uOttawa

Faculté de génie
Faculty of Engineering

Hydrological Impacts of Irrigation Schemes and Dams Operation in the Upper Niger Basin and Inner Niger Delta.

Thesis presented by:

Fatoumata Maiga

Thesis Supervisor: Dr. Seidou Ousmane

Submission date: February 17th, 2019.

Abstract

The Upper Niger Basins (UNB) and the Inner Niger Delta (IND) are integral parts of the Niger River Basin, which flows through 10 countries and constitutes the third longest river in Africa. Natural climate variability and human interventions are two major factors affecting the hydrological regime in the UNB and IND. This study focuses on the later factor, by assessing the hydrological impacts of key existing and planned manmade structures and irrigation schemes in the UNB: the Sélingué (existing dam in Mali), four variants of the Fomi/Moussako dam (planned in Guinea), and Office du Niger (irrigation scheme located in Mali). The Fomi /Moussako dam will be located in the headwaters of the UNB and therefore, is expected to alter the hydrological regime in large parts of the watershed. Expected impacts include a reduction of the flood peak which will adversely affect critical ecosystems in the IND, and higher flows directly downstream of the dams in the dry season to sustain irrigation. These higher flows will, however, be consumed by Office du Niger irrigation scheme, leading to possible severe water shortages downstream of the irrigation scheme and in the IND. This is likely to affect the Malian economy and the poorest parts of its population, as the IND is crucial for the socio-economic and ecological preservation and development of the population surrounding it. The hydrological impacts of the dams and the irrigation scheme were evaluated in this study by developing a model of the IND and UNB using SWAT (Soil and Water Assessment Tool). After the model was calibrated, the effects of the dams and the irrigation scheme on selected flow statistics (mean and standard deviation) were determined at fourteen hydrological stations. In general, the results have shown that (1) the Fomi/Moussako dam will noticeably reduce the downstream high flows, and reduce the average flow; (2) if the Fomi/Moussako dam was to be built, the alternatives with the least storage volume (Moussako 388.5') will have the least impacts on the downstream flows. To assist in related decision making for various users, a Decision Support System (DSS) was also developed. The goal of the DSS is to help users analyze the effects of dams and irrigation on the flow regime by performing a comparative analysis (presence and absence of dams and irrigation in the river). A number of potential adaptation measures were also proposed.

Contents

List of Figures

List of Tables

Chapter 1 - Background and Objectives

1.1. The Inner Niger Delta and the Upper Niger Basin

The Inner Niger Delta (IND) and the Upper Niger Basin (UNB) are part of the Niger River basin (Figure 1), the third longest river in Africa. The Niger River watershed has a total area of 2.262 million Km^2 and flows through 10 African countries starting in Guinea, where the river headwater is located, then flows 4100 km into the Atlantic Ocean in coastal Nigeria. The majority of the river is located in Nigeria, Mali, and Niger with respectively 25.7%, 25.5% and 24.8% of the total area. Over 1 million people depend on the Niger River resources. The Inner Niger Delta is a large floodplain located on the edge of the Sahara Desert (Mali) and is one of the world most productive temporary wetlands.

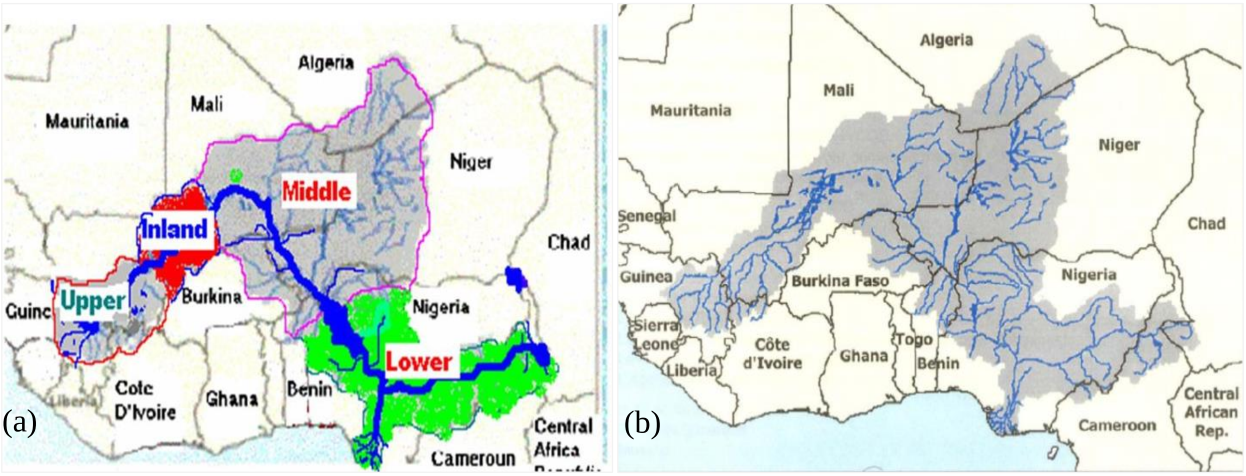


Figure 1: The Niger River Basin. It originates from Guinea and Ivory Coast then runs through Mali, Niger, and Nigeria where it pours into the Atlantic Sea. The river tributaries extend over Burkina Faso, Benin, Algeria, Cameroon, and Chad. a) Retrieved from *https://slideplayer.com/slide/723926/*. b) Reprinted from: Al-Gamal et al. (2009).

The IND climate is dry most of the year and the wet season usually expands from July to September/October, leading more water availability water. Figure 2 shows the average monthly flow for the IND and UNB hydrological stations for up to 50 years of observation (1961 to 2010). The communities surrounding the IND depend mainly on the agriculture and fishing culture. The wetland provides natural resources and livelihoods for over 10 % of Mali’s population and 80% of Mali fish production. The wetland also produces food for about 40% of the country’s cattle (Liersch et al, 2018; RH et al., 2010).

The two main factors affecting the IND and the UNB hydrological regimes are human-made structures and natural climate variabilities. Climate change, presumed to be one of the most direct consequences of global warming is exerting considerable influence on the water cycle driven by hydrological changes. During the great drought in the early eighties, the Sélingué dam was thought to be the cause of the diminishing water level in the delta each year. Later on, water shortage and flooding have shown to be the consequences of enormous seasonal variation in rainfall and river flow. The climate projections for the Niger River Basin suggest that the climate would be warmer during all months and drier during the rainy months (Oguntunde et al, 2012). The hot and dry climate in the area surrounding the IND is a major problem that has caused drought in the region multiple times.

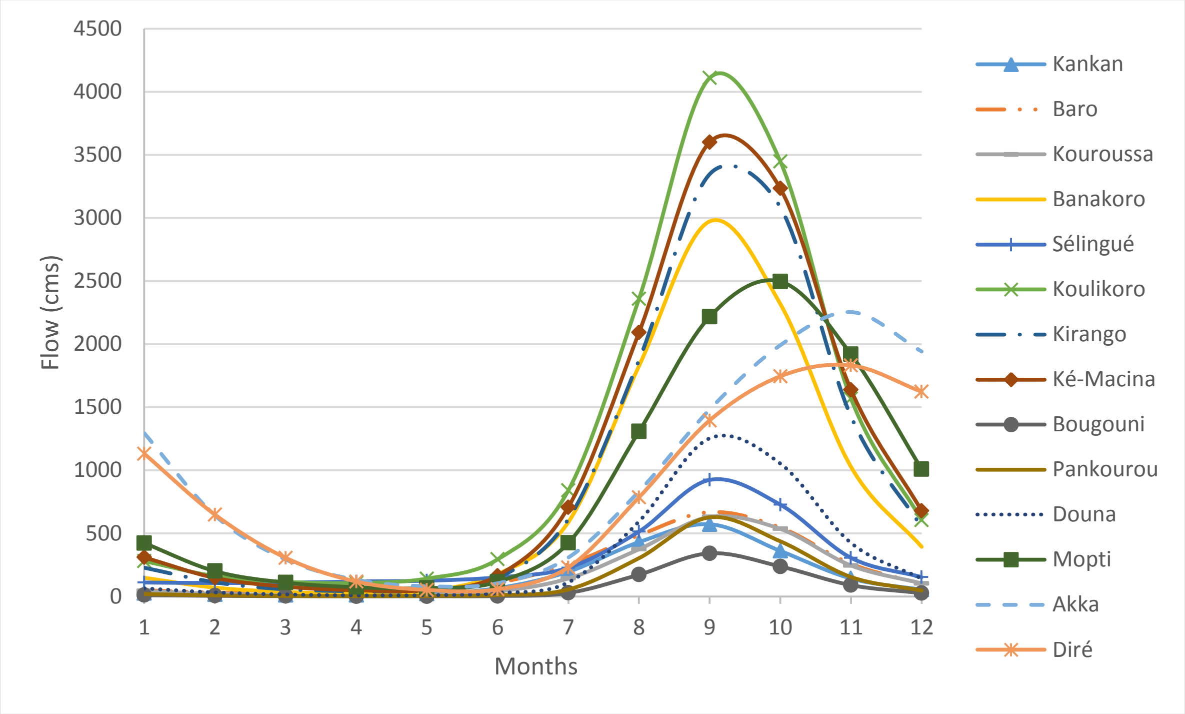
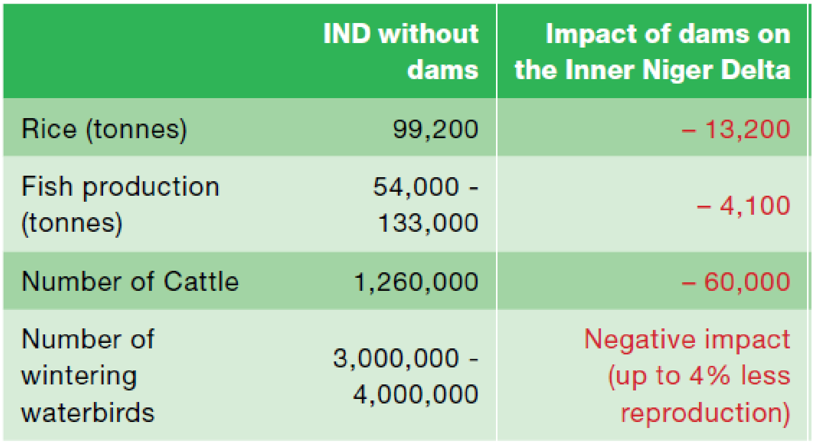


Figure 2: The UNB and IND Average Monthly flow (up to 50 years of observations).

Besides climate change, the Sélingué dam and a large-scale irrigation scheme called Office du Niger (alimented by the Markala dam), also have an important impact on the hydrology of IND (social, economic and environmental benefits). The Office du Niger scheme is located upstream of the IND and occupies around 100,000ha, for a potentially irrigable area of more than 1,000,000ha. The Malian authorities are eager to expand the irrigated area in the future. As in all part of the Sahel, the river flows in Mali have drastically decreased in the 1970-2010 period compared to the 1950-1970 periods. Decreasing precipitation and depleted groundwater reserves are thought to be the main causes, but the Sélingué dam and Office du Niger (OdN) have also contributed to the decrease in mean flow. The upcoming Fomi dam is likely to dive flows even lower. Low flows can lead to restrictions on the water uptake for irrigation. This was the case for about one-third of 2015, 2016 and 2017, where the minimum flow of 40 m^3/s for OdN was not met (Liersch et al, 2018). Consequently, there is a reduction in economic activities such as rice agriculture, cattle raising, and fisheries. These problems could severely affect Mali since it is a river-dependent-economy country.

The alteration in the flow regime (generally toward lower average) and the change in annual cycle is expected to also challenge the integrity of the IND ecosystem, as the inundated area directly relates to the ecosystem services it provides (spawning and nursing of young fishes, growth of grasses like Bourgou used as cattle fodder) (Liersch et al, 2018). Birth population breading 5,000 to 10,000 away is determined by the flooding of the IND (Zwarts, L. et al., 2005). Figure 3 shows how existing dams in the IND affect different sectors (reduce production).



	IND without dams	Impact of dams on the Inner Niger Delta
Rice (tonnes)	99,200	– 13,200
Fish production (tonnes)	54,000 - 133,000	– 4,100
Number of Cattle	1,260,000	– 60,000
Number of wintering waterbirds	3,000,000 - 4,000,000	Negative impact (up to 4% less reproduction)

Figure 3: The impact of the existing dams on the IND. Reprinted from Zwarts et al. (2005).

In addition, the IND cultural diversity is also at risk. For many ethnic groups present in this region, the profession they occupy (farmer, fisherman, herdsmen, traders, etc.) is an integral part of their cultural identity, passed on from generation to generations. Hence, there is a vital need for extreme events within a year (flood and drought) to maintain the integrity of the IND. The planned FOMI/Moussako dam in Guinea and projected increase of irrigated areas in OdN brought many concerns. This last dam and the extension of OdN will most likely alter furthermore the IND hydrological regime, which could lead to disastrous impacts.

1.2. Objectives

The objectives of this study are as follow:

- Determine the impacts of the Sélingué dam (existing), the Fomi/Moussako dam (planned), and the planned irrigation expansion project (by Office du Niger) on the flow regime of the Upper Niger River and Inner Niger Delta;
- Determine the least impactful alternative of the Fomi dam on the flow regime of the Upper Niger River and Inner Niger Delta;
- Develop an open source Decision Support System (DSS) to help various users (technical and non-technical) in decision-making related to the planning of the Fomi dam.

Chapter 2: Water Management Challenges in the IND and UNB

2.1. Presentation of the study area

The area for this study constitutes of the upper part (UNB) and the inner part (IND) of the Niger River. The Upper Niger covers the upstream portion of the Niger River basin, up to the Inner Delta. The IND is located in the semi-arid Sahel area of central Mali and is composed of fluvial wetlands, flood plans, and lakes. The IND is also home to Mali's largest and most important irrigation scheme (OdN). In addition to OdN, the major water users of the UNB and the IND are the Sélingué (a 2.2 km^3 power and irrigation dam, built in 1982 in Mali), Markala (OdN irrigation dam, built in 1947 in Niger), Sotuba (a power and irrigation dam, built in 1929 in Mali), and Talo (a 0.2 km^3 irrigation dam, built in 2006 in Mali).

Ecological importance

In addition to the one million people living in the Delta, the IND is also home to a rich biodiversity composed of fish, birdlife, and small populations of large African mammals and other terrestrial and aquatic wildlife (limited by intensive human exploitation). Most of this population and the biodiversity are dependent on the IND natural resources. The productivity of the resources varies from year to year due to variation in rainfall and flood level. Consequently, there is important depopulation in certain regions of the Delta. A large decrease was observed in the livestock population, which mainly consists of cattle (bovines), sheep (ovine) and goats (caprine). Zwarts et al. (2005) found out that 'the maximum sustainable population of livestock is limited by the availability of Bourgou (grass) in the Inner Delta and thus by the flow' entering into the Inner Delta. Herders migrate with their cattle, and fishermen follow the shifting waterfront. They go after the flood to make optimal use of the variation in productivity in different ecological zones.

The growing population has led to more extensive fishing practices and consequently, fish older than one year have become increasingly scarce in the Inner Delta (Zwarts et al., 2005). The flood level constitutes also a significant factor for fisheries in the Inner Niger Delta. In 2005, about one-third of the 900,000 rural people (Zwarts et al., 2005) in the Inner Delta depended on the fishery for their living. However, fish is not a secure food source in the Inner Delta. Welcomme (1986) studies have shown that' in years with a high flood the catches were three times higher than in years with a low flood' (Zwarts et al., 2005). Zwarts et al. (2005) confirms this finding (Figure 4) by comparing the IND fluctuation in annual fish catch and fluctuation in flood level in the year, at Akka station between 1966 and 2003.

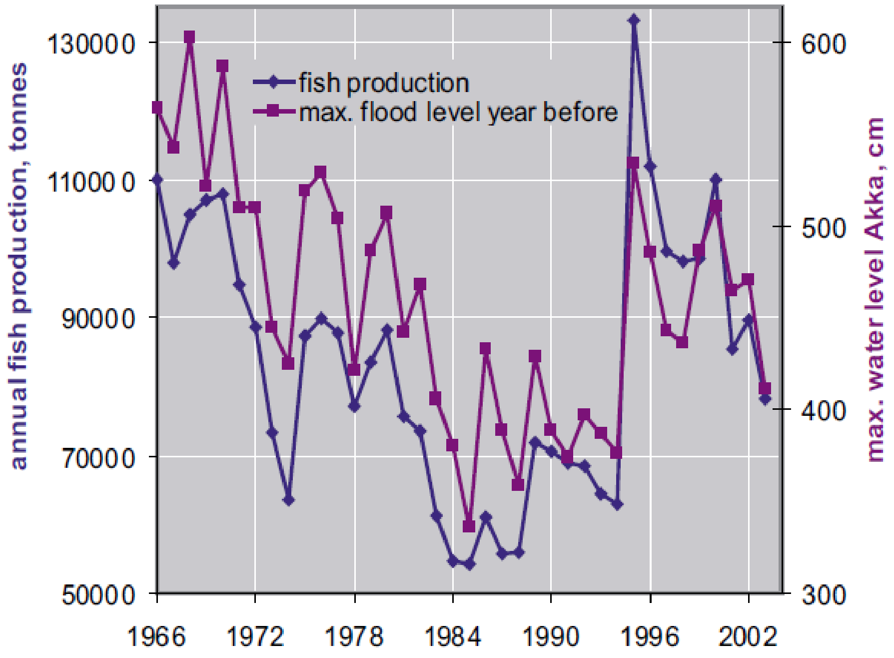


Figure 4: The fluctuation in annual fish catch in the Inner Delta between 1966 and 2003 compared to the fluctuation in flood level (Akka, cm) in the year before. Reprinted from Zwarts et al. (2005).

For the waterbirds, estimated at 3 to 4 million, environmental conditions in the IND play a major role in determining population density. When the flooded area reduces, waterbirds, and other species groups like aquatic living mammals and reptiles, are forced to concentrate around the few remaining wet spots in the Inner Delta. This leads to high feeding densities, large concentrations, and competition with local people. Thus, this puts the ecological values of the Inner Delta at stake. (Zwarts et al., 2005)

Throughout the years, there has been an important decline in the Delta forest cover. The area used to be occupied by extensive forests on the higher grounds and several forests on the lower floodplains. Nowadays, this area is an open landscape with low vegetation of grass, rice, and Bourgou. This green biomass is characterized by a large seasonal variation related to rainfall and flooding. In certain areas, the water depth can reveal the type of vegetation present in the zone.

For instance, Bourgou occurs where water depth exceeds 3m, and wild rice and cultivated rice grow in approximately 2m of water (Zwarts et al., 2005).

Effect of the peak flow on the extent of the IND

The UNB and IND discharge levels are significantly correlated to various factors. These factors include the climate, groundwater aquifers, seasonal variations, and hydrological structures. In the wet season, the Inner Niger Delta flood plan (including tributaries, channels, swamps, and lakes) can reach 30 000 km^2. This size is largely determined by the river discharge, which in turn, depends on local precipitation. Figure 5 shows the UNB and IND average monthly rainfall in the period of 1961-1990. On this last figure, the pic flow happens in the month of August, but it takes additional time for the floodwater to arrive in the IND (usually in September). Figure 6 presents the relationship between local rainfall (Mopti region in Mali) and water level (flood). Thus, Figure 6 demonstrates that limited rainfall is associated with low floods and abundant rainfall is associated with height flood levels in the IND. However, the IND is a very flat area and therefore, its water loss increases with flood level. In other words, evaporation increases when a larger area is flooded.

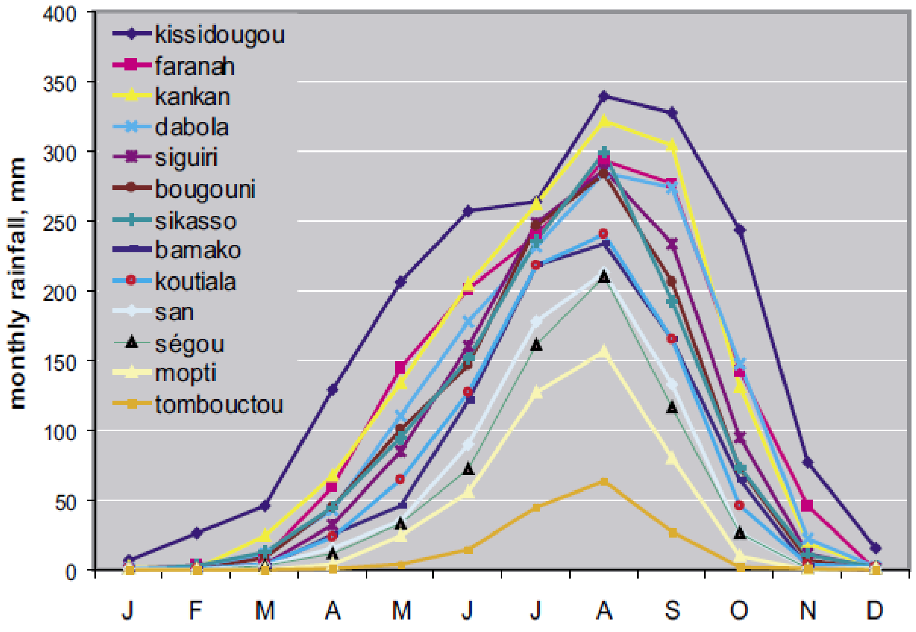


Figure 5: Average monthly rainfall (mm) in the period 1961-1990 at 13 sites situated in the UNB and IND. Reprinted from: Zwarts et al. (2005).

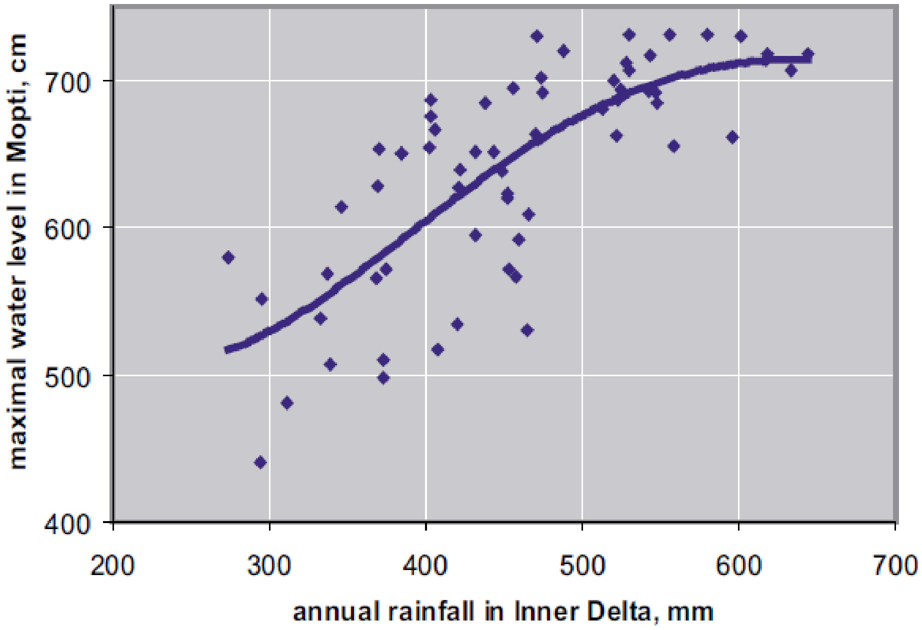


Figure 6: The relationship between local rainfall in the inner delta and the maximum water level in Mopti. Reprinted from: Zwarts et al. (2005).

Anticipated Impacts of Climate Change on the Hydrology of Inner Niger Delta

Climate change is exerting a significant influence on the water cycle driven by hydrological changes. The Niger basin is susceptible to large seasonal and annual variation of rainfall and river flow. Global Circulation Models (GCM) has predicted that the increase in temperature of Africa in the 21st century varies between 0.2°C and 0.5°C per decade (Caminade *et al.* 2006). The warming is expected to be even greater in the Sahel than the overall rate of global warming. Zwarts (2010) stated that the GCMs has predicted ‘rainfall until 2020-2040 at about the same low level as the last twenty years of the 20th century, but will then gradually decrease by about 20% in the next 50-100 years’. This will greatly affect the inundation of IND because a small reduction in rainfall has a large impact on the flood extent as shown in Figure 7.

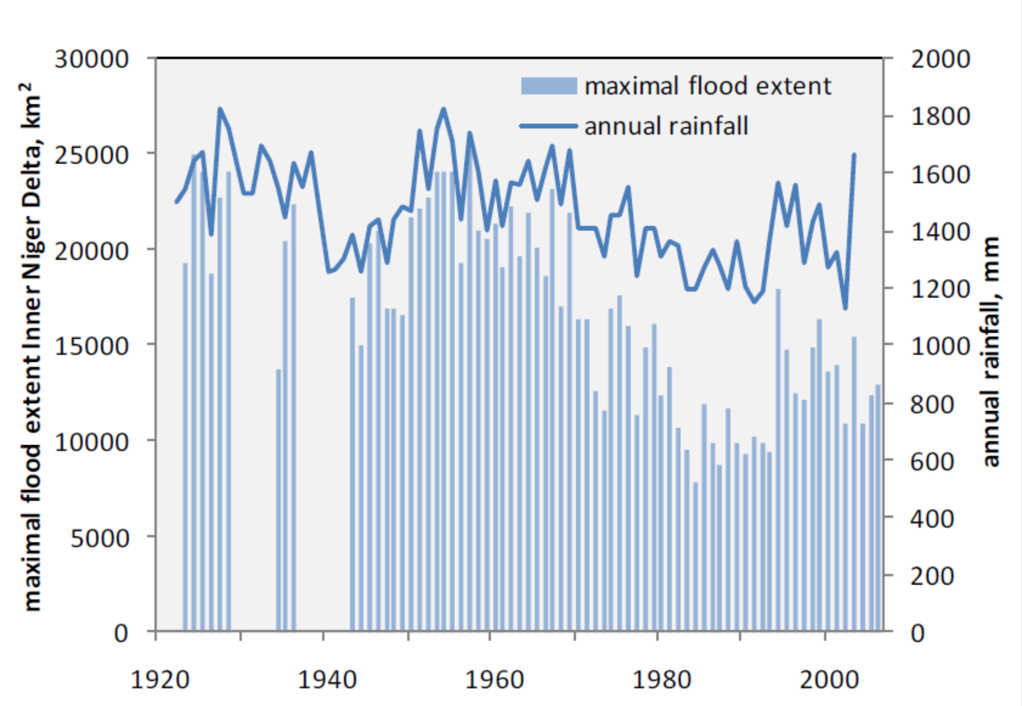


Figure 7: The flood extent of the Inner Niger Delta (columns; left-handed axis) and annual rainfall in the Upper Basin of the Niger. Reprinted from: Zwarts et al. (2010).

A small reduction in rainfall results in a significant drop in the river flow. During the Great Drought, the decline in rainfall was estimated to 20%, leading to a decline in the flood extent of approximately 60%, due to the decline in the river flow of the Niger (50%) and the Bani (80%). Furthermore, a comparison between the inflow of the Niger and the Bani into the Inner Niger Delta and the outflow has shown a large difference, which may be attributed to water loss due to evaporation (Mahé *et al.* 2009).

Liersch et al. used a statistical regional climate model (STAR) in 2013 to project three climate scenarios assuming no temperature increase (0 °C), and temperature increase by 1 °C and 2 °C by 2050. The 1 °C and 2 °C scenarios projected a substantial decrease in rainfall. The projections were pessimistic showing drying future with negative impacts on discharges and spatiotemporal inundation patterns in the IND.

Thompson et al. (2016) investigated GCM-related uncertainty in climate change impacts for the IND using seven GCMs for a 2°C increase in global mean temperature (i.e., the hypothesized threshold of ‘dangerous’ climate change). Their study results have shown a decline in precipitation for most GCMs, and an increase in evapotranspiration for all the scenarios. Consequently, all the GCMs projected a decrease in the river inflows to the Delta except for one

GCM (HadGEM1) that projected a very small increase (3.9%). If the rainfall declined as projected by the hydrological models, the IND flooded area will significantly decrease in the future. Hence, this climate change could result in severe malfunctioning of the ecological and economic systems of IND.

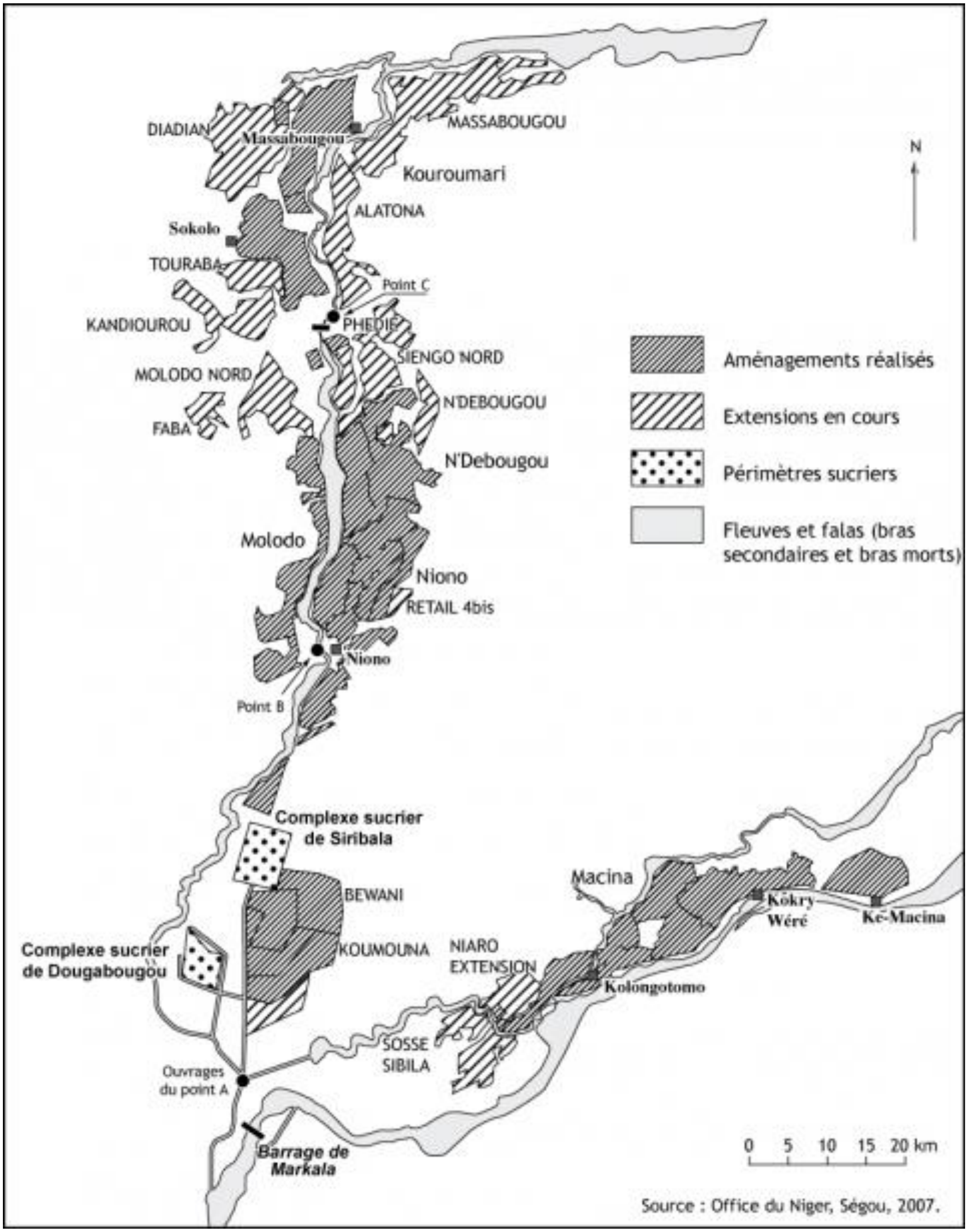
Various studies (Zwarts, 2010; Thompson et al., 2016; Liersch et al., 2013) have predicted divergent precipitation changes in the future based on GCMs. Thus, due to the many uncertainties associated with the study area climate change projections, future climate change was not considered in the present study, but rather, the study focus on the current climate.

Future developments: dams, reservoirs, and irrigation

In terms of future developments, there are three new planned dams and reservoirs in the UNB including the Djenné reservoir, the Tossaye dam and the Fomi Dam. The Djenné will be a small reservoir with a volume of 0.4 km^3, located upstream of the IND. The construction of this last reservoir was proposed in response to the concerns raised by the people living along the Bani (downstream) about the negative impact of water diversion. The Tossaye dam is planned downstream of the IND with a volume of 4.5 km^3. It is intended for hydropower, irrigation, possible feeding of Lac Faguibine (550 km upstream), improvement of navigation, and to ensure a minimum flow of 75 m^3/s to Niger. The Fomi Dam is the largest hydroelectrical dam planned in the UNB (in Guinea), with an approximate volume of 6.4 km^3. The Fomi dam is discussed in more details in section 2.2.

On the other hand, Mali’s rapid population growth is directing the country toward sustainable development goals to prevent long-term food insecurity. This combined with an opportunity of economic profits have drawn the attention of major investors (national and international). Thus, massive investments have been guided towards the extension of OdN irrigated area (Figure 8), which in 2008 produced 500,000 tons of rice corresponding to half of the country’s rice production (Bondeau, F., 2009). The “schéma directeur de développement régional” (regional development master plan) from BCEOM (2001) anticipated an extension of the irrigated area of 120000 hectares by 2020, while the “Sexagon” (main farmers’ union of OdN) evaluated the extension to 360,000 hectares (Brondear, F., 2009). Figure 9 shows the developments and extensions (as of 2007) of OdN.

Figure 8: The Inner Niger Delta and Office du Niger area. Reprinted from: Brondeau, F. (2013).



Source : Office du Niger, Ségou, 2007.

Figure 9: Expansion of Office du Niger. Reprinted from: Brondeau, F. (2009). Legend translation: “Aménagements réalisés” = Completed developments; “Extensions en cours” = Curent extensions; “Périmètres sucriers” = Sugar perimeters; “Fleuves et falas (bras secondaires et bras morts)” = rivers and falas (secondary arms and dead arms).

Challenges linked to the opportunities

The main purposes of hydrological interventions in the Niger (i.e., dams and irrigation schemes) are to increase economic stability, food security, and human well-being. However, using the Niger's flow is not without consequences. Zwarts et al. (2005) envisage a drop of 45 cm in the IND flood level after the planned Fomi dam water impoundment, halving the flooded area.

The average monthly withdrawal carried out for the benefit of the Office du Niger on the flow of the river varies from 3% during floods to 74% in March. In very dry years (ex., 1999), these monthly withdrawals represent almost the entire monthly flow between February and May (Brondear, F., 2009). The extension of OdN will increase the water intake from the Niger River and therefore, suggests an increase in the risk for a seasonal shortage. This shortage entails an inevitable negative impact on the ecosystems as well as on the downstream populations in Mali and in Niger. The extension works of OdN are also associated with an increase in the risk for agricultural pollution and huge costs evaluated between 2,500 and 5,000 euros per hectare (Brondear, 2009). Up-to-date, agricultural pollution is limited, but has been growing for the last several years in certain regions. Brondear (2009) reported that Nitrate traces were found in 14 wells at Niono, out of 48 analyzed (AGEFORE 1998). Thus, there is a constant and increasing pressure on the country authorities to ensure potable drinking water supply for local populations.

Hydrological interventions have in the past required the displacement and relocation of several villages (population and animals); this will most likely be the case for future developments as well.

Zwarts et al. (2005) study has concluded that the Fomi dam will negatively affect the maximum number of livestock in the IND, especially the sheep and goats in Tombouctou, that present a decrease in the average number of animals between 10 to 15%. They also concluded that in the absence of Office du Niger and Sélingué, the number of cattle, sheep, and goats in the regions of Mopti and Tombouctou are expected to increase on average by 4 to 5% per year.

Dams and reservoirs also significantly affect the IND fisheries sector. Zwarts et al. (2005) have estimated the average impact of Office du Niger and Sélingué on fish trade, by establishing the relationship between annual fish trade in Mopti and flood level in the preceding year. The study concluded that OdN reduces fish trade by 6% and the Sélingué reservoir reduces it by an additional 13%. The study also predicted that fish trade would be reduced by another 37% with the Fomi Dam.

2.2. The Sélingué dam, the Fomi/Moussako dam, and Office du Niger

Constructed in 1982 and renovated between 1996 and 2001, the Sélingué embankment dam (Figure 10) is located in the Sankarani River. It is an important center of energy production in Mali with a hydropower capability of 47.6 MW and a reservoir volume of 1.8 Km^3. The reservoir has a spread surface of approximately 34.2 Km² and witnesses an evaporation of about 5 km^3 annually. Between the wet and dry seasons, the hydropower generation from the dam varies considerably due to the losses in volume. Though Sélingué is primarily used for hydropower generation, the Sélingué also supplies agricultural areas nearby with water for irrigation (Liersch et al, 2018; Kuper, 2002), as food production is one the most important components of the sustainable development goals in the region (Liersch et al, 2018). It produces 13 GWh/month of power, 9000 ton of rice, and catches 4000 ton of fish/year in the reservoir (Zwarts, L. et al., 2005).

Figure 10: Sélingué Dam. Reprinted from: https://www.iied.org/files/styles/main-image/public/dam_Lucile_web_0.jpg?itok=f8RTAIQh.

Office du Niger (OdN) is a semi-autonomous government agency in Mali, located upstream of the IND. It was formed in 1932 and rehabilitated in 1992. This irrigation scheme is crucial for Mali's rice production. The area is irrigated through the Markala gravitational dam. It is the largest irrigation schemes in West Africa and currently the largest water user in the Upper Niger.

The water demand becomes nearly that of the natural river flow in the dry season. OdN is supplied with water from the Niger River via a system of canals diverting water from the Markala barrage (Liersch et al, 2018). To irrigate more than 700 km^2 in the "Delta mort", Office du Niger uses 2.7 km^3 of water annually. This is equivalent to 8.3% of total annual river flow (The Niger a lifeline, 2005). OdN produces 320,000 tons of rice per year, which corresponds to 40% of the national consumption and income for 250 000 people (Zwarts, L. et al., 2005). Figure 11 shows a satellite imagery of Office du Niger area.

Figure 11: Office du Niger irrigation scheme in Segou (Mali).

The Fomi dam is a newly planned dam in the Niandan tributary, in Guinea (upper Niger), primarily for electricity production. The Fomi reservoir storage volume is planned to be approximately 2.5 times that of the Sélingué (about 6.4 km^3). The construction of the new dam upstream will presumably affect the downstream users (Office du Niger), leading to the need for new water management rules implementation in OdN and the Sélingué dam. The new dam impacts on the flow will primarily depend on the structure design decision (like the storage volume) and its operating rules. The dam is expected to alter the minimum discharges in the dry season and the flood peaks in the wet season. This alteration will surely affect the IND ecosystem integrity, but could also put at risk the current and planned upstream land (OdN expansion) and water management activities (Liersch et al, 2018). Fomi is expected to produce 26 GWh/month, irrigate 300 km^2 inland, and catch 4000 ton of fish in the reservoir (Zwarts, L. et al., 2005).

As an alternative to the Fomi site, the Moussako dam was considered with three alternative reservoir sizes. The proposed Moussako dam will be located approximately 21.7 km upstream of Fomi, with comparable properties and impacts. Moussako 402 (m.a.s.l), Moussako 396 and Moussako 388.5 are the three alternatives that were proposed for Moussako, with a total volume of 4.9 km^3, 2.8 km^3 and 1.2 km^3, respectively. Figure 12 shows the locations of Fomi and Moussako relative to Sélingué.

