under future climate change.

Due to the above mentioned uncertainties and the need for accurate precipitation input, the irrigation and reservoir operation scenario simulations were based on 40 years of historical weather data from the years 1961 to 2000. This period captures the recent rainfall variability quite well with periods above (1960s) and below (1980s) the 20th century average rainfall. The last occurrence of an extremely wet decade was in the 1950s, about 70 years ago. This period has not been considered in this study, because an important basis of the gridded climate dataset (Weedon et al., 2011) is the ERA40 reanalysis product that starts in September 1957 only (Uppala et al., 2005). A limitation of not applying climate change scenarios is that increasing air temperature and its impact on water demand for irrigation and water availability due to higher evapotranspiration rates from land and water surfaces is neglected. We are aware that this would put additional pressure on, e.g., crop productivity, human health or the feasibility of irrigation expansion. A simple analysis revealed that simulated discharge at Ké-Macina would decrease by 1.5% and 2.8% if 1 °C or 2 °C are added to the daily temperature time series, respectively. This gives an indication how changes in temperature only may influence actual evapotranspiration.

The assessment of the feasibility of plans to expand irrigated agriculture in the UNBB and its impacts on the downstream flow regime is based on globally available data, such as daily climate data from a gridded dataset, observed discharges, land use and soil maps, and on published data to parameterise irrigation and reservoir operation scenarios (e.g. reports, development plans, environmental impact assessments). We found contradicting information on water use efficiency, crop rotations, reservoir properties etc. Therefore, management data used in this study have to be treated with caution as the data vary from one reference to another. Such inconsistencies are a source of uncertainties in application-oriented impact assessment studies. Other unknown variables are related to the management itself as it is not clear how the dams will be managed, how fast the irrigated area will increase or if the minimal flow threshold at Markala will be respected or not. Employing scenarios is therefore a useful approach to capture the range of possible future pathways based on uncertain input data.

4.2. Hydropower production

A small Fomi dam with a storage capacity of 2.4 Bm^3, operated to largely preserve the natural flow regime (ENV scenario), could produce 40.5 MW hydro-electric power on average between July and November, but either no or only very little in the dry season. The average production corresponds to 18.4 MW (157 GW h/a). To guarantee electricity production throughout the year, such an electricity system could be complemented by hybrid solar and/or wind power generators, contributing to a more sustainable and stable energy mix.

A large Fomi dam with a storage capacity of 5.3 Bm^3, operated to optimise hydropower production (HPP scenario), could produce 28 MW (240 GW h/a) on an annual average with a firm yield of 16 MW with an exceedance probability of 90%.

4.3. Feasibility of agricultural development and impacts on inflows into the Inner Niger Delta

The high seasonality of the Niger and Bani River discharges requires separate assessments of the feasibility of development plans for the dry (December to May) and the wet season (June to November). Assuming hydro-climatic conditions comparable to the period 1961–2000, the Niger River provides naturally enough water to theoretically supply the demands in the wet season even in the 2045 irrigation scenario with an area of ˜460,000 ha. Hertzog et al. (2012) assume for instance that the Niger River provides theoretically enough water to irrigate one million hectares. However, water withdrawals for dry-season cropping are already at a limit today, particularly in dry years. It should be noted that current dry-season water demands in OdN would not sufficiently be supplied without the existing Sélingué dam, which increases the discharge between January and June. Under dry hydro-climatic conditions comparable to the late 1970s or 1980s, supply gaps would amount up to 80% without this dam. Hence, a further extension in the dry season can only be achieved by either reducing the water demands per area or by increasing river discharge. A provision of higher dry-season discharge can only be realised by the construction of a new dam in the Niger headwaters, which is already planned since decades and was prioritised as a key infrastructure in the Shared Vision and Sustainable Development Plan for the Niger (NBA, 2007).

