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Hydro-economic modelling for basin management of the Senegal River

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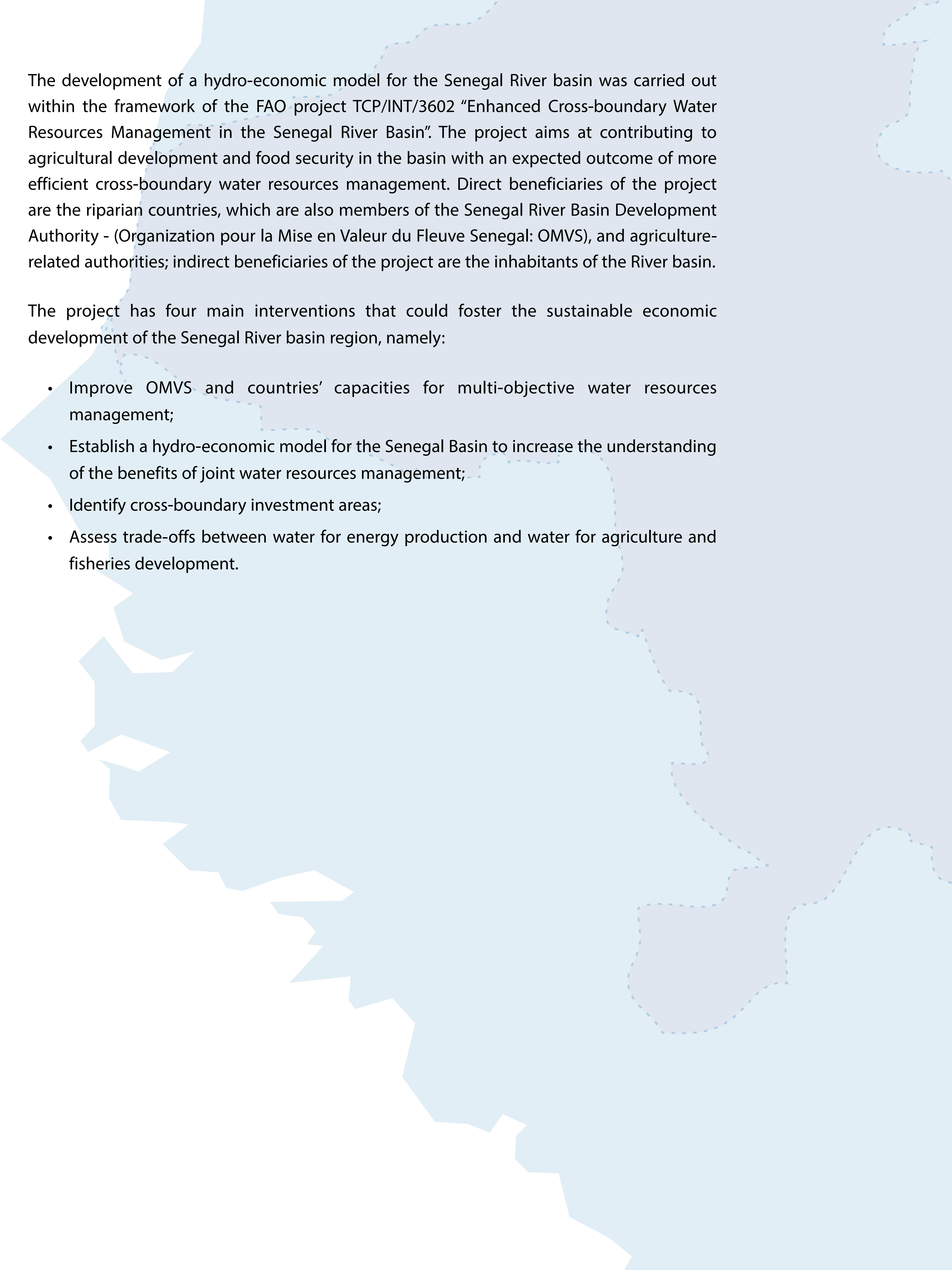
Introduction



The development of a hydro-economic model for the Senegal River basin was carried out within the framework of the FAO project TCP/INT/3602 “Enhanced Cross-boundary Water Resources Management in the Senegal River Basin”. The project aims at contributing to agricultural development and food security in the basin with an expected outcome of more efficient cross-boundary water resources management. Direct beneficiaries of the project are the riparian countries, which are also members of the Senegal River Basin Development Authority - (Organization pour la Mise en Valeur du Fleuve Senegal: OMVS), and agriculture-related authorities; indirect beneficiaries of the project are the inhabitants of the River basin.

The project has four main interventions that could foster the sustainable economic development of the Senegal River basin region, namely:

- Improve OMVS and countries’ capacities for multi-objective water resources management;
- Establish a hydro-economic model for the Senegal Basin to increase the understanding of the benefits of joint water resources management;
- Identify cross-boundary investment areas;
- Assess trade-offs between water for energy production and water for agriculture and fisheries development.

What is hydro-economic modelling?

A hydro-economic model is both a computational method and a tool to analyze water resources management problems. As its name indicates, hydro-economic modelling combines economic management concepts with an engineering level of understanding of a hydrologic system. Hydro-economic models integrate spatially distributed water resources, economic values, infra- structure, and management policies. The model optimizes water allocation between different uses across time and space taking into account various physical, economical, environmental and institutional constraints.