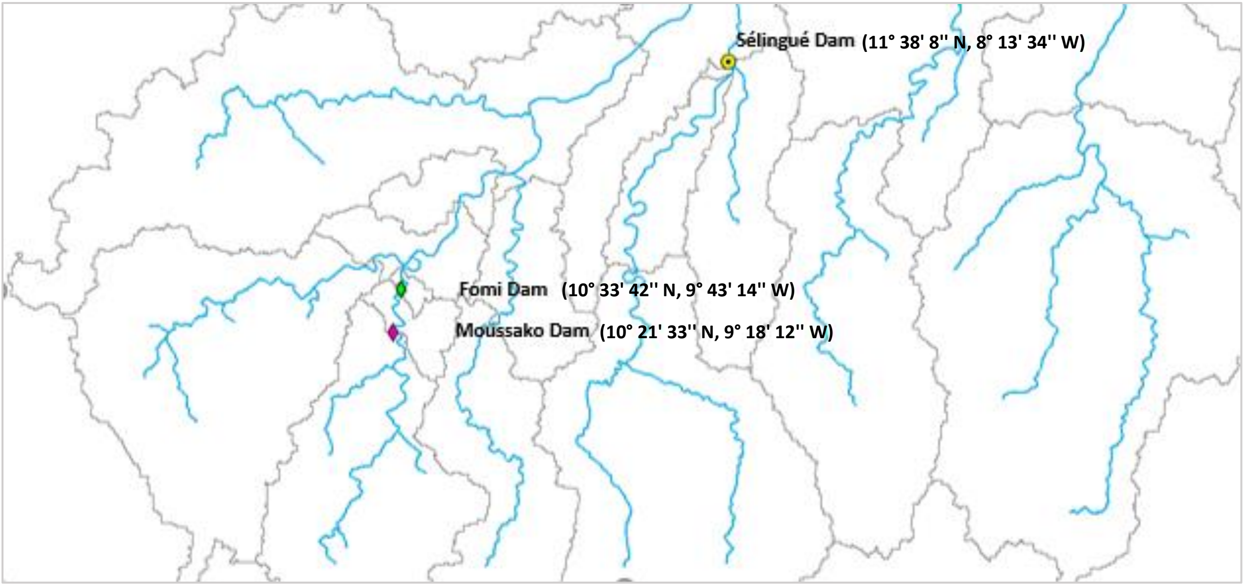


Figure 12: Upper Niger River: Locations of Fomi and Moussako relative to Sélingué.

Chapter 3 – Literature review

3.1. Integrated Water Resources Management (IWRM)

Water is a key natural resource that is critical for the economic and social development of all regions around the world. It plays an important function in maintaining the integrity of the natural environment. However, water-quantity and water-quality problems are increasing worldwide. While fresh water is a finite and vulnerable resource, there is an increasing demand due to demographic and economic growth (ex., agricultural and industrial expansion), especially in third world countries like Mali. Climate change and human interventions are the most significant stressors that influence the global water cycle. It has been reported that over the last 30 years, the average rainfall over Mali's entire territory has decreased by at least 20% compared to the period of previous years (Ministere de l'energie et de l'eau du Mali, 2017). A number of studies (Zwarts, 2010; Thompson et al., 2016; Liersch et al., 2013) have predicted a general decrease in precipitation in the Delta by the end of the current century (i.e., 2100) due to climate change. Paradoxically, climate change has increased precipitation in other areas, putting people who live near rivers and streams more at risk for flooding.

Water scarcity, floods, and pollution are global persisting problems. Two-thirds of the world population faces water scarcity for at least one month every year (Escher et al., 2016). According to the World Resources Institute (Schleifer, 2017), the fifteen countries accounting for 80% of the world population with the greatest exposure to river floods are also the least developed or developing countries, which makes them even more vulnerable to climate change and natural disasters. To fulfill their water need, some countries are extensively using their groundwater resources, which is causing a fast decrease in the groundwater reserves. In India for instance, 54% of the groundwater wells are decreasing because the water is pumped at a dangerously unsustainable rate, faster than it is replenished (Schleifer, 2017). If this continues, India's aquifers will be in a critical condition in the next few decades (Schleifer, 2017). Giant freshwater sources in North America such as Lake Mead (Arizona) and the Colorado River are threatened by drought and pollution; as a result, they may not be able to keep pumping to residents' homes and businesses much longer.

To reduce many water-related problems, water infrastructures (treatment plants, dams, reservoirs, pipes, etc.) have been greatly used and still constitute a long-term solution for many countries. Nevertheless, these human interventions attempting to solve spatiotemporal water problems are not without consequences. Hydrological structures are acknowledged for disturbing and putting at risk the aquatic ecosystem preservation and compromising the comfort and health of populations. In addition to that, there is significant water loss associated with these structures (leakage, infiltration, evaporation). In the United States alone, six billion gallons of treated water is lost every day from leaky pipes (Schleifer, 2017). The construction and reparations costs linked to these massive structures are often considerably more expensive than the cost related to the water lost; therefore, the issues are ignored by many localities.

Hence, there is a need for leaders to adopt a more comprehensive approach to the way this water is managed. To that matter, the development of Integrated Water Resources Management (IWRM) was recommended by water-related-problems experts in the 1992 International Conference on Water and the Environment in Dublin (Ireland). The Global Water Partnership defines IWRM as “a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment.” It incorporates key components such as the management of water resources at the lowest level, the establishment of improved and integrated policy, an equitable access to water resources, supply optimization, meeting water demand, protecting the environment, the support of economical growth and sustainable agricultural development, the improvement of human health, the promotion of democratic participation, and transparency in governance and management. (Global Water Partnership, 2018). The Dublin statement also recognizes that women play a central part in the provision, management, and safeguarding of water. Hence, one of the major fields of focus has been to increase women's involvement in drinking water and sanitation projects, especially in developing countries (IWA, 2018).

IWRM can be summarized in three principles: social equity, economic efficiency, and environmental sustainability. The principles are described as follow.

- Social equity: ensures equal access for all users, particularly marginalized and poorer users group, to an adequate quantity and quality of water necessary to sustain human well being. Water should be allocated considering the benefits gained by all the users. These benefits may include enjoyment of resources through recreational use or financial benefits generated from the use of water for economic purposes.

- Economic efficiency: Maximize benefits to profit the greatest number of users possible, with the available financial and water resources (i.e., selection of the most economically efficient option). In addition to price, the economic value should also consider the current and future social and environmental costs and benefits.
- Environmental sustainability: acknowledge aquatic ecosystems users and make an adequate allocation to sustain their natural functioning. To do so, the land use and developments that negatively affect these systems should be avoided or limited.

(IWA, 2018).

IWRM requires every decision-maker to ask themselves questions such as, “Will my decision result in the most efficient use of the resources?”, “How will my decision affect other water users’ needs and benefits?”, “How will my decision impact the natural systems?”, etc. This process requires a coordinated action from decision-makers across the various sectors that impact water resources. It brings all stakeholders to the table to set policies that devise and implement efficient, equitable and sustainable solutions to water and development problems. However, IWRM implementation is usually not straightforward. Different countries can adopt a slightly different approach to IWRM implementation.

Some important conditions for implementing IWRM include:

- Political will and commitment;
- Basin management plan and clear vision;
- Participation and coordination mechanisms, fostering information sharing and exchange;
- Capacity development;
- Well-defined flexible and enforceable legal frameworks and regulation;
- Water allocation plans;
- Adequate investment, financial stability, and sustainable cost recovery;
- Good knowledge of the natural resources present in the basin;
- Comprehensive monitoring and evaluation.

(IWA, 2018)

In Thailand, IWRM was first endorsed on the national level and then implemented in specific areas. The Chao-Phraya River and the Yom River Basin are two examples of areas in Thailand where IWRM was implemented.

The Chao-Phraya River is considered the most important river in Thailand. It provides water for irrigation and supplies raw water for Bangkok industries and populations; it is considered the rice-bowl of Thailand. The Chao-Phraya River, therefore, carries an enormous economic significance. Rapid industrialization, land conversion, housing development, and urbanization have caused frequent flooding and water shortages in the area, which raised serious concerns about how to manage the basin's water resources more effectively and sustainably.

The Yom River is one of the four tributaries of the Chao-Phraya River, with the least extensively developed water infrastructure of the tributaries. Plans were made for the development of new water infrastructure, which has created emerging disputes between civil society and promoters. IWRM was implemented for these two areas through the following steps:

- A clear and common interpretation of IWRM
- Awareness raising and participatory processes to produce outputs
- Integration of the three key principles of IWRM
- IWRM institutionalization into Government system through highest level endorsement
- Establishment of water ”champions“ to catalyze and pursue the policy and implementation process.

(Anukularmphai, A. 2010)

Yet, not all countries (especially third world countries) dispose of the necessary tools to facilitate the implementation of IWRM. For that matter, the current study developed a Decision Support System (DSS) to facilitate the implementation of IWRM in the UNB and IND. This DSS is specific to the Niger River basins but can be adjusted to reflect other hydrological systems.

3.2. Decision Support Systems in Water Resources Management

Nowadays in water resources management, the interests and goals of numerous stakeholders are involved (Loucks et al., 2017). This makes the decision-making process more complex as it will require negotiation and compromises among the different stakeholders. Using scientific technics, researchers have developed computer-based hydraulics/hydrological models to analyze important aspects of decision-making including economics, ecology, and engineering. However, the transmission of the information generated by these models form the technical to the non-technical stakeholders can be an important challenge. This last challenge has arisen questions such as, How to include multiple optimization objectives that benefit various users into a model? How to efficiently transmit technical information to decision-makers and stakeholders with various background? How to make the results credible to decision-makers to help them select the best design/management alternative? Such questions were addressed in the last few decades through the development and implementation of Decision Support Systems (DSS) (Loucks et al., 2017), that is a computer-based system for problem-solving. In water resources management DSSs are built to support decision makers and stakeholders in decision problems related to the planning and management of the natural resources, cost, environment, and socio-ecosystem. The tool usually develops an analysis based on scientific knowledge and a reliable methodology to help decision makers achieve more robust decisions. The interactive nature of the modeling tool allows the users to have some flexibility with the data inputs, calculations, and outputs. Figure 13 (reprinted from Loucks et al., 2017) shows common components of many decision support systems. Since various decision-makers (experts and non-experts) are involved in the process, a DSS should be user-friendly and require little training and technical background knowledge.

The need for the integration of multiple disciplinary components while considering multiple objectives in water resources management led to the development of a specific category of DSS called “IWRM-DSS” (Integrated Water Resources Management Decision Support System) (Giupponi et al., 2013).

Droubi et al. (2009) developed and applied a DSS for water resources management in two pilot areas: the Zabadani basin in Syria and the Berrechid basin in Morocco. The DSS consisted of a project database, a groundwater flow model (MODFLOW2000) and a water evaluation and planning software (WEAP). The modeling components MODFLOW and WEAP were dynamically linked during the calculations process. The paper states that via the WEAP interface, ‘the users can manipulate inputs and evaluate and compare results of various current as well as future scenarios in the target area, such as human activities (population growth, urbanization, domestic demands); agriculture activities (land use, crop types, irrigation practices); climate impacts (climate change models, regional climate cycles); network characteristics (transmission link losses and limits, well field characteristics, well depths); Additional resources (artificial recharge, wastewater reuse)’.

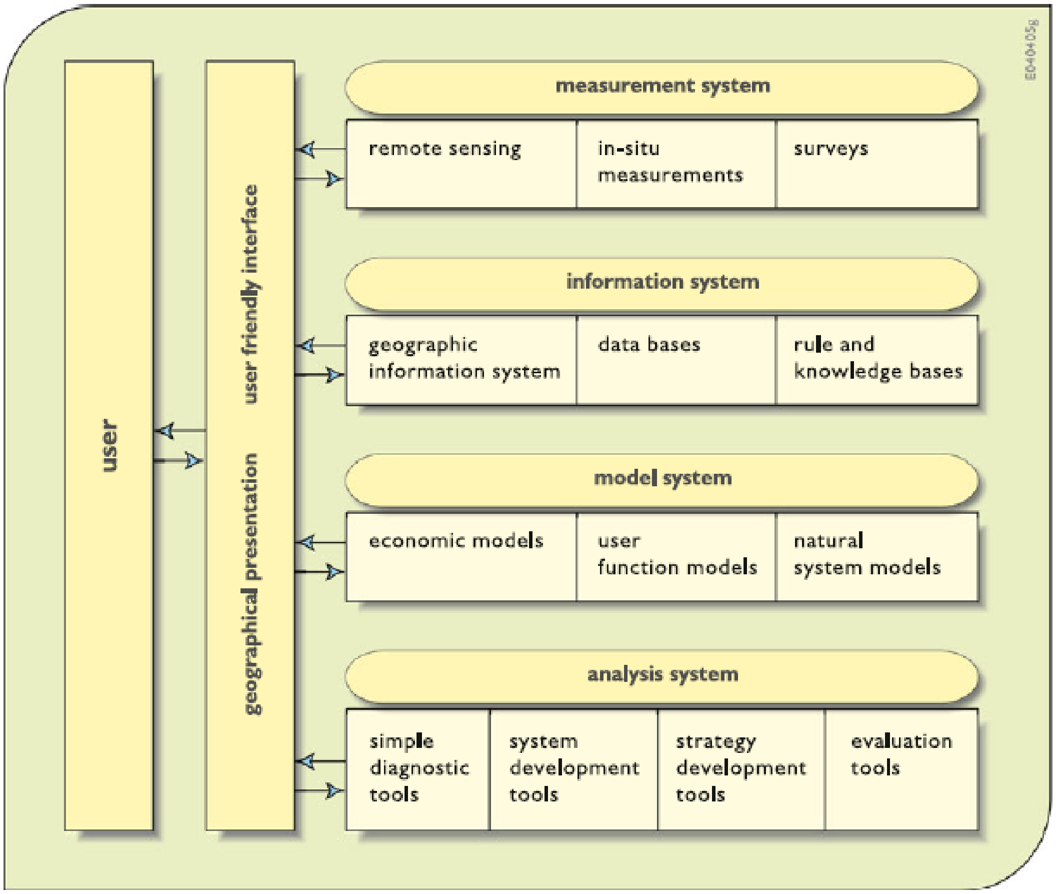


Figure 13: Common components of many decision support systems. Reprinted from: Loucks et al. (2017).

According to UNESCO, the IWRM approach combined with DSSs will handle the conflicting demands between stakeholders, economies and the environment on the development and management of water resources. This last organization carried out a study on Decision Support System for Integrated Water Resources Management considering business processes of stakeholders (UNESCO, 2014). The objectives of the research were listed as follow: establish IWRM methodologies for securing water efficiency; identify the potential method for climate change adaptation in river basins by considering stakeholders' business process; identify room for improvement in water efficiency concealed in business processes; support communication, negotiation and mutual understanding among stakeholders; and clarify what kind of information is required by whom, when, where and how, by assessing the requirements of stakeholders' business processes and providing information on them.

Through their study implemented in Africa, Giupponi et al. (2013) identify three main methodologies that played an important role in the IWRM-DSS approaches: Participatory

Planning, Simulation Modelling, and Decision Analysis. The paper defines the methodologies as follow:

- Participatory Planning: the will to balance the rights of majorities and minorities in public decisions and the belief that inefficient policies and practices in environmental management are often a consequence of top-down approaches, failing to integrate stakeholders’ concerns, aspirations, and constraints;
- Simulation Modelling: the disciplinary scientific knowledge of phenomena, physical or otherwise, and as such, is crucial in analyzing socio-ecosystems for their sustainable management;
- Decision Analysis: methods and reference frameworks to structure decision problems, generate, elicit and aggregate preferences (value judgments) on different aspects of pursued policies; it plays a fundamental role when problems are complex and dynamic, such as the case of IWRM, and when robustness and transparency is required for mitigating the biases caused by humans’ limited capacity to compare multi-dimensional problems and possible solutions and make trade-offs between costs and benefits explicit and manageable.

The state-of-the-art in DSS has shown a particular interest in climate change and water demand for irrigation. According to Rowshon et al. (2019), the development of mitigation plans for water management problems is importantly challenged by climate projection at a local scale. To that matter, their study develops a water management tool (Climate-Smart Decision-Support System or CSDSS) for modeling water demand for rice irrigation schemes under climate change impacts. The model was developed to “evaluate the impacts of climate change on irrigation water demand and other key hydro-climatic parameters in Tanjung Karang rice irrigation scheme in Malaysia for the period 2010–2099 with reference to the baseline period of 1976–2005” (Rowshon et al., 2019). It considers ten Global Climate Models (GCMs) and three emission scenarios (RCP 4.5, 6.0 and 8.5).

Hernández et al. (2019) on the other hand, developed a Decision Support System for Precision Irrigation Using Interactive Maps and Multi-agent Concepts. Thus, they integrated different technologies currently found in engineering to develop methodologies based on measurement, decision support and action on crops. The goal was to use a technique called Precision Agriculture (PA) to determine when, where and how to apply the inputs on crops.

3.3. Impacts of dams and reservoirs on water resources

Dams and reservoirs are intended to increase water-related benefits for humans. They permit hydroelectricity production, domestic and industrial water supply, food production through irrigation, recreational activities, navigation during low flow, and reduce the risks for natural disasters like floods and drought. Liersch et al. (2018) while assessing water management impacts on the water resources, have demonstrated that the UNB without any dam would only provide enough water in extraordinary wet years (ex., end of the 1960s) for dry season cropping, with a gap of 23% on the average flow (1961-2000). This gap reduces to 4% with the Sélingué dam.

However, water infrastructures also negatively affect the hydrological regime and thus affect many users upstream and downstream. Dams and reservoirs can cause upstream flooding that can destroy animals, plants, ecosystems and private property; downstream alteration of terrain, ecosystems, plants, and wildlife; impediment of fish migration and the death of fishes that pass through turbines. More than 400,000 km^2 have been lost worldwide from reservoirs flooding (McCully, 2001).

The effects of a dam on the flow highly depend on the reservoir size and operating rules. The more dam in the river, the more altered the river flow is expected to be. The effect a dam has on a river and it associated ecosystem is specific, as every river has their own flow patterns, landscapes, species it supports, design and operating pattern. According to International Rivers (McCully, 2001), no one yet has managed to determine with any accuracy the global extent of the fragmentation of river ecosystems by dams and water diversions. This last source also reports the findings of two Swedish ecologists (Mats Dynesius and Christer Nilsson from the University of Umeå), that estimated the degree of damage to river systems in the US, Canada, Europe, and the former USSR. They found out that of the 139 largest river systems in these countries, 77% of the total water discharge is 'strongly or moderately affected by fragmentation of the river channels by dams and by water regulation resulting from reservoir operation, interbasin diversion and irrigation'. Dynesius and Nilsson concluded that as a result of habitat destruction and obstruction to organism dispersal, many riverine species may have become extinct or fragmented with a risk of future extinction.

In Sri Lanka, the construction of a five-dam mega-scheme in the Mahaweli River to expand irrigation has submerged and turned into agricultural land the habitat of seven endangered (counting 800 elephants) and two threatened animal species (the purple-faced langur and the toque macaque). The reservoirs and canals have cut off an important migratory route for the elephants that have become a dangerous pest for the farmers. The construction of dams and reservoir can also lead to deforestation. This was the case for Thailand, where the construction of large reservoirs in the forest area facilitated access to previously remote areas (construction of roads); which attracted cruisers as well as developers who have built golf courses and resorts along the edges of reservoirs. (McCully, 2001)

Through their studies, Wetland International found out that the Sélingué reservoir and OdN have lowered the IND water level by 20-25 cm and the inundated area by 900 km^2. They also concluded that if the Fomi dam were to be built, the IND water levels will drop by an additional 45 cm and the inundated area will be further reduced by 1400 km^2. Zwarts et al. (2005) determined the effects of the Sélingué and Fomi dams on the Niger River average monthly flow (from 1980 to 2001) at Ké-Macina hydrological station, based on four numerical experiments (river setup scenarios). Their model maximizes the electricity production for the Fomi dam, as initially intended. The results (Figure 14) show that compare to the natural river flow, the presence/addition of dams in the river will increase the flow during the dry months but decrease the flow during the wet months.

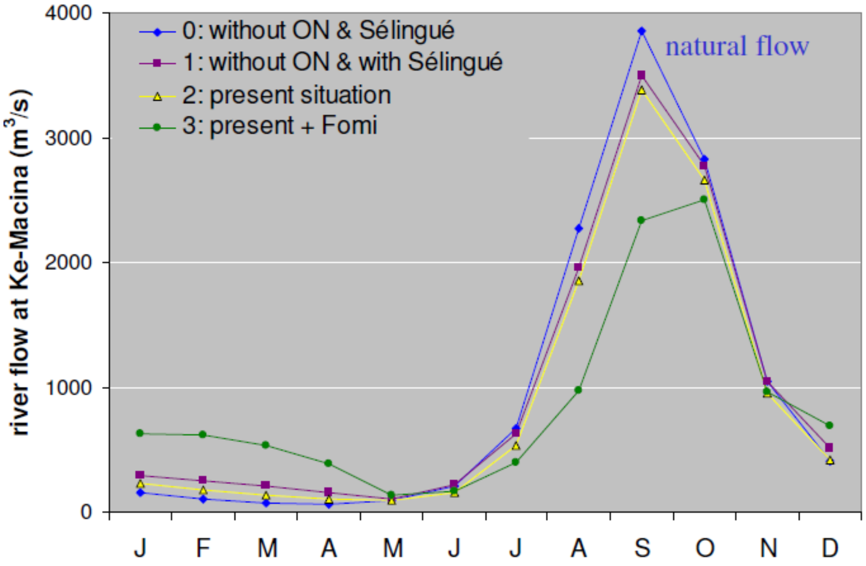


Figure 14: The average monthly flow of the Niger at Ké-Macina, calculated over the period 1980-2001. Reprinted from Zwarts et al. (2005).

Thus, the large storage capacity of the Fomi dam has the potential to substantially alter the flow regime by further increasing flows during the dry season and decreasing the high flows during the wet season (reservoir filling period).

Liersch et al. (2018) study results have shown the same general observations. The study concluded that 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, but The Fomi dam would almost eradicate those gaps, except in extraordinary dry years where irrigation deficits were about 20% in February. In addition, they concluded that both dams show similar impacts by decreasing discharges in the high flow season up to 10% and increasing discharges in the low flow season by 10% and more.

Dams can also affect the water quality. They can trap river born nutrients leading to a massive bloom of toxic algae. This was the case in ex-USSR, South Africa and California where the reservoir's water was rendered unfit for drinking and swimming. In addition, water stored for a long period behind a dam can become fatal to many lives in the reservoir, as well as downstream the reservoir, especially water coming from a treated effluent upstream.

Dams also lead to riverbed deepening that can in return lower the groundwater along a river. In tropical areas, aquatic plants are known for often colonizing reservoirs, which can lower reservoir levels through evaporation and transpiration. According to International Rivers (Pottinger, L., 2009), weed-covered reservoirs can be up to six times higher than those from evaporation in open water. This last source also states, “About 170 cubic kilometers of water evaporates from the world's reservoirs every year, more than 7% of the total amount of freshwater consumed by all human activities.”

Thus, Zwarts et al. (2005) study has shown that on one hand dams can deliver additional and stable electricity supply and increased food production. On the other hand, they can lead to a reduction in navigation, a drop in cattle, a reduction in fish and agricultural production, and a loss in biodiversity.

3.4. Hydrological modeling

Hydrological models have been developed to analyze, understand, and explore solutions to water-related challenges based on the water spatial and temporal distribution. A hydrological model is usually a set of equations or a computer algorithm trying to mimic the behavior of a system. It allows the estimation of non-observed variables (such as evapotranspiration, surface runoff, and infiltration) and can simulate the behavior of a system under different climate change scenarios for a certain area. Many important applications can be derived from the development of hydrological models. They can assist decision support processes for drought/flooding-hazard assessment, monitoring, and management; aid groundwater management (Kuwayama et al., 2017); evaluate the benefits that can be expected from a given water resources system; evaluate the social, economic, and environmental risks of the spatial and temporal distribution of water (Seidou O., 2018). There are three main types of hydrological models, including rainfall-runoff models (or watershed models), time series models, and statistical extreme events models. The current paper uses a rainfall-runoff model to simulate the flow at the watershed outlet given climate variables such as precipitation and temperature.

However, hydrological models can present many uncertainties, mostly related to the model structure and parametrization, conceptual simplifications, assumptions, spatial resolution, and the omission of certain processes occurring in the watershed. Vetter et al. (2015) found out that hydrological models uncertainty increases with more complex hydrological processes or with a dominance of certain processes affecting runoff (ex. evapotranspiration). On the other hand, Hattermann et al. (2018) found out that Global Circulation Models (GCMs) are the biggest source of uncertainty in the UNB and hydrological models contribute only a small part to uncertainty.

Many tools are available for hydrological modeling and some of the most popular software are HEC-HMS (Hydrologic Engineering Center’s Hydrologic Modeling System), SWAT (Soil and Water Assessment Tool), WEAP (Water Evaluation And Planning), SPHY (Spatial Processes in Hydrology), PRMS (Precipitation Runoff Modeling System), Green Kenue, GoldSim, GMS, MODFLOW, and ArcGIS (Geographic Information System).

3.5. Multiple Reservoir Modelling of a River System

The modeling of a multi-reservoir system is usually not straightforward, as the upstream reservoirs affect the flow going to the downstream ones. The number of parameters needed to be considered in the analysis increase with the number of reservoirs. Another important limitation of multi-reservoir water resources systems is the non-linearity of the system, especially for those with different operating rules. There is a lack of application of optimization models to the practical management due to the multiple simplifications of these models; this leads to low confidence in water managers model projections results for making important decisions (Lerma et al., 2013).

According to Yeh (1985) (as cited in Lerma et al., 2013) the optimization of reservoir operations does not have a general method and the approach can range from simulation to optimization models. However, optimization models suffer from high dimensionality and simplifications that are often not reflective of the real-world system. Optimization methods include (but are not limited to) linear programming, non-linear programming, mixed-integer programming, dynamic programming, evolutionary optimization, artificial neural networks, genetic algorithms.

In 2013, George et al. presented a novel way of simulating water and sediment fluxes through high-density reservoir networks, by assessing water and sediment retention in those structures. The objective of the study was to present the improvements made to the WASA-SED model concerning the impacts on water and sediment routing of a cascading network of reservoirs. The novel approach was combined with the fully process-oriented and semi-distributed hydrological WASA-SED model for semiarid hydro-climatological characteristics. The study area was the Benguê catchment located in the northeast of Brazil, characterized by a semiarid climate. The Benguê covers an area of 933 km2 with 114 reservoirs sizing from 0.003 to 350 ha (George et al., 2013). In particular, the study grouped the small reservoirs into size classes according to their storage capacity and a cascade routing scheme was applied to describe the upstream-downstream position of the classes. The results have shown that the dynamics of water and sediment within the Benguê catchment were strongly impacted by the presence of multiple reservoirs, which were able to retain approximately 21% of the generated runoff from 2000 to 2012.

The operation and management of a multi-reservoir system become more complex with multiple optimization objectives, which can create important political, social and economic conflict among the various beneficiaries. An approach often use among many to solve multi-objective in multiple reservoir modeling is the Bellman stochastic dynamic programming (SDP). However, this last approach is limited by a dimensionality problem: “the computational effort increases exponentially with the complexity of the considered system (i.e., number of reservoirs), and thus becomes rapidly intractable” (Sangiorgio et al., 2018). To address that matter, Sangiorgio et al. (2018) proposed an implicit stochastic optimization approach. Their study uses artificial Neural

Networks (NN) to design release rules and approximate the optimal policies obtained by an open-loop approach. The trained NNs will then be used to take decisions in real time. The main management objectives were the minimization of the irrigation water deficit and the maximization of the hydropower production. The methodology was verified on the Nile River basin, which has been subject to many infrastructures development in recent years by the upstream countries. However, the authors recognize that “NNs are not very popular in practice since they often appear as a rather cryptic black-box”.

Tan et al. (2017) derived optimal joint operation rules for multi-purpose multi-reservoir water supply system for the Li River in China. The methodology consisted of developing an aggregation-decomposition model, including ‘an aggregated model based on the improved hedging rule to ensure the long-term water-supply operating benefit; a decomposed model to allocate the limited release to individual reservoirs for the purpose of maximizing the total profit of the facing period; and a doublelayer simulation-based optimization model to obtain the optimal time-varying hedging rules using the non-dominated sorting genetic algorithm II, whose objectives were to minimize maximum water deficit and maximize water supply reliability’ (Tan et al., 2017). To reduce the number of decision variables, the multi-reservoir system was simplified into a virtual reservoir. The aggregation model was used to obtain an overall system decision and the decomposition model was used to decentralize the decision into individual reservoirs. The study used was based on the aggregated Hedging Rules (HRs) for the outer optimal model and the optimization was done by non-dominated sorting genetic algorithm II (NSGA-II). Based on their results, the authors have concluded that the aggregated HRs are superior to conventional operating rules and to aggregated standard operating policy, in both water supply and hydropower generation because of the use of the hedging mechanism and the optimal allocation of the release among reservoirs.

3.6. Identified gaps and justification of the study

Similarly to the current paper, as part of their study Liersch et al. (2018) have assessed the impact of water management on the water resources in the UNB. The main objective of their study was to ‘investigate the most recent development plans by analyzing different reservoir operation strategies, including the planned Moussako dam in the Niger headwaters, and their impacts on the feasibility of the plans to expand irrigated agriculture in the scheme operated by

Office du Niger (OdN)'. In addition, the study evaluated the likely impacts of increasing agricultural water demands on the discharges entering the IND. Based on the results, they came to the following conclusions:

- The extension of Office du Niger irrigated area could be achieved for all the irrigation scenarios (2005, 2015, 2025, 2035, and 2045), for the wet season from August to October only. However, the considerable withdrawals would be a threat to the downstream ecosystems (IND).
- During the dry season from January to June, the plans are severely challenged starting at the 2025 irrigation scenarios. But with the Fomi dam, the plans for 2025 could be realized by optimizing hydropower production and by considerably increasing the discharges in the low flow season. Beyond 2025, irrigation demands in the dry season become unrealistic.

The two studies present some important difference in the methodology used. While the present study developed a SWAT Model, Liersch et al. (2018) study used the Soil and Water Integrated Model (SWIM) to simulate the impacts of currently existing and planned land and water management activities on river discharges. In addition, Liersch et al. (2018) study focus on the Upper Niger and the Bani River Basins and their results are simulated in the period of 1961-2000, while the present study focuses on the Upper Niger Basins and the Inner Niger Delta with a simulation period of 1979-2016.

The main contribution (novelty) of the present study is the conception of an easy-to-use Decision Support System (graphical interface) available to various users. Contrary to Liersch et al. (2018) study, the current study develops an open source and accessible tool that incorporates a data package and allows the users to conceive their own scenarios instead of predefined scenarios. The DSS is intended to facilitate decision making related to the planning and management of the Fomi dam for various users (engineers, hydrologists, or other decision-makers, with or without coding background). It is a tool that can provide a good understanding of the overall effect of irrigation, dams, and reservoirs, and determine the least impactful alternative for the Fomi/Moussako dam on the flow regime of the UNB and the IND. Thus, the DSS can help Mali decision-makers prepare for the impacts that the Fomi/Moussako dam will potentially have on the UNB and the IND flow regime. It allows the users to create different river scenarios (ex.: Sélingué + Fomi, Sélingué + Office du Niger + Moussako 402, etc.) by adding or removing a structure and by running an analysis. Further, reservoir parameters can be manually modified in the SWAT text files if desired. The DSS performs the analysis by running the SWAT software. Once the analysis is successfully completed, the DSS will display the mean, standard deviation, and timeseries of the desired subbasin or reservoir. The mean and the standard deviation are available for the annual flow, the month with the wettest flow, and the month with the driest flow.

Chapter 4 – Methodology

The analysis is carried out as follows:

- Collection of climate data from the WFDEI meteorological forcing data.
- Development of a SWAT model for the UNB and IND, including the Sélingué dam, the Fomi/Moussako dam and Office du Niger.
- Calibration and validation of the SWAT model.
- Estimation of additional reservoir data for the Fomi/Moussako dam.
- Conduct a set of numerical experiments where the dams and the irrigation scheme are added/removed to the analysis, to assess the individual impact of each dam and the irrigation scheme. Each experiment assesses the change in the annual flow, the change in the flow of the wettest month of the year, the change in the flow of the driest month of the year, and the change in the flow of the driest month of the driest year. The Numerical experiments are presented in Chapter 5.
- Development of a Decision Support System (graphical interface) for an easy transmission to non-technical end users.

4.1. SWAT Model Input Data

The climate data (daily precipitation and temperature) used for this study were obtained from the WFDEI meteorological forcing data set (WATCH Forcing Data methodology applied to ERA-Interim reanalysis). WATCH (Water and Global Change) provides a large number of data sets including metrological data used for hydrological or land surface models. WFDEI was derived using the same methodology as WFD (WATCH Forcing Data) applied to ERA-Interim data available from 1979 to 2012 (Weedon et al. 2014).

4.2. Swat Model development in ArcSWAT

The SWAT project was set up in ArcSWAT GIS (Geographic Information System) interface. The model was developed for the entire Niger River, but the analysis was limited to the UNB and the IND. The steps for the SWAT model development include the watershed delineation and parametrization, the HRU (Hydrological Response Unit) analysis, and the weather data definition. The projected and the geographic coordinate system used was the WGS_1984_UTM_Zone_30N and the GCS_WGS_1984, respectively.

The watershed delineation and the parametrization of the stream reach are achieved using a DEM (Digital Elevation Model). To define the reaches, the program fills all the sinks in the DEM then calculates the flow direction and accumulation grids. Once the stream network was completed, the subbasins' outlet were manually added to the stream junctions of interest. This allows the program to perform the calculation for the watersheds' boundary. In total, 178 subbasins were delineated for the entire area (Niger River). Fourteen main hydrological gauges were considered in this study including include Kankan, Baro, Kouroussa, Banakoro, Koulikoro, Kirango, Ké-Macina, Bougouni, Pankourou, Douna, Sélingué, Mopti, Akka, and Diré (most downstream gauge, in the IND). Figure 15 shows the UNB and IND subbasins configuration, the subbasins' names (regions where the gauges are located), the flow paths, as well as the locations of Sélingué, Fomi, Moussako, and OdN. Table 1 shows the stations' longitude, Latitude, and relative location to the dams (Sélingué and Fomi/Moussako) and to OdN.

The next step was the HRU (Hydrological response unit) analysis. HRUs represent natural homogenous areas that assume non-variability of the data and parameters within its delineation. This notion was introduced to reduce the heterogeneities due to climate, soil types, topography and geology that influence hydrologic response (ArcSWAT interface for swat2012: User's guide). Each subwatershed contains at least one HRU. The three main datasets used to perform the HRU analysis are land use, soils, and Slope. In the entire area, there was a total of twelve land cover classes and 55 soils types. This led to the definition of 595 HRUs.

The last step before running the model is the weather data definition. The inputs consisted of weather generator data, rainfall data, and temperature data. Weather generator information is needed by SWAT to fill in the missing data and to generate relative humidity, solar radiation and wind speed (ArcSWAT interface for swat2012: User's guide).

Once the simulation is completed, SWAT creates a number of output files that provide summary information. The primary Output files include the summary input file (input.std), the summary output file (output.std), the HRU output file (output.hru), the subbasin output file (output.sub), and the reach or main channel output file (output.rch).

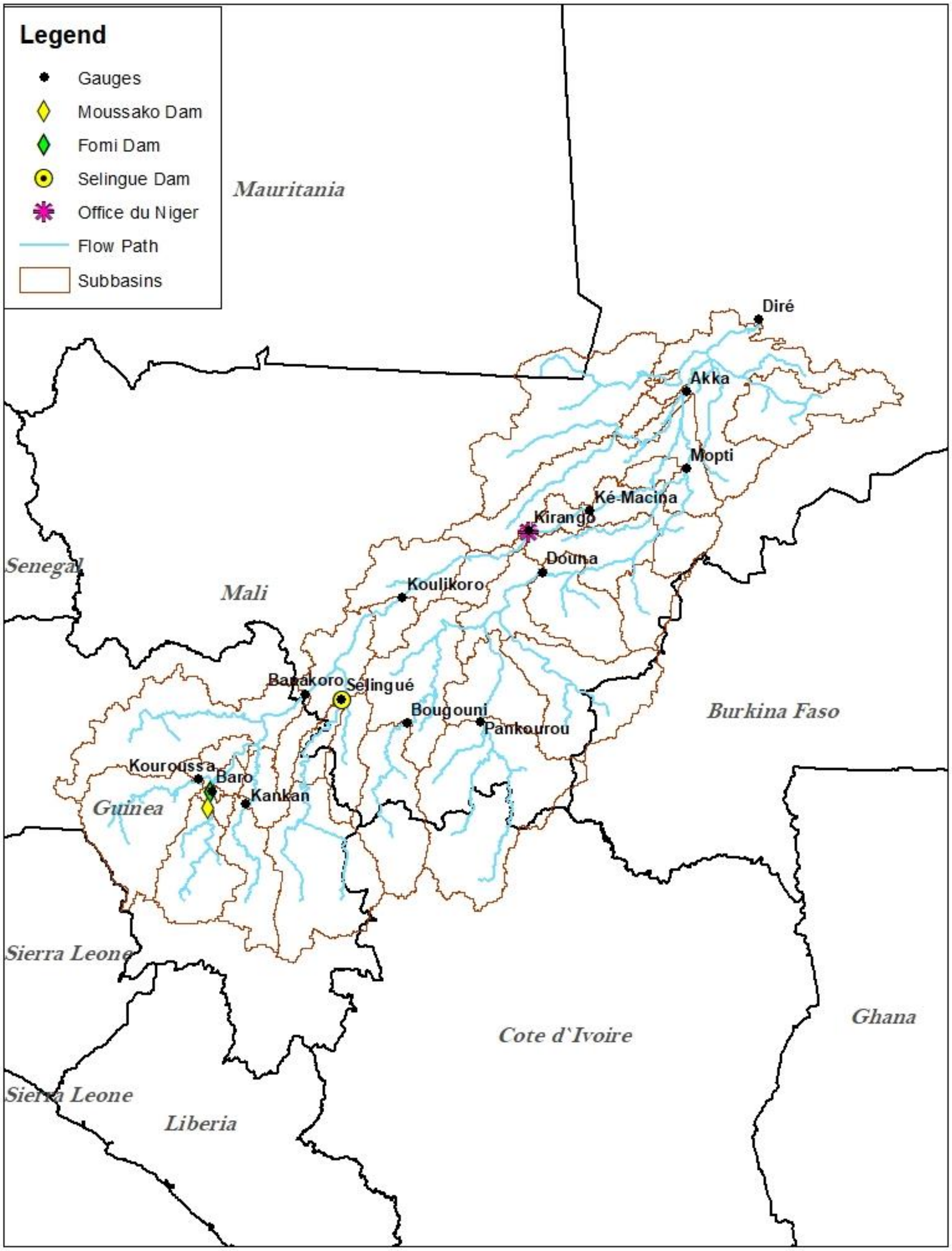


Figure 15: The Inner Niger Delta and Upper Niger Basins Configuration in SWAT.

Table 1: Hydrological stations (gauges) coordinates, and relative locations to the Dams and to OdN.

Hydrological Gauges Location	Latitude (Deg.)	Longitude (Deg.)	Location relative to Sélingué, Fomi/Moussako, and OdN
Kankan	10.38	-9.31	Upstream
Baro	10.51	-9.72	Downstream of Fomi/Moussako
Kouroussa	10.64	-9.88	Upstream
Banakoro	11.68	-8.67	Downstream of Fomi/Moussako
Sélingué	11.64	-8.24	Upstream
Koulikoro	12.85	-7.56	Downstream of Sélingué and Fomi/Moussako
Kirango	13.69	-6.08	Downstream of Sélingué, Fomi/Moussako, and OdN
Ké-Macina	13.95	-5.36	Downstream of Sélingué, Fomi/Moussako, and OdN
Bougouni	11.39	-7.45	Upstream
Pankourou	11.44	-6.58	Upstream
Douna	13.21	-5.9	Upstream
Mopti	14.49	-4.21	Upstream
Akka	15.4	-4.24	Downstream of Sélingué, Fomi/Moussako, and OdN
Diré	16.27	-3.39	Downstream of Sélingué, Fomi/Moussako, and OdN

4.3. Calibration

To increase the model performance, three SWAT parameters were used to calibrate the model to match the measured flow. The model was calibrated using SWAT parameters obtained from a previous study (Seidou O., 2017). Refer to Seidou O. (2017) for more details on the parameters sensitivity analysis and the calibration process. The calibration parameters include the CN2, the

RCHRG_DP, and the RES_K. A brief description (from the SWAT 2012 Input/output document) of parameters are as follows:

- CN2: represents the initial SCS runoff curve number for moisture condition II. It is a function of the soil's permeability, land use, and antecedent soil water conditions. For this calibration, the CN2 was incremented by 17 for all the subbasins.
- RCHRG_DP: is the percolation fraction that recharges deep aquifer from the root zone (should range between zero and one). For the current project, the RCHRG_DP was incremented by 0.01 for all the subbasins.
- RES_K: is the hydraulic conductivity of the reservoir bottom expressed in mm/hr. By default, the hydraulic conductivity was zero (for seepage occurring in the water body). This value was 1.8 mm/hr for Sélingué, 0.0227 mm/hr for Mopti, 3.3 mm/hr for Akka, and 0.1 mm/hr for Diré.

The calibration results (timeseries of observed vs simulated data) are presented in Appendix A.