According to Hertzog et al. (2012) and Vandersypen et al. (2006), the gravity-based irrigation system, over-dimensioned tertiary canals, minimal efforts in managing the OdN irrigation scheme, and the abundance of water in the wet season lead to low efficiencies in water use. Vandersypen et al. (2006) state that the operation of the irrigation network is inadequate and water use is unsustainable, because guidelines and procedures for operation are not followed in practice. This leads to avoidable losses due to excess water delivery and a permanent filling of secondary canals. Where crop demands in OdN are estimated to be about 1000 mm/a, the supply is in the order of 2000–2500 mm/a (Hertzog et al., 2012). In theory, under an optimised water management, the same amount of water would either reduce the estimated supply gaps in the irrigation scenarios or may contribute to an extension of the irrigated area. In practice, this would involve costly investments, e.g., for advanced irrigation techniques, maintenance of irrigation canals, or water pumping to achieve equality in water supply over the whole irrigation scheme. A realistic quantification of the impact of improved water use efficiency is difficult and requires local knowledge and detailed data on the irrigation canal network, water control practices, crop calendar etc., and was therefore beyond the scope of this study.

The expected impacts of a new dam depend primarily on its storage volume and operation rules for impoundment and release. It was found that a smaller dam with a storage capacity of 2.4 Bm^3, operated to largely preserve the natural flow regime (ENV scenario), does not support an extension of dry-season cropping in OdN, because dry-season discharges would be comparable to those today. Harvest losses could be substantial in dry years already in the 2025 irrigation scenario, where supply gaps of up to 60% are simulated in February and March. Such a dam would result in rather low trade-offs with downstream ecosystems, while supporting irrigation in adjacent areas. The impact on the discharge peak arriving at Ké-Macina before entering the IND in September would be negligible, provided that withdrawals for irrigation are on a today level. The reduction of the average maximal inundated area in the IND caused by an additional dam (ENV scenario) and current withdrawals is only 1% compared to the current state.

An additional large dam with a storage capacity of 5.3 Bm^3 operated to optimise hydropower production (HPP scenario) is expected to have a substantial impact on the flow regime. Such a dam would have the potential to increase the low flows in the dry season from about 20 m^3/s to about 100-200 m^3/s at its outlet, thereby enabling the irrigation extension plans in OdN envisaged for the years 2025 and 2035. However, in 2035 supply gaps between 20–40% can be expected in dry years, which would certainly lead to considerable yield losses. An extension of the OdN irrigation scheme as is planned for the year 2045 would be compromised in many years during the dry season where the average supply gap over the entire simulation period between January and March is 30% and can be as large as 60% in extraordinary dry years. Where current irrigation and reservoir operations reduce the average annual Niger discharge by about 10%, the 2045 irrigation scenario in combination with the large dam may reduce the average discharge by a third, compared to natural flows. Current management practices reduce the peak discharge, essential for inundation processes in the IND, already by 500 m^3/s in September. In the 2045 irrigation scenario, the average discharge peak may decrease by about 1300 m^3/s, thereby reducing September discharge of an average year to the level of the second driest year observed in the period 1961–2000. It is not surprising but noticeable that the impact of irrigation and reservoir operations are relatively lower in wet decades, like in the 1960s, than in dry decades, like in the 1980s. Likewise is the decrease of flood dynamics and its associated impacts much higher in dry years. In the 2045 irrigation scenario, for instance, the water demand would correspond to 50% of discharge in the year with lowest discharge and to 19% in the year with highest discharge in the entire simulation period.

In addition to the reduction of Niger River discharge, the recently built Talo and Djenné dams and adjacent irrigation schemes in the Bani River basin are further shortening the water resources in the IND by another 4%. On average, the reduction between September and November amounts to about 23% compared to natural flows. Adding this share to the reduction of peak inflows from the Niger River in 2045 (34% in September), a total reduction of the discharge peak of about 40% can be expected.

A strongly altered hydrological regime would have large negative impacts on the inundated area in the IND, not only leading to severe shrinking of the wetland ecosystem but also jeopardising its integrity. Discharge reductions, like in the 2045 irrigation scenario would compromise the IND's potential to yield fish, fodder, and rice and hence reduce livelihood options for many inhabitants. The year 1984, the driest year in the simulation period, is often used to illustrate the destructive forces of such conditions, which led to mass animal deaths and famines. Situations comparable to the year 1984 with an inundated area below 9000 km^2 occurred once between 1961 and 2000 but may occur twice under the 2035 and 2045 irrigation and HPP scenarios. The threshold of 10,000 km^2 was undercut twice in the simulation of the past but in seven years in the 2045 irrigation and HPP scenario. The large dam (HPP scenario) under current irrigation management would reduce the average maximal inundated area by 5% compared to current conditions. Together with irrigation withdrawals in 2045, the inundated area would experience an average reduction of 14% compared to the current situation, which corresponds to a total reduction of 21% compared to natural conditions. Coyne and Bellier (2009) assume that the large dam would reduce the area by 10%, BRL and DHI (2007) estimate a reduction of 14%, and AECOM (2017) a reduction between 8–12%. A direct comparison among these studies is extremely difficult, because different time periods, modelling approaches, and assumptions on dam characteristics have been used, which are not always transparently reported. However, compared to the other studies, it seems that our estimations underestimate the impact of the Fomi dam on the average maximal inundated area.