4.4. Evaluation of the Calibration

The goodness of the calibration was evaluated through the Nash Sutcliffe model Efficiency (NSE) coefficient as shown in equation 1 (*Eq. 1*):

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(OBS_i - SIM_i)^2}{\sum_{i=1}^{n}(OBS_i - \overline{OBS})^2}\right] \qquad eq.1$$

Where n is the total number of data, OBS represents the observed data (measured flow), SIM represents the simulated data, and $\overline{OBS}$ corresponds to the mean value of the observed data.

The NSE coefficient (raging between -∞ and 1) is a normalized statistic that determines the relative magnitude of the residual variance compared to measured data variance. It is an indication of how well the plot of observed versus simulated data fits the 1:1 line (Bigiarini, M. Z.). The upper limit of the NSE '1' represents the ideal scenario (i.e., the model perfectly mimic the behavior of the observed data). Thus, the closer to '1', the more accurate the model is. An NSE of '0' signifies that the model predictions are as accurate as the mean of the observed data, while an NSE of -∞ signifies that the observed data mean gives better estimations than the model. The observed data was converted into monthly flow by calculating the average of daily flows over a monthly basis. The simulated monthly flow for each subwatersheds was extracted from the model reservoir output file using a custom MATLAB code. The NSE was determined using another custom code, by building a correspondence table between the observed and simulated flow for the period of 1979-2010.

Most of the stations Nash Sutcliffe value was greater than 0.7. According to Seidou O. (2017), the calibration can be considered excellent if the Nash Sutcliffe coefficient lies in the range of 0.7 to 0.9. Despite multiple attempts to improve the calibration for Baro and Douna, their Nash Sutcliffe values remained below that 0.7 limit. This could be explained by the many gaps present in their dataset (missing data for many months or years). However, a low Nash value is to be expected for the Sélingué dam. This is because the observed data for this last station are outflow data from the reservoir, while the simulated data are over the subbasin. In other words, the Sélingué Nash was determine by comparing the reservoir outflow to the subbasin inflows. Thus, the Nash Sutcliffe coefficients obtained (presented in Table 2) were considered acceptable for the current study.

Table 2: Nash Sutcliffe Coefficients.

Hydrologic Gauge (Station)	**Nash Sutcliffe**
Kankan	0.78
Baro	0.38
Kouroussa	0.74
Banakoro	0.89
Sélingué	0.18
Koulikoro	0.88
Kirango	0.65
Ké-Macina	0.82
Bougouni	0.76
Pankourou	0.80
Douna	0.55
Mopti	0.79
Akka	0.70
Diré	0.85

4.5. Additional Input Reservoir Data

To better reflect dam management practices, some input parameters were evaluated and added to the model reservoirs files (*.res) after validation. Refer to Appendix C for more details on the structure of SWAT reservoir files. The Sélingué dam operation parameters representing the actual management practices were readily available. This was not the case for Fomi and Moussako, where most of the parameters were estimated. Thus, Fomi and Moussako maximum daily outflow were determined using a Gamma distribution flood frequency analysis (method of moments). The 100-year design value was 1658 m^3/s. Their target reservoir storage was estimated from the Sélingué dam, by dividing this last dam 'target reservoir storage' by its 'spillway emergency volume', and by multiplying this product by the Fomi/Moussako 'spillway emergency volume'. The consumptive water use (irrigation) is neglectable for the Fomi/Moussako dam and consequently, was not added to the analysis. For all three dams, the monthly turbine efficiency was set to a conservative value of 0.7, and the monthly tailwater level was set equal to the turbine height. The turbine height was estimated by subtracting the dam toe height from the minimum level of exploitation. Some of the parameters used for Fomi and Moussako are presented in Table 3. These parameters include the installed power, the monthly target electricity production, the turbine maximum flow, the height to the dam toe, the minimum level of exploitation, and the turbine height. Most of these values were found in Liersch, S. et al. (2018).

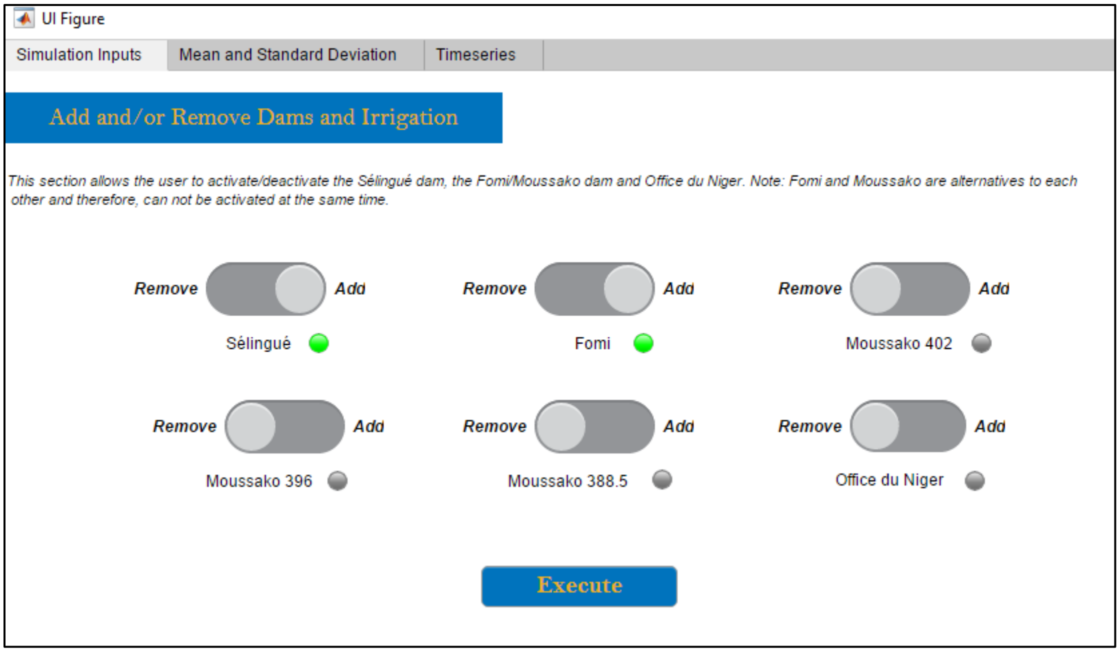
Table 3: Fomi and Moussako Dams Main Parameters.

Parameters	**Fomi**	**Moussako 402**	**Moussako 396**	**Moussako 388.5**
Installed power (MW)	118	113	87	60
Monthly target electricity production (MW)	47.1	45.3	34.4	23. 9
Turbine maximum flow (m^3/s)	458	408	384	364
Height to dam toe (m)	33	35	29	21.5
Minimum level of exploitation (m.a.s.l.)	386	394	390	382
Turbine height (m.a.s.l.)	353	359	361	360.5

4.6. Development of the Decision Support System

The Decision Support System (DSS) is a Graphical User Interface (GUI) developed through the App Designer in MATLAB R2017b. It is intended to assist various users in decision-making related to the Fomi/Moussako dam planning and management in the Upper Niger River. It allows the users to perform a comparative analysis by simulating different scenarios (presence or absence of dams and irrigation in the river). The analysis is intended to determine the effects of dams and irrigation on the flow regime at different hydrological stations within the UNB and IND. The outflows are monthly (January-December) and the simulation happens over 38 years (between 1979 and 2016). The analysis results present statistical data such as the annual flow mean and standard deviation, the wettest month flows mean and standard deviation, the driest month flows mean and standard deviation, and the corresponding time-series graph for a selected subwatershed or reservoir station. The interface includes the existing Sélingué dam, the planned Fomi dam and it's alternative sites (Moussako 402, Moussako 396, Moussako 388.5), and Office du Niger (irrigation). At this stage, the app is divided into three tabs groups.

The first tab group (Figure 16) is where the user creates a scenario, by activating (Add) or deactivating (Remove) the hydrological structures (dams) and the irrigation scheme (Office du Niger) from the analysis. Initially, when the app is launched, all the elements are inactive. In other words, there is no alteration in the river natural flow regime due to Sélingué, Fomi/Moussako or Office du Niger. An element can be added/removed from the analysis by a simple right click on the button. The switch light turns green when an element is added. Since Moussako is an alternative to Fomi, the app does not allow the user to activate both dams at the same time (one is automatically removed when the other one is added). That way, the app reflects a feasible real life scenario. After a scenario is created and before moving onto the next step, the user needs to "Execute" the Swat program to perform the analysis. This will allow SWAT to run the analysis via the interface by reading the data of interest (from the data package) and perform the required calculations. If the program is successfully run, a confirmation message will appear at the end. Else, an error message will appear suggesting the user verify the inputs and try again. It is important that SWAT is run ("Execute" button) every time the user modifies the first tab to create a new scenario.



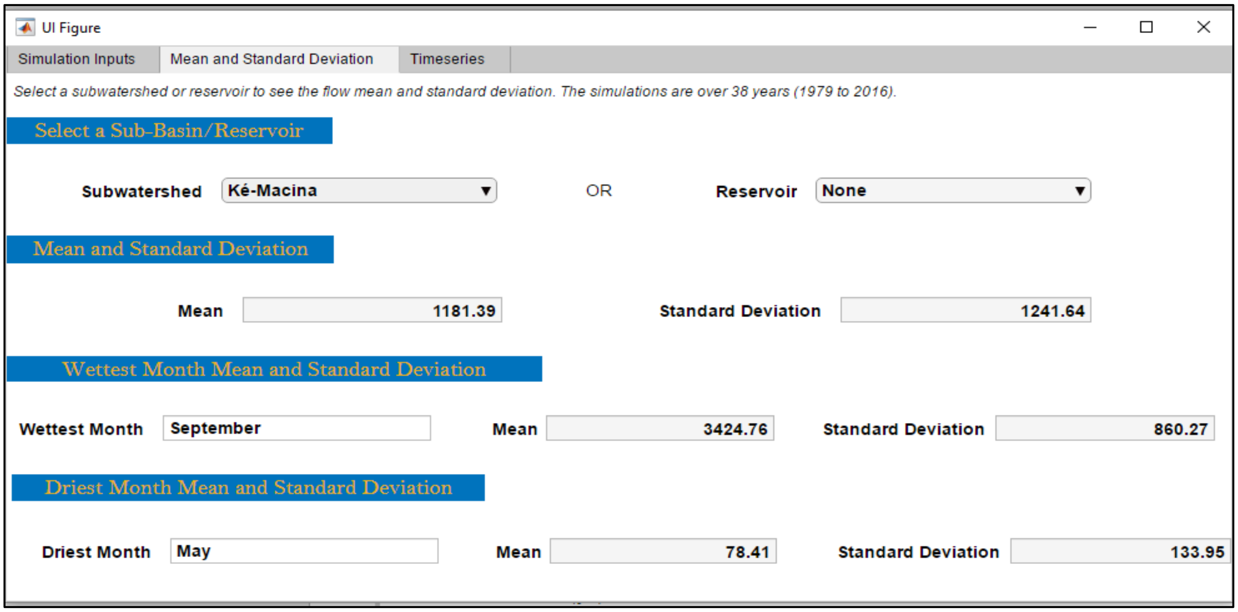
Add and/or Remove Dams and Irrigation

This section allows the user to activate/deactivate the Sélingué dam, the Fomi/Moussako dam and Office du Niger. Note: Fomi and Moussako are alternatives to each other and therefore, can not be activated at the same time.

Remove / Add — Sélingué ●
Remove / Add — Fomi ●
Remove / Add — Moussako 402 ●
Remove / Add — Moussako 396 ●
Remove / Add — Moussako 388.5 ●
Remove / Add — Office du Niger ●

Figure 16: DSS first tab group

In the second tab group (Figure 17), the user can select a subwatershed or reservoir to display the results specific to that station. The results displayed in this tab are the mean and the standard deviation for the annual flow, the wettest month flow, and the driest month flows. It also displays the wettest and driest month names corresponding to the selected station.



Select a subwatershed or reservoir to see the flow mean and standard deviation. The simulations are over 38 years (1979 to 2016).

Select a Sub-Basin/Reservoir

Subwatershed Ké-Macina OR **Reservoir** None

Mean and Standard Deviation

Mean 1181.39 **Standard Deviation** 1241.64

Wettest Month Mean and Standard Deviation

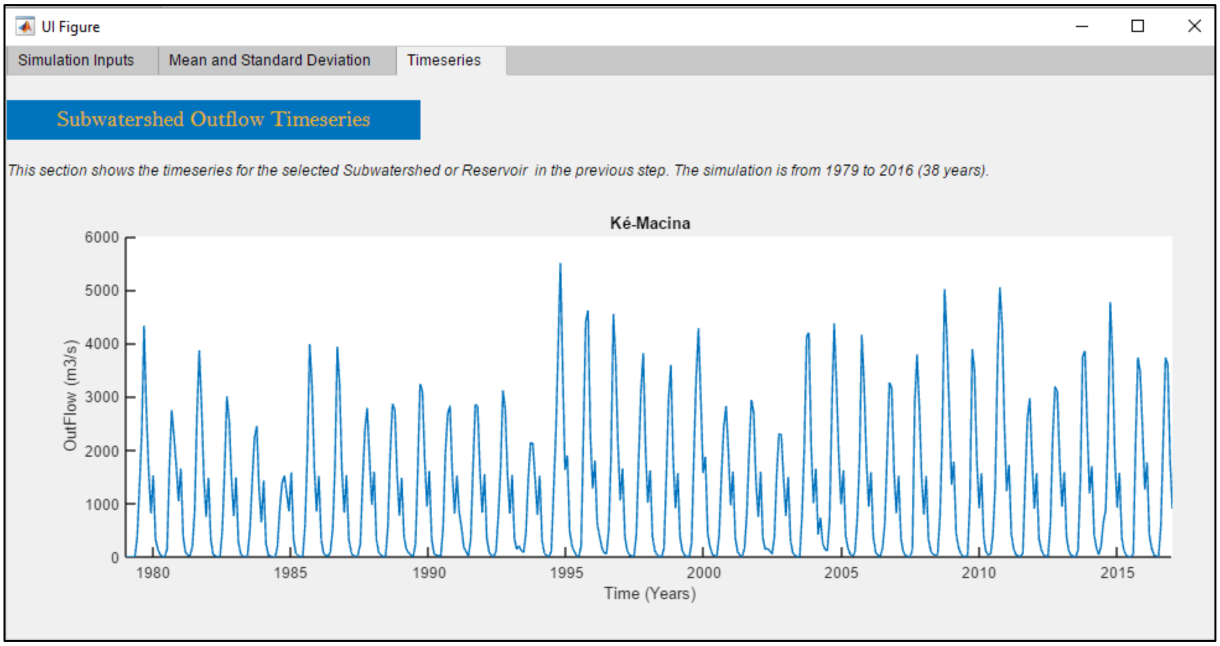
Wettest Month September **Mean** 3424.76 **Standard Deviation** 860.27

Driest Month Mean and Standard Deviation

Driest Month May **Mean** 78.41 **Standard Deviation** 133.95

Figure 17: DSS second tab group

The third tab (Figure 18) automatically displays the outflows timeseries (1979-2016) for the selected watershed or reservoir from the previous step (tab 2). The user can go back to the second tab to select a different station, and the time-series will update on the third tab.



Subwatershed Outflow Timeseries

This section shows the timeseries for the selected Subwatershed or Reservoir in the previous step. The simulation is from 1979 to 2016 (38 years).

Figure 18: DSS third tab group

Chapter 5 – Numerical Experiments

For the numerical experiments, twelve different configuration scenarios were considered: (0-a) no dams and no OdN, (0-b) no dams with OdN, (1-a) Sélingué only, (1-b) Sélingué with OdN, (2-a) Sélingué with Fomi, (2-b) Sélingué with Fomi and OdN, (3-a) Sélingué with Moussako 402, (3-b) Sélingué with Moussako 402 and OdN, (4-a) Sélingué with Moussako 396, (4-b) Sélingué with Moussako 396 and OdN, (5-a) Sélingué with Moussako 388.5, and (5-b) Sélingué with Moussako 388.5 and OdN. The scenarios are described as follow:

- Scenario 0 - No dams: this scenario assumes that there are no dams in the study area (i.e., no Sélingué, no Fomi/Moussako). It represents the reference (baseline) scenario, that corresponds to the behavior of the natural flow regime of the UNB and IND.
- Scenario 1 - Sélingué with no Fomi/Moussako: In this scenario, only the Sélingué dam is included in the analysis (no Fomi/Moussako).
- Scenario 2 - Sélingué with Fomi: In this scenario, both the Sélingué and Fomi dams are operational.
- Scenario 3 - Sélingué with Moussako 402: this is similar to scenario 2, but the Fomi dam is replaced by Moussako 402.
- Scenario 4 - Sélingué with Moussako 396: this case is similar to scenario 2, but the Fomi dam is replaced by Moussako 396.
- Scenario 5 - Sélingué with Moussako 388.5: this case is similar to scenario 2, but the Fomi dam is replaced by Moussako 388.5.

The experiments were completed for the annual flow, the flow of the wettest month of the year, the flow of the driest month of the year, and the driest month of the driest year flow, over the simulation period (1979-2016). Each analysis determines first the effects of dams on the flow assuming there is no irrigation (OdN); then the effects of dams on the flow taking OdN into account; and finally the influence of OdN on the flow. This is done by evaluating the Mean and Standard Deviation for each scenario at each station. These statistics were determined through a MATLAB code developed to read SWAT outputs files, filter the data, extract the flow data of interest, then calculate the data mean and standard deviation. The last flow analysis (driest month of the driest year) directly assess the change in flow between the two scenarios.

For the three first flow analysis (annual flow, flow of the wettest month, flow of the driest month), the ensuing procedure was followed:

- To determine the effects of the dams only on the UNB and IND, the mean and the standard deviation were evaluated for each stations removing OdN irrigation from the analysis. OdN water use was removed from the analysis by changing the beginning of the simulation to a later date (i.e., 2100 for example) in the Water Use Input SWAT file (*.Wus) of interest.
- From those last results, the percent reduction in the mean and the standard deviation were calculated. The change is relative to the "Scenario 0" (no dams in the river), when there is no OdN irrigation withdrawal happening. For example, the "Sélingué Only" scenario values represent the change in the flow (at the basin outlet) when only the Sélingué dam is present in the river (i.e., no Fomi or Moussako). For both the mean and the standard deviation, the percent change was calculated using *eq. 2*, as follow:

$$\%Change = \frac{(Scenario\ 0) - (Scenario\ _{1,2,3,4,5})}{(Scenario\ 0)} \times 100 \qquad eq.2$$

A negative reduction in the mean value implies an increase in the river flow and a positive value implies a decrease in the river flow. In the same perspective, a negative value for the standard deviation means an increase and a positive value means there is a reduction.

- Next, the mean and the standard deviation were one more time evaluated for each station, but this time accounting for OdN irrigation. Then the same procedure as the previous case (*Eq. 2*) was followed to determine the percent change in the mean and standard deviation.
- Based on the results obtained (mean and standard deviation) from the "No irrigation" and the " With irrigation" cases, the change in flow due to OdN was calculated as follow:

$$\%Change_{OdN} = \frac{(Flow\ without\ OdN) - (Flow\ with\ OdN)}{(Flow\ without\ OdN)} \times 100 \qquad eq.3$$

The same general procedure was followed for the driest month of the driest year flow analysis, except that this time only the relative change in the flow is assessed. The flow for the different scenarios corresponds to a single value (i.e., no mean or standard deviation calculations).

For the annual flow, the effect of irrigation was determined for five different irrigation withdrawal scenarios (2005, 2015, 2025, 2035 and 2045). However, only the 2005 irrigation withdrawal scenario was used for the three remaining analysis. The monthly withdrawal at OdN for 2005, 2015, 2025, 2035 and 2045 irrigation scenarios are presented in Table 4. The future irrigation scenarios reflect the estimated water demand for the planned expansions of OdN (estimated by Office du Niger).

Table 4: OdN Irrigation withdrawal Scenarios (m^3/s).

Month	**Year (Period)**				
	2005	***2015***	***2025***	***2035***	***2045***
January	48.9	70.5	143	240.6	364.7
February	47.2	69.5	140.3	236.8	357.6
March	52.6	72.5	110	165.9	227.6
April	66	85.5	110.4	149.7	189.3
May	55.1	71.3	86.4	112.1	134.5
June	60.9	83.1	123.6	171.5	218.2
July	112.6	145.6	209.8	287.2	381.1
August	86.5	113.3	162.3	221.8	294.7
September	155.9	204.1	293.9	397.1	515.6
October	157.6	207.6	303.2	423.5	567.3
November	81.1	110.2	163.4	220.6	271.3
December	26.7	40.9	72	112.6	153.4
Average	79.3	106.2	159.9	228.3	306.3

Chapter 6 – Results and Discussion

This chapter presents and discusses the results of the alterations caused by the Sélingué dam, the Fomi/Moussako dam, and OdN on the streamflow at various locations of the study area. It is divided into four main sections. The first section shows the annual flow analysis; the second section presents the analysis for the month with the highest flow; the third section presents the analysis of the month with the lowest flow; the fourth section presents the analysis of the driest month of the driest year. Each of the four sections evaluates (a) the impacts of only dams (i.e., Sélingué and Fomi/Moussako) on the flow, (b) the impact of dams and irrigation (OdN) on the flow, and the impacts of only OdN on the flow. The results are analyzed and compared as they are presented.

6.1. Effects of Sélingué, Fomi/Moussako and OdN on the Annual Flow

a. Effects of Sélingué and Fomi/Moussako on the annual flow (without OdN)

This section examines the effects of the dams only (without irrigation) on the UNB and the IND flow. The results (graphs) of the annual flow mean and the standard deviation are presented in Appendix B (only for the hydrological stations showing a change in flow). Table 5 and Tableau 6 show the percent reduction in the mean and standard deviation, respectively. The percent reduction in the mean is also presented on a map for each scenario (Figure l9 to Figure 23). Surely, only the basins located downstream of the dams and/or OdN experience a change in flow (increase or decrease).

As a general observation for all the scenarios, the mean of the annual flow experiences the least impact at Banakoro with a neglectable decrease smaller than 1.5%, followed by Baro with a decrease in mean flow smaller than 5%, Akka (less than 5%), and Diré (less than 4%). The most decrease in the mean flow is observed at Koulikoro, Kirango, and Ké-Macina with values of 10.6%, 10.4%, and 10.2%, respectively. Koulikoro station is downstream of both dams, and Kirango and Ké-Macina are located further downstream. Akka and Diré experience the lowest impact on their flow. This can be explained by the fact that these stations are located further downstream of the dams and OdN, compared to the other stations.

Looking at the different scenarios, the “Sélingué only” option seems to have the least impact on the streamflow, but the most impact on the flow of the IND at Akka and Diré. Comparing Fomi to the Moussako alternative sites, the “Sélingué + Moussako 388.5” option usually shows the least decrease on the subwatersheds mean annual flow, but the most decrease at Akka and Diré. The “Sélingué + Moussako 402” option seems to be the least favorable scenario for the average streamflow.

Table 5: Reduction in the mean of the annual flow (%) for different river scenarios without OdN.

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	3.289	4.961	1.347	0.619
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	0.881	1.333	0.357	0.162
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	9.921	10.399	10.629	10.115	10.008
Kirango	9.714	10.156	10.370	9.893	9.793
Ké-Macina	9.664	10.069	10.249	9.829	9.738
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.312	-0.106	-0.909	3.858	4.868
Diré	2.981	-0.934	-1.699	2.667	3.560

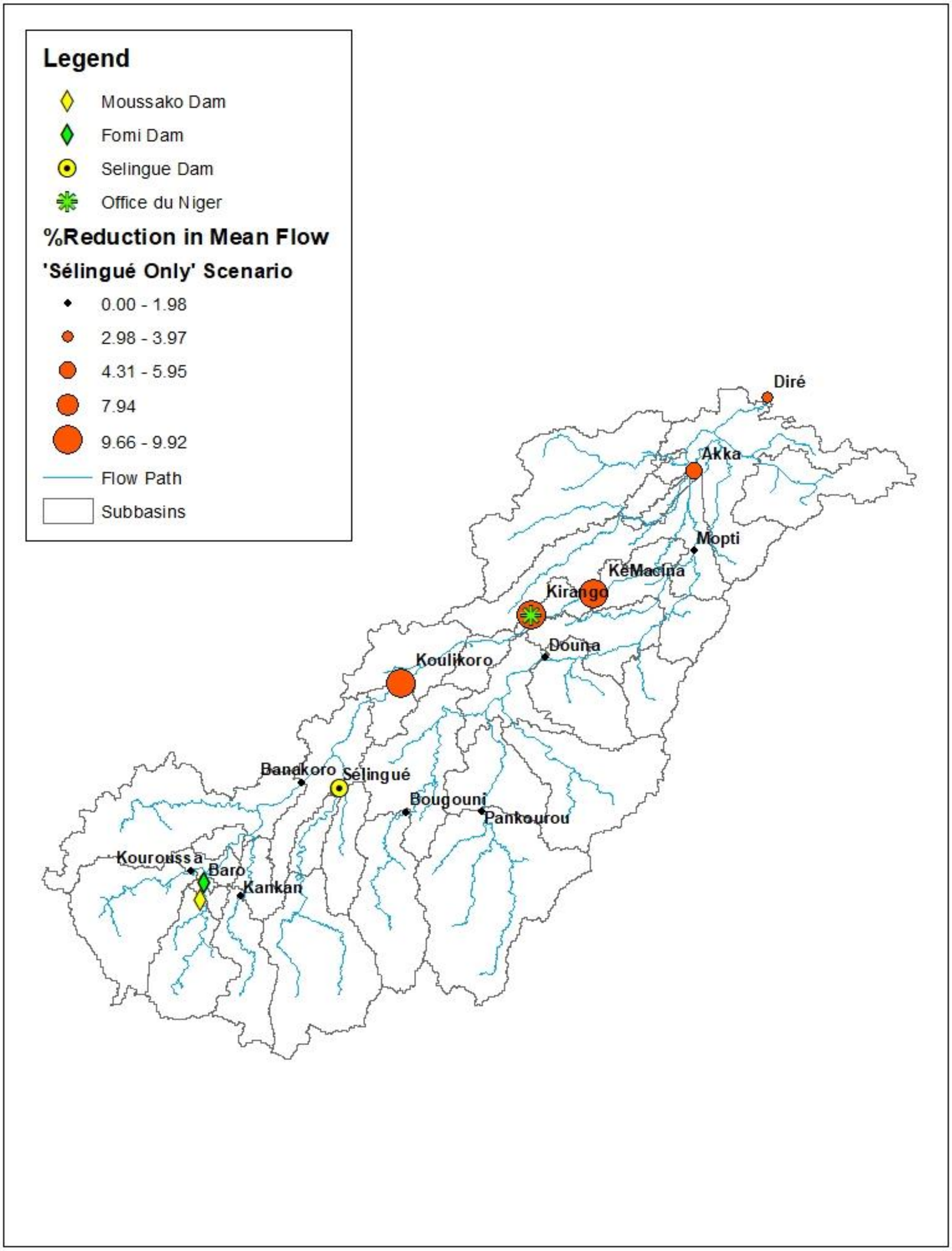


Figure 19: Percent reduction in the mean of the annual flow for the 'Sélingué Only' scenario.

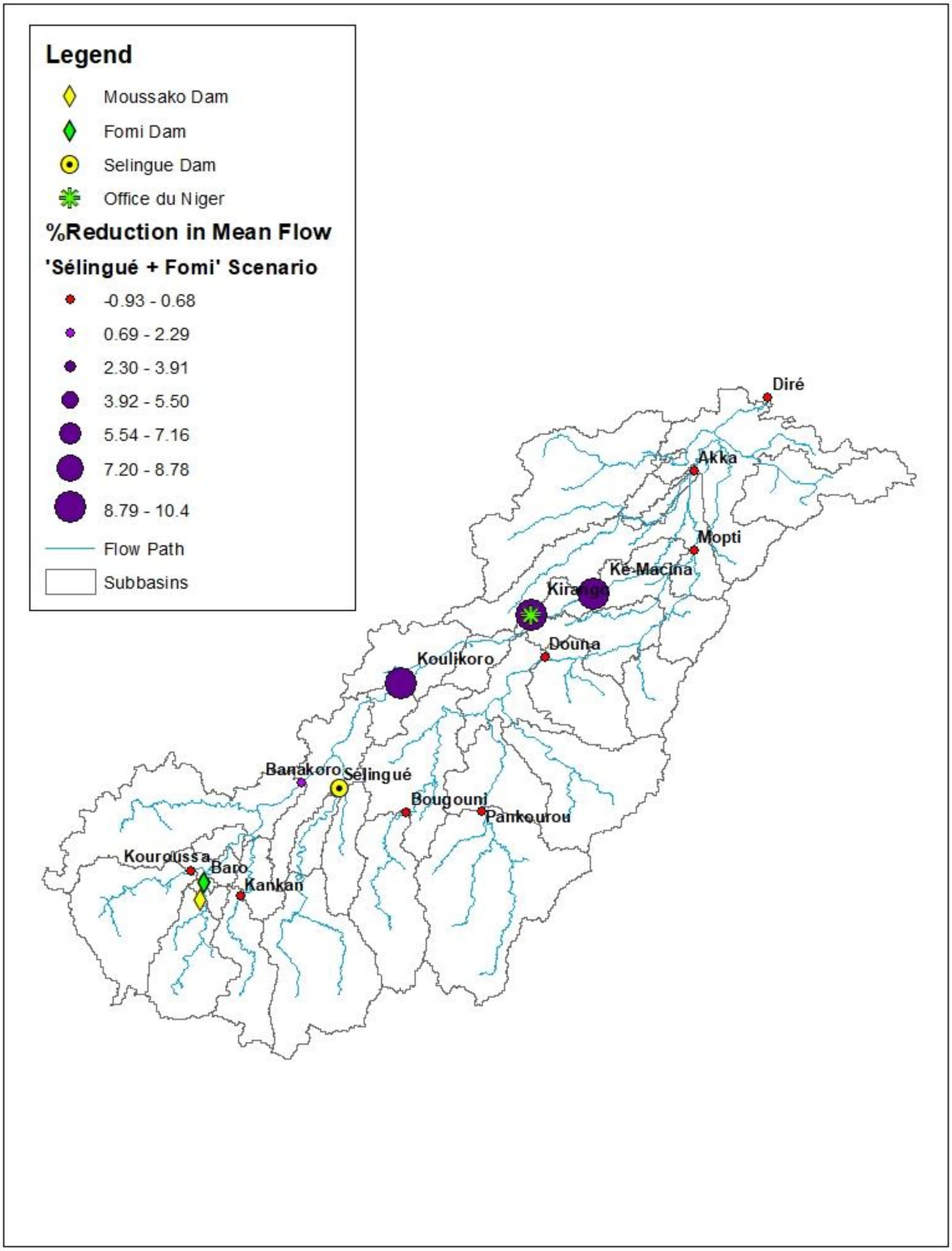


Figure 20: Percent reduction in the mean of the annual flow for the ‘Sélingué + Fomi’ scenario.

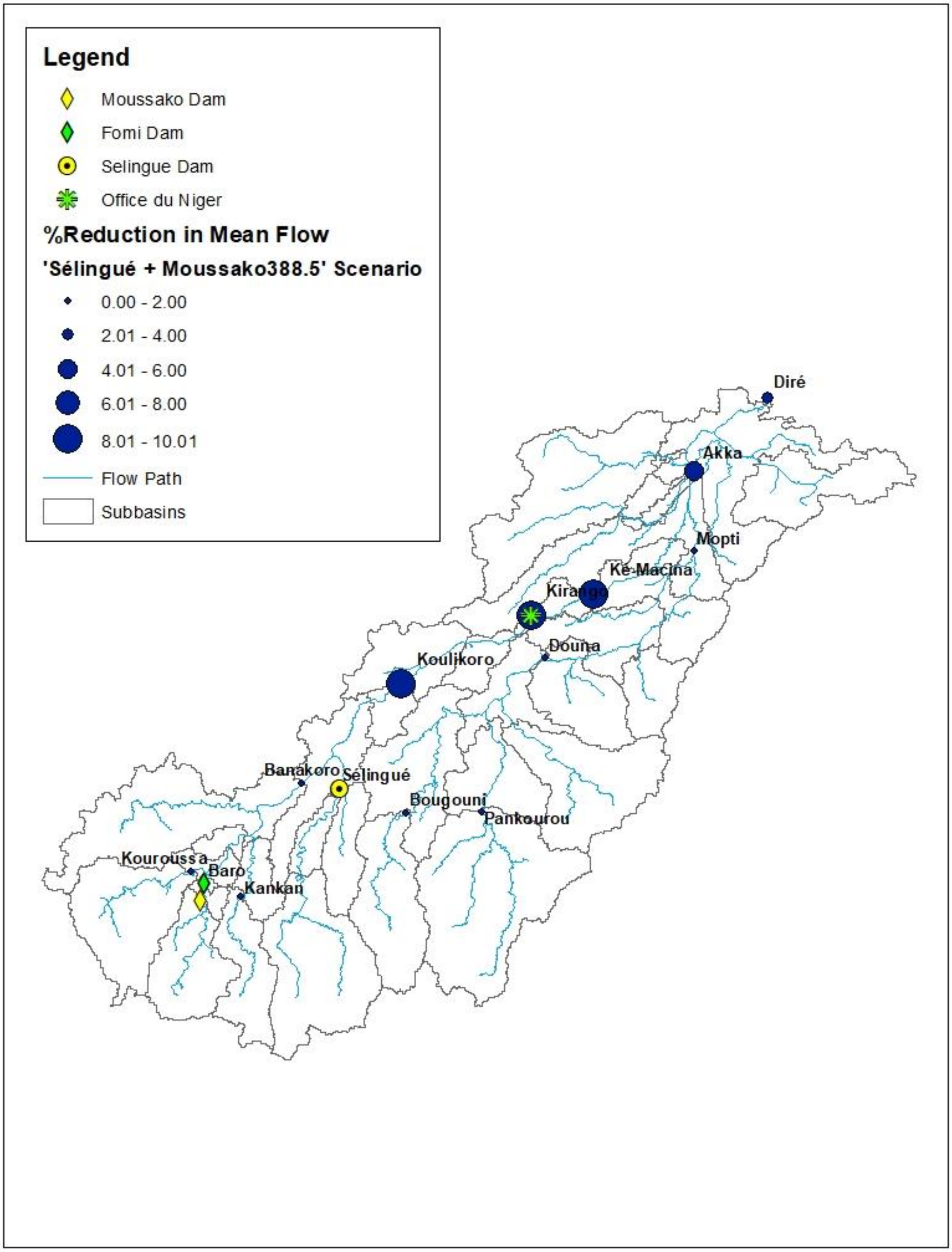


Figure 21: Percent reduction in the mean of the annual flow for the 'Sélingué + Moussako 388.5' scenario.

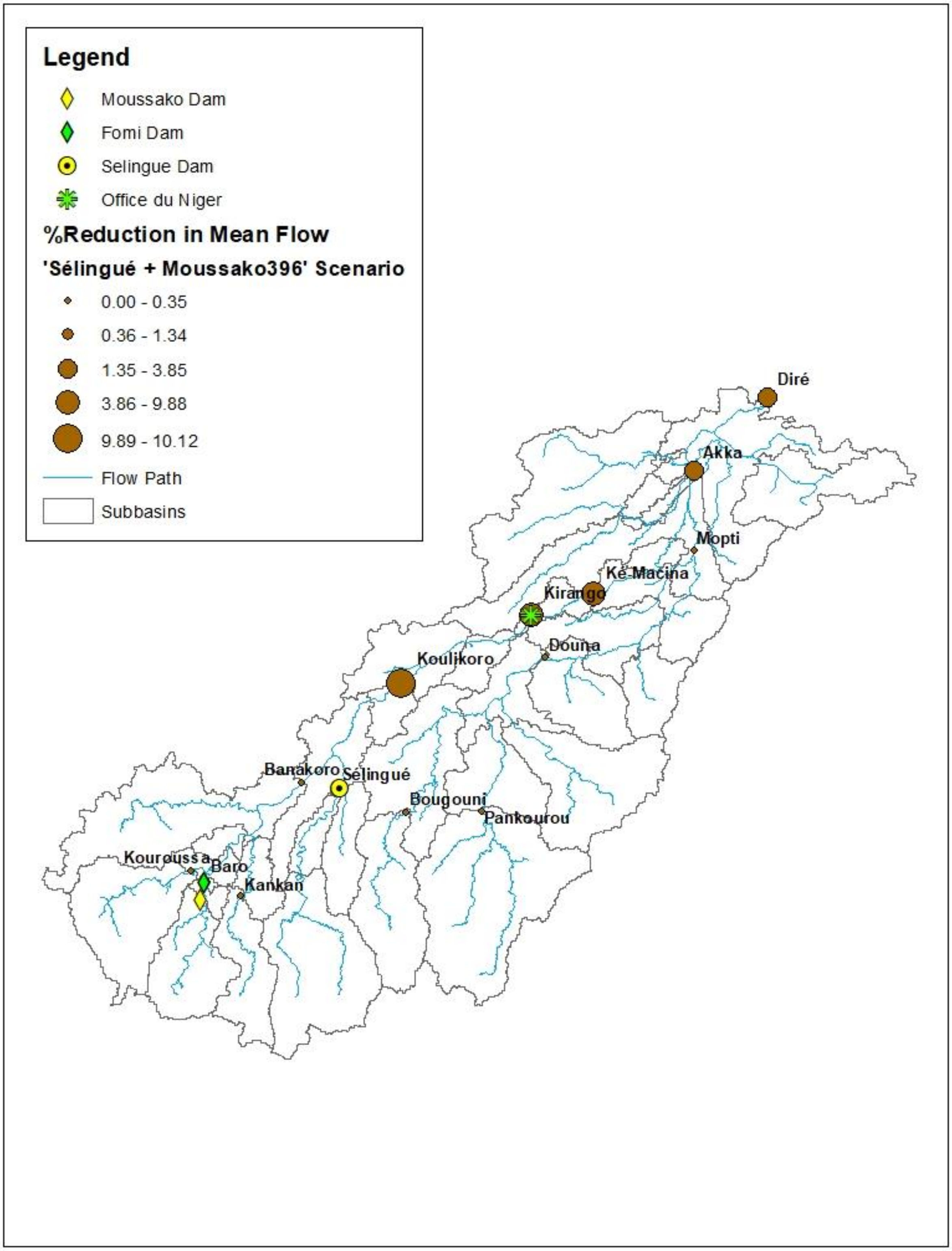


Figure 22: Percent reduction in the mean of the annual flow for the 'Sélingué + Moussako 396' scenario.

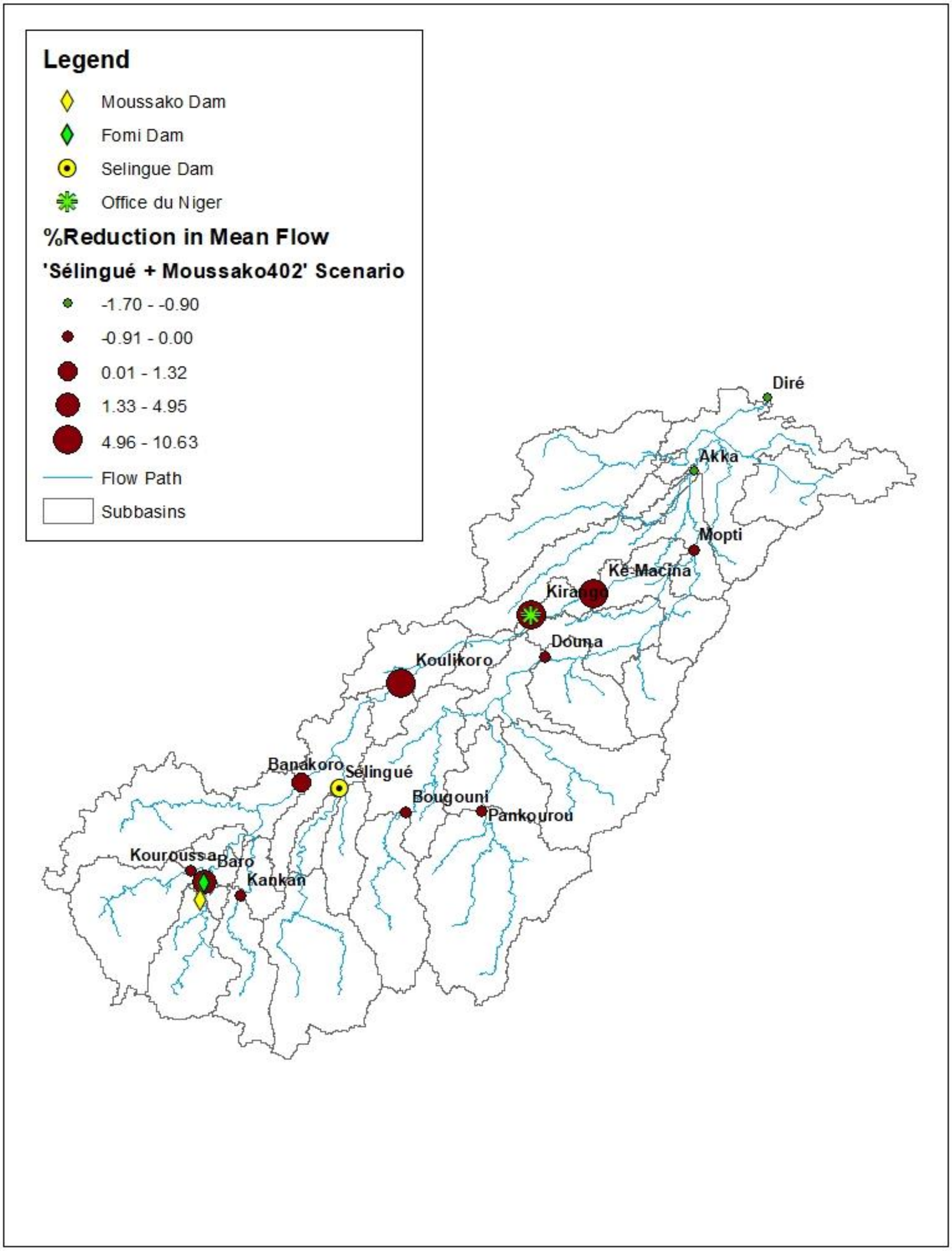


Figure 23: Percent reduction in the mean of the annual flow for the 'Sélingué + Moussako 402' scenario.