Minimising or even losing the IND's ecosystem services would create tremendous costs, not only from a monetary perspective, which have to be taken into consideration in the development of management plans in the UNBB. Not investing in improved water use efficiency today but relying on increased dry-season discharge from a new dam would only postpone several issues that have to be tackled in the long-term anyway, such as meeting sustainable development goals, meeting the food production for the growing population in future etc. Studies investigating trade-offs and synergies from an economic and/or ecosystem service perspective, considering the different management scenarios addressed here, would provide crucial information for decision making.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2018.12.006.

References

Abdelhadi, A., Hata, T., Tanakamaru, H., Tada, A., Tariq, M., 2000. Estimation of crop water requirements in arid region using Penman–Monteith equation with derived crop coefficients: a case study on Acala cotton in Sudan Gezira irrigated scheme. Agric. Water Manag. 45, 203–214. https://doi.org/10.1016/S0378-3774(99)00077-3.
AECOM, 2017. Actualisation de l'étude d'impact environnemental et social du barrage à buts multiples de Fomi en Guinée, Phase 1:, « Scoping » pour déterminer la configuration du barrage de Fomi. Commissionné par Ministère de l'Agriculture, Direction Nationale du Génie Rural, Rapport provisoire de la Phase 1 Novembre 2017.
Aich, V., Liersch, S., Vetter, T., Huang, S., Tecklenburg, J., Hoffmann, P., Koch, H., Fournet, S., Krysanova, V., Müller, E.N., Hattermann, F.F., 2014. Comparing impacts of climate change on streamflow in four large African river basins. Hydrol. Earth Syst. Sci. Discuss. 18, 1305–1321. https://doi.org/10.5194/hess-18-1305-2014.
Aich, V., Liersch, S., Vetter, T., Andersson, J.C.M., Müller, E.N., Hattermann, F.F., 2015. Climate or land use?—attribution of changes in River Flooding in the Sahel Zone. Water 7 (6), 2796–2820. https://doi.org/10.3390/w7062796.
Aich, V., Liersch, S., Vetter, T., Fournet, S., Andersson, J.C., Calmanti, S., van Weert, F.H., Hattermann, F.F., Paton, E.N., 2016. Flood projections within the Niger River Basin under future land use and climate change. Sci. Total Environ. 562, 666–677. https://doi.org/10.1016/j.scitotenv.2016.04.021.
Archer, D.R., Forsythe, N., Fowler, H.J., Shah, S.M., 2010. Sustainability of water resources management in the Indus Basin under changing climatic and socio economic conditions. Hydrol. Earth Syst. Sci. Discuss. 14, 1669–1680. https://doi.org/10.5194/hess-14-1669-2010.
Bartholomé, E., Belward, A., 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. Int. J. Remote Sens. 26, 1959–1977. https://doi.org/10.1080/01431160412331291297.
Biasutti, M., 2013. Forced Sahel rainfall trends in the CMIP5 archive. J. Geophys. Res. Atmos. 118, 1613–1623. https://doi.org/10.1002/jgrd.50206.
BRL (Ingéniérie BRL), 2007a. Assessment of Water Abstraction and Requirements for the Niger Basin Simulation Model. Niger Basin Authority Executive Secretary., Niamey, Niger.
BRL (Ingéniérie BRL), 2007b. Inventory of Dams (existing, Being Studied or Envisaged). Niger Basin Authority Executive Secretary, Niamey, Niger.
BRL (Ingéniérie BRL), Betico, 2016. Projet d'Accroissement de la Productivité Agricole au Mali, Étude du programme d'aménagement hydroagricole de la zone Office du Niger, Rapport provisoire de Phase 4. Ministère de l'Agriculture de la république du Mali, Bamako, Mali.
BRL (Ingéniérie BRL), DHI, 2007. Establishment of a Water Management Model for the Niger River Basin, Final Report. Niger Basin Authority Executive Secretary, Niamey, Niger.
BRL (Ingéniérie BRL), GEF, 2012. Study of Elaboration of an Action Plan for the Sustainable Development of the Niger Basin, Phase 2: Master Plan for the Development and Management, Revised Version, Annex: Assessment of Water Abstraction and Requirements for the Niger Basin Simulation Model. Niger Basin Authority Executive Secretary, Niamey, Mali.
CIESIN, 2016. Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals. Center for International Earth Science Information Network Columbia University, NASA Socioeconomic Data and Applications Center (SEDAC)https://doi.org/10.7927/H4SF2T42.