In Table 6, Baro is the only station with an increase in standard deviation for all the scenarios (between -10.6% and -86.8%), except for the “Sélingué + Moussako 388.5” scenario (only 0.2%). This increase is explained by the fact that Baro receives a regulated flow since it is directly located downstream of the Fomi/Moussako dam. Based on *Eq. 2*, this means that Baro station flow data are spread out over a wider range of values (farther away from the mean). The least changes in standard deviation are usually observed at Akka and Diré with less than 10% for all the scenarios, implying that the flow data are closer to the mean flow. The “Sélingué only” option has the least change in the standard deviation followed by “Sélingué + Moussako 388.5”, “Sélingué + Moussako 396”, “Sélingué + Fomi”, and “Sélingué + Moussako 402”. This implies that “Sélingué + Moussako 402” has the highest decrease in standard deviation.

Table 6: Reduction in the standard deviation of the annual flow (%) for different river scenarios without OdN.

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-62.494	-86.830	-10.584	0.195
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	8.196	9.043	3.402	0.323
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	13.023	20.420	22.362	15.417	13.185
Kirango	12.732	20.272	22.337	15.136	12.901
Ké-Macina	12.678	20.408	22.727	15.070	12.854
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.761	7.990	8.697	6.392	4.895
Diré	2.318	8.027	9.018	4.952	3.007

b. Effects of Sélingué, Fomi/Moussako and OdN on the Annual Flow

The effect of irrigation was determined on the IND for five different irrigation scenarios (2005, 2015, 2025, 2035 and 2045). The results for the mean and standard deviation (graphics) can be found in Appendix B. Based on *Eq. 3* results, only the stations located downstream of OdN (i.e., Kirango, Ké-Macina, Akka and Diré) experienced a change in flow. Therefore, only the results for those stations will be presented and discussed.

OdN 2005 irrigation scenario:

Table 7 and Table 8 show the '2005 irrigation scenario' analysis results for the reduction in annual flow mean and standard deviation, respectively. These results agree with the general observations from the previous case (i.e., reduction in annual flow mean and standard deviation without OdN), with slight differences in values.

Table 9 and Table 10 show the corresponding change in the mean and the standard deviation, respectively, of the average annual flow due to OdN. For all the scenarios, the mean shows that OdN reduces the annual streamflow by less 1.5%. This flow increases (<5%) when it reaches Akka and Diré, for the "Sélingué + Moussako 396" scenario. This last scenario also shows the biggest reduction in the standard deviation (between 2.3% and 8.1%).

Table 7: Reduction in the mean of the annual flow (%) for different river scenarios with OdN (2005 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	2.727	4.961	4.090	0.619
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	0.731	1.333	1.096	0.162
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	9.821	10.220	10.530	10.406	9.908
Kirango	9.675	10.043	10.330	10.213	9.751
Ké-Macina	9.622	9.959	10.206	10.100	9.688
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.265	0.601	-0.978	-0.947	4.821
Diré	2.965	-0.241	-1.724	-1.677	3.538

Table 8: Reduction in the standard deviation of the annual flow (%) for different river scenarios with OdN (2005 irrigation scenario).

Hydrological Station	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-49.623	-86.830	-82.380	0.195
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	7.289	9.043	8.816	0.323
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	12.852	19.121	22.210	21.670	13.015
Kirango	12.600	18.974	22.229	21.658	12.769
Ké-Macina	12.545	19.048	22.622	21.968	12.720
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.642	7.558	8.581	8.360	4.770
Diré	2.279	7.394	8.959	8.793	2.942

Table 9: Reduction in the mean of the annual flow (%) due to Office du Niger (2005 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	0.742	0.699	0.617	0.697	1.094	0.694
Ké-Macina	0.740	0.693	0.618	0.692	1.038	0.685
Akka	0.504	0.456	1.208	0.436	-4.469	0.456
Diré	0.398	0.382	1.082	0.374	-4.047	0.375

Table 10: Reduction in the standard deviation of the annual flow (%) due to Office du Niger (2005 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	0.471	0.322	-1.149	0.332	8.120	0.321
Ké-Macina	0.469	0.318	-1.232	0.334	8.554	0.316
Akka	0.179	0.055	-0.289	0.053	2.278	0.047
Diré	0.110	0.071	-0.578	0.045	4.147	0.043

OdN 2015 irrigation scenario:

Table 11 and Table 12 show the '2015 irrigation scenario' analysis results for the flow mean and standard deviation, respectively. One again, the results agree with the general observations from the previous case (i.e., reduction in annual flow mean and standard deviation without OdN), usually with slight differences in values.

Table 13 and Table 14 show the change in the mean and the standard deviation, respectively, of the average annual flow due to OdN. For all the scenarios according to the mean values, OdN 2015 irrigation scenario reduces the annual streamflow by less than 1.5%. This flow increases (<5%) when it reaches Akka and Diré subwatersheds, for the "Sélingué + Moussako 396" and "Sélingué + Moussako 388.5" scenarios. These last two scenarios also present the biggest reduction in the standard deviation due to OdN (up to 9% at Ké-Macina).

Table 11: Reduction in the mean of the annual flow (%) for different river scenarios with OdN (2015 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	3.289	4.961	4.090	3.289
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	0.881	1.333	1.096	0.881
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	9.921	10.399	10.629	10.506	10.399
Kirango	9.800	10.240	10.455	10.338	10.240
Ké-Macina	9.748	10.146	10.327	10.221	10.146
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.331	-0.100	-0.915	-0.885	-0.100
Diré	3.009	-0.905	-1.680	-1.632	-0.905

Table 12: Reduction in the standard deviation of the annual flow (%) for different river scenarios with OdN (2015 irrigation scenario).

Hydrological Station	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-62.494	-86.830	-82.380	-62.494
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	8.196	9.043	8.816	8.196
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	13.023	20.420	22.362	21.823	20.420
Kirango	12.773	20.321	22.384	21.814	20.321
Ké-Macina	12.718	20.454	22.774	22.121	20.454
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.754	7.969	8.686	8.465	7.969
Diré	2.349	8.018	9.008	8.844	8.018

Table 13: Reduction in the mean of the annual flow (%) due to Office du Niger (2015 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	0.895	0.989	0.987	0.989	1.384	1.386
Ké-Macina	0.892	0.983	0.976	0.978	1.322	1.340
Akka	0.658	0.678	0.664	0.653	-4.243	-4.530
Diré	0.544	0.573	0.572	0.562	-3.849	-4.062

Table 14: Reduction in the standard deviation of the annual flow (%) due to Office du Niger (2015 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	0.322	0.369	0.384	0.382	8.165	8.814
Ké-Macina	0.321	0.367	0.380	0.382	8.597	9.014
Akka	0.018	0.011	-0.005	0.006	2.232	3.249
Diré	0.024	0.056	0.014	0.013	4.118	5.189

OdN 2025 irrigation scenario:

Table 15 and Table 16 show the ‘2025 irrigation scenario’ analysis results for the annual flow mean and standard deviation, respectively. The results are similar to the ‘2015 irrigation scenario’, with slight differences in values.

Table 17 and Table 18 show the change in the mean and the standard deviation, respectively, of the average annual flow due to OdN. For all the scenarios according to the mean values, OdN 2025 irrigation scenario reduces the annual streamflow by less than 2%. This flow increases (<4.5%) when it reaches Akka and Diré, for the “Sélingué + Moussako 396” and “Sélingué + Moussako 388.5” scenarios. These last two scenarios also present the biggest reduction in the standard deviation due to OdN (up to 9.2% at Ké-Macina).

Table 15: Reduction in the mean of the annual flow (%) for different river scenarios with OdN (2025 irrigation scenario).

Hydrological Station	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	2.727	4.961	4.090	3.289
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	0.731	1.333	1.096	0.881
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	9.921	10.320	10.629	10.506	10.399
Kirango	9.835	10.267	10.559	10.370	10.342
Ké-Macina	9.783	10.186	10.432	10.254	10.248
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.336	0.778	-0.811	-0.852	0.005
Diré	3.020	-0.097	-1.590	-1.601	-0.810

Table 16: Reduction in the standard deviation of the annual flow (%) for different river scenarios with OdN (2025 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-49.623	-86.830	-82.380	-62.494
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	7.289	9.043	8.816	8.196
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	13.023	19.280	22.362	21.823	20.420
Kirango	12.799	19.144	22.401	21.884	20.332
Ké-Macina	12.743	19.219	22.793	22.193	20.466
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.758	7.634	8.666	8.499	7.939
Diré	2.365	7.413	8.967	8.847	7.981

Table 17: Reduction in the mean of the annual flow (%) due to Office du Niger (2025 irrigation scenario).

Hydrological Station	**No Dams**	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kirango	1.272	1.404	1.394	1.479	1.795	1.872
Ké-Macina	1.264	1.394	1.392	1.465	1.729	1.822
Akka	0.859	0.883	1.735	0.956	-3.999	-4.209
Diré	0.710	0.750	1.533	0.816	-3.644	-3.790

Table 18: Reduction in the standard deviation of the annual flow (%) due to Office du Niger (2025 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	0.499	0.576	-0.909	0.580	8.411	8.988
Ké-Macina	0.496	0.571	-0.990	0.582	8.842	9.187
Akka	0.095	0.092	-0.291	0.061	2.344	3.292
Diré	0.077	0.125	-0.591	0.020	4.171	5.201

OdN 2035 irrigation scenario:

Table 19 and Table 20 show the ‘2035 irrigation scenario’ analysis results for the flow mean and standard deviation, respectively. The results are similar to the ‘2025 irrigation scenario’, with usually slightly lower values for the mean.

Table 21 and Table 22 show the change in the mean and the standard deviation, respectively, of the average annual flow due to OdN. For all the scenarios according to the mean values, OdN 2035 irrigation scenario reduces the annual flow by less than 3%. This flow increases (<4%) when it reaches Akka and Diré, for the “Sélingué + Moussako 396” and “Sélingué + Moussako 388.5” scenarios. These last two scenarios also present the highest reduction in the standard deviation due to OdN (up to 9.4% at Ké-Macina).

Table 19: Reduction in the mean of the annual flow (%) for different river scenarios with OdN (2035 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	3.375	4.961	4.730	3.289
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	0.929	1.333	1.292	0.881
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	9.921	10.440	10.629	10.625	10.399
Kirango	9.897	10.374	10.546	10.546	10.328
Ké-Macina	9.844	10.292	10.420	10.431	10.236
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.358	0.795	-0.881	-0.768	-0.055
Diré	3.034	-0.085	-1.636	-1.536	-0.847

Table 20: Reduction in the standard deviation of the annual flow (%) for different river scenarios with OdN (2035 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-49.391	-86.830	-82.280	-62.494
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	7.626	9.043	9.102	8.196
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	13.023	19.485	22.362	22.008	20.420
Kirango	12.811	19.441	22.504	22.113	20.430
Ké-Macina	12.757	19.514	22.896	22.426	20.563
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.759	7.832	8.767	8.648	8.034
Diré	2.363	7.509	9.010	8.896	8.030

Table 21: Reduction in the mean of the annual flow (%) due to Office du Niger (2035 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	1.900	2.099	2.138	2.092	2.611	2.482
Ké-Macina	1.888	2.084	2.131	2.075	2.543	2.429
Akka	1.308	1.356	2.196	1.335	-3.442	-3.799
Diré	1.082	1.136	1.914	1.143	-3.190	-3.439

Table 22: Reduction in the standard deviation of the annual flow (%) due to Office du Niger (2035 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	0.586	0.677	-0.450	0.800	8.760	9.181
Ké-Macina	0.583	0.673	-0.534	0.801	9.194	9.377
Akka	0.033	0.032	-0.138	0.110	2.443	3.332
Diré	0.033	0.080	-0.531	0.024	4.180	5.210

OdN 2045 irrigation scenario:

Table 23 and Table 24 show the ‘2045 irrigation scenario’ analysis results for the flow mean and standard deviation, respectively. The results follow the same trend as the ‘2035 irrigation scenario’, usually with slightly lower values for the mean.

Table 25 and Table 26 show the change in the mean and the standard deviation, respectively, of the average annual flow due to OdN. For all the scenarios according to the mean values, OdN 2045 irrigation scenario reduces the annual flow by less than 3.5%. This flow increases (<3.5%) when it reaches Akka and Diré, for the “Sélingué + Moussako 396” and “Sélingué + Moussako 388.5” scenarios. These last two scenarios also present the highest reduction in the standard deviation due to OdN (up to 9.7% at Ké-Macina).

Table 23: Reduction in the mean of the annual flow (%) for different river scenarios with OdN (2045 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	3.375	5.605	4.730	3.289
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	0.929	1.531	1.292	0.899
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	9.937	10.440	10.750	10.625	10.416
Kirango	9.978	10.434	10.726	10.606	10.404
Ké-Macina	9.922	10.347	10.596	10.487	10.309
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.478	0.853	-0.772	-0.731	0.085
Diré	3.124	-0.026	-1.545	-1.496	-0.742

Table 24: Reduction in the standard deviation of the annual flow (%) for different river scenarios with OdN (2045 irrigation scenario).

Hydrological Station	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-49.391	-86.653	-82.280	-62.494
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	7.626	9.331	9.102	8.249
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	13.068	19.485	22.543	22.008	20.459
Kirango	12.880	19.517	22.771	22.201	20.550
Ké-Macina	12.824	19.585	23.166	22.510	20.680
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	4.888	7.878	8.915	8.712	8.200
Diré	2.431	7.502	9.053	8.891	8.072

Table 25: Reduction in the mean of the annual flow (%) due to Office du Niger (2045 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	2.536	2.821	2.837	2.923	3.307	3.196
Ké-Macina	2.520	2.799	2.821	2.897	3.231	3.137
Akka	1.700	1.870	2.642	1.834	-2.992	-3.243
Diré	1.404	1.549	2.291	1.553	-2.812	-2.994

Table 26: Reduction in the standard deviation of the annual flow (%) due to Office du Niger (2045 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	0.746	0.914	-0.193	1.300	9.009	9.463
Ké-Macina	0.743	0.909	-0.283	1.307	9.439	9.656
Akka	0.053	0.187	-0.068	0.292	2.530	3.526
Diré	0.045	0.161	-0.525	0.084	4.188	5.265

6.2. Effects of Sélingué, Fomi/Moussako and OdN on the Flow of the Wettest Month of the Year

a. Effects of Sélingué and Fomi/Moussako on the Flow of the Wettest Month of the Year (without OdN)

This section determines the effects of dams (without irrigation) on the UNB and the IND wettest month flow of the year. The results for the flow mean and the standard deviation at each station are shown in Appendix B. The corresponding percent reduction in the mean and standard deviation are presented in Table 27 and Tableau 28, respectively. Table 27 also shows the wettest month of the year for the different stations. From this last table, the mean flow of the wettest month faces the least impact at Diré with a decrease smaller than 6%, followed by Akka with a decrease in flow smaller than 12%. A more significant decrease is observed on the stream flow at Banakoro (12.5% to 22.7%), Ké-Macina (13.2% to 26.4%), Kirango (13.3% to 26.3%), Koulikoro (13.6% to 26.8%), and Baro (45.7% to 82.5%).

Looking at the different scenarios, the “Sélingué only” option shows the least impact on the flows for all the stations. Comparing Fomi to the Moussako alternative sites, “Sélingué + Fomi” shows the least decrease on mean flow, follow by “Sélingué + Moussako 388.5”. For the wettest month flow of the year, the “Sélingué + Moussako 402” option also seems to be the least favorable scenario, but this time for all the stations.

Comparing the results of the annual flow to the current results, it can be observed that the reservoirs (Sélingué and Fomi/Moussako) have a much bigger impact on the wettest month flow of the year than on the annual flow. As previously discussed (Chapter 3), one of the main functions of reservoirs is to reduce the pic flows during the wet season by storing the water and releasing it during low flow season, to compensate for water deficits. This means for the IND that in addition to the Sélingué dam, the Fomi/Moussako dam could help reduce the risks for floods. The Fomi reservoir can deliver additional and stable electricity supply in the UNB and increased food production to meet the needs of the growing population in the IND, at least during the wet season.

Table 27: Reduction in the mean (%) of the wettest month flow of the year for different river scenarios without OdN.

Hydrological Station	Wettest Month of the Year	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kankan	September	0.000	0.000	0.000	0.000	0.000
Baro	September	0.000	45.707	82.483	77.779	61.764
Kouroussa	September	0.000	0.000	0.000	0.000	0.000
Banakoro	September	0.000	12.493	22.649	21.346	16.920
Sélingué	September	N/A	0.000	0.000	0.000	0.000
Koulikoro	September	13.571	21.311	26.791	26.103	23.743
Kirango	September	13.275	20.974	26.266	25.607	23.328
Ké-Macina	September	13.241	21.447	26.442	25.842	23.716
Bougouni	September	0.000	0.000	0.000	0.000	0.000
Pankourou	September	0.000	0.000	0.000	0.000	0.000
Douna	September	0.000	0.000	0.000	0.000	0.000
Mopti	October	0.000	0.000	0.000	0.000	0.000
Akka	October	6.672	10.145	11.967	11.930	11.236
Diré	November	2.692	4.482	5.370	5.299	4.835

While all the other stations show a decrease in the standard deviation, Baro (-40.7% to -62.6%), Banakoro (-1.6% to -15.4%), and Diré (-4.6% to -12.6%) show an increase for all the scenarios. Akka that previously (in the annual flow) showed the least change in the standard deviation, now shows the highest decrease in standard deviation with values between 10.3% and 20.5%. This could indicate that for the wettest month of the year at Akka, the presence of dams further reduces the gap between the mean and the flow values, compared to the yearly flow.

Table 28: Reduction in the standard deviation (%) of the wettest month flow of the year for different river scenarios without OdN.

Hydrological Station	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-61.487	-40.739	-47.384	-62.648
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	-15.403	-1.638	-3.002	-13.103
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	14.945	6.316	15.249	13.889	7.670
Kirango	14.690	6.392	15.219	13.920	7.876
Ké-Macina	14.341	6.256	15.534	14.176	8.244
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	10.260	15.356	20.489	20.218	17.744
Diré	-4.615	-12.657	-11.465	-11.670	-12.263

b) Effects of Sélingué, Fomi/Moussako and OdN on the Flow of the Wettest Month of the Year

This section determines the effects caused by the ‘2005 irrigation scenario’ on the IND wettest months flows. The results for the mean and standard deviation of the flow are shown in Appendix B. As expected, only the stations located downstream of OdN (i.e., Kirango, Ké-Macina, Akka and Diré) experienced a change in flow. Therefore, only the results for those stations are presented.

Table 29 and Table 30 show the ‘2005 irrigation scenario’ analysis results for the reduction in the wettest month flow mean and standard deviation, respectively. These results agree with the same general observations as the previous case (i.e., reduction in the wettest month flow mean and standard deviation without OdN), with slight differences in values.

Table 31 and Table 32 show the change in the mean and the standard deviation, respectively, of the wettest month flow due to OdN. For all the scenarios, the mean shows that OdN reduces the wettest month flow for each station by less 0.6%. The change in the standard deviation is neglectable for all the cases with a maximum value of -0.5% at Diré station.

Table 29: Reduction in the mean (%) of the wettest month flow of the year for different river scenarios with OdN (2005 irrigation scenario).

Hydrological Station	**Wettest Month**	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	September	0.000	0.000	0.000	0.000	0.000
Baro	September	0.000	45.707	82.483	77.779	61.764
Kouroussa	September	0.000	0.000	0.000	0.000	0.000
Banakoro	September	0.000	12.493	22.649	21.346	16.920
Sélingué	September	N/A	0.000	0.000	0.000	0.000
Koulikoro	September	13.571	21.311	26.791	26.103	23.743
Kirango	September	13.329	21.061	26.374	25.712	23.424
Ké-Macina	September	13.294	21.531	26.547	25.945	23.810
Bougouni	September	0.000	0.000	0.000	0.000	0.000
Pankourou	September	0.000	0.000	0.000	0.000	0.000
Douna	September	0.000	0.000	0.000	0.000	0.000
Mopti	October	0.000	0.000	0.000	0.000	0.000
Akka	October	6.642	10.115	11.904	11.821	11.163
Diré	November	2.726	4.500	5.392	5.311	4.843

Table 30: Reduction in the standard deviation (%) of the wettest month flow of the year for different river scenarios with OdN (2005 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	-61.487	-40.739	-47.384	-62.648
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	-15.403	-1.638	-3.002	-13.103
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	14.945	6.316	15.249	13.889	7.670
Kirango	14.689	6.399	15.220	13.921	7.879
Ké-Macina	14.344	6.251	15.539	14.178	8.231
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	10.342	15.250	20.496	19.933	17.429
Diré	-4.414	-12.560	-11.484	-11.780	-12.341

Table 31: Reduction in the mean (%) of the wettest month flow of the year due to Office du Niger (2005 irrigation scenario).

Hydrological Station	**No Dams**	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kirango	0.411	0.473	0.521	0.557	0.552	0.536
Ké-Macina	0.401	0.462	0.508	0.544	0.539	0.523
Akka	0.222	0.190	0.189	0.151	0.099	0.141
Diré	0.112	0.146	0.131	0.135	0.125	0.120

Table 32: Reduction in the standard deviation (%) of the wettest month flow of the year due to Office du Niger (2005 irrigation scenario).

Hydrological Station	**No Dams**	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kirango	-0.0001	-0.0010	0.0069	0.0006	0.0005	0.0029
Ké-Macina	0.0063	0.0098	0.0009	0.0114	0.0086	-0.0075
Akka	0.0025	0.0947	-0.1224	0.0112	-0.3553	-0.3802
Diré	-0.4259	-0.2331	-0.3389	-0.4430	-0.5242	-0.4959

6.3. Effects of Sélingué, Fomi/Moussako and OdN on the Flow of the Driest Month of the Year

Before discussing the results for this section, it is important to acknowledge that the software used to perform the simulations (SWAT) is not very suitable for low flows. In real life practice, a reservoir volume is normally prevented from reaching zero at all time. Dams are operated in a way that the flow in the reservoir does not go below a certain threshold (minimum flow). SWAT does not have a function that can associates a reservoir operation rules to the low flows. In others words, the program does not allow the user to set a minimum flow for the reservoirs during low flows. Therefore, the dams will not show an increase in the flow during the low season as expected. Rather, the results give an indication of how drought can affect the UNB and IND flows.

a) Effects of Sélingué and Fomi/Moussako on the Flow of the Driest Month of the Year (without OdN)

This section determines the effects of dams (without irrigation) on the flow of the UNB and the IND driest month of the year. The flow mean and standard deviation at each station are shown in Appendix B. The results for the percent reduction in the mean is shown in Table 33 and for the standard deviation, in Table 34. Table 33 also shows the driest month of the year for the different stations. For most cases (scenarios) the mean flow of the driest month experiences the least impact at Diré (-8.4% to 2%), followed by Akka (6.6% to 23.3%), Banakoro (12.5% to 22.7%), Ké-Macina (4.0% to 31.4%), Kirango (4.5% to 32.7%), Koulikoro (4.7% to 33.1%). Baro (located directly downstream of Fomi) has a very dramatic flow decrease varying from 58.5% for "Sélingué + Moussako 388.5" to 99.6% for "Sélingué + Fomi". In other words, this means that for the driest month of the year there is practically no water left to flow through Baro station if the Fomi dam existed in the river. The negative values in the mean flow of Diré imply an increase in flow, which does not comply with the tendency and expected results for the driest month of the year. This kind of result is most likely explained by the limitations (sources of errors) of this model, discussed later on in the report. Looking at the different scenarios, the "Sélingué only" option shows the least impact on the flow for all the stations (except Diré). Comparing Fomi to the Moussako alternatives, "Sélingué + Fomi" produces the highest impact and 'Sélingué + Moussako 388.5' usually produces the lowest impact on the mean flow.

Comparing the results of the annual mean flow to the current results, it can be observed that the Fomi/Moussako reservoir have a bigger impact on the driest month flow of the year than on the annual flow (except for Diré). However, the 'Sélingué Only' option shows the opposite behavior with a bigger impact on the annual flow, except at Akka station.

Now comparing the results of the wettest month of the year to the current results, for most scenarios the Fomi/Moussako reservoir shows a bigger impact on the driest month flow than on the wettest month flow (except for Diré). Although, the 'Sélingué + Moussako 388.5' scenario shows relatively similar values to those of the wettest month flow. Here again the 'Sélingué Only' scenario shows the opposite behavior, with a bigger impact on the annual flow than on the driest month flow of the year, except at Akka station.

Table 33: Reduction in the mean (%) of the driest month flow of the year for different river scenarios without OdN.

Hydrological Station	**Driest Month of the Year**	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	April	0.000	0.000	0.000	0.000	0.000
Baro	April	0.000	99.588	93.854	93.666	58.394
Kouroussa	April	0.000	0.000	0.000	0.000	0.000
Banakoro	April	0.000	28.036	26.360	25.925	16.111
Sélingué	May	N/A	0.000	0.000	0.000	0.000
Koulikoro	May	4.684	33.103	30.763	28.759	24.073
Kirango	May	4.484	32.692	30.347	27.729	23.494
Ké-Macina	May	4.062	31.430	29.130	26.255	22.847
Bougouni	June	0.000	0.000	0.000	0.000	0.000
Pankourou	June	0.000	0.000	0.000	0.000	0.000
Douna	may	0.000	0.000	0.000	0.000	0.000
Mopti	June	0.000	0.000	0.000	0.000	0.000
Akka	June	6.655	23.339	21.542	10.979	10.137
Diré	June	0.804	-8.368	-4.401	-0.318	2.026

All the stations show a decrease in the standard deviation. Baro usually shows the highest decrease in standard deviation up to 99.6% for the ‘Sélingué + Fomi’ scenario and Diré shows the lowest (up to 20.6%).

Table 34: Reduction in the standard deviation (%) of the driest month flow of the year for different river scenarios without OdN.

Hydrological Station	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	99.605	92.651	92.149	10.726
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	32.549	31.086	30.150	5.540
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	2.610	46.765	42.566	42.117	34.328
Kirango	2.328	47.481	43.359	42.134	35.274
Ké-Macina	1.768	45.825	42.009	40.335	35.317
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	8.197	32.844	30.111	17.782	15.602
Diré	7.580	12.914	13.573	20.626	14.326

b) Effects of Sélingué, Fomi/Moussako and OdN on the Flow of the Driest Month of the Year

This section determines the effects caused by the ‘2005 irrigation scenario’ on the IND driest months flows. The mean and standard deviation of the flow are shown in Appendix B. Table 35 and Table 36 show the reduction in the mean and the standard deviation, respectively, of the driest month flow for the 2005 irrigation scenario. These results mostly agree with the previous case general observations (without OdN), with slight differences in values.

Table 35: Reduction in the mean (%) of the driest month flow of the year for different river scenarios with OdN (2005 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	99.588	93.854	93.666	58.394
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	28.036	26.360	25.925	16.111
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	4.684	33.103	30.763	28.759	24.073
Kirango	0.070	33.278	30.554	30.554	24.248
Ké-Macina	-0.687	30.868	28.271	28.271	23.004
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	-3.746	13.535	11.732	11.257	9.559
Diré	0.199	-9.483	-5.075	-0.337	1.969

Table 36: Reduction in the standard deviation (%) of the driest month flow of the year for different river scenarios with OdN (2005 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	99.605	92.651	92.149	10.726
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	32.549	31.086	30.150	5.540
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	2.610	46.765	42.566	42.117	34.328
Kirango	0.084	45.615	41.551	41.551	33.355
Ké-Macina	-1.062	43.602	39.847	39.847	33.543
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	-3.923	20.878	17.918	16.992	13.468
Diré	12.372	15.505	19.402	21.003	14.176

Table 37 and Table 38 show the change in the mean and the standard deviation, respectively, of the driest month flow due to OdN. For all the scenarios, the mean shows that OdN reduces the driest month flow between 10.1% and 17.4% for Kirango, 8.2% to 14.9% at Ké-Macina, up to 11.6% at Akka and less than 1.5% at Diré. For most cases, the change in the standard deviation is no greater than 5%, except for Akka with a decrease in standard deviation of up to 18%.

Table 37: Reduction in the mean (%) of the driest month flow of the year due to Office du Niger (2005 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	14.05	10.08	14.80	14.31	17.41	14.90
Ké-Macina	12.50	8.16	11.78	11.44	14.89	12.67
Akka	11.29	1.40	-0.06	0.19	11.56	10.71
Diré	1.10	0.50	0.08	0.46	1.08	1.04

Table 38: Reduction in the standard deviation (%) of the driest month flow of the year due to Office du Niger (2005 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	1.3417	-0.9258	-2.1637	-1.8072	0.3490	-1.5844
Ké-Macina	1.6548	-1.1786	-2.3814	-2.0109	0.8516	-1.0414
Akka	-0.149	-13.370	-17.993	-17.621	-1.112	-2.681
Diré	-0.186	5.009	2.794	6.570	0.289	-0.362

6.4. Effects of Sélingué, Fomi/Moussako and OdN on the Driest Month of the Driest Year Flow

This section determiner the effects of dams and irrigation on the flow of the UNB and the IND during extreme drought, by evaluating the driest month of the driest year flow. The results give an indication of how extreme drought can affect the UNB and IND flows. The flow values (graphs) are shown in Appendix B.

a) Effects of Sélingué and Fomi/Moussako on the Flow of the Driest Month of the Driest Year (without OdN)

Table 39 shows the percent reduction in the driest month of the driest year flow, as well as the driest month of the year for the different scenarios. The change in flow is not very relevant here since the simulated flow is very low (less than 10 m^3/s), except for Diré where the flow varies between 85 m^3/s and 100 m^3/s for the different scenarios. At many of the stations, the simulated flow was nearly zero (Appendix B). As explained in the previous section, this is not a reflection of realistic dam management practices (i.e., a reservoir minimum flow is usually maintained greater than zero at all time). On the other hand, the observed data for the driest month of the driest year flow also present low values (0 m^3/s - 16 m^3/s) except for the Sélingué reservoirs with a minimum flow of 21.6 m^3/s. This also means that the simulated flow for Diré was greatly overestimated, therefore not very conclusive. Comparing the scenarios, the results suggest that 'Sélingué + Fomi' is usually the least favorable scenario, which is in agreement with the driest month flow analysis results.

An extreme drought will have detrimental effects on the IND ecosystem and populations. Some of the impacts could include the following:

- Vital resources such as food and water will be very limited or worse, completely depleted. Consequently, the people in surrounding villages and the animals will have no other choice than to leave the area and relocation to other cities or abroad, for their survival.
- Loss in the IND ecosystem diversity through migration and death of many species and plants. The available limited resources will cause high feeding densities, high population concentrations, and competition with local people.
- In general, the drought will affect Mali's population and the economy as the country main sources of energy production is hydropower. Presently, during the dry season, Mali is not

able to meet electricity demand for many regions, which leads to frequent power shortage. This power shortage will be even more aggravated in periods of extreme drought.

Thus, Mali will face a challenge in making the choice between releasing more water during the dry season to meet OdN agricultural demand and moving toward food security or keeping the water in the reservoir to produce more hydropower and meet the power demand.

Table 39: Reduction in the flow (%) of the driest month and year for different river scenarios without OdN.

Hydrological Station	**Period (Month-Year)**	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	4-1982	0.000	0.000	0.000	0.000	0.000
Baro	4-1992	0.000	96.210	0.000	0.000	0.000
Kouroussa	4-1984	0.000	0.000	0.000	0.000	0.000
Banakoro	4-1984	0.000	1.923	0.000	0.000	0.000
Sélingué	5-1984	N/A	0.000	0.000	0.000	0.000
Koulikoro	5-1984	20.463	21.639	20.463	20.463	20.463
Kirango	5-1984	22.681	24.095	22.681	22.681	22.681
Ké-Macina	5-1984	22.059	23.433	22.059	22.059	22.059
Bougouni	6-1985	0.000	0.000	0.000	0.000	0.000
Pankourou	6-1987	0.000	0.000	0.000	0.000	0.000
Douna	5-2003	0.000	0.000	0.000	0.000	0.000
Mopti	6-1985	0.000	0.000	0.000	0.000	0.000
Akka	6-1985	12.408	13.284	12.408	12.408	12.408
Diré	6-1983	0.283	-4.595	0.283	7.201	10.802

b) Effects of Sélingué, Fomi/Moussako and OdN on the Flow of the Driest Month of the Driest Year

This section determines the effects of the '2005 irrigation scenario' on the IND flow for the driest month of the driest year. Table 40 shows the percent reduction in the driest month of the driest year flow for the 2005 irrigation scenario. These results follow the same general observations as the previous case (flow of the driest month of the driest year without OdN) but with a further decrease in the values, especially at Kirango. Again, since the flow values are quite small, these percent changes are not very significant.

Table 41 shows the corresponding flow change due to OdN (from *Eq. 3*). For all the scenarios, the mean shows that OdN reduces the driest month flow between 89.4% and 97.5% for Kirango, 66.5% to 71.0% at Ké-Macina, 57.9% to 62.8% at Akka, and by less than 1.5% at Diré.

Table 40: Reduction in the flow (%) of the driest month and year for different river scenarios with OdN (2005 irrigation scenario).

Hydrological Station	**Sélingué Only**	**Sélingué + Fomi**	**Sélingué + Moussako 402**	**Sélingué + Moussako 396**	**Sélingué + Moussako 388.5**
Kankan	0.000	0.000	0.000	0.000	0.000
Baro	0.000	96.210	0.000	0.000	0.000
Kouroussa	0.000	0.000	0.000	0.000	0.000
Banakoro	0.000	1.923	0.000	0.000	0.000
Sélingué	N/A	0.000	0.000	0.000	0.000
Koulikoro	20.463	21.639	20.481	20.481	20.481
Kirango	80.546	82.277	81.166	81.166	81.166
Ké-Macina	32.469	33.648	32.658	32.658	32.658
Bougouni	0.000	0.000	0.000	0.000	0.000
Pankourou	0.000	0.000	0.000	0.000	0.000
Douna	0.000	0.000	0.000	0.000	0.000
Mopti	0.000	0.000	0.000	0.000	0.000
Akka	21.957	23.403	22.490	22.490	22.490
Diré	0.074	-5.022	0.518	7.401	11.186

Table 41: Reduction in flow (%) of the driest month and year due to Office du Niger (2005 irrigation scenario).

Hydrological Station	No Dams	Sélingué Only	Sélingué + Fomi	Sélingué + Moussako 402	Sélingué + Moussako 396	Sélingué + Moussako 388.5
Kirango	89.40	97.33	97.52	97.42	97.42	97.42
Ké-Macina	66.49	70.97	70.96	71.05	71.05	71.05
Akka	57.89	62.48	62.80	62.73	62.73	62.73
Diré	1.00	0.80	0.60	1.24	1.22	1.43

Chapter 7 – Conclusions and Recommendations

As expected, only the basins located downstream of the dams and/or OdN experience a change in flow (increase or decrease). For all the analysis, the “Sélingué only” option had the least impact on the subwatersheds mean flow.

Comparing Fomi to the Moussako alternative sites, the ‘Sélingué + Moussako 388.5’ option generally led to the smallest decrease on the subwatersheds mean annual flow, but led to the largest decrease on the reservoirs flow. The ‘Sélingué + Moussako 402’ option was the least favorable scenario for the subwatersheds annual flow. For the stations located downstream of OdN, the annual flow was generally reduced by not more than 1.5% for the 2005 and 2015 irrigation scenarios, 2% for the 2025 irrigation scenario, 3% for the 2035 irrigation scenario, and by less than 3.5% for the 2045 irrigation scenario. This means that as OdN water demand grows in the future, there will be less and less water going to the hydrological stations located directly downstream of the river (i.e., Kirango and Ké-Macina). Although for Akka and Diré, the annual flow mostly showed an increase (by less than 5%) for the ‘Sélingué + Moussako 396’ and ‘Sélingué + Moussako 388.5’scenarios.

For the wettest month flow of the year, the ‘Sélingué + Moussako 388.5’ caused the least impact compared to the Fomi and the two other Moussako alternatives. The “Sélingué + Moussako 402” option was the least favorable scenario for all the stations. For all the scenarios, the mean shows that OdN 2005 irrigation scenario reduces the wettest month flow for each station by less than 0.6%. Thus, the results show that the reservoirs (Sélingué and Fomi/Moussako) have a much bigger impact on the wettest month flow of the year than on the annual flow.

For the driest month flow of the year, the “Sélingué + Moussako 388.5” once again led to the least impact compared to the Fomi and the two other Moussako alternatives. This time, the “Sélingué + Fomi” scenario had the highest impact. The mean shows that OdN reduces the driest month flow by up to 17.4% for the ‘Sélingué + Moussako 396’ at Kirango. Comparing the general results of the annual mean flow, the wettest month flow of the year, and the driest month flow of the year, the Fomi/Moussako reservoir had the highest impact on the flow of the driest month of the year. However, the Sélingué reservoir had the biggest impact on the annual flow. A flow decrease of up to 99.6% was observed at Baro station for the “Sélingué + Fomi” scenario, implying that for the driest month of the year there is practically no water left to flow through

Baro station, if the Fomi dam existed in the river. Importantly, SWAT does not have a function that can change a reservoir's operation rules in response to the low flows.

For the driest month of the driest year, the mean flow values also suggested 'Sélingué + Fomi' as the least favorable scenario for most cases, and shows that OdN reduces the driest month flow by up 97.5% for Kirango. However, since the flow values for this last analysis were quite small, the percent changes are not very significant.

To summarize, the results of this study have shown that building the Fomi/Moussako dam will reduce the annual flow and noticeably reduce the high flows. After all, if the Fomi/Moussako dam were to be built, the 'Moussako 388.5' and the 'Moussako 396' alternatives seemed to cause the least impact on the downstream flow, respectively. The big question remains "Should priority be given to hydropower or agriculture?". Thus, Mali decision-makers will have to decide whether to release more water during the dry season to meet OdN agricultural demand and move toward food security or keep the water in the reservoir to produce more hydropower and meet the power demand. Nevertheless, despite its many limitations (discussed below) this study was able to demonstrate significant findings. In particular, the study was able to give an understanding on the effects that the existing Sélingué dam, the planned Fomi/Moussako dam, and Office du Niger can cause on the flow regime of the Inner Niger Delta and the Upper Niger Basin. The study also determine the least impactful alternative (Moussako 388) for the Fomi dam.

Study Limitations

Many limitations can be associated with the results obtained from the current study. The quality of the collected climate dataset (WFDEI) varied regionally, and therefore, many stations had missing flow measurement data. Another data limitation was the absence of Moussako reservoir parameters. To perform the analysis, the missing Moussako dam parameters were estimated based on those from the Fomi dam.

In general, hydrological models uncertainties are due to the model structure and parametrization, the conceptual simplifications, the assumptions, the spatial resolution, the omission of certain processes occurring in the watershed (unknown to the modeler or unaccountable because of data limitation).

Poulin et al. (2011) in their investigation aiming to find the uncertainty related to hydrological modeling in climate change impact, concluded that the uncertainty due to the model structure is higher than the uncertainty caused by parameters. They also concluded that the use of hydrological models with different levels of complexity remains part of the uncertainty. Vetter et al. (2017) confirmed these last findings for the entire Niger River Basin. The last study also concluded that hydrological models are the lowest contributors of uncertainty for high flows (Q_{10}) and the mean flow, but contribute more significantly to low flows (Q_{90}).