Cook, K.H., Vizy, E.K., 2006. Coupled model simulations of the west african monsoon system: twentieth- and twenty-first-Century simulations. J. Climate 19, 3681–3703. https://doi.org/10.1175/JCLI3814.1.
Coyne and Bellier, 2009. Projet d'aménagement du barrage de Fomi, étude d'impact environnemental et social, rapport provisoire. Niger Basin Authority Executive Secretary / Ministère des Mines, de l'Energie et de l'Hydraulique de la république du Mali, Niamey / Bamako, Niger / Mali.
Dai, A., Lamb, P.J., Trenberth, K.E., Hulme, M., Jones, P.D., Xie, P., 2004. The recent Sahel drought is real. Int. J. Climatol. 24, 1323–1331. https://doi.org/10.1002/joc.1083.
Dolo, M., Sako, M.A., Diarra, S., 2005. Evaluation de la contribution socio-économique de la pèche au PIB et au développement rural au Mali. Edition de l' Organisation des Nations Unies pour l'Agriculture et la Pêche, FAO.
FAO, 2011. The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing Systems at Risk. Food and Agriculture Organization of the United Nations.
FAO (FAO/IIASA/ISRIC/ISSCAS/JRC), 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria [dataset].
Fomi directorate, 2017. Direction Generale du projet d'amenagement du barrage a buts multiples de Fomi. Projet de dévelopment des ressources en eau et de gestion durable des ecosystems. PDREGDE APL1-Volet Guinée. Mission d'assistance à la mise en oeuvre du 6 au 0 mars 2017.
GFSI (Global Food Security Index), 2017. Measuring Food Security and the Impact of Resource Risk. The economist intelligence unit (Accessed 4 April 2018). http://foodsecurityindex.eiu.com/.
Giannini, A., 2010. Mechanisms of climate change in the semiarid african sahel: the local view. J. Climate 23, 743–756. https://doi.org/10.1175/2009JCLI3123.1.
Hargreaves, G., Hargreaves, G., Riley, J., 1985. Irrigation water requirements for Senegal River Basin. J. Irrig. Drain. Eng. 111 (3). https://doi.org/10.1061/(ASCE)0733-9437(1985)111:3(265).
Hattermann, F.F., Vetter, T., Breuer, L., Su, B., Daggupati, P., Donnelly, C., Fekete, B., Flörke, F., Gosling, S.N., Hoffmann, P., Liersch, S., Masaki, Y., Motovilov, Y., Müller, C., Samaniego, L., Stacke, T., Wada, Y., Yang, T., Krysnaova, V., 2018. Sources of uncertainty in hydrological climate impact assessment: a cross-scale study. Environ. Res. Lett. 13 (1), 015006. https://doi.org/10.1088/1748-9326/aa9938.
Held, I.M., Delworth, T.L., Lu, J., Findell, K.L., Knutson, T.R., 2005. Simulation of Sahel drought in the 20th and 21st centuries. Proc. Natl. Acad. Sci. U. S. A. 102 (50), 17891–17896. https://doi.org/10.1073/pnas.0509057102.
Hertzog, T., Adamczewski, A., Molle, F., Poussin, J.C., Jamin, J.Y., 2012. Ostrich like strategies in sahelian sands? Land and water grabbing in the Office du Niger, Mali. Water Alternat. 5 (2), 304–321.
Hulme, M., 2001. Climatic perspectives on Sahelian desiccation: 1973-1998. Global Environ. Chang. 11, 19–29. https://doi.org/10.1016/S0959-3780(00)00042-X.
Jarvis, A., Reuter, H., Nelson, A., Guevara, E., 2008. Hole-filled Seamless SRTM Data V4. International Centre for Tropical Agriculture (CIAT). srtm.csi.cgiar.org (Accessed 12.10.2016).
Keita, N., Bélières, J.F., Sidibé, S., 2002. Extension de la zone aménagée de l'Office du Niger. In: Orange, D., Arfi, R., Kuper, M., Morand, P., Poncet, Y. (Eds.), Gestion Intégrée Des Ressources Naturelles En Zones Inondables Tropicales., ird éditions. pp. 929–952.
Koch, H., Liersch, S., Hattermann, F., 2013. Integrating water resources management in eco-hydrological modelling. Water Sci. Technol. 67 (7), 1525–1533. https://doi.org/10.2166/wst.2013.022.
Koch, H., Selge, F., de Azevedo, J.R.G., da Silva, G.N.S., Siegmund-Schultze, M., Hattermann, F.F., 2018a. Reconciling ecology and reservoir operation: options for the sub-middle and Lower São Francisco River basin, Brazil. Ecohydrology. https://doi.org/10.1002/eco.2026. (online available).
Koch, H., Silva, A.L.C., de Azevedo, J.R.G., Souza, W.M., Köppel, J., Souza Júnior, C.B., Barros, A.M.L., Hattermann, F.F., 2018b. Integrated hydro- and wind power generation: a game changer towards environmental flow in the Sub-middle and Lower São Francisco River Basin? Reg. Environ. Change 18, 1927–1942 DOI:10.1007/s10113-018-1301-2[dataset].