The software used to develop the hydrological model for this study (SWAT) presents its own constraints. It assumes that the reservoirs have a horizontal water surface and invariant stage-discharge relationship at the outlet of the watershed. In his study, Seidou O. (2017) demonstrates that these assumptions are not true for the IND, since the flood peaks do not occur at the same time at Mopti, Akka, and Diré and the relationship between water levels and flows at all three stations are looped. He also adds that the original SWAT model can only assume a linear variation of the volume versus elevation in reservoirs. Moreover, SWAT is known for not being satisfactory at simulating low flows and the flow for the first few years. The program does not allow the user to set a minimum flow for reservoirs during low flows. Another limitation to SWAT models is that they use empirical formulas to perform the analysis.

Proposed Mitigation Measures

The results suggest a decrease in the river water flow, which could be detrimental for the UNB and IND. A lack of water sometimes leads to a drought that can in return cause considerable socio-economic and ecological damages (please refer to Chapter 2). The extremes cases include the death of vegetation, animals, and humans (due to the lack of drinking water and food), economic crisis, loss of diversity, depopulation, electricity shortage, and more. Thus, there is a need to reach some sustainable development goals such as promoting sustainable agriculture to meet the food demand for the growing population; have affordable, clean and reliable energy; and ensure responsible consumption and production. To mitigate and prepare for the identified impacts, the current study proposes some potential adaptation measures. The adaptation measures are based on literature review and therefore, they have not been verified or implemented by the current study. They are as follow:

- Invest in improved water use efficiency techniques such as pressurized systems (drip and sprinkler irrigation), and cultivate less water-demanding crops.
- Consider using chemical products (such as the monomolecular organic surface films) to cover the water in the reservoir to decrease the evaporation rate. Although, one should be

careful while using these regarding the toxicity as well as the cost. In particular, the monomolecular organic surface films (a monomolecular layer of long-chain fatty alcohols) was found to be the most suitable and effective for evaporation, with no side effects (AIT, 1982). Plastic firms, geomembranes, and shade balls (floating cover) can also be used to cover the reservoir and minimizing the evaporation rate.

- Increase the vegetation cover for large dams. More green vegetation will lead to an increase in relative humidity around the reservoir area, which in return can help decrease the evaporation rate.
- Establish and restore riparian buffers to maintain/improve water quality by trapping and removing various nonpoint source pollutants from both overland and shallow subsurface flow. Buffer strips also provide (additional) habitat for aquatic species and may result in increased recharge of groundwater (European Climate Adaptation Platform, 2017).
- Establish a Drought Early Warning System (DEWS) for the regions.
- Develop financial risk management tools.
- Consider other sources of Green energy as a complement to hydropower (ex. solar panels could be a great alternative for this area).
- Use water management techniques such as Desert Agriculture to grow crops well suited for arid conditions. This technique has been around for thousands of years but has been modernized and is widely used in countries like Egypt, Australia, Israel, Saudi Arabia, and southern California.
- Further develop rainwater harvesting and micro-dosing fertilization in agriculture rather than large-scale irrigation or field-scale fertilizer applications (Mortimore, M., 2010).
- Exploit more groundwater aquifers: part of the Office du Niger rainfall-runoff is stored underground the area. Exploring more the region aquifers could be a solution to reduce drought in the region. According to Mali’s “Ministere de l’energie et de l’eau”, the country has an available groundwater volume of 10 km^3 renewable each year.
- Alter the reservoir operating rules (optimization of water allocation rules).
- Improve water retention in agricultural areas to prevent the rapid surface runoff by storing the water in soil, which can decrease the negative impacts of droughts. Depending on the soil characteristics, runoffs can be delayed by tillage methods combined with high root density and lush surface cover plants. It reduces evaporation from the soil surface

preserving the soil organic matter in the upper soil layers and, consequently, increasing water retention capacity of the soil. (European Climate Adaptation Platform, 2017)

- Plan awareness campaign for behavioral change toward the population.
- Recycle wastewater from domestic sources (baths, showers, sinks) for non-consumptive purposes such as toilet flushing, laundry, and irrigation.
- Livestock breeding must recognize that performance under Sahelian conditions is more important to smallholders than productivity at all costs. (Mortimore, M., 2010)

Implementation of some of the proposed mitigation measures in SWAT

Some of the above adaptation measures can be simulated in SWAT through the modification of some parameters/variables in the input files. For example, to maximize the water retention and prevent rapid surface runoff, some of the variables in the URBAN.DAT file (contains parameters used by the model to simulate different types of urban areas) can be modified. One of these variables is the FIMP (fraction total impervious area) used to reduce infiltration and therefore, increases the hydraulic efficiency of the flow. In the same optic, variables can be modified in the HRU input files to reduce the evaporation rate. These parameters include the ESCO (Soil Evaporation Compensation Factor) and the HRU_FR (fraction of the total watershed area contained in HRU). The land use in the HRU can also be modified by increasing the percentage of green vegetation, leading to a decrease in evaporation rate. Plant growth can be simulated by changing variables in the CROP.DAT input file.

References

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Klove, B. 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of hydrology* 524 (2015) 733-752.

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.

Anukularmphai, A. 2010. Implementing Integrated Water Resources Management (IWRM): based on Thailand's experience. (IUCN Mekong Water Dialogues Report No. 1305).

Asian Institute of Technology (AIT). 1982. Evaporation Control Using Monomolecular Organic Surface Films. AIT Research Report No. 1982-2, *Division of Water Resources Engineering, AIT*, Bangkok.

Asian Institute of Technology. Sourcebook of Alternative Technologies for Freshwater Augumentation in Some Countries in Asia. *Water Engineering and Management Program*, Bangkok, Thailand. Retrieved November 16, 2018 from: http://www.unep.or.jp/ietc/publications/ techpublications/techpub-8e/evapo.asp.

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S. L. 2012. Soil and Water Assessment Toll, Input/Output Documentation. Texas Water Resources Institute.

BCEOM. 2001. Schéma Directeur Développement Régional, Zone Office du Niger. Rapport de synthèse, Montpellier, *BCEOM*, 22 p.

Bigiarini, M. Z. Nash-Sutcliffe Efficiency. Package *hydroGOF* version 0.3-10. Retrieved on November 18, 2018 from: https://www.rforge.net/doc/packages/hydroGOF/NSE.html.

Bila, M., Sedick, A. Planning for the Lake Chad Basin Water Cycle Integrator. Vernon Phelps. Retrieved on August 25, 2018 from: https://slideplayer.com/slide/4628555/.

Bista, R., Larose, L. A., Maiga, F., Paul, C. 2017. Climate Change Generation for the Inner Niger Delta. University of Ottawa.

Brondeau, F. 2009. Un « grenier pour l'Afrique de l'Ouest » ?. *Géocarrefour* [En ligne], vol. 84/1-2 | 2009. Retrieved december 2, 2018 from: http://journals.openedition.org/geocarrefour/7213 ; DOI : 10.4000/geocarrefour.7213.

Brondeau, F. 2013. Confrontation de systèmes agricoles inconciliables dans le delta intérieur du Niger au Mali ?. *Études rurales* [En ligne], 191 | 2013. Retrieved december 2, 2018 from: http://journals.openedition.org/etudesrurales/9748 ; DOI : 10.4000/etudesrurales.9748.

Caminade, C., Terray, L., Maisonnave, E. 2006. West African monsoon response to greenhouse gas and sulphate aerosol forcing under two emission scenarios. *Climate Dynamics*, Vol 26,531-547.

Giupponi, C., Sgobbi, A. 2013. Decision Support Systems for Water Resources Management in developing Counties: Learning from Experiences in Africa. *Water*. Retrieved March 15, 2019 from:
https://www.researchgate.net/publication/277681123_Decision_Support_Systems_for_Water_Resources_Management_in_Developing_Countries_Learning_from_Experiences_in_Africa.

Dodo, A. K., Al-Gamal, S. A. 2009. Impacts of climate changes on water resources in Africa with emphasis on groundwater. Retrieved August 25, 2018 from https://www.researchgate.net/figure/Location-map-of-the-Niger-River-Basin_fig2_293101083.

Droubi, A., Al-Sibai, M., Abdallah, A., Zahra, S. & Obeissi, M., Wolfer, J., Huber, M., Hennings, V. & Schelkes, K. 2009. A Decision Support System (DSS) for Water Resources Management, – Design and Results from a Pilot Study in Syria. *Env ironmental Science and Engineering*, ISBN: 978-3-540-85046-5.

European Climate Adaptation Platform. Case Studies: Climate-ADAPT. Retrieved April 20, 2017 from: http://climate-adapt.eea.europa.eu/knowledge/adaptation-information/adaptation-measures.

Escher, A; Kolodny, L. 2016. Causes of the global water crisis and 12 companies trying to solve it. Retrieved on December 05, 2018 from: https://techcrunch.com/2017/03/22/causes-of-the-global-water-crisis-and-12-companies-trying-to-solve-it/

EU WATCH (Water and Global Change). 2011. Data Availability. *WATCH*. Retrieved on November 18, 2018 from: http://www.eu-watch.org/data_availability.

Mamede, G. L., Guentner, A., Medeiros, P., Araújo, J. C., Bronstert, A. 2018. Modeling the Effect of Multiple Reservoirs on Water and Sediment Dynamics in a Semiarid Catchment in Brazil. *J. Hydrol. Eng.*, 23(12): 05018020.

Guipponi, C., Sgobbi, A. 2013. Decision Support Systems for Water Resources Management in Developing Countries: Learning from Experiences in Africa. *Water*, 5(2):798-818. Retrieved on March 28, 2019 from: https://www.researchgate.net/publication/277681123_Decision_Support_Systems_for_Water_Resources_Management_in_Developing_Countries_Learning_from_Experiences_in_Africa.

Global Water Partnership. 2018. About IWRM. *C/o International Water Management Institute (IWMI).* Retrieved on November 24, 2018 from: https://www.gwp.org/en/gwp-SAS/ABOUT-GWP-SAS/WHY/About-IWRM/.

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. and Krysnaova, V. 2018. Sources of uncertainty in hydrological climate impact assessment: a cross-scale study. *Environmental Research Letters* 13(1): 015006.

Hernández, G., Jimenez, A.F., Ortiz, B.V., Lamadrid, A.P., Cardenas, P.F. 2019. Decision Support System for Precision Irrigation Using Interactive Maps and Multi-agent Concepts. *Advances in Intelligent Systems and Computing*, Vol 893, 21-41.

International Water Association (IWA). 2018. Integrated Water Resources Management: Basic Concepts. Retrieved on December 05, 2018 from: https://www.iwapublishing.com/news/integrated-water-resources-management-basic-concepts.

Kuper, M., Hassane, A., Orange, D., Chohin-Kuper, A. and Sow, M. 2002. Régulation, utilisation et partage des eaux du fleuve Niger. In Orange, D., Arfi, R., Kuper, M., Morand, P. and Poncet, Y. (Eds). Gestion intégrée des ressources naturelles en zones inondables tropicales. pp. 411–430. IRD Éditions.

Kuwayama, Y., Young, R., Brozović, N. 2017. Chapter 3.1.5 - Groundwater Scarcity: Management Approaches and Recent Innovations. Pp. 332-350. ELSEVIER.

Lerma, N., Arquiola, J. P., Andreu, J., Solera, A. 2013. Development of Operating rules for a complex multi-reservoir system by coupling genetic algorithms and network optimization. *Hydrological Sciences Journal*, Vol 58(4): 797-812. Retrieved on April 01, 2019 from: https://www.tandfonline.com/doi/full/10.1080/02626667.2013.779777.

Liersch, S., Fournet, S., Koch, H. 2018. Assessment of Climate and Water Management Impacts on the Water Resources in the Upper Niger and Bani River basins" Draft Version 0.9. PostDam Institute For Climate Impact Research.

Liersch, S., Fournet, S., Koch, H, Hattermann, F. F.,Reinhardt, J., Djibo, A. G., Kortlandt, J., Weert, F. V., Seidou, O., Wymenga, E., Baker, C. 2018. Water resources planning in the Upper Niger river basin: Are there gaps between water demand and supply? Mali / the Netherlands.

Liersch, S., Cools, J., Kone, B., Koch, H., Diallo, M., Reinhardt, J., Fournet, S., Aich, V., Hattermann, F.F. 2013. Vulnerability of rice production in the Inner Niger Delta to water resources management under climate variability and change. *Environmental Science and Polic*y, Vol 34, 18-33.

Loucks, D. P., Beek, E. V. 2017. Water Resource Systems Planning and Management. An Introduction to Methods, Models, and Applications. *Springer Nature*. DOI 10.1007/978-3-319-44234-1.

Mahe, G., Bamba, F., Soumaguel, A., Orange, D., and Olivry, J., 2009. Water losses in the inner delta of the River Niger: water balance and flooded area.

Ministère de l'énergie et de l'eau du Mali. 2017. Termes de référence pour le diagnostic de la mise a niveau du système de collecte, de gestion et de diffusion des données hydrologiques du Mali. *République du Mali*.

McCully, P. 2001. Rivers No More: The Environmental Effects of Large Dams. *International Rivers*. Retrieved on December 08, 2018 from: https://www.iwapublishing.com/news/integrated-water-resources-management-basic-concepts.

Mortimore, M. 2010. Adapting to drought in the Sahel: lessons for climate change. *John Wiley & Sons, Ltd*, 134-143.

Model Primer. 2015. Soil Water Assessment Tool. Retrieved November 13, 2018 from: http://www.appsolutelydigital.com/ModelPrimer/chapter5_section6.html.

Nyeko, M. 2014. Hydrologic Modelling of Data Scarce Basin with SWAT Model: Capabilities and Limitations. Water Resour Manage (2015) 29:81–94.

Oguntunde, P., and Babatunde, A. 2012. The impact of climate change on the Niger River Basin hydro-climatology, West Africa.

Pechlivanidis, I., Donley, C. 2016. Forecasting over international borders: limitations and solutions for large-scale or continental forecasting systems. *HEPEX*. Retrieved November 15, 2018 from: https://hepex.irstea.fr/forecasting-over-international-borders-limitations-and-solutions-for-large-scale-or-continental-forecasting-systems/.

Poulin, A, Brissette, F., Leconte, R., Arsenault, R., Malo, J-S. 2011. Uncertainty of hydrological modelling in climate change impact studies in a Canadian, snow-dominated river basin. *Journal of Hydrology* 409 (2011) 626–636.

Pottinger, L. 2009. How Dams Affect Water Supply. International Rivers. Retrieved November 27, 2018 from: https://www.internationalrivers.org/resources/how-dams-affect-water-supply-1727.

RH (Royal Haskoning), Altenburg & Wymenga ecologisch onderzoek and GID. 2010. Etat des lieux du Delta Intérieur, -vers une vision commune de développement-. Bamako, Mali: Ministère de l'environnement et de l'assainissement, République du Mali.

Rowshon, M.K., Dlamini, N.S., Mojid, M.A., Adib, M.N.M., Amin, M.S.M., Lai, S.H. 2019. Modeling climate-smart decision support system (CSDSS) for analyzing water demand of a large-scale rice irrigation scheme. *Agriculture Water Management*, Vol 216, 138-152.

Sangiorgio, M., Guariso, G. 2018. NN-Based Implicit Stochastic Optimization of Multi Reservoir Systems Management. *Water*, Vol 10: 3.

Schleifer, L. 2017. 7 Reasons We're Facing a Global Water Crisis. *World Resources Institute*. Retrieved December 05, 2018 from: https://www.wri.org/blog/2017/08/7-reasons-were-facing-global-water-crisis.

Seidou, O. 2018. Introduction to Engineering Hydrology. University of Ottawa, Department of Civil Engineering.

Seidou, O. 2017. Support to the implementation of the Bamgire project. Wetland International / University of Ottawa.

Tan, Q., Xu, W., Hao, W., Wang, C., Lei, X., Xiong, Y., Zhang, W. 2017. Derivation of optimal joint operating rules for multi-purpose multi-reservoir water-supply system. *Journal of Hydrology*, 551 (2017) 253–264.

UN. 2014. Integrated Water Resources Management. Retrieved on November 24, 2018 from: http://www.un.org/waterforlifedecade/iwrm.shtml.

UNESCO. 2014. Decision Support System for Integrated Water Ressources Management Considering Business Processes of Stakeholders. Retrieved on March 28, 2019 from: https://en.unesco.org/fellowships/keizo-obuchi/summary-research-carried-out/decision-support-system-integrated-water-ressources-management.

Vetter, T., Huang, S., Aich, V., Yang, T., Wang, X, Krysanova, V. and Hattermann, F. 2015. Multi-model climate impact assessment and intercomparison for three large-scale river basins on three continents. *Earth System Dynamics*, 6(1): 17-43.

Vetter T., Reinhardt J., Flörke M., van Griensven A., Hattermann F.F., Huang S., Koch H., Pechlivanidis I., G, Plötner S., Seidou O. and Krysanova V. 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. *Climatic Change* 141(3): 419-433.

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., Viterbo, P. 2014. The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA- Interim reanalysis data. *Water Resources Research*, 50, doi:10.1002/2014WR015638. Retrieved November 13, 2018 from: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014 WR015638.

Welcomme, R. L. 1986a. Fish of the Niger system. In: B. R. Davies & K. F. Walker (eds.). *The ecology of river systems*, pp. 25-47. Dordrecht: Junk.

Welcomme, R. L. 1986b. The effects of the Sahelian drought on the fisheries of the Central delta of the Niger river. Aquat. Fish. *manage*. 147-154.

Wetland International. Impact of dams on the people of Mali. *Wetland International*, The Netherlands.

Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J. 2013. ArcSWAT interface for swat2012; User's guide. Blackland Research and Extension Center / Grassland, Soil and Water Research Laboratory.

Yeh, W. 1985. Reservoir management and operations models: a stateof-the-art review. *Water Resources Research*, 21(12): 1797–1818.

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

Zwarts, L., P. van Beukering, B. Kone & E. Wymenga 2005. The Niger, a lifeline. Effective water management in the Upper Niger Basin.” *RIZA, Lelystad / Wetlands International, Sévaré / Institute for Environmental studies (IVM), Amsterdam / A&W ecological consultants, Veenwouden*. Mali / the Netherlands.

Appendices

Appendix A: Monthly Flow Data Calibration Results

This appendix presents the flow calibration results for all fourteen stations. The graphs (Figure 24 to Figure 37) compare the current state of the river observed and simulated time series.

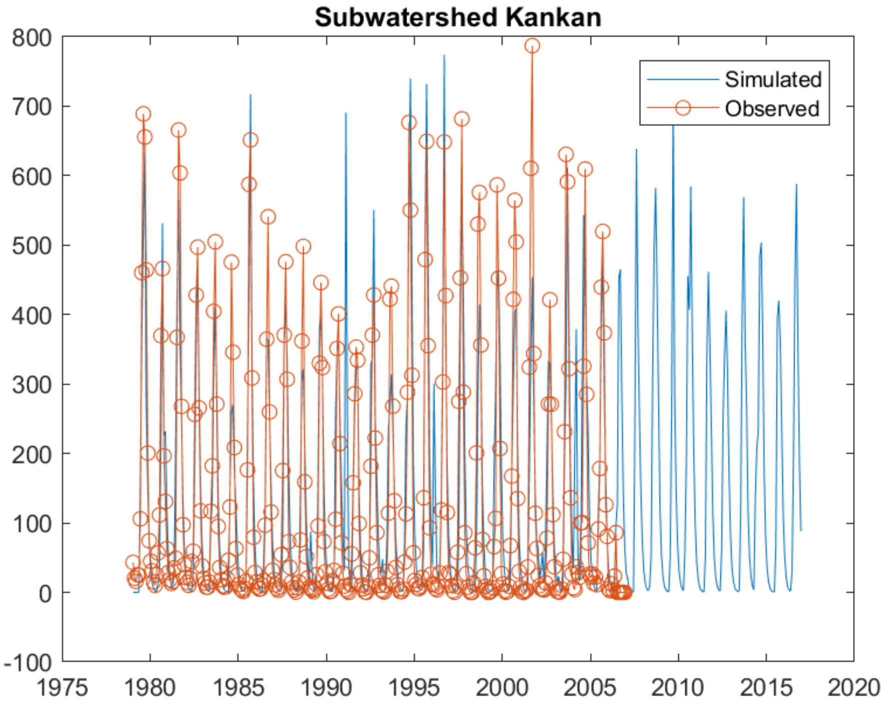


Figure 24: Kankan Subwatershed Observed and Simulated Time series.

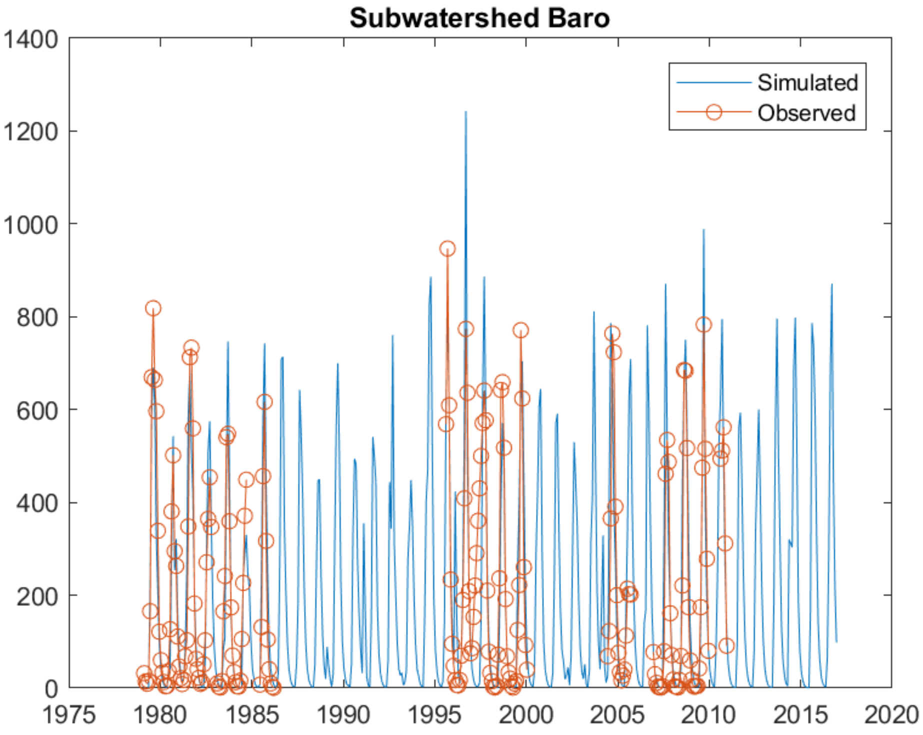


Figure 25: Baro Subwatershed Observed and Simulated Time series.

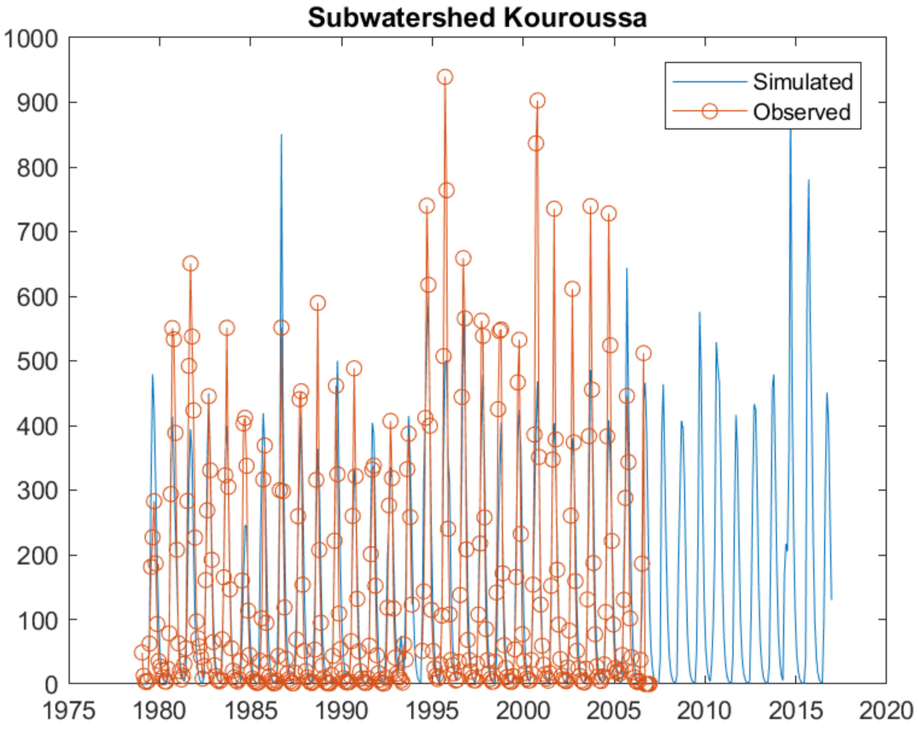


Figure 26: Kouroussa Subwatershed Observed and Simulated Time series.

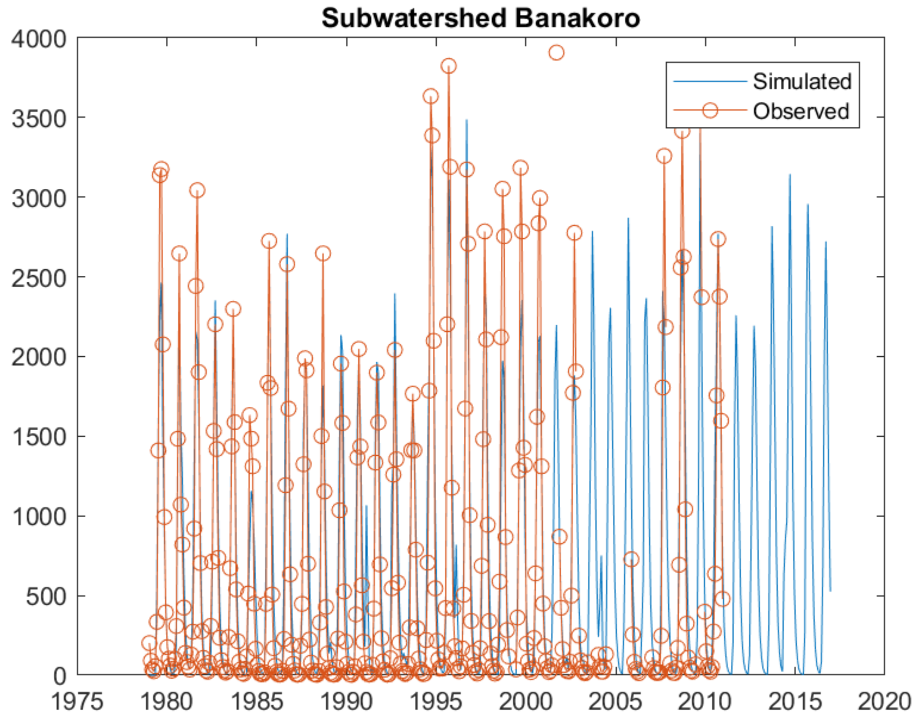


Figure 27: Banakoro Subwatershed Observed and Simulated Time series.

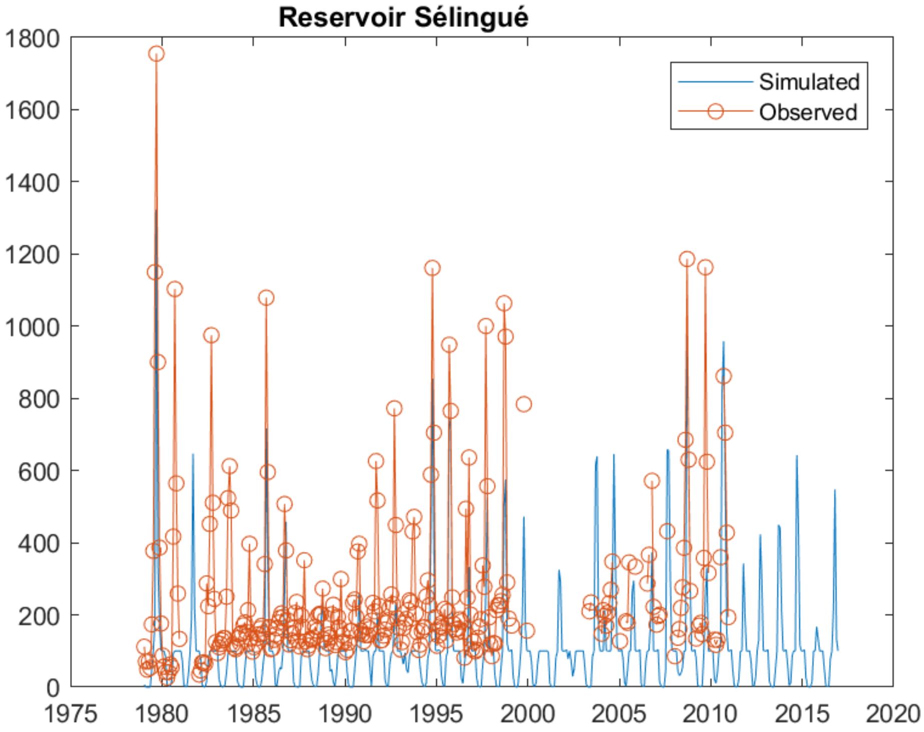


Figure 28: Sélingué Subwatershed Observed and Simulated Time series.

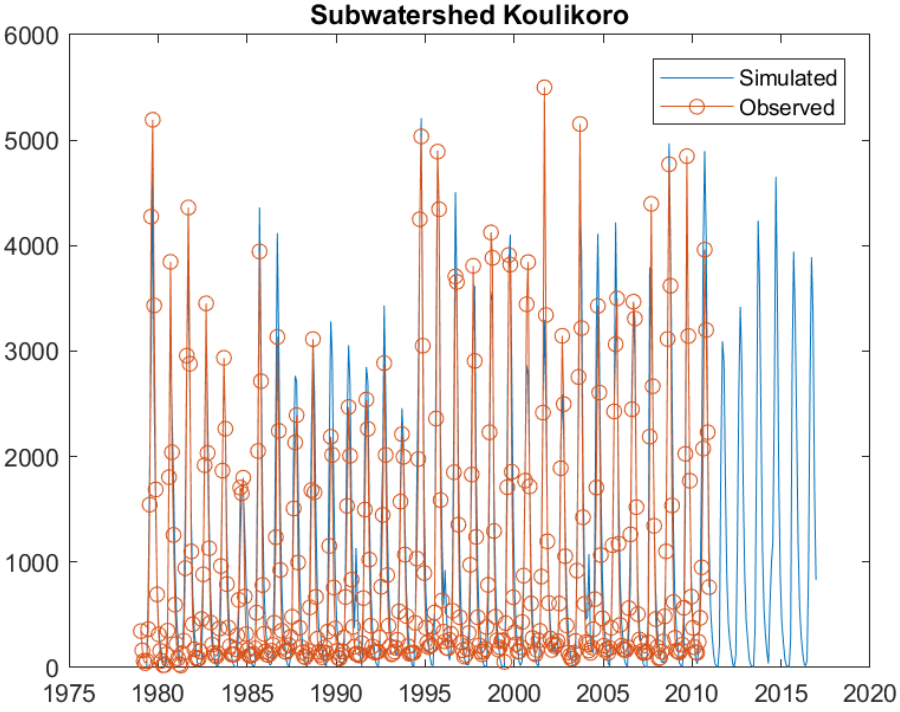


Figure 29: Koulikoro Subwatershed Observed and Simulated Time series.

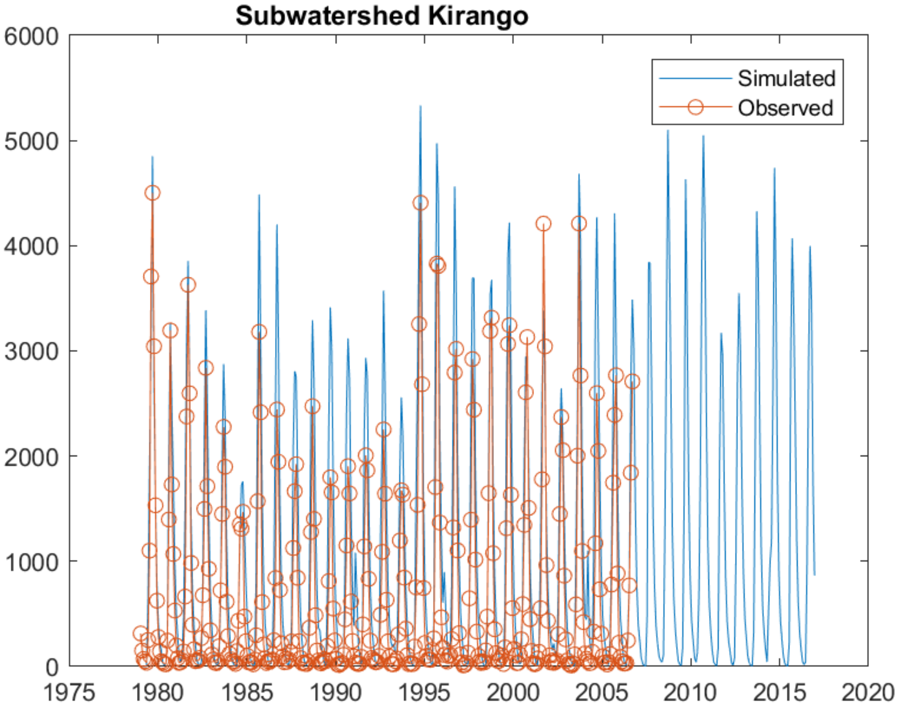


Figure 30: Kirango Subwatershed Observed and Simulated Time series.

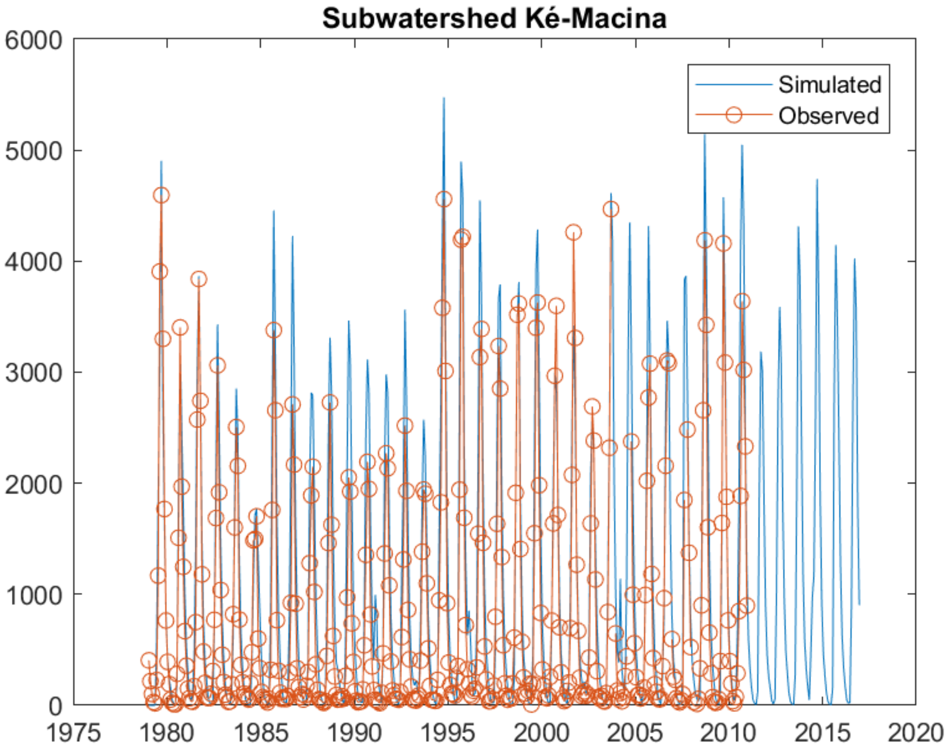


Figure 31: Ké-Macina Subwatershed Observed and Simulated Time series.

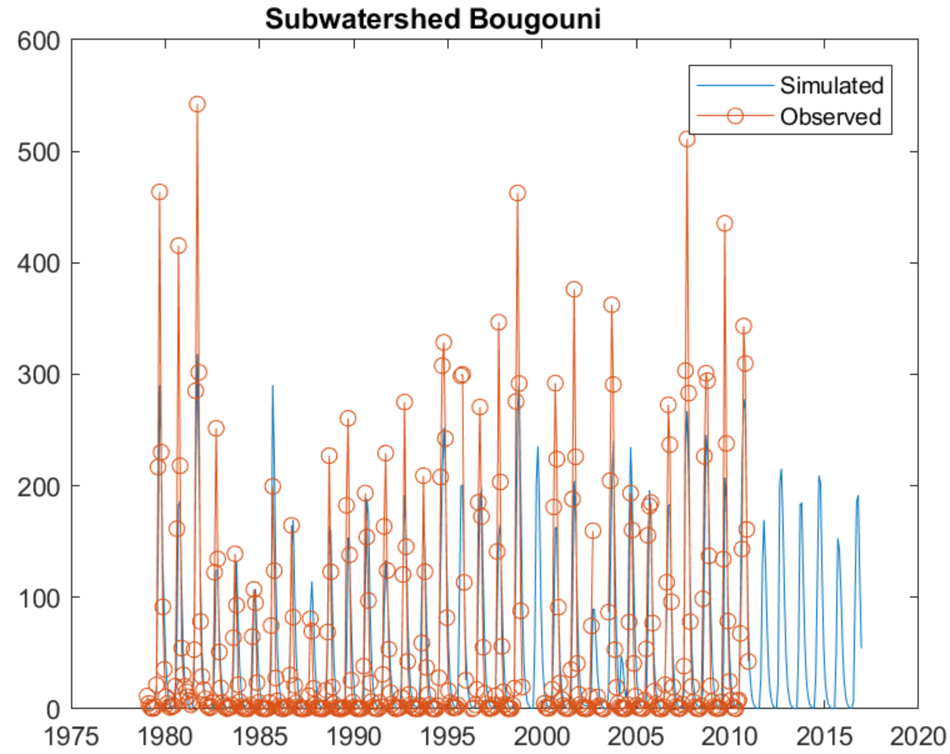


Figure 32: Bougouni Subwatershed Observed and Simulated Time series.

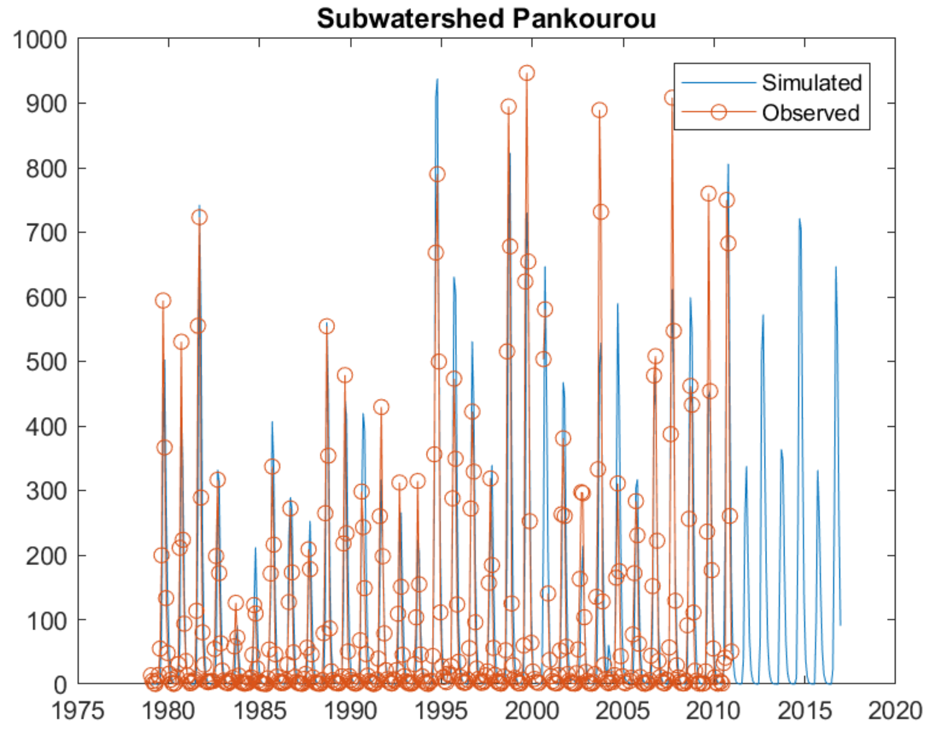


Figure 33: Pankourou Subwatershed Observed and Simulated Time series

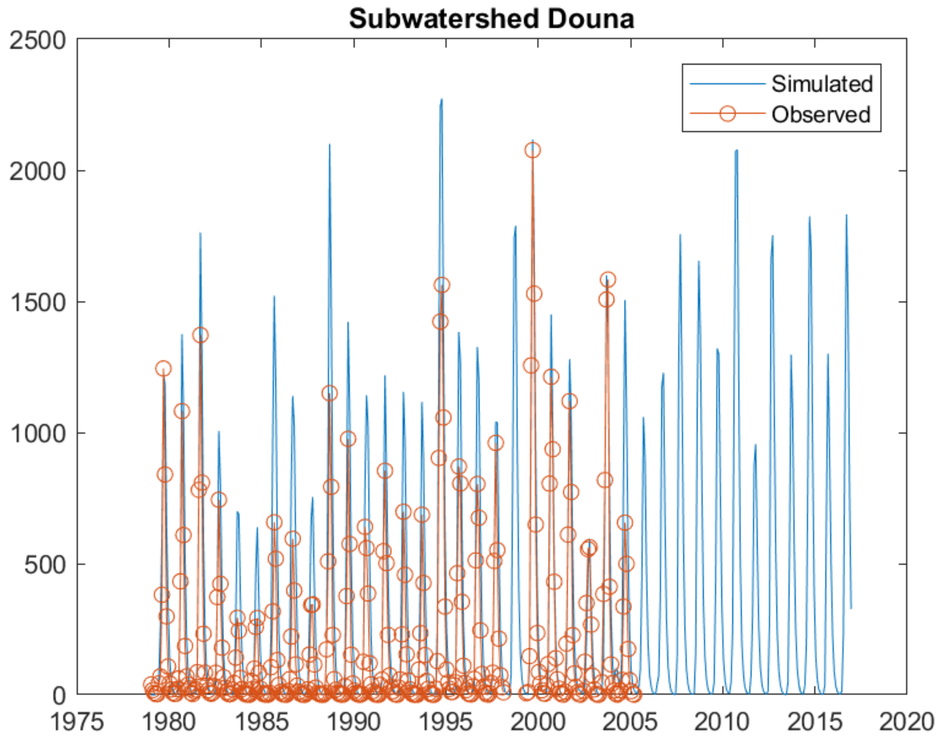


Figure 34: Douna Subwatershed Observed and Simulated Time series.