Koch, H., Selge, F., de Azevedo, J.R.G., da Silva, G.N.S., Siegmund-Schultze, M., Hattermann, F.F., 2018c. Reconciling ecology and reservoir operation: options for the sub-middle and Lower São Francisco River basin, Brazil. Ecohydrology. https://doi.org/10.1002/eco.2026. (online available).
Krysanova, V., Hattermann, F., Wechsung, F., 2005. Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. Hydrol. Process. 19 (3), 763–783. https://doi.org/10.1002/hyp.5619.
Krysanova, V., Hattermann, F., Huang, S., Hesse, C., Vetter, T., Liersch, S., Koch, H., Kundzewicz, Z.W., 2015. Modelling climate and land use change impacts with SWIM: lessons learnt from multiple applications. Hydrol. Sci. J. Des Sci. Hydrol. 60 (4), 606–635. https://doi.org/10.1080/02626667.2014.925560.
Kuper, M., Hassane, A., Orange, D., Chohin-Kuper, A., Sow, M., 2002. Régulation, utilisation et partage des eaux du fleuve Niger. In: Orange, D., Arfi, R., Kuper, M., Morand, P., Poncet, Y. (Eds.), Gestion Intégrée Des Ressources Naturelles En Zones Inondables Tropicales, ird éditions. pp. 411–430.
Liersch, S., Koch, H., Aich, V., Reinhardt, J., Fournet, S., Hattermann, F.F., 2012. Constraints of future freshwater resources in the Upper Niger Basin – has the human-environmental system of the inner Niger Delta a chance to survive? In: Seppelt, R., Voinov, A., Bankamp, D. (Eds.), Managing Resources of a Limited Planet. International Congress on Environmental Modelling and Software (iEMSs).
Liersch, S., Cools, J., Kone, B., Koch, H., Diallo, M., Reinhardt, J., Fournet, S., Aich, V., Hattermann, F.F., 2013. Vulnerability of food production in the Inner Niger Delta to water resources management under climate variability and change. Environ. Sci. Policy 34, 18–33. https://doi.org/10.1016/j.envsci.2012.10.014.
Liersch, S., Koch, H., Hattermann, F.F., 2017. Management Scenarios of the Grand Ethiopian Renaissance Dam and Their Impacts Under Recent and Future Climates. Water 9 (10). https://doi.org/10.3390/w9100728. 24p.
Liersch, S., Tecklenburg, J., Rust, H., Dobler, A., Fischer, M., Kruschke, T., Koch, Hattermann, F.F., 2018. Are we using the right fuel to drive hydrological models? A climate impact study in the Upper Blue Nile. Hydrol. Earth Syst. Sci. Discuss. 22 (4), 2163–2185. https://doi.org/10.5194/hess-22-2163-2018.
Lobanova, A., Koch, H., Liersch, S., Hattermann, F.F., Krysanova, V., 2016. Impacts of changing climate on the hydrology and hydropower production of the Tagus River basin. Hydrol. Process. 30 (26), 5039–5052. https://doi.org/10.1002/hyp.10966.
Lobanova, A., Liersch, S., Tàbara, J.D., Koch, H., Hattermann, F.F., Krysanova, V., 2017. Harmonizing human-hydrological system under climate change: a scenario-based approach for the case of the headwaters of the Tagus River. J. Hydrol. 548, 436–447. https://doi.org/10.1016/j.jhydrol.2017.03.015.
Marie, J., Morand, P., N'Djim, H., 2007. L´Avenir du fleuve Niger, ird éditions. - Collection : IRD Éditions, Expertise collégiale, Paris.