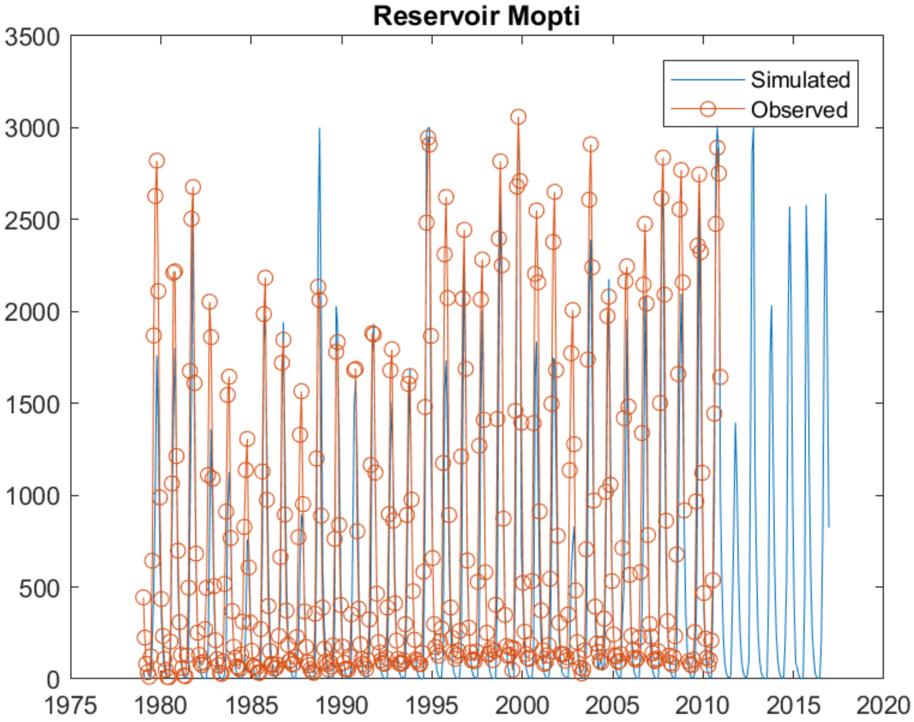


Figure 35: Mopti Subwatershed Observed and Simulated Time series.

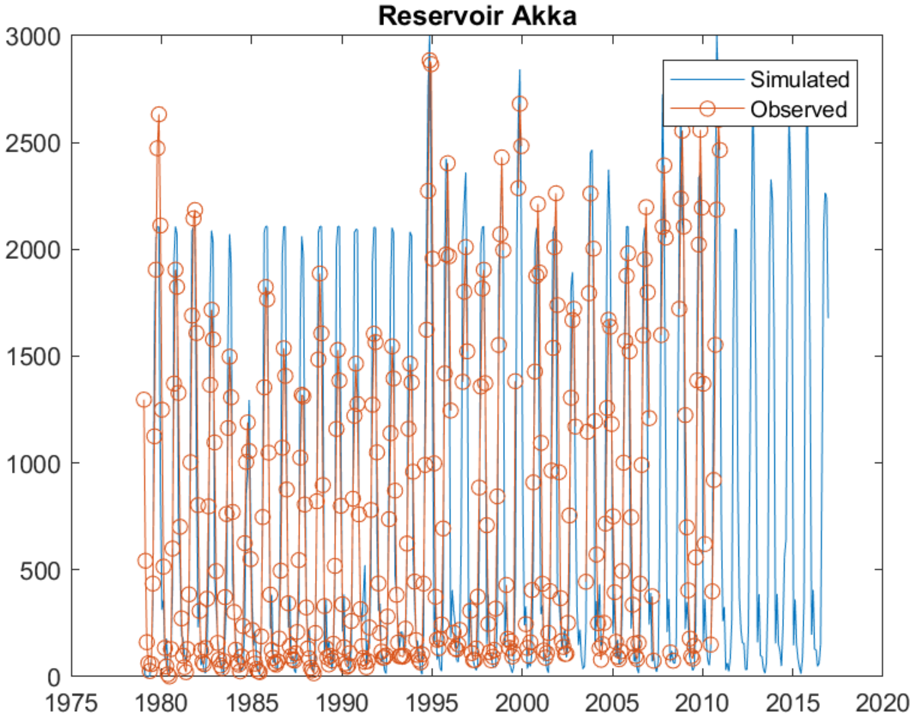


Figure 36: Akka Subwatershed Observed and Simulated Time series.

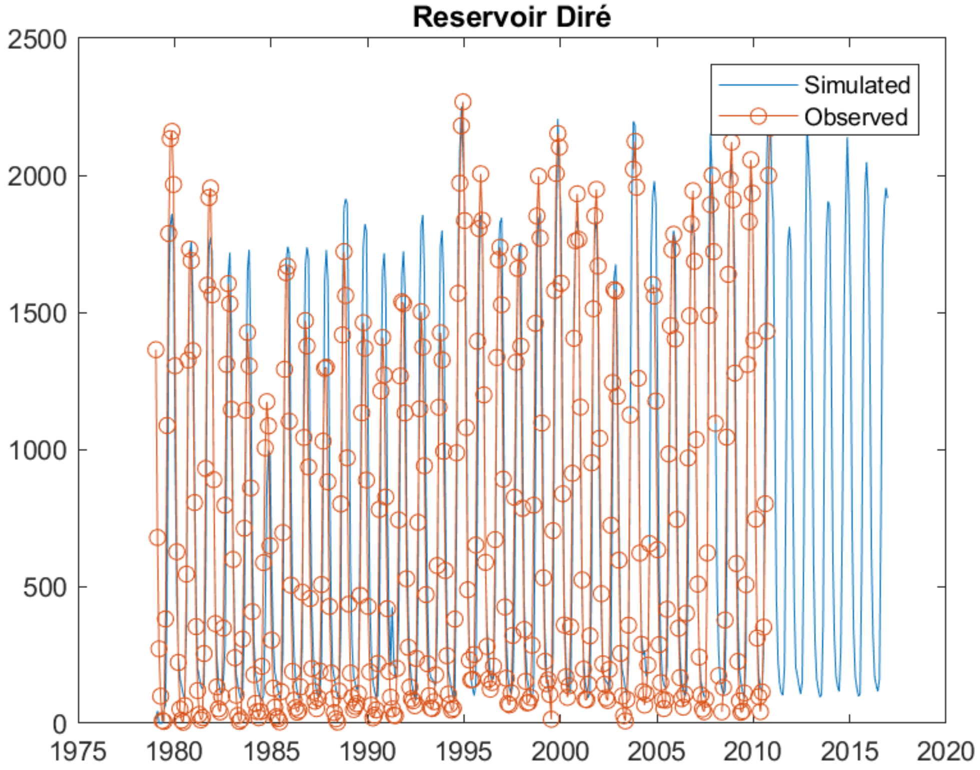


Figure 37: Diré Subwatershed Observed and Simulated Time series.

Appendix B: Effects of Sélingué, Fomi/Moussako and OdN on the Flow

This appendix presents supplementary information to the results presented in Chapter 6. Figure 38 to Figure 64 show the mean and standard deviation of the annual flow, Figure 65 to Figure 75 show the mean and standard deviation of the wettest month flow, Figure 76 to Figure 86 show the mean and standard deviation of the average flow of the driest, and Figure 87 to Figure 93 show the flow of the driest month of the driest year under different scenarios. Only results from stations that experienced a change in flow are presented. All the results are in m^3/s.

a. Effects on the Annual Flow

Without Office du Niger

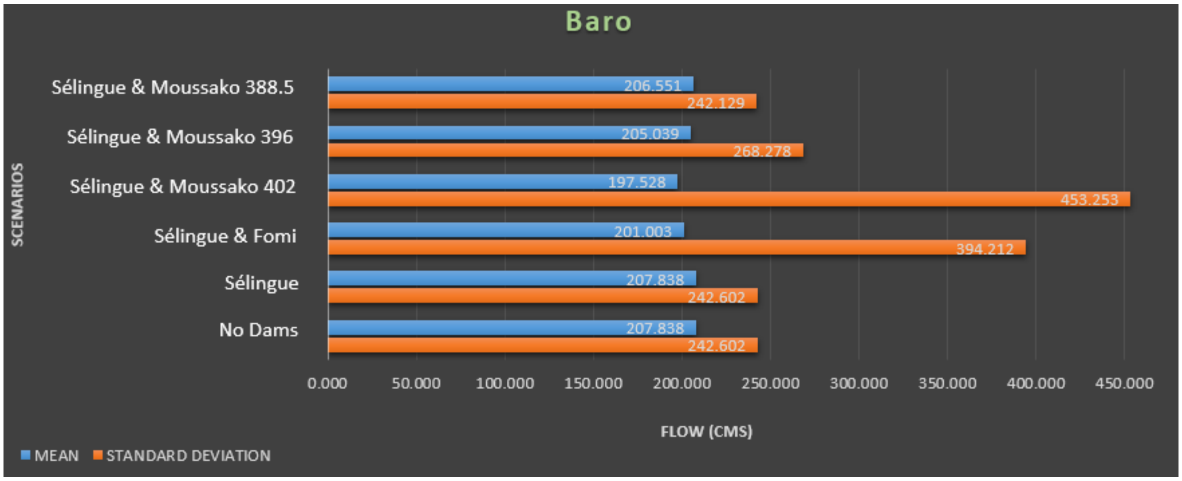


Figure 38: Baro subwatershed annual flow mean and standard deviation under different scenarios without OdN.

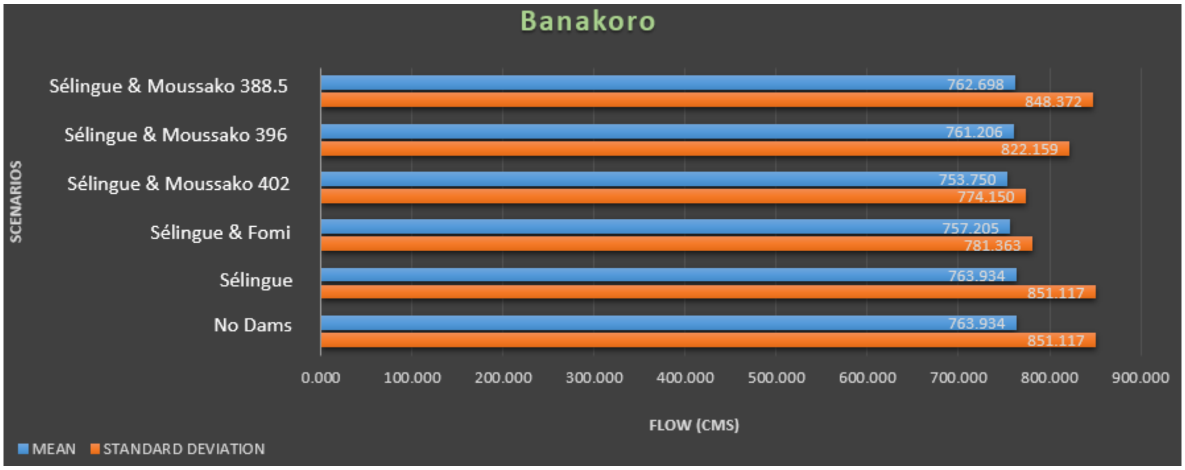


Figure 39: Banakoro subwatershed annual flow mean and standard deviation under different scenarios without OdN.

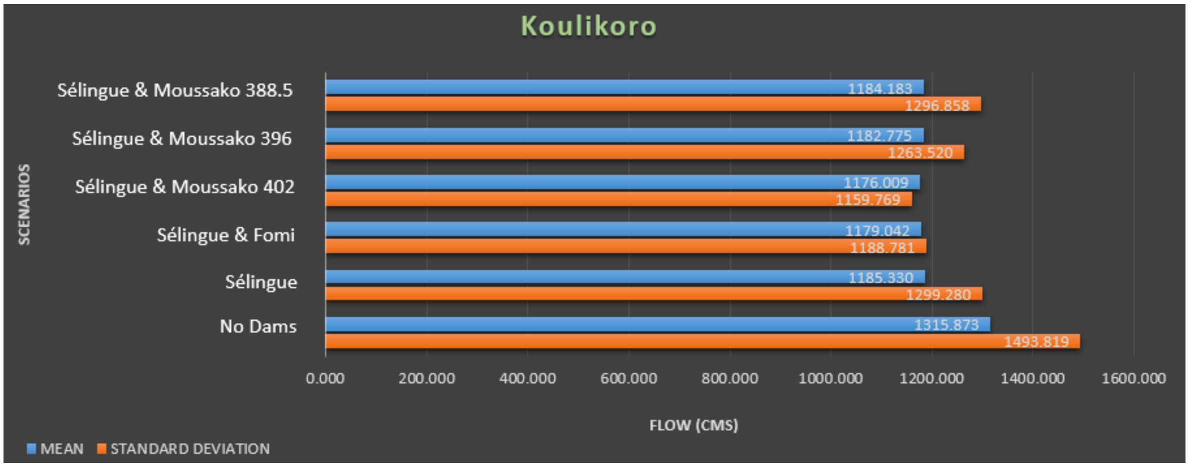


Figure 40: Koulikoro subwatershed annual flow mean and standard deviation under different scenarios without OdN.

Figure 41: Kirango subwatershed annual flow mean and standard deviation under different scenarios without OdN.

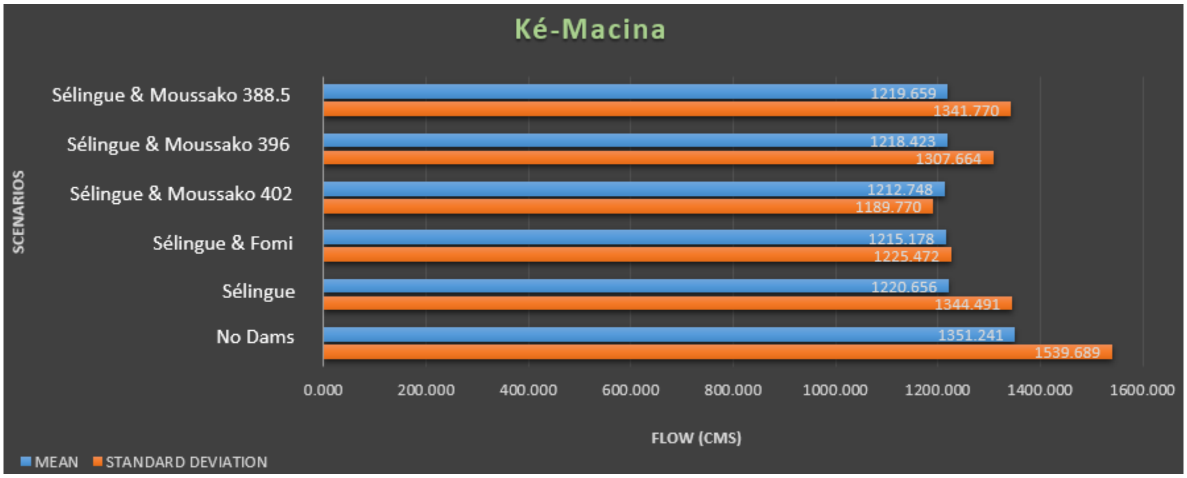


Figure 42: Ké-Macina subwatershed annual flow mean and standard deviation under different scenarios without OdN.

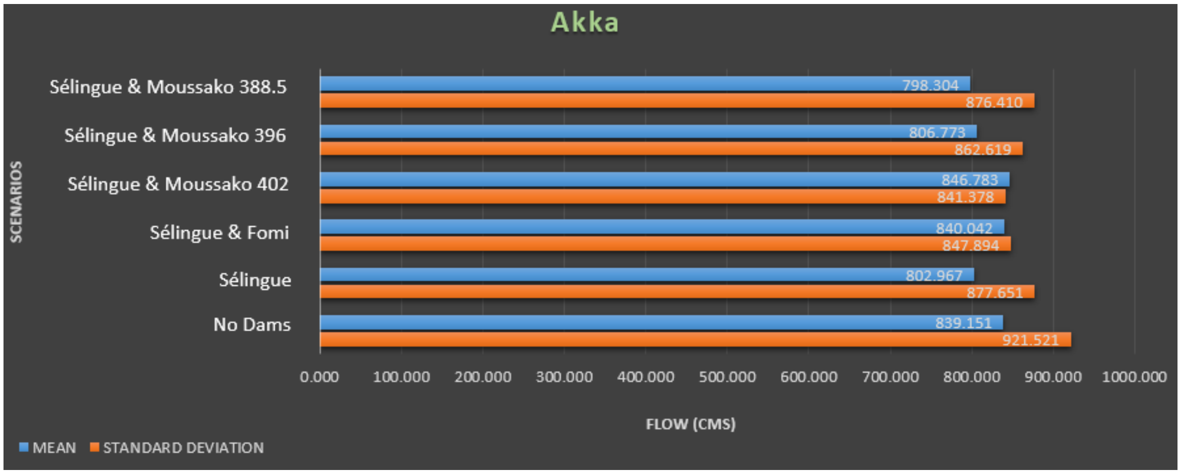


Figure 43: Akka subwatershed annual flow mean and standard deviation under different scenarios without OdN.

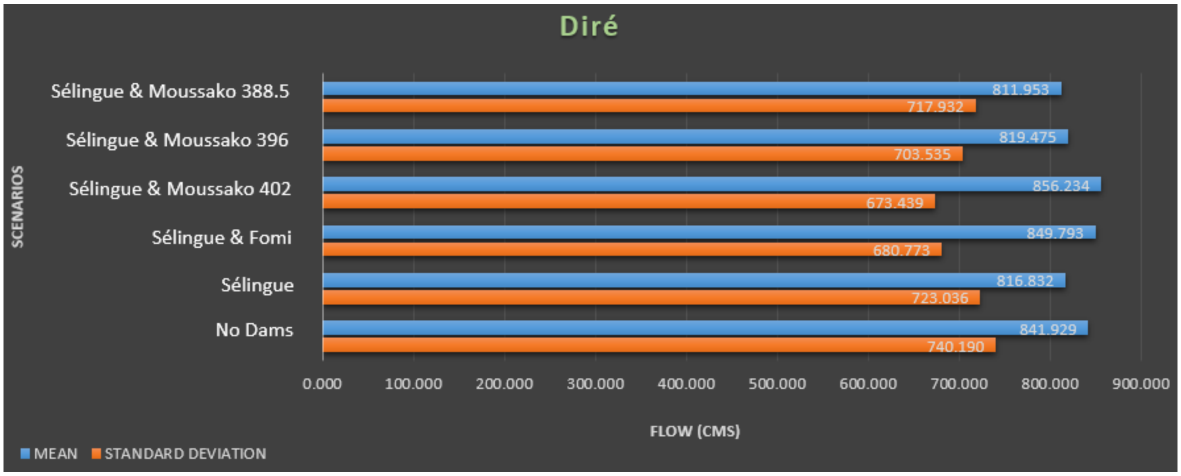


Figure 44: Diré subwatershed annual flow mean and standard deviation under different scenarios without OdN.

With Office du Niger

2005 Irrigation Scenario:

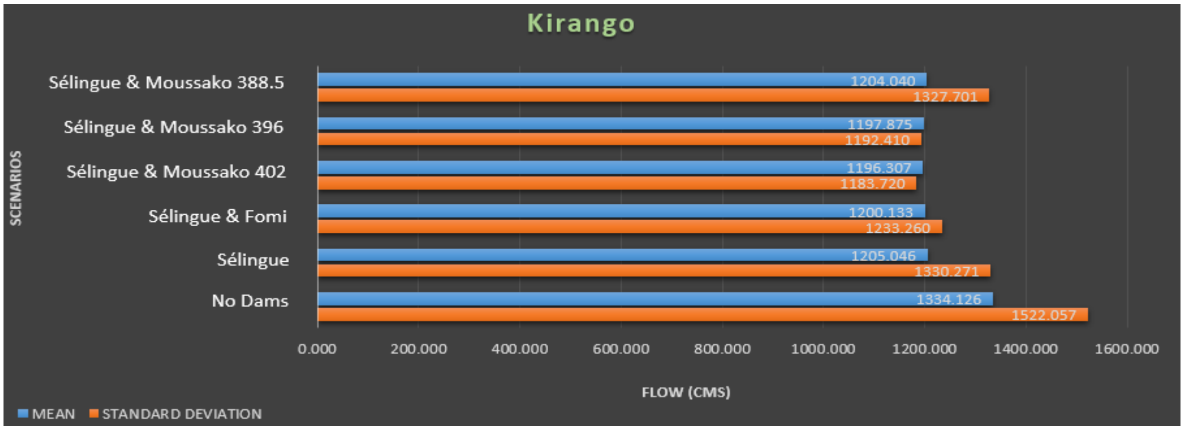


Figure 45: Kirango subwatershed annual flow mean and standard deviation under different scenarios with OdN (2005 Irrigation Scenario).

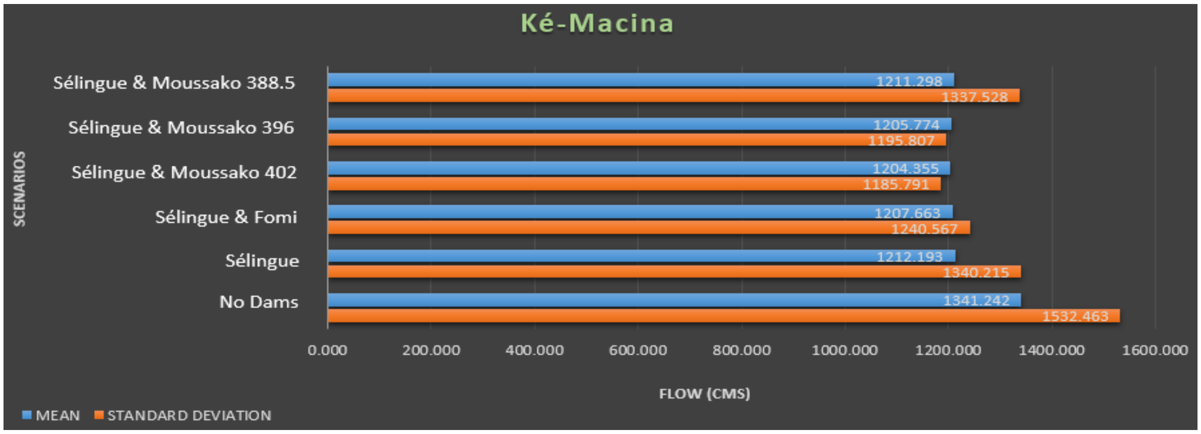


Figure 46: Ké-Macina subwatershed annual flow mean and standard deviation under different scenarios with OdN (2005 Irrigation Scenario).

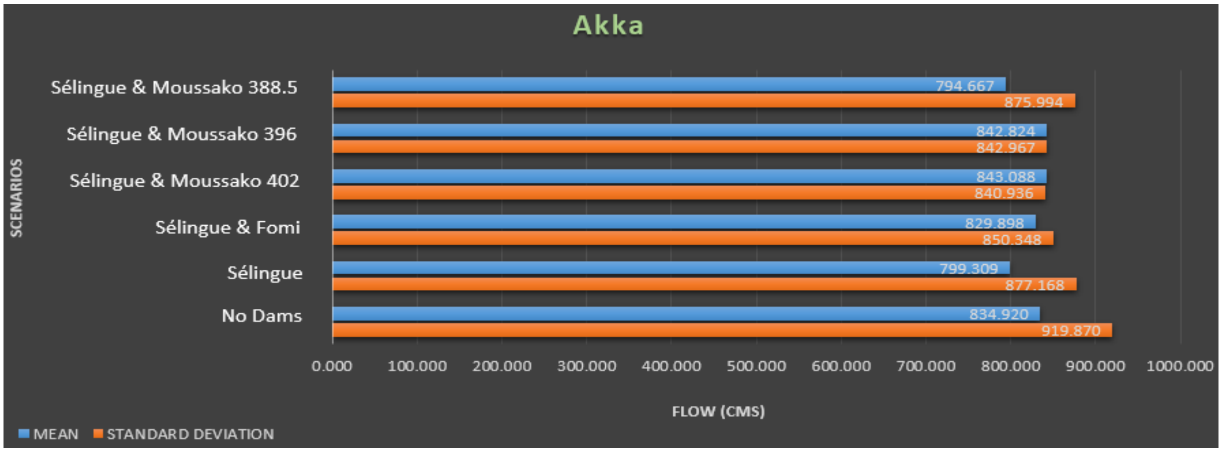


Figure 47: Akka subwatershed annual flow mean and standard deviation under different scenarios with OdN (2005 Irrigation Scenario).

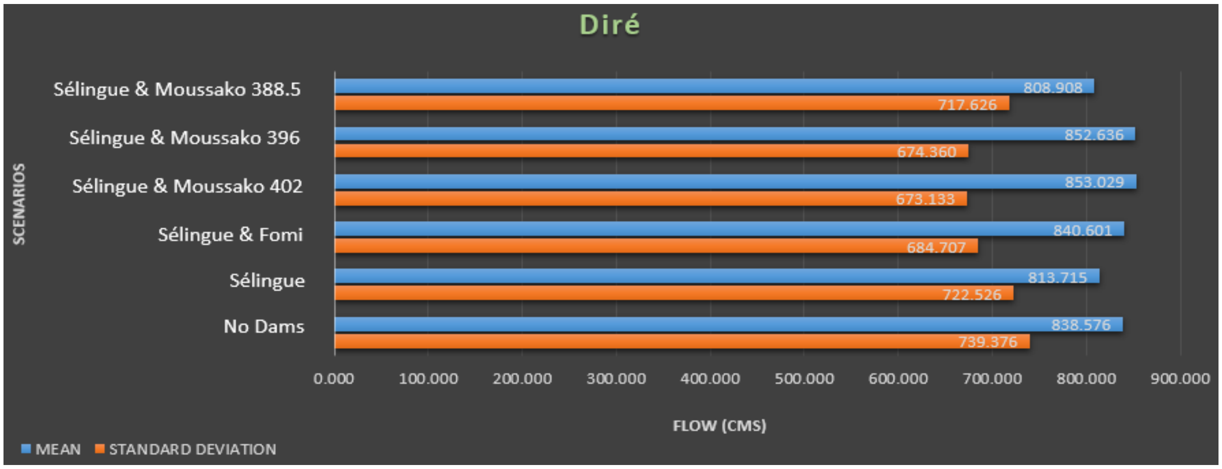


Figure 48: Diré subwatershed annual flow mean and standard deviation under different scenarios with OdN (2005 Irrigation Scenario).

2015 Irrigation Scenario:

Figure 49: Kirango subwatershed annual flow mean and standard deviation under different scenarios with OdN (2015 Irrigation Scenario).

Figure 50: Ké-Macina subwatershed annual flow mean and standard deviation under different scenarios with OdN (2015 Irrigation Scenario).

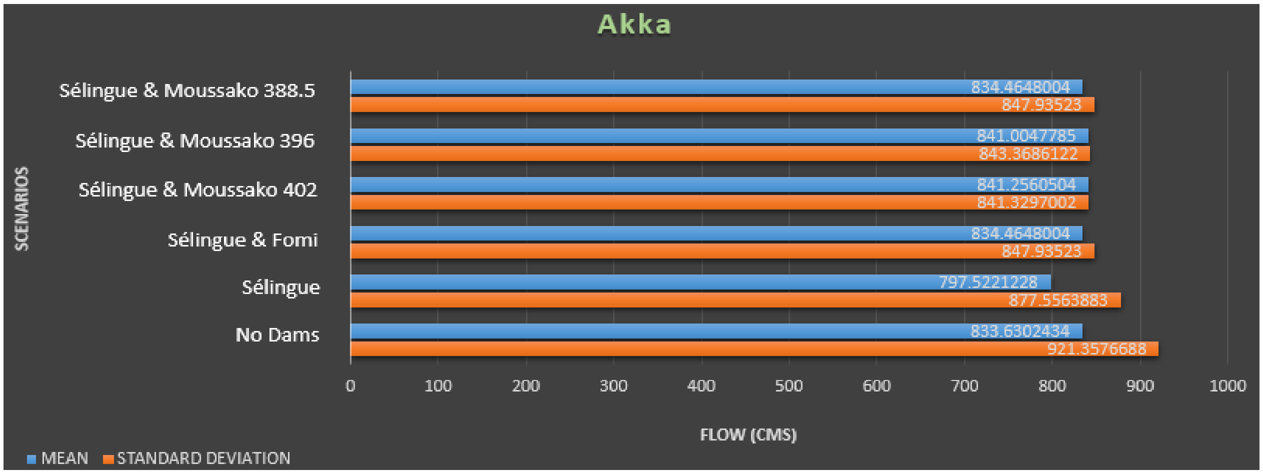


Figure 51: Akka subwatershed annual flow mean and standard deviation under different scenarios with OdN (2015 Irrigation Scenario).

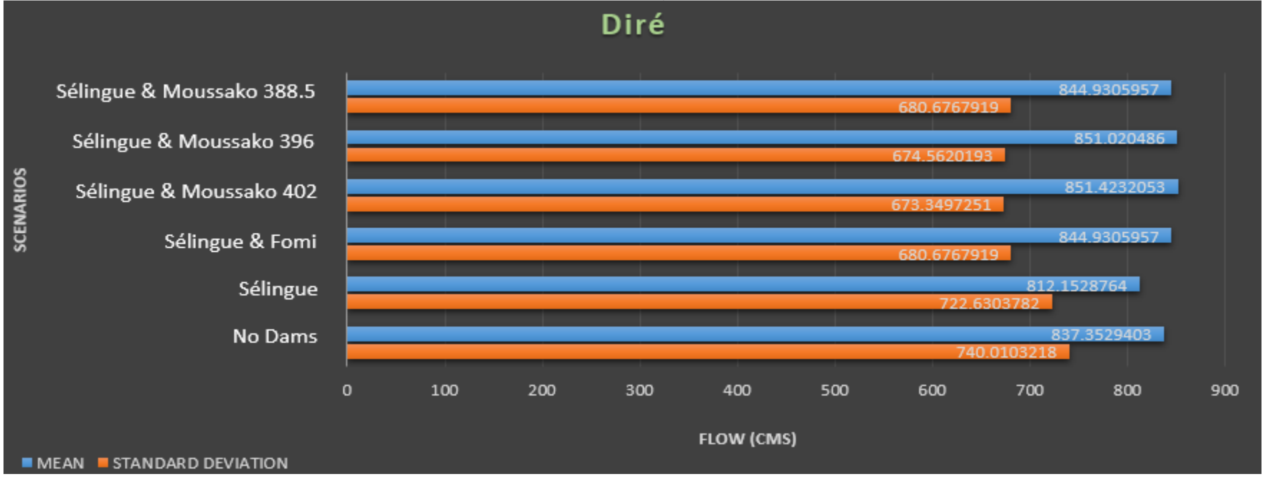


Figure 52: Diré subwatershed annual flow mean and standard deviation under different scenarios with OdN (2015 Irrigation Scenario).

2025 Irrigation Scenario:

Figure 53: Kirango subwatershed annual flow mean and standard deviation under different scenarios with OdN (2025 Irrigation Scenario).

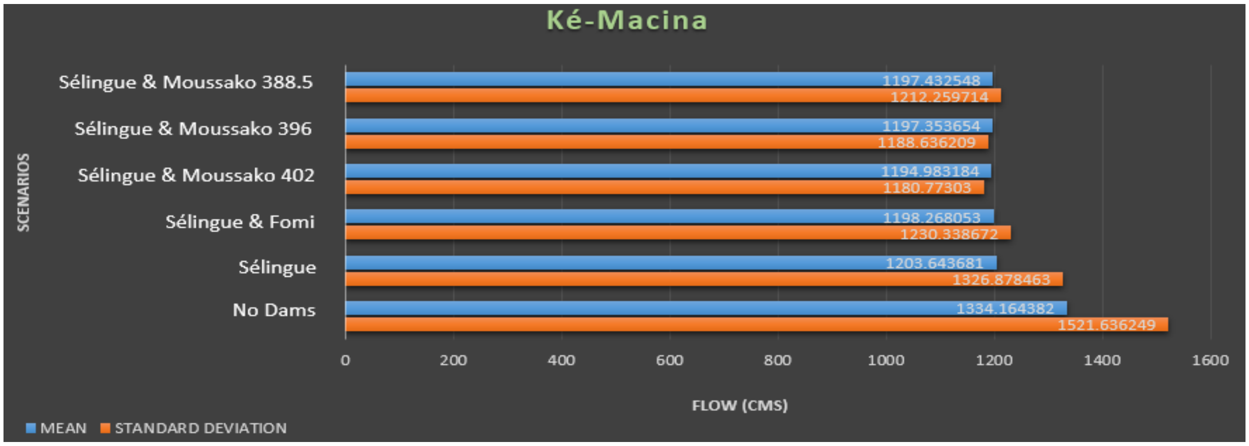


Figure 54: Ké-Macina subwatershed annual flow mean and standard deviation under different scenarios with OdN (2025 Irrigation Scenario).

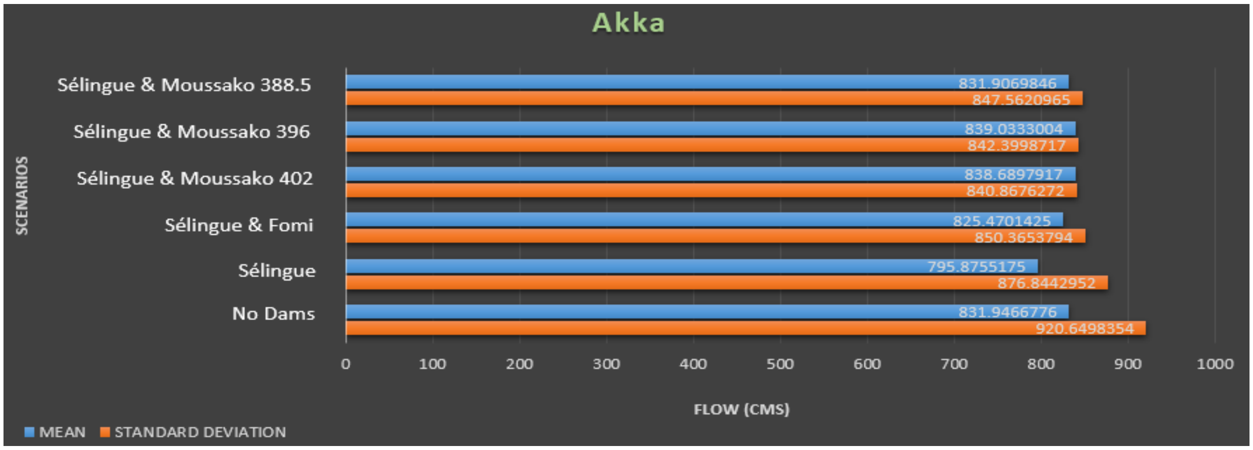


Figure 55: Akka subwatershed annual flow mean and standard deviation under different scenarios with OdN (2025 Irrigation Scenario).

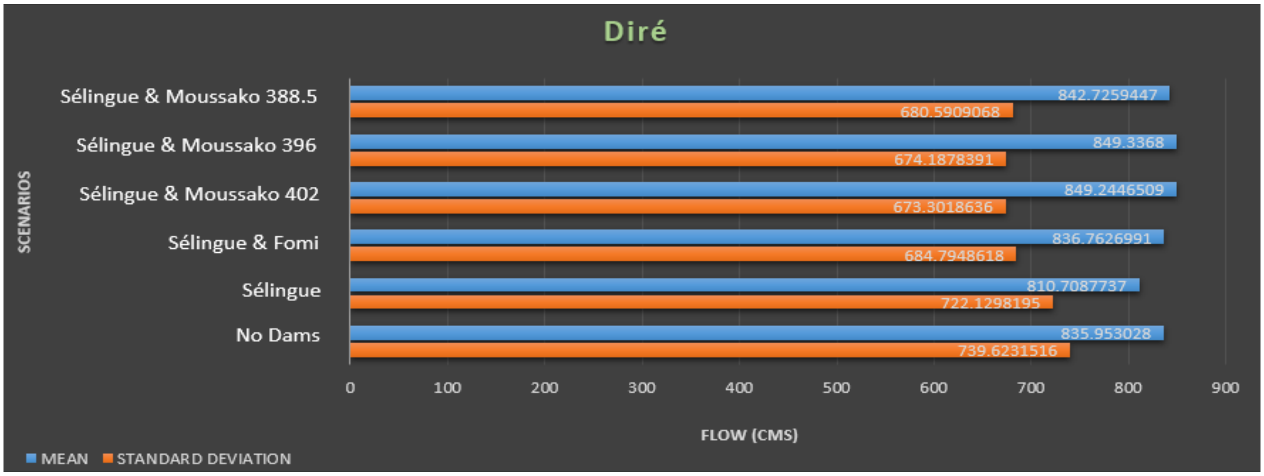


Figure 56: Diré subwatershed annual flow mean and standard deviation under different scenarios with OdN (2025 Irrigation Scenario).

2035 Irrigation Scenario:

Figure 57: Kirango subwatershed annual flow mean and standard deviation under different scenarios with OdN (2035 Irrigation Scenario).

Figure 58: Ké-Macina subwatershed annual flow mean and standard deviation under different scenarios with OdN (2035 Irrigation Scenario).

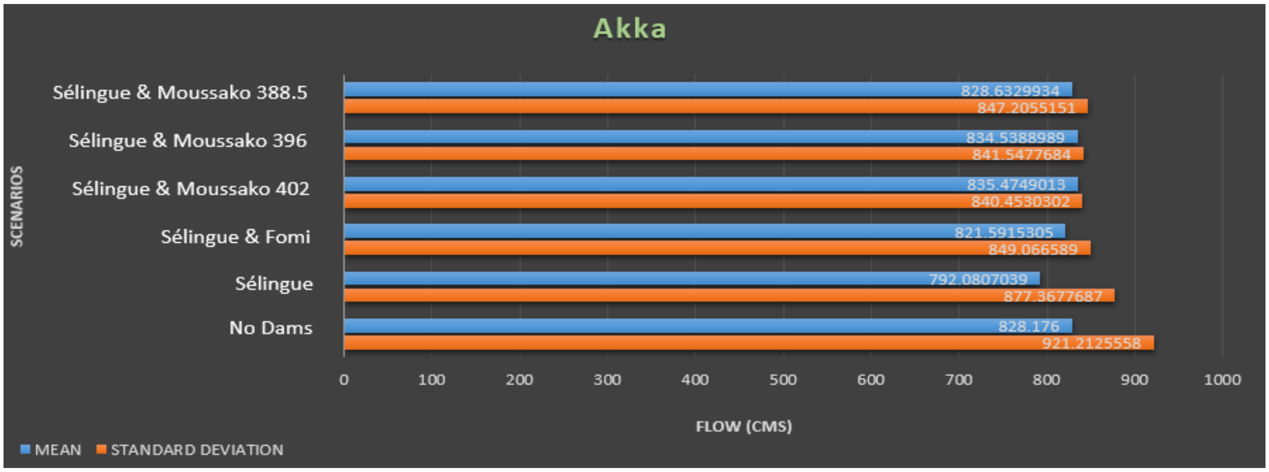


Figure 59: Akka subwatershed annual flow mean and standard deviation under different scenarios with OdN (2035 Irrigation Scenario).

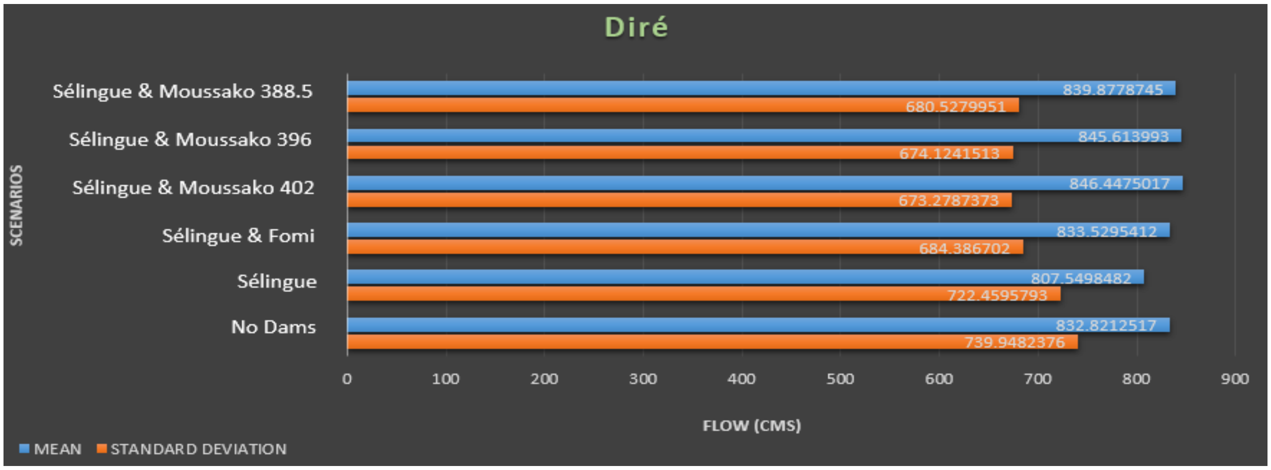


Figure 60: Diré subwatershed annual flow mean and standard deviation under different scenarios with OdN (2035 Irrigation Scenario).

2045 Irrigation Scenario:

Figure 61: Kirango subwatershed annual flow mean and standard deviation under different scenarios with OdN (2045 Irrigation Scenario).

Figure 62: Ké-Macina subwatershed annual flow mean and standard deviation under different scenarios with OdN (2045 Irrigation Scenario).

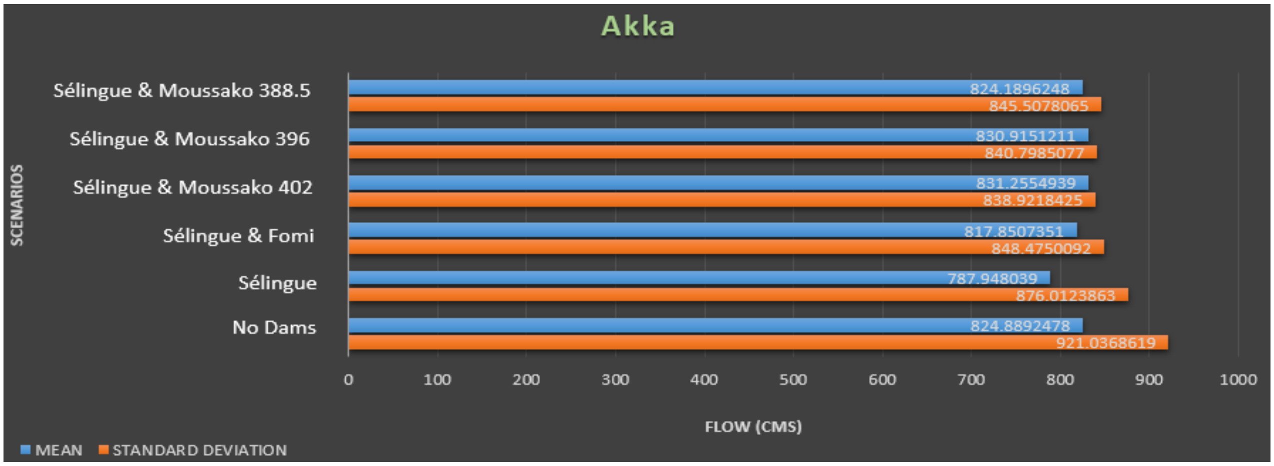


Figure 63: Akka subwatershed annual flow mean and standard deviation under different scenarios with OdN (2045 Irrigation Scenario).

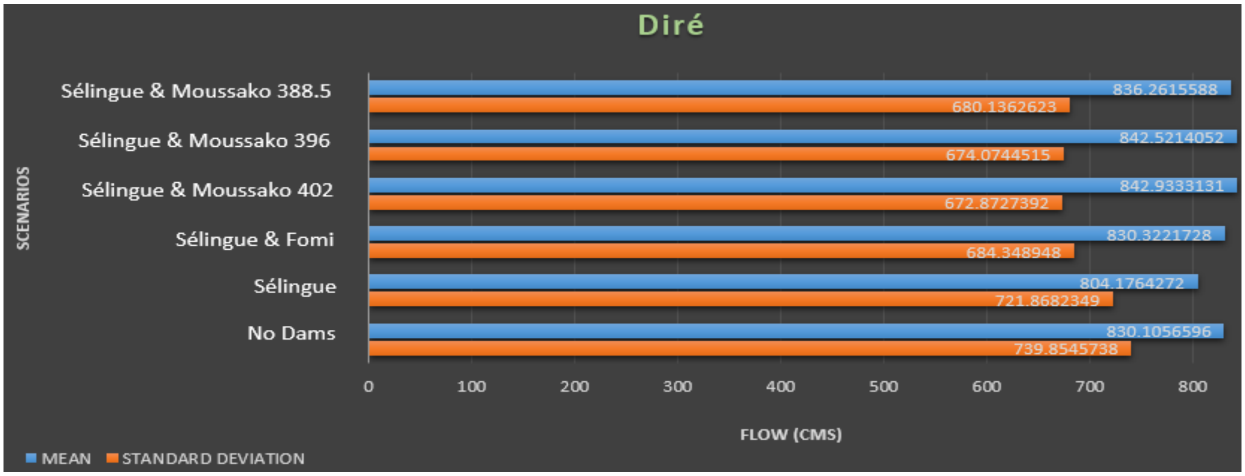


Figure 64: Diré subwatershed annual flow mean and standard deviation under different scenarios with OdN (2045 Irrigation Scenario).

b. Effects on the Flow of the Wettest Month of the Year

Without Office du Niger

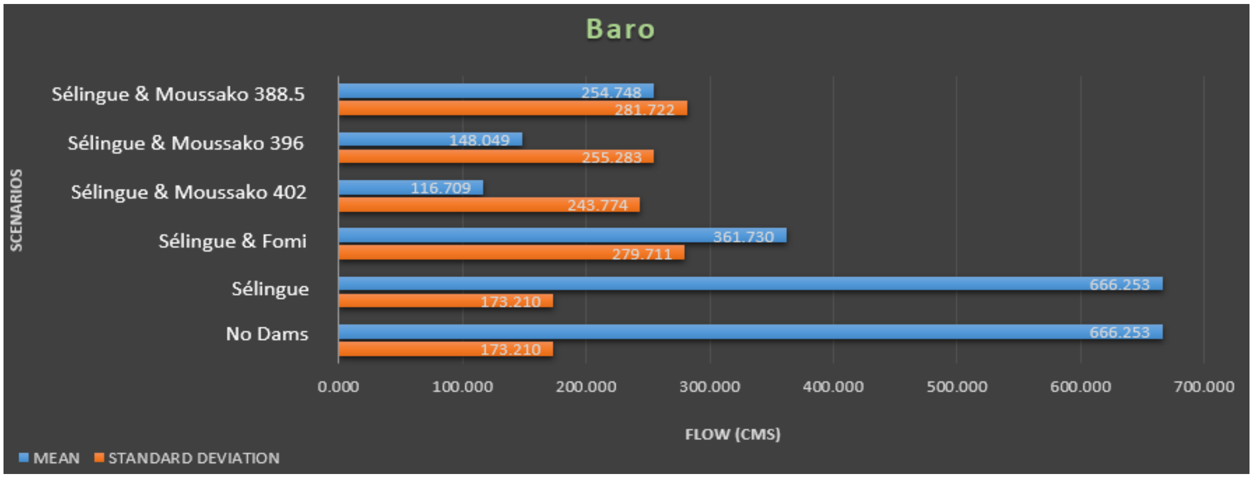


Figure 65: Baro subwatershed wettest month flow mean and standard deviation under different scenarios, without OdN.

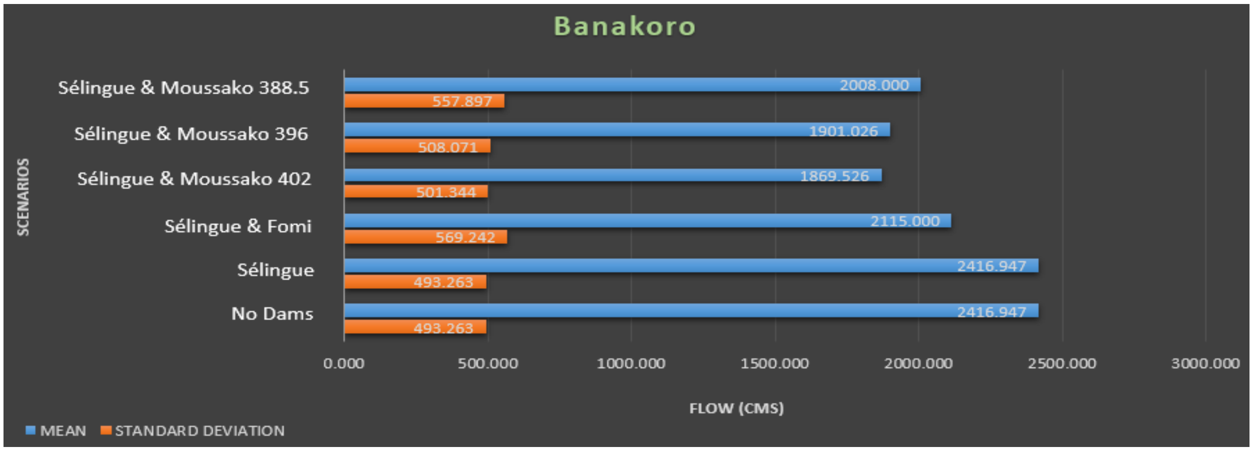


Figure 66: Banakoro subwatershed wettest month flow mean and standard deviation under different scenarios, without OdN.

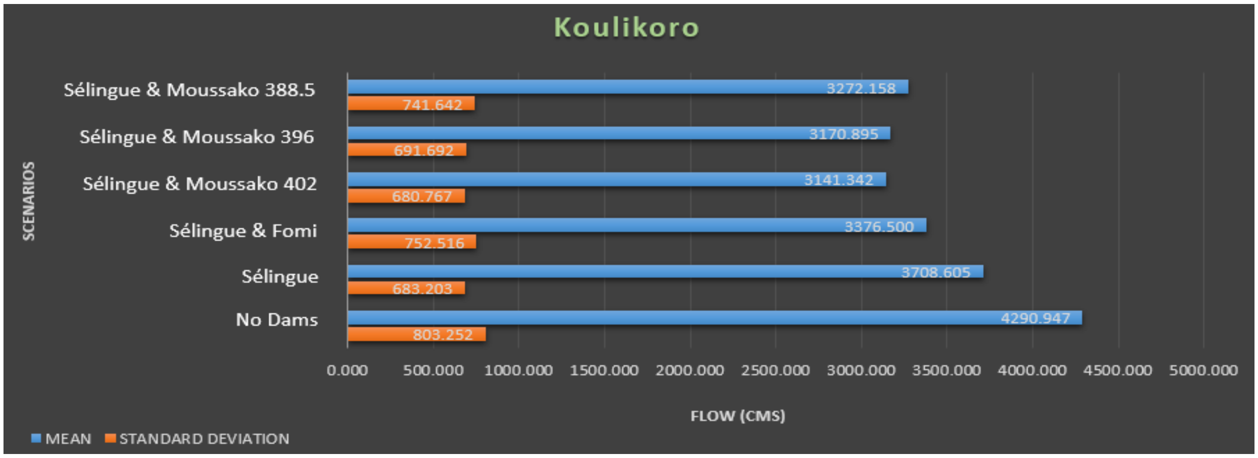


Figure 67: Koulikoro subwatershed wettest month flow mean and standard deviation under different scenarios, without OdN.

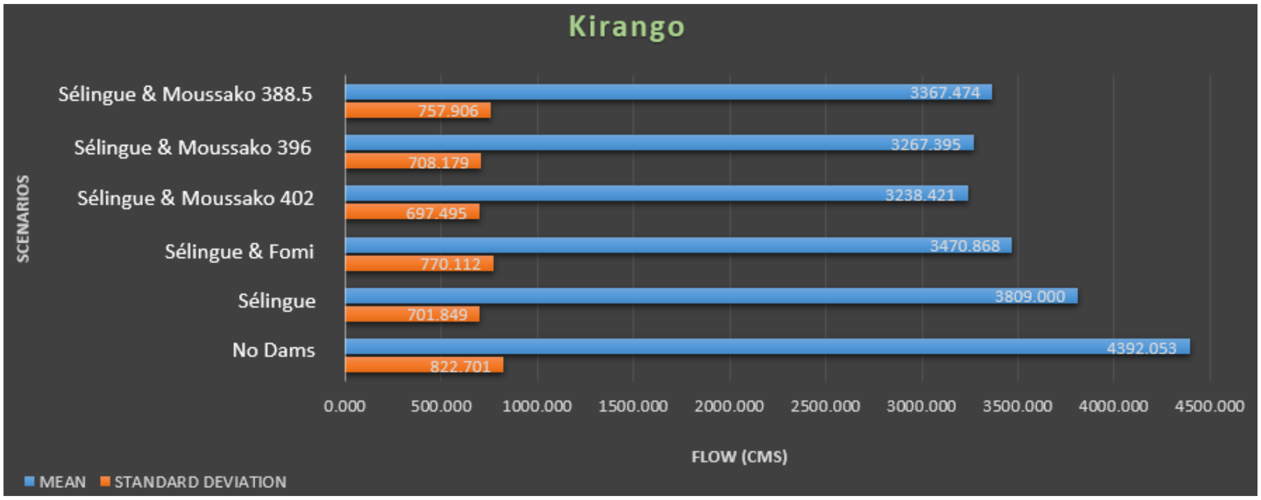


Figure 68: Kirango subwatershed wettest month flow mean and standard deviation under different scenarios, without OdN.

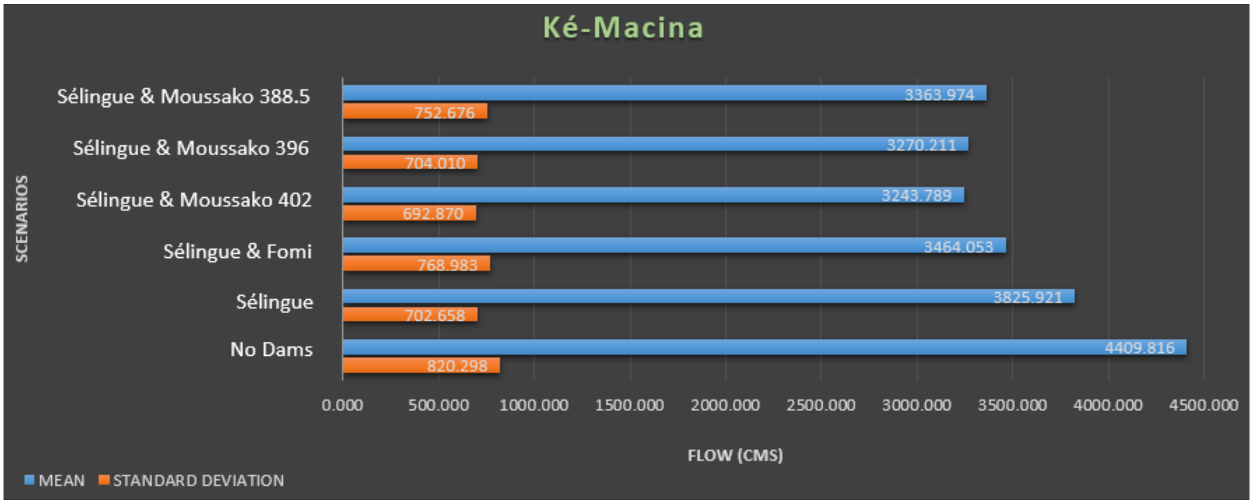


Figure 69: Ké-Macina subwatershed wettest month flow mean and standard deviation under different scenarios, without OdN.

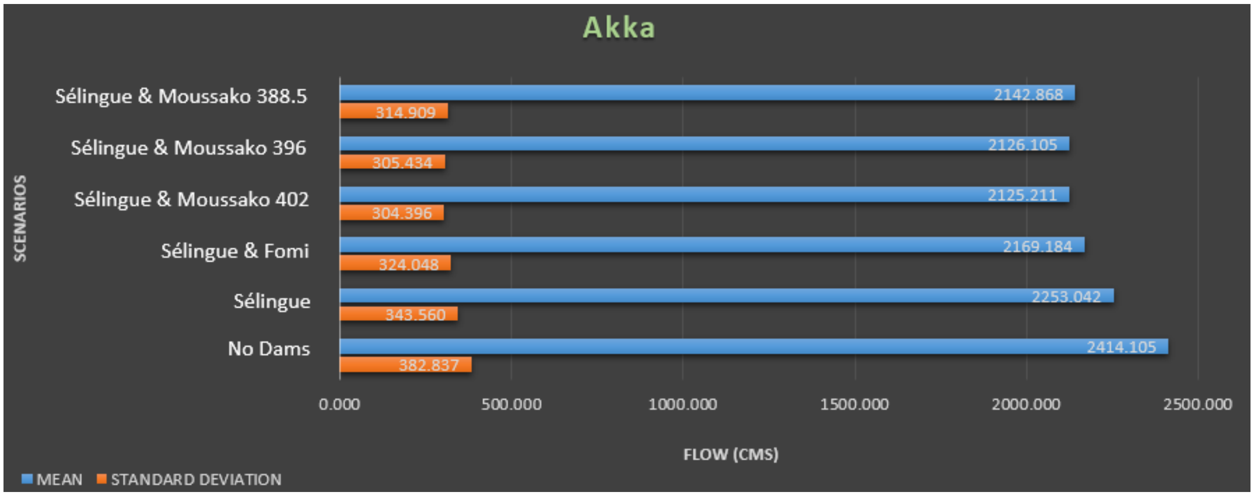


Figure 70: Akka subwatershed wettest month flow mean and standard deviation under different scenarios, without OdN.

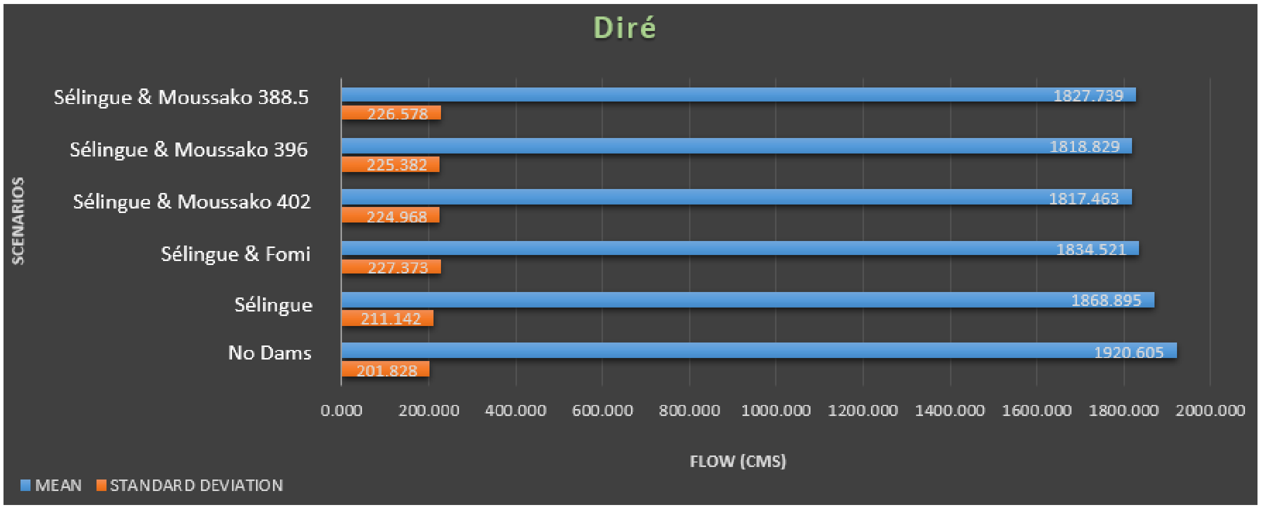


Figure 71: Diré subwatershed wettest month flow mean and standard deviation under different scenarios, without OdN.

With Office du Niger

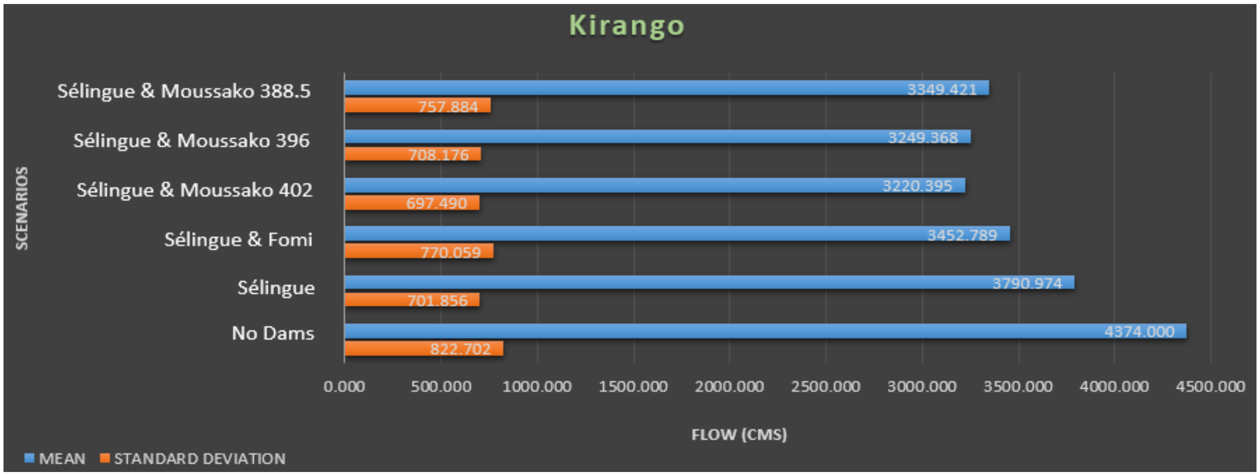


Figure 72: Kirango subwatershed wettest month flow mean and standard deviation under different scenarios, with OdN.

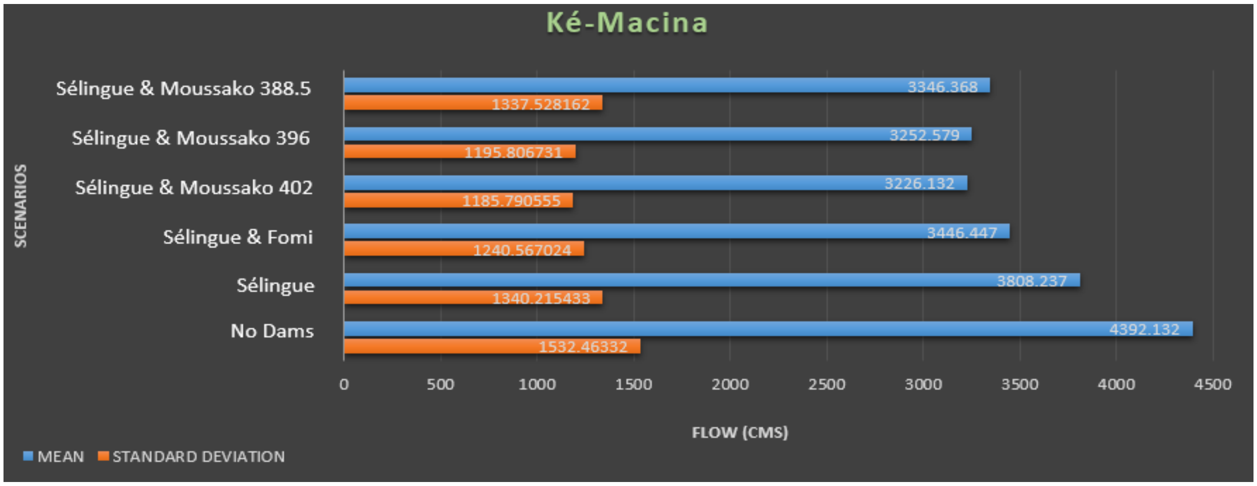


Figure 73: Ké-Macina subwatershed wettest month flow mean and standard deviation under different scenarios, with OdN.

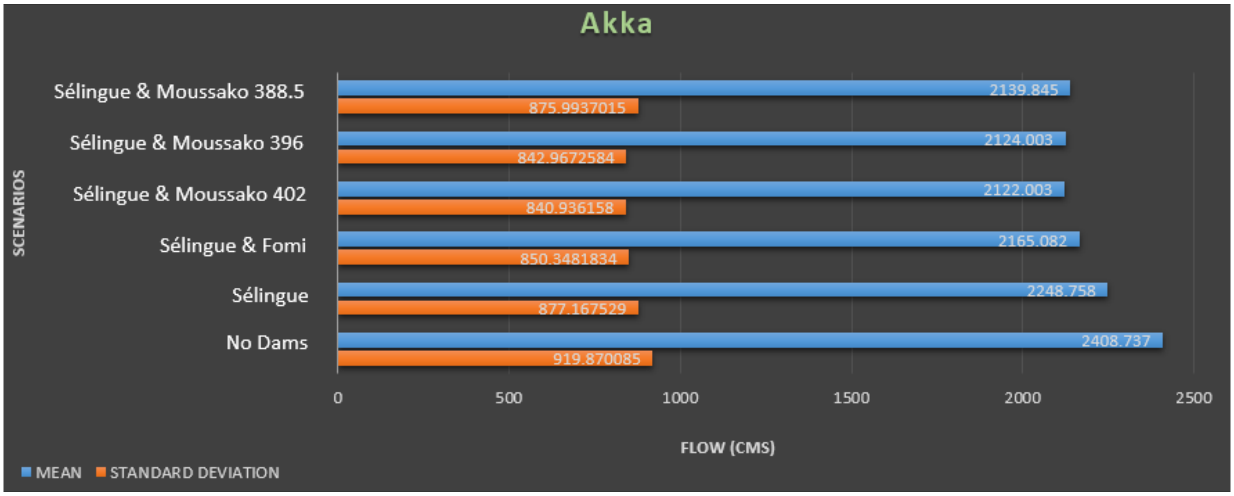


Figure 74: Akka subwatershed wettest month flow mean and standard deviation under different scenarios, with OdN.

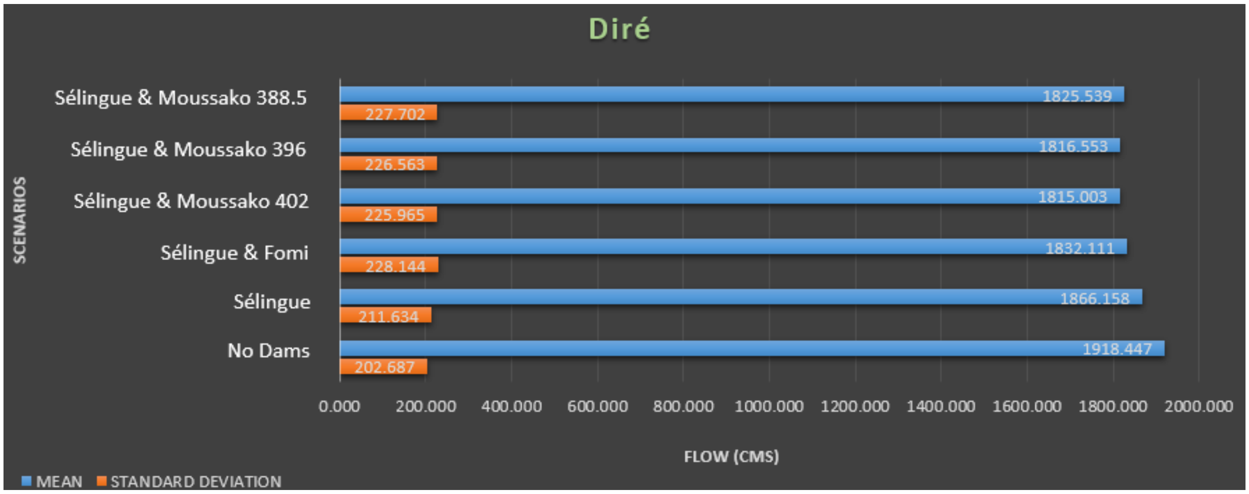


Figure 75: Diré subwatershed wettest month flow mean and standard deviation under different scenarios, with OdN.

c. Effects on the Flow of the Driest Month of the Year

Without Office du Niger

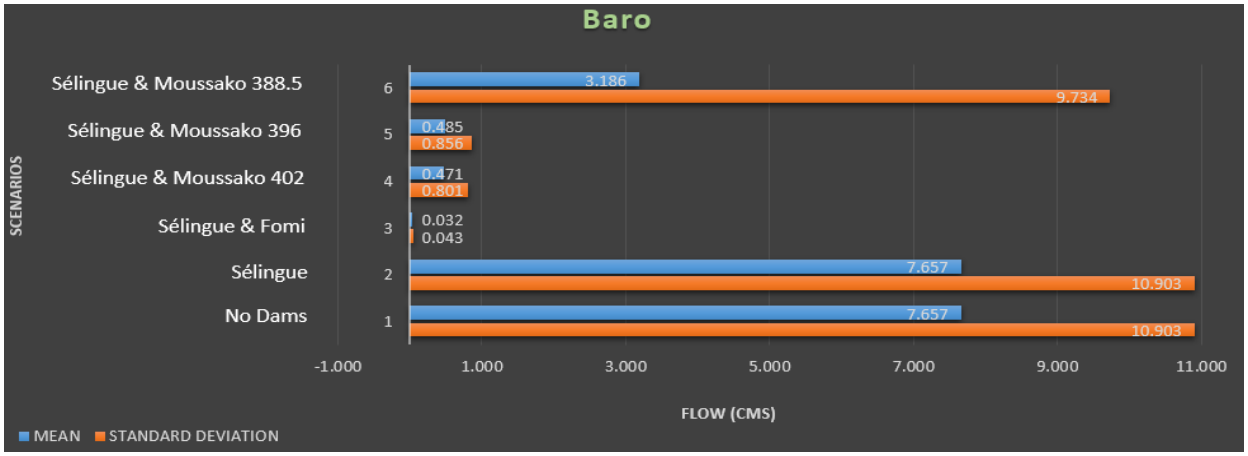


Figure 76: Baro subwatershed driest month flow mean and standard deviation under different scenarios, without OdN.

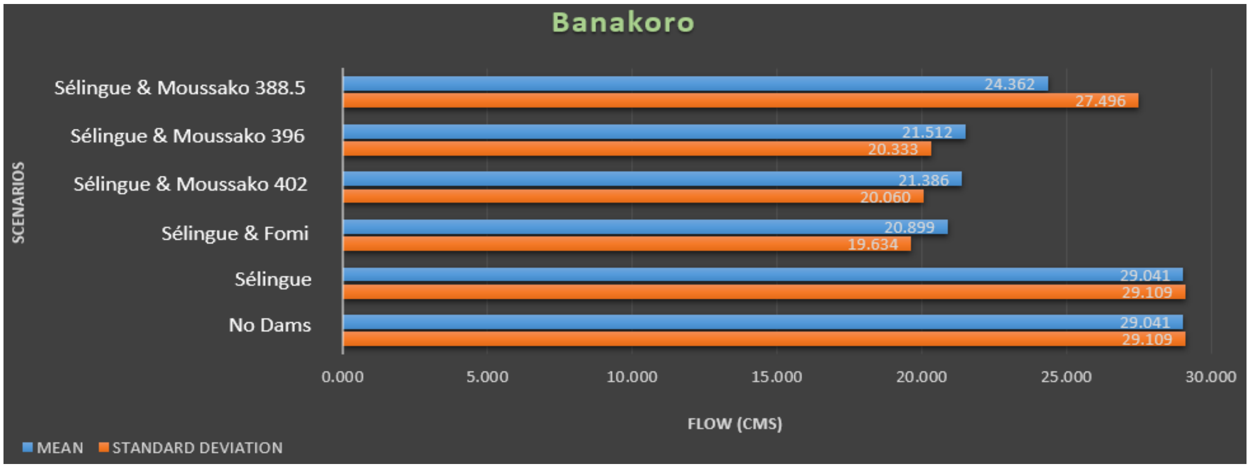


Figure 77: Banakoro subwatershed driest month flow mean and standard deviation under different scenarios, without OdN.

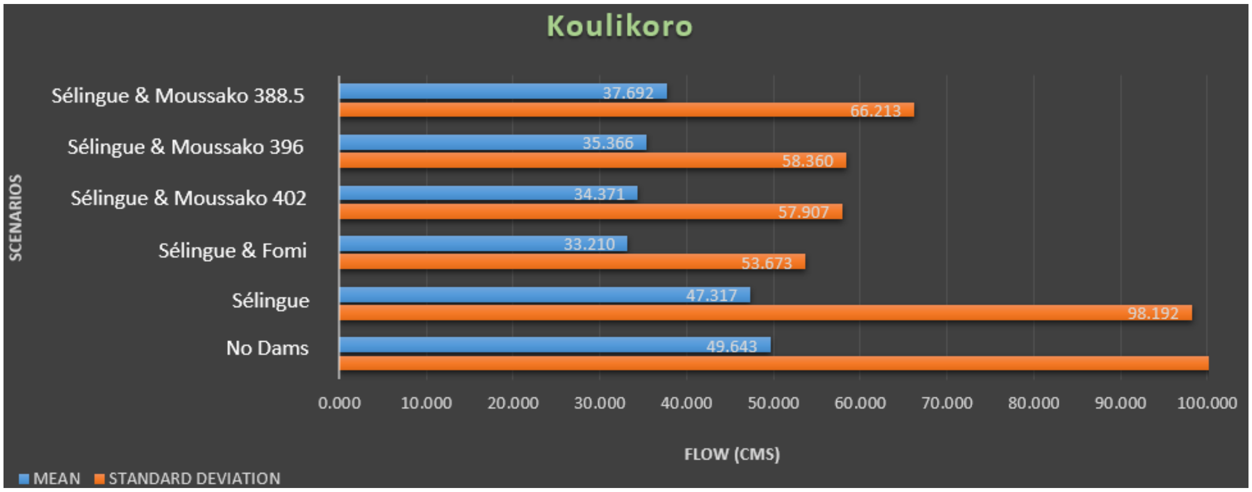


Figure 78: Koulikoro subwatershed driest month flow mean and standard deviation under different scenarios, without OdN.

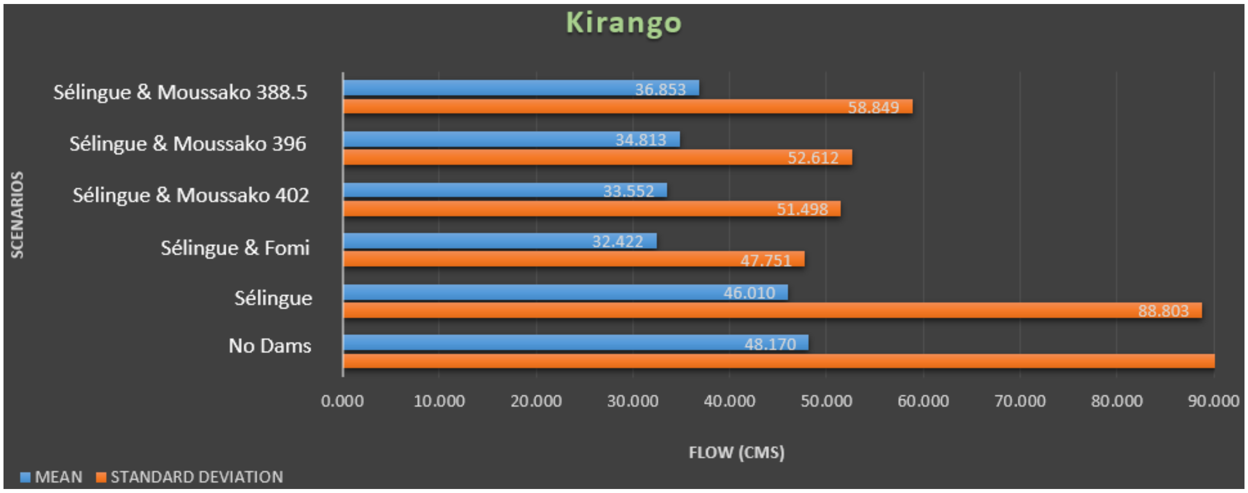


Figure 79: Kirango subwatershed driest month flow mean and standard deviation under different scenarios, without OdN.

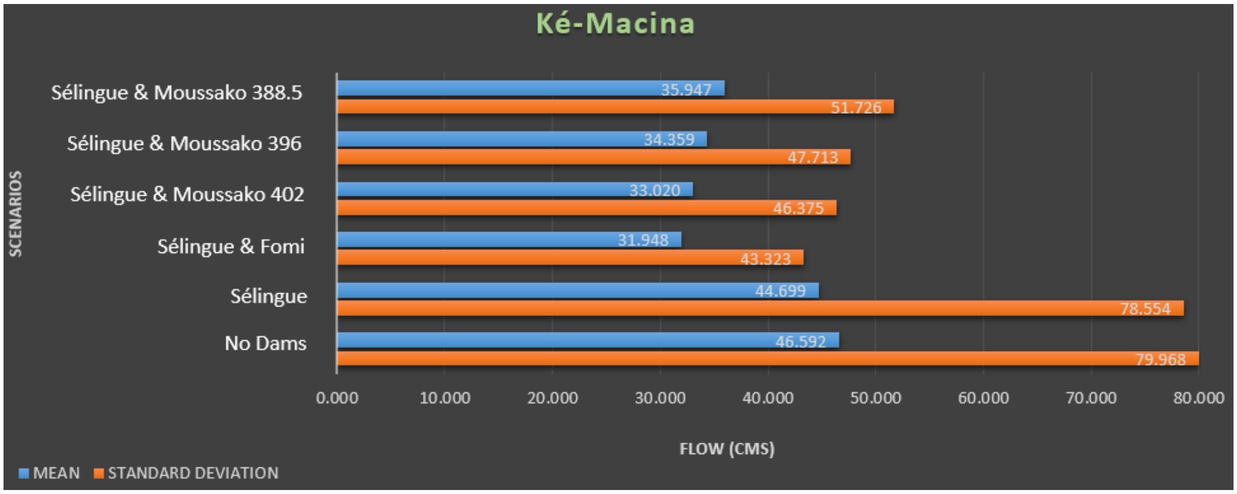


Figure 80: Ké-Macina subwatershed driest month flow mean and standard deviation under different scenarios, without OdN.