MEME (Ministère de l'Energie, des Mines et de l'Eau), 2007. Plan d'Action National de Gestion Intégrée des Ressources en Eau. République du Mali, Bamako, Mali.
Monerie, P.-A., Sanchez-Gomez, E., Pohl, B., Robson, J., Dong, B., 2017. Impact of internal variability on projections of Sahel precipitation change. Environ. Res. Lett. 12, 114003. https://doi.org/10.1088/1748-9326/aa8cda.
NBA (Niger Basin Authority), 2007. Sustainable Development Action Plan (SDAP) for the River Niger Basin. Synthesis of the Report. Niger Basin Authority, Executive Secretariat, Niamey, Niger.
Observatoire, 2018. Flood Dynamics Inner Niger Delta. Accessed 15.11.2018. http://www.onisdin.org/.
Ogilvie, A., Mahé, G., Ward, J., Serpantié, G., Lemoalle, J., Morand, P., Barbier, B., Diop, A.T., Caron, A., Namarra, R., Kaczan, D., Lukasiewicz, A., Paturel, J.-E., Liénou, G., Clanet, J.C., 2010. Water, agriculture and poverty in the Niger River basin. Water Int. 35 (5), 594–622. https://doi.org/10.1080/02508060.2010.515545.
Ogilvie, A., Belaud, G., Delenne, C., Bailly, J.-S., Bader, J.-C., Oleksiak, A., Ferry, L., Martin, D., 2015. Decadal monitoring of the Niger Inner Delta flood dynamics using MODIS optical data. J. Hydrol. 523, 368–383. https://doi.org/10.1016/j.jhydrol.2015.01.036.
RH (Royal Haskoning), GID, ISADES, 2007. Plan d'action Guinée-Mali pour la gestion intégrée des ressources en eau du bassin du Niger supérieur. Ministère de l'Hydraulique et de l'Energie (MHE) / Ministère de l'Energie, des Mines et de l'Eau (MEME), République de Guinée / République du Mali, Conakry / Bamako, Guinée / Mali.
RH (Royal Haskoning), Altenburg & Wymenga ecologisch onderzoek, GID, 2010. Etat des lieux du Delta Intérieur, -vers une vision commune de développement-. Ministère de l'environnement et de l'assainissement, République du Mali, Bamako, Mali.
Rowell, D.P., Senior, C.A., Vellinga, M., Graham, R.J., 2015. Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? Clim. Change 134, 621–633. https://doi.org/10.1007/s10584-015-1554-4.
Schewe, J., Levermann, A., 2017. Non-linear intensification of Sahel rainfall as a possible dynamic response to future warming. Earth Syst. Dyn. Discuss. 8, 495–505. https://doi.org/10.1073/pnas.1312330110.
Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Ziese, M., 2015. GPCC Full Data Reanalysis Version 7.0 at 0.5°: Monthly Land-Srface Precipitation From Rain-Gauges Built on GTS-based and Historic Data. DWDhttps://doi.org/10.5676/DWD_GPCC/FD_M_V7_050. [dataset].
Schüttrumpf, R., Bökkers, T., 2008. Analyse du potentiel d'irrigation lors de la saison sèche dans la zone de l'Office du Niger. L´Office du Niger, Ministère de l'agriculture, République du Mali, Bamako, Mali.
Tractebel, 2017a. Actualisation de la Faisabilité Relative aux Travaux d'Aménagement du Barrage de Fomi sur le Haut Niger (Phase 1), Rapport sur le Dimensionnement des Ouvrages Aménagement de Moussako. Commissionné par Ministère de l'Agriculture – Direction Nationale du Génie Rural, République de Guinée, P.010186 RP-2-001-Volume 4b rév.00.