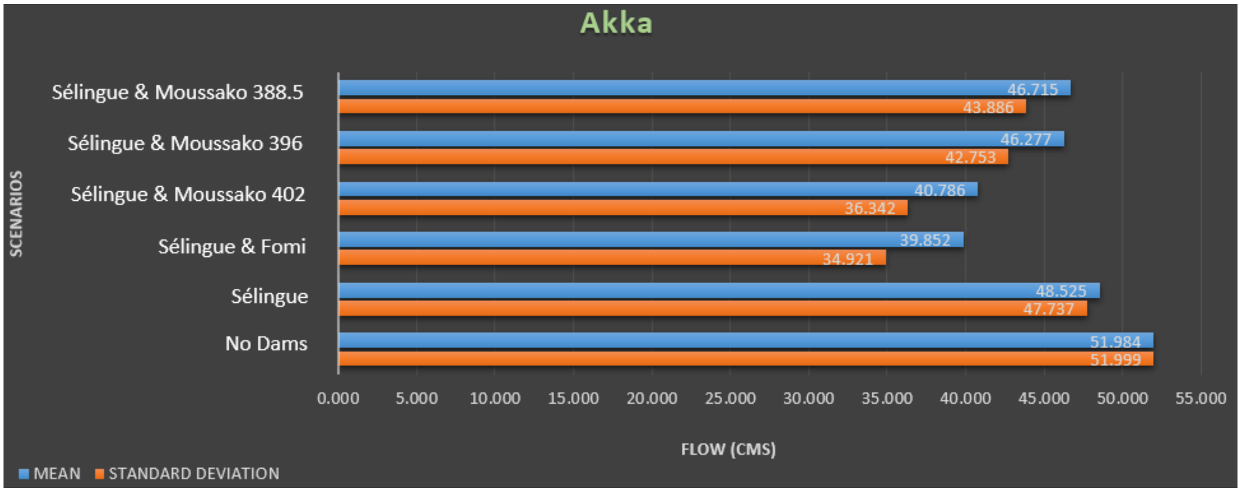


Figure 81: Akka subwatershed driest month flow mean and standard deviation under different scenarios, without OdN.

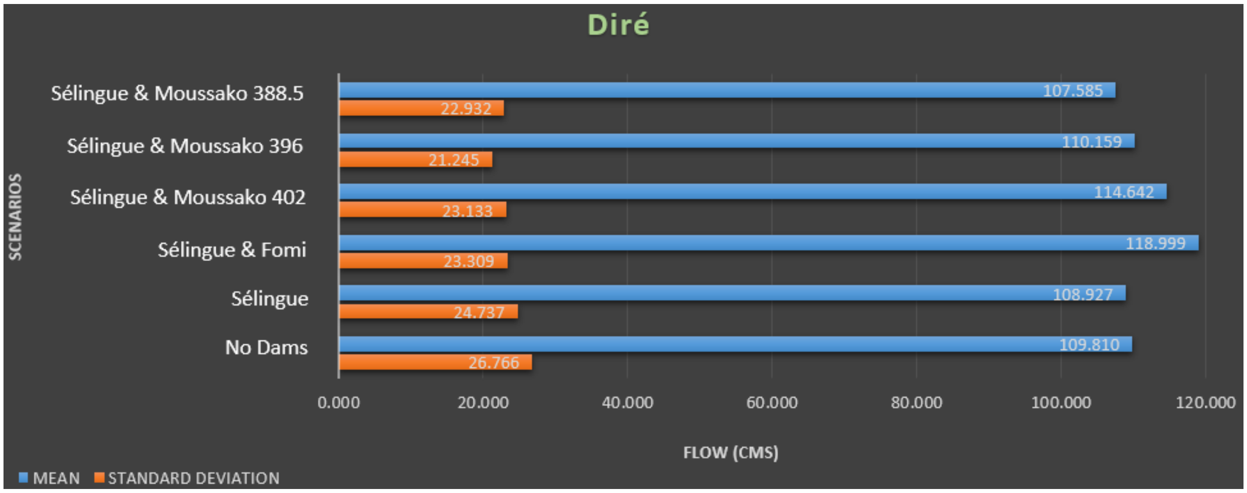


Figure 82: Diré subwatershed driest month flow mean and standard deviation under different scenarios, without OdN.

With Office du Niger

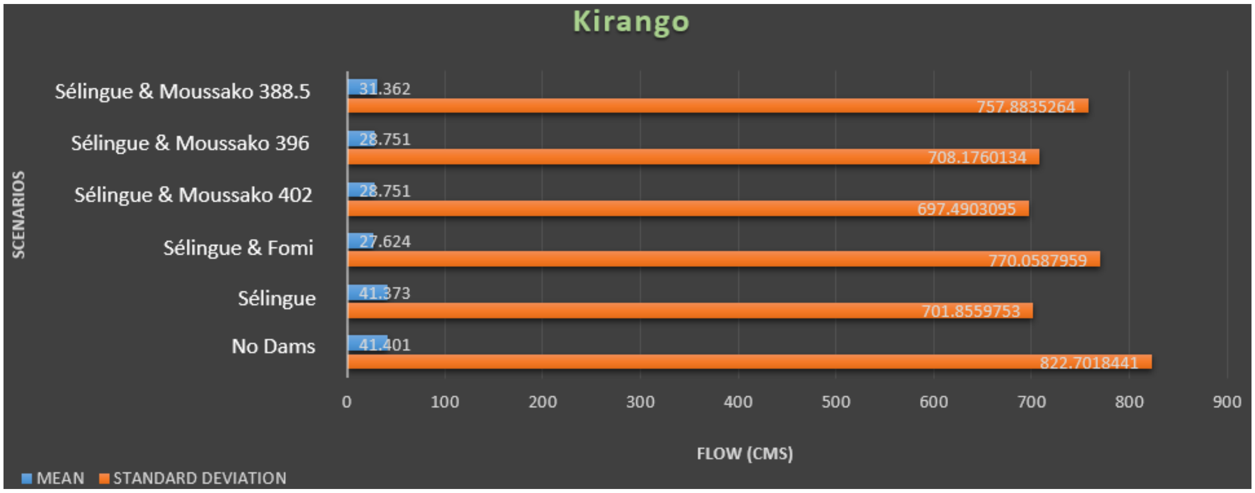


Figure 83: Kirango subwatershed driest month flow mean and standard deviation under different scenarios, with OdN.

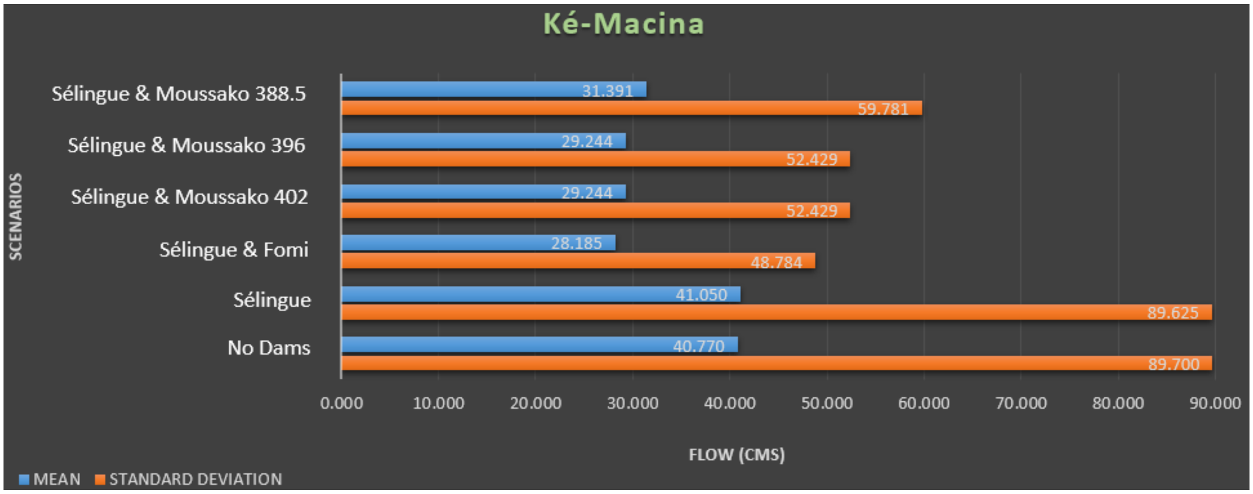


Figure 84: Ké-Macina subwatershed driest month flow mean and standard deviation under different scenarios, with OdN.

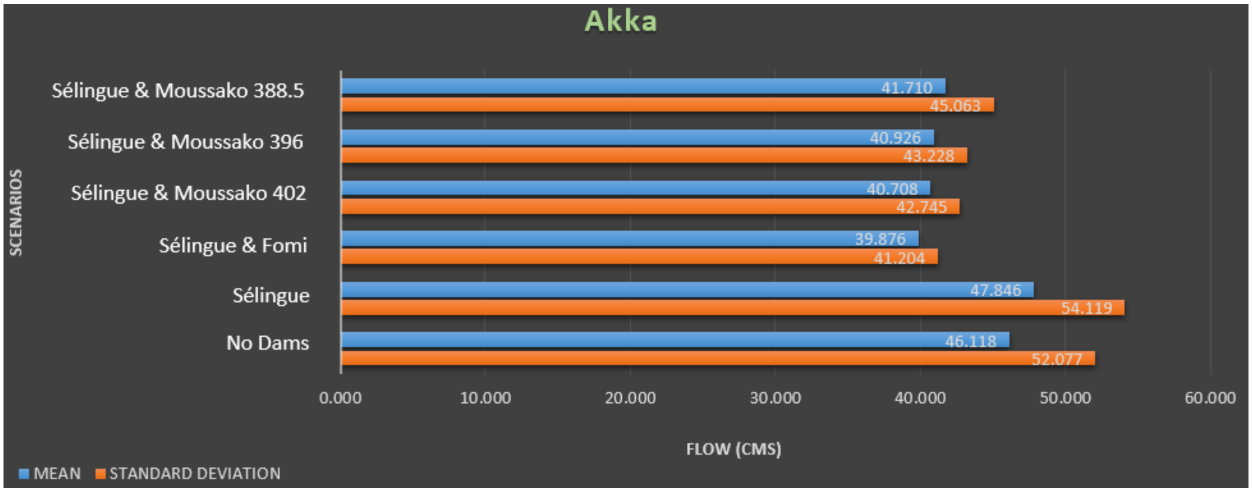


Figure 85: Akka subwatershed driest month flow mean and standard deviation under different scenarios, with OdN.

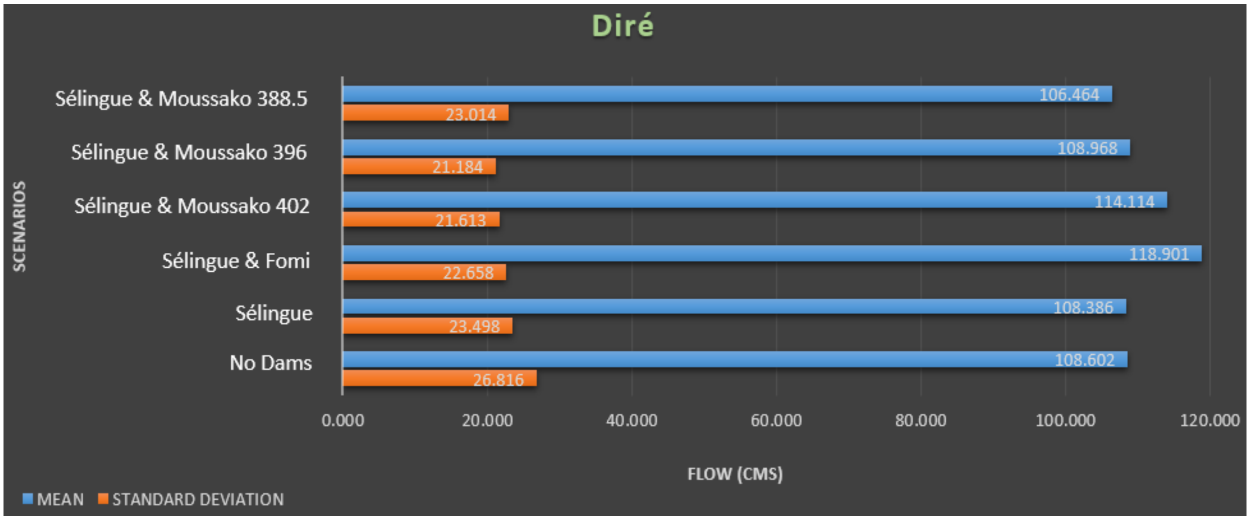


Figure 86: Diré subwatershed driest month flow mean and standard deviation under different scenarios, with OdN.

d. Effects on the Flow of the Driest Month of the Driest Year

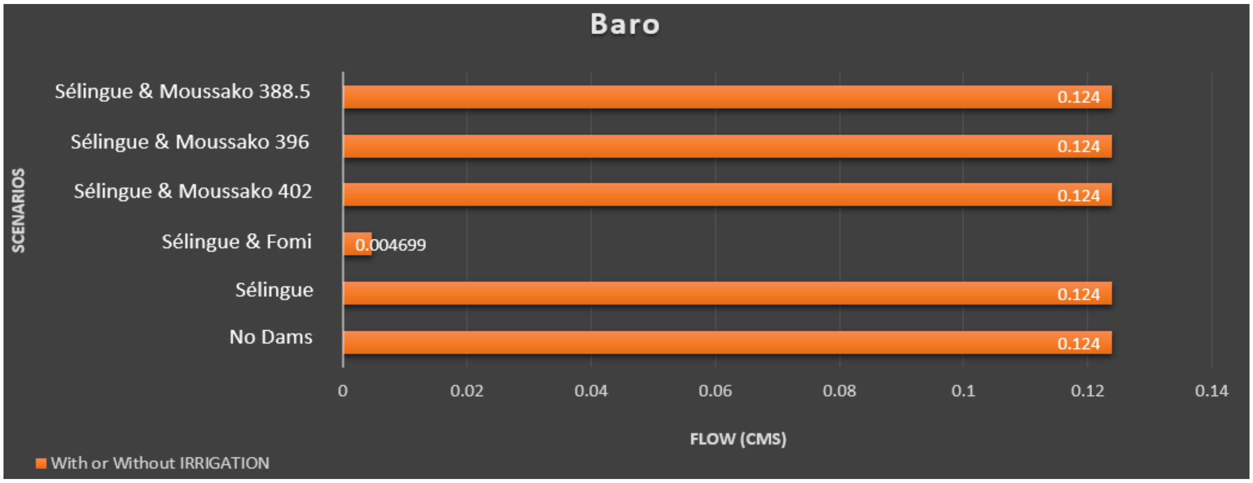


Figure 87: Baro subwatershed flow for the driest month of the driest year under different scenarios.

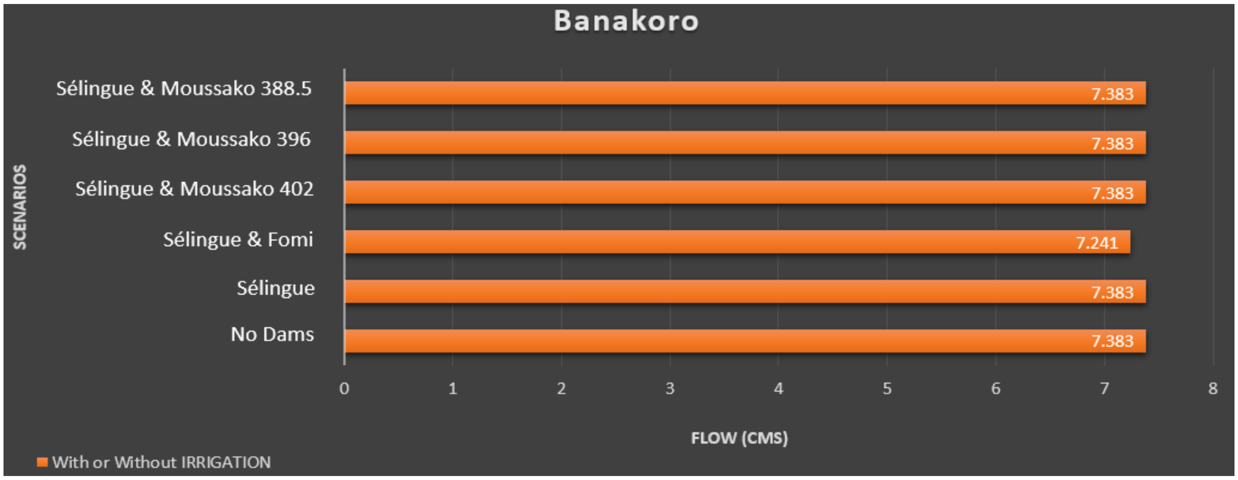


Figure 88: Banakoro subwatershed flow for the driest month of the driest year under different scenarios.

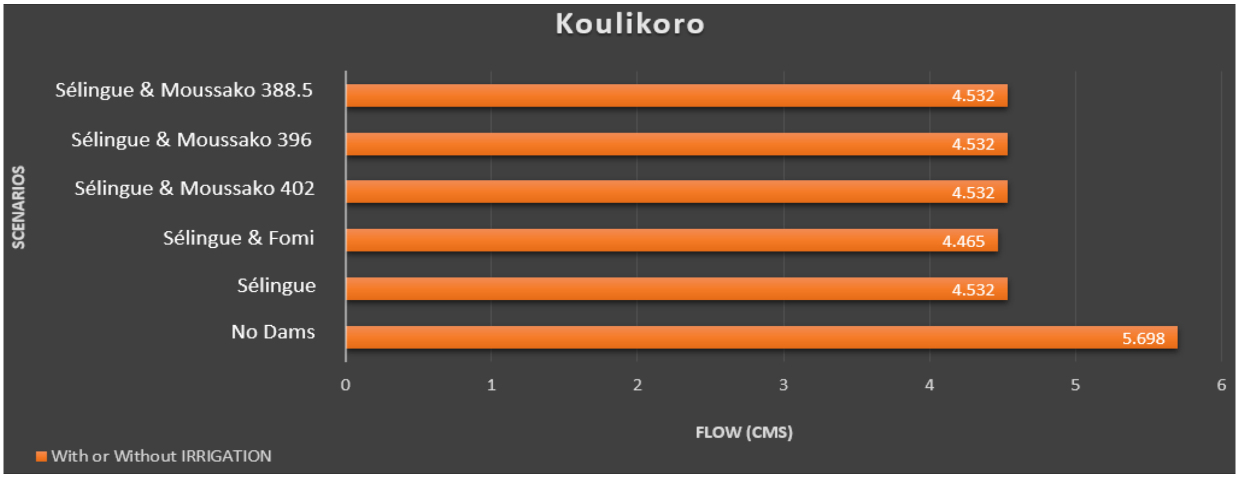


Figure 89: Koulikoro subwatershed flow for the driest month of the driest year under different scenarios.

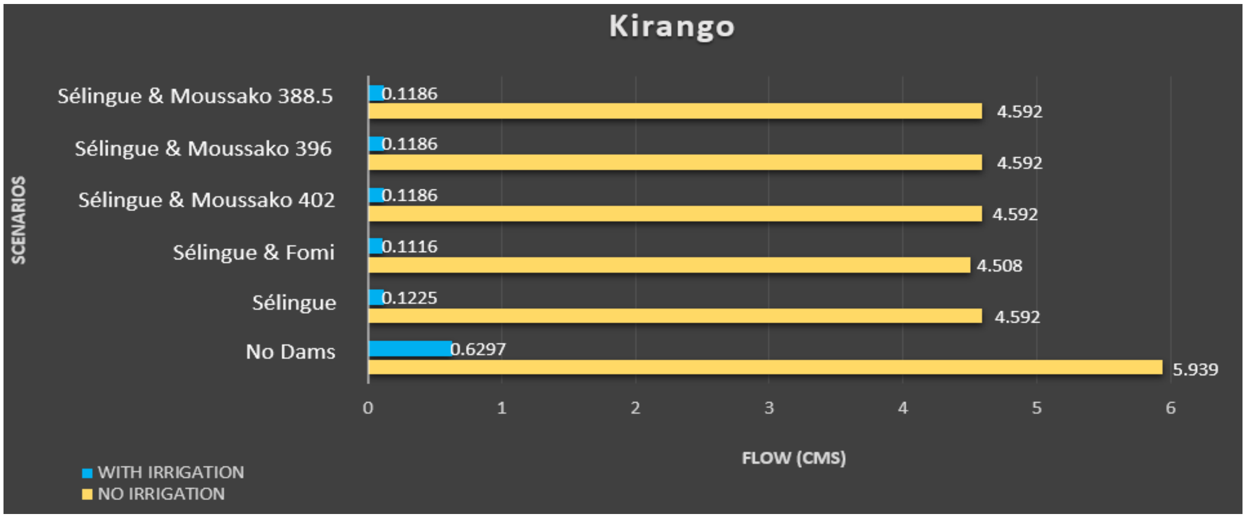


Figure 90: Kirango subwatershed flow for the driest month of the driest year under different scenarios.

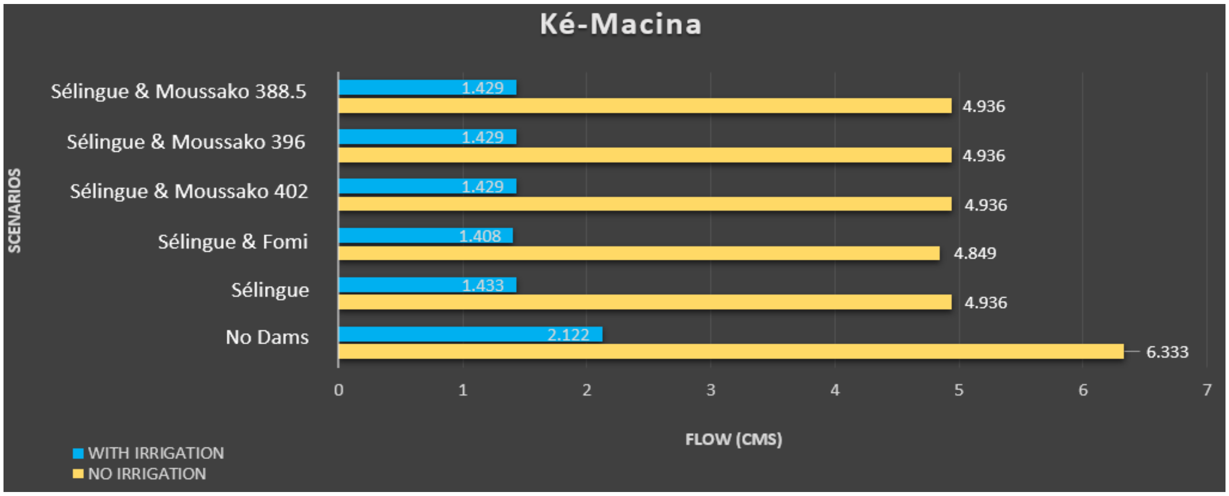


Figure 91: Ké-Macina subwatershed flow for the driest month of the driest year under different scenarios.

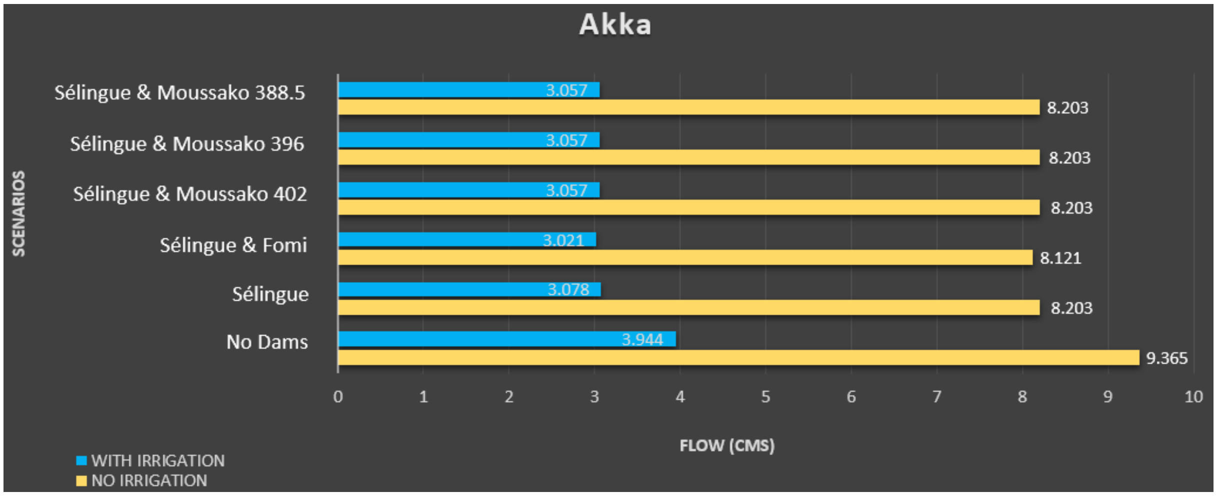


Figure 92: Akka subwatershed flow for the driest month of the driest year under different scenarios.

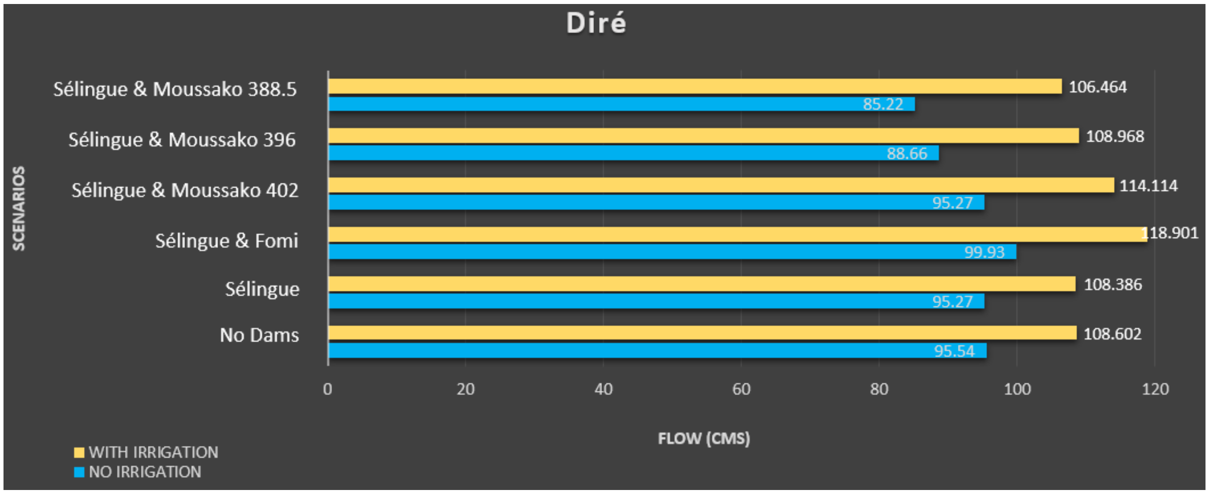


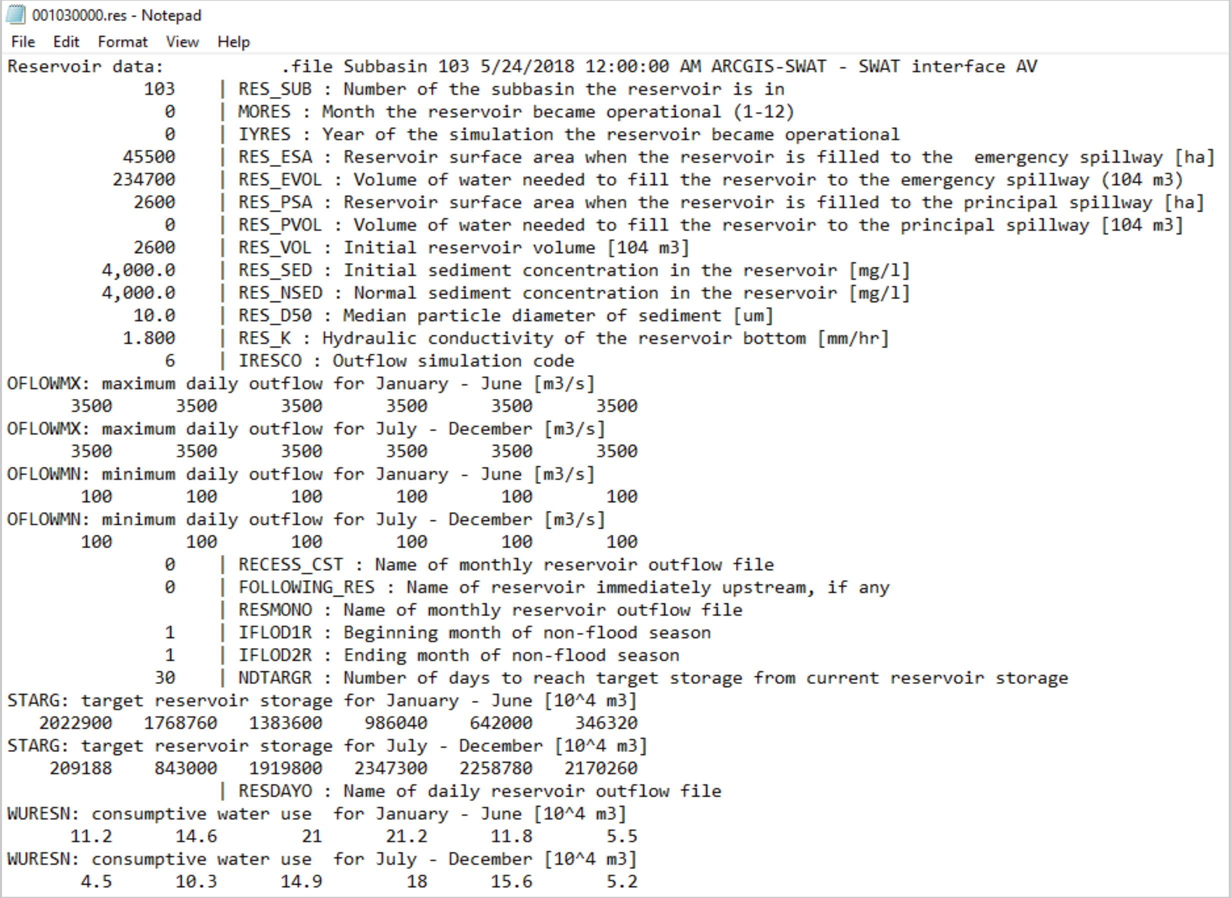
Figure 93: Diré subwatershed flow for the driest month of the driest year under different scenarios.

Appendix C: Swat Reservoir Input File (Modified Format)

This appendix presents complementary information on the SWAT reservoir file format used for this study. It lists in order (from top to bottom) the different sections of the file.

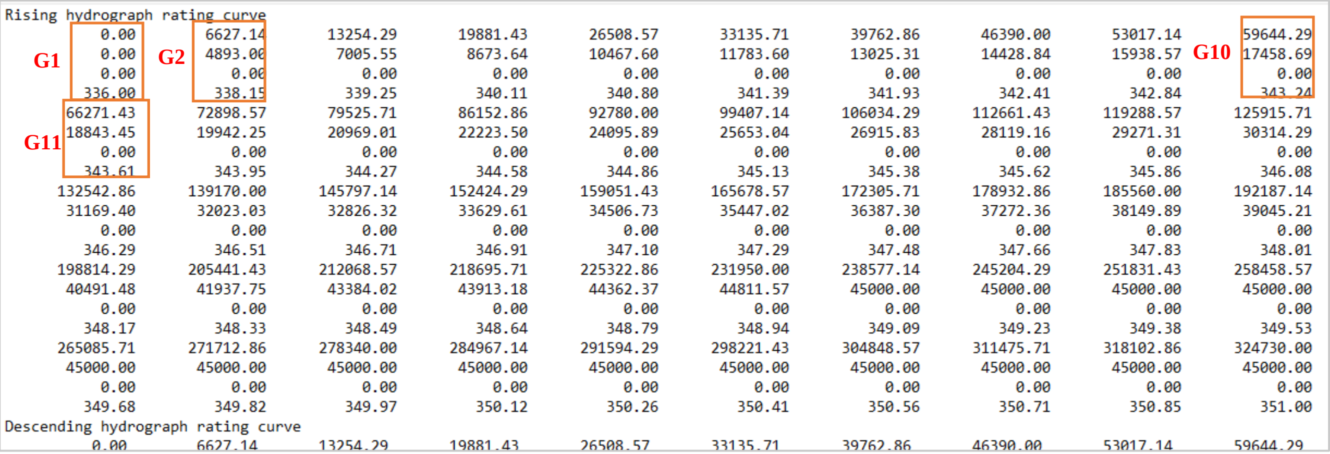
File Name: Located in the right top corner, it comprises of nine characters. The five first characters correspond to the subwatershed number. If the subwatershed number is less than five characters, the name is preceded by zeros. The four last characters are zeros. The name is followed by the file extension (.res). Ex: the file 000920000.res is for reservoir 92.

Reservoir data: The first line is information about the file and is not used by the program. The next lines contain the following swat simulation parameters: res_sub, mores, iyres, res_esa, res_evol, res_psa, res_pvol, res_vol, res_sed, res_nsed, res_d50, res_k, iresco, oflowmx, oflowmn, recess_cst. following_res, resmonio, iflod1r, iflod2r, ndtargr, starg, wuresn, wurtnf, evrsv, oflowmn_fps, and starg_fps). Please refer to the SWAT-IO-Documentation-2012 for parameters description.



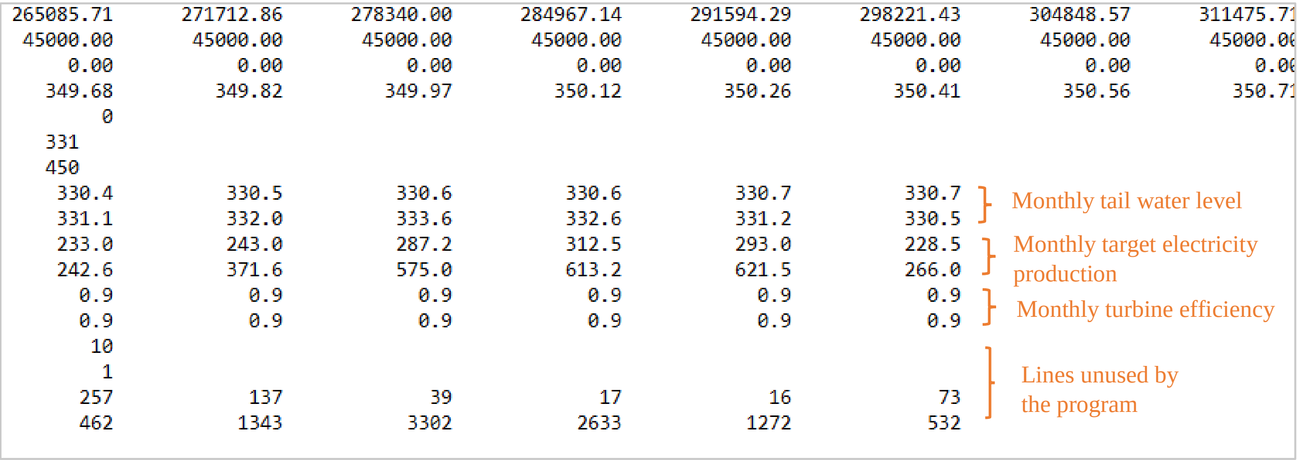
```
Reservoir data:           .file Subbasin 103 5/24/2018 12:00:00 AM ARCGIS-SWAT - SWAT interface AV
             103    | RES_SUB : Number of the subbasin the reservoir is in
               0    | MORES : Month the reservoir became operational (1-12)
               0    | IYRES : Year of the simulation the reservoir became operational
           45500    | RES_ESA : Reservoir surface area when the reservoir is filled to the  emergency spillway [ha]
          234700    | RES_EVOL : Volume of water needed to fill the reservoir to the emergency spillway (104 m3)
            2600    | RES_PSA : Reservoir surface area when the reservoir is filled to the principal spillway [ha]
               0    | RES_PVOL : Volume of water needed to fill the reservoir to the principal spillway [104 m3]
            2600    | RES_VOL : Initial reservoir volume [104 m3]
         4,000.0    | RES_SED : Initial sediment concentration in the reservoir [mg/l]
         4,000.0    | RES_NSED : Normal sediment concentration in the reservoir [mg/l]
            10.0    | RES_D50 : Median particle diameter of sediment [um]
           1.800    | RES_K : Hydraulic conductivity of the reservoir bottom [mm/hr]
               6    | IRESCO : Outflow simulation code
OFLOWMX: maximum daily outflow for January - June [m3/s]
      3500      3500      3500      3500      3500      3500
OFLOWMX: maximum daily outflow for July - December [m3/s]
      3500      3500      3500      3500      3500      3500
OFLOWMN: minimum daily outflow for January - June [m3/s]
       100       100       100       100       100       100
OFLOWMN: minimum daily outflow for July - December [m3/s]
       100       100       100       100       100       100
               0    | RECESS_CST : Name of monthly reservoir outflow file
               0    | FOLLOWING_RES : Name of reservoir immediately upstream, if any
                    | RESMONO : Name of monthly reservoir outflow file
               1    | IFLOD1R : Beginning month of non-flood season
               1    | IFLOD2R : Ending month of non-flood season
              30    | NDTARGR : Number of days to reach target storage from current reservoir storage
STARG: target reservoir storage for January - June [10^4 m3]
   2022900   1768760   1383600    986040    642000    346320
STARG: target reservoir storage for July - December [10^4 m3]
    209188    843000   1919800   2347300   2258780   2170260
                    | RESDAYO : Name of daily reservoir outflow file
WURESN: consumptive water use  for January - June [10^4 m3]
      11.2      14.6        21      21.2      11.8       5.5
WURESN: consumptive water use  for July - December [10^4 m3]
       4.5      10.3      14.9        18      15.6       5.2
```

Hydrograph rating curve: The data is divided into subsets of four elements (see square G1 in the screenshot below). In each subset, the first line corresponds to the volume, the second line to the surface area, the thirds line is a zero line, and the fourth line is the corresponding water level (stage). The columns (ten in total) are a series of increasing stages with the corresponding volumes and surface areas (from G1 to G2 in the screenshot below). At the end of the ten columns, the series continues with the next four lines (G11 in the screenshot below). In the end, there should be fifty groups of 4x1 matrices (five groups in each column and ten in the horizontal direction). The same data is used for the rising and descending hydrographs. The rating curve end with a zero or a space on the next line (not used by swat).



```
Rising hydrograph rating curve
           0.00        6627.14       13254.29       19881.43       26508.57       33135.71       39762.86       46390.00       53017.14       59644.29
           0.00        4893.00        7005.55        8673.64       10467.60       11783.60       13025.31       14428.84       15938.57       17458.69
           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00
         336.00         338.15         339.25         340.11         340.80         341.39         341.93         342.41         342.84         343.24
       66271.43       72898.57       79525.71       86152.86       92780.00       99407.14      106034.29      112661.43      119288.57      125915.71
       18843.45       19942.25       20969.01       22223.50       24095.89       25653.04       26915.83       28119.16       29271.31       30314.29
           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00
         343.61         343.95         344.27         344.58         344.86         345.13         345.38         345.62         345.86         346.08
      132542.86      139170.00      145797.14      152424.29      159051.43      165678.57      172305.71      178932.86      185560.00      192187.14
       31169.40       32023.03       32826.32       33629.61       34506.73       35447.02       36387.30       37272.36       38149.89       39045.21
           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00
         346.29         346.51         346.71         346.91         347.10         347.29         347.48         347.66         347.83         348.01
      198814.29      205441.43      212068.57      218695.71      225322.86      231950.00      238577.14      245204.29      251831.43      258458.57
       40491.48       41937.75       43384.02       43913.18       44362.37       44811.57       45000.00       45000.00       45000.00       45000.00
           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00
         348.17         348.33         348.49         348.64         348.79         348.94         349.09         349.23         349.38         349.53
      265085.71      271712.86      278340.00      284967.14      291594.29      298221.43      304848.57      311475.71      318102.86      324730.00
       45000.00       45000.00       45000.00       45000.00       45000.00       45000.00       45000.00       45000.00       45000.00       45000.00
           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.00
         349.68         349.82         349.97         350.12         350.26         350.41         350.56         350.71         350.85         351.00
Descending hydrograph rating curve
           0.00        6627.14       13254.29       19881.43       26508.57       33135.71       39762.86       46390.00       53017.14       59644.29
```

The next line is the Turbine Height in meters (331m in this example), followed by the Turbine Max Flow (450). The other values are described in the screenshot below.



```
 265085.71      271712.86      278340.00      284967.14      291594.29      298221.43      304848.57      311475.7
  45000.00       45000.00       45000.00       45000.00       45000.00       45000.00       45000.00       45000.0
      0.00           0.00           0.00           0.00           0.00           0.00           0.00           0.0
    349.68         349.82         349.97         350.12         350.26         350.41         350.56         350.7
         0
    331
    450
     330.4          330.5          330.6          330.6          330.7          330.7
     331.1          332.0          333.6          332.6          331.2          330.5
     233.0          243.0          287.2          312.5          293.0          228.5
     242.6          371.6          575.0          613.2          621.5          266.0
       0.9            0.9            0.9            0.9            0.9            0.9
       0.9            0.9            0.9            0.9            0.9            0.9
        10
         1
       257            137             39             17             16             73
       462           1343           3302           2633           1272            532
```