Tractebel, 2017b. Rapport de l'étude hydrologique (P.010186 RP-2-001-Volume 1a rév.01). Actualisation de la faisabilité relative aux travaux d'aménagement du barrage de Fomi sur le Haut Niger (Phase 1). 114pp. .
Turner, A., Sperber, K., Slingo, J., Meehl, G.A., Mechoso, C., Kimoto, M., Giannini, A., 2011. Modelling monsoons: understanding and predicting current and future behaviour. In: In: Chang, C., Ding, Y., Lau, N., Johnson, R., Wang, B., Yasunari, T. (Eds.), The Global Monsoon System., vol. 5. World Scientific Series on Asia-Pacific Weather and Climate. World Scientific, pp. 421–454. https://doi.org/10.1142/9789814343411_0025.
UN-DESA, 2017. United Nations Department of Economic and Social Affairs. Population Division. World Population Prospects: The 2017 Revision (Accessed 9 March 2018). https://esa.un.org/unpd/wpp/.
UNDP, 2016. Human Development Report 2016. Human Development for Everyone. United Nations Development Programme, New York, USA.
Uppala, S.M., KÅllberg, P.W., Simmons, A.J., et al., 2005. The ERA-40 re-analysis. Q. J. R. Meteorol. Soc. 131, 2961–3012. https://doi.org/10.1256/qj.04.176.
Vandersypen, K., Bengaly, K., Keita, A.C., Sidibe, S., Raes, D., Jamin, J.-Y., 2006. Irrigation performance at tertiary level in the rice schemes of the Office du Niger (Mali): Adequate water delivery through over-supply. Agr. Water Manage. 83, 144–152.
Vetter, T., Huang, S., Aich, V., Yang, T., Wang, X., Krysanova, V., Hattermann, F., 2015. Multi-model climate impact assessment and intercomparison for three large-scale river basins on three continents. Earth Syst. Dyn. Discuss. 6 (1), 17–43. https://doi.org/10.5194/esd-6-17-2015.
Vetter, T., Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F.F., Huang, S., Koch, H., Pechlivanidis, I.G., Plötner, S., Seidou, O., Krysanova, V., 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. Clim. Change 141 (3), 419–433. https://doi.org/10.1007/s10584-016-1794-y.
Weedon, G.P., Gomes, S., Viterbo, P., Shuttleworth, W.J., Blyth, E., Österle, H., Adam, J.C., Bellouin, N., Boucher, O., Best, M., 2011. Creation of the WATCH Forcing Data and its use to assess global and regional reference crop evaporation over land during the twentieth century. J. Hydrometeorol. 12, 823–848. https://doi.org/10.1175/2011JHM1369.1.
You, L., Ringler, C., Nelson, G.C., Wood-Sichra, U., Robertson, R.D., Wood, S., Guo, Z., Zhu, T., Sun, Y., 2010. What Is the Irrigation Potential for Africa? IFPRI. http://www.ifpri.org/publication/what-irrigation-potential-africa.
Zwarts, L., 2010. Le Delta Intérieur du Niger s´assèchera-t-il du fait du changement climatique et de l'utilisation de l'eau en amont? A&W rapport 1556. Altenburg & Wymenga ecologisch onderzoek, Feanwâlden, Netherlands.
Zwarts, L., van Beukering, P., Kone, B., Wymenga, E. (Eds.), 2005. The Niger, a Lifeline. Effective Water Management in the Upper Niger Basin. RIZA, WI, IVM, Altenburg & Wymenga Ecologisch Onderzoek, The Netherlands.