Hydro-economic models have emerged as an effective tool for studying various water resources management problems around the globe: inter-sectoral water allocation, reservoir operation, transboundary water management, conjunctive management, water-food-energy nexus, climate change adaptation, investment planning, etc.

There are basically two categories of hydro-economic models: simulation-based versus optimization-based. Simulation-based hydro-economic models can be used to answer specific “what if” scenarios in which allocation policies are specified by the analyst like any other input. Simulation-based hydro-economic models have emerged from the hydrological sciences and can be considered as an extension of rainfall–runoff models that are widely used in hydrology. Optimization-based hydro-economic models, instead, can identify the most appropriate management decision based on the maximization or minimization of a stated mathematical objective function subject to physical, institutional and/or economical constraints. Since water allocation problems often involve multiple periods (day, week, month, year), the objective function of the optimization-based hydro-economic models is usually the sum of the one-stage benefit (cost) functions over the planning period.

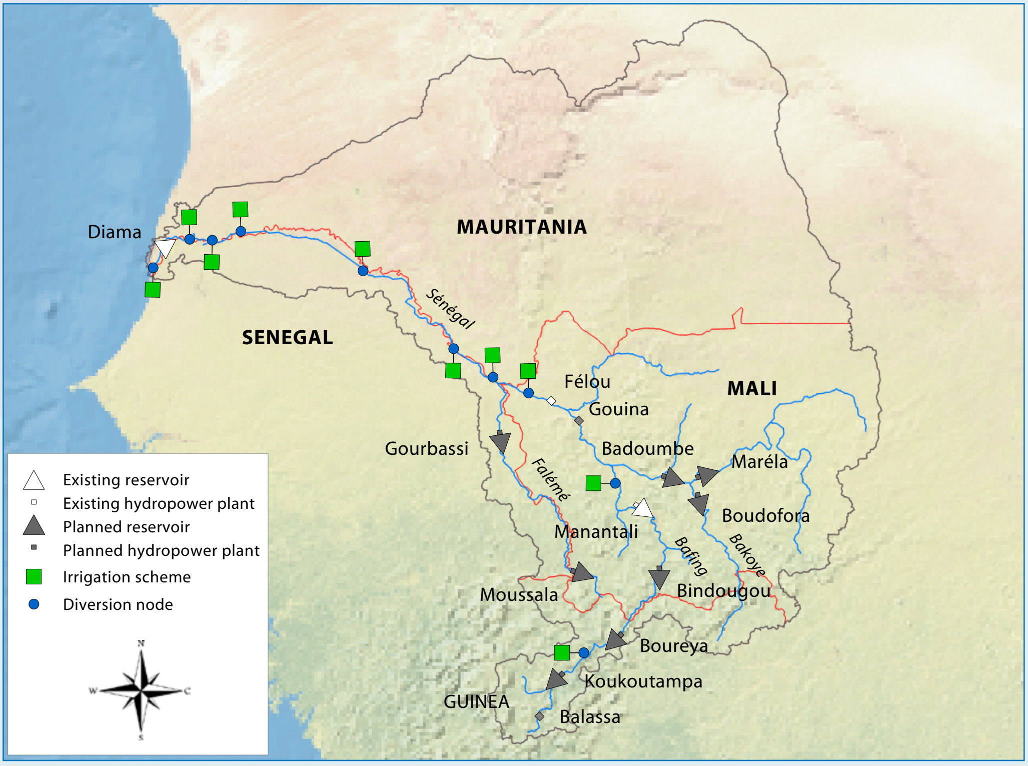
Most hydro-economic optimization problems naturally have several objectives to be achieved, normally conflicting with each other. When developed in collaboration with decision-makers, they serve as useful tools to guide the policy making process based on a clear understanding of trade-offs arising from conflicting stakeholders’ objectives.

Why is a hydro-economic model needed for the Senegal River basin?

The Senegal River drains an area of 337 000 km^2 in western Africa. The basin is shared by four countries: Guinea, Mali, Mauritania and Senegal. Water in the Senegal River Basin has traditionally been put to use for transportation (navigation) and food production through irrigation and flood recession agriculture. More recently, Senegal River flows have been used to generate hydroelectricity, and two hydropower plants are now operational: Manantali, which is a 200-MW power station supplied by a 11km^3 multipurpose reservoir, and Félou, which is a 62-MW run-of-river power plant. The flow regime is characterized by two seasons, a high-flow season from July until October followed by a low-flow season during the rest of the year. The year-to-year variability of the river discharges during the high flow season is significant and exposes water users to a high hydrological risk, especially subsistence farmers/herders whose livelihoods rely on the banks of the Senegal River.

In general, as river basins develop and their water resources are increasingly committed, it becomes more and more relevant to seek efficient allocation policies. Optimization-based hydro-economic models can help determining efficient allocation policies and assess their economic, hydrologic and institutional impacts.

Figure 1. The Senegal River Basin



In the Senegal River basin, maximizing the basin-wide economic benefits requires the arbitrage between the following hydro-economic principles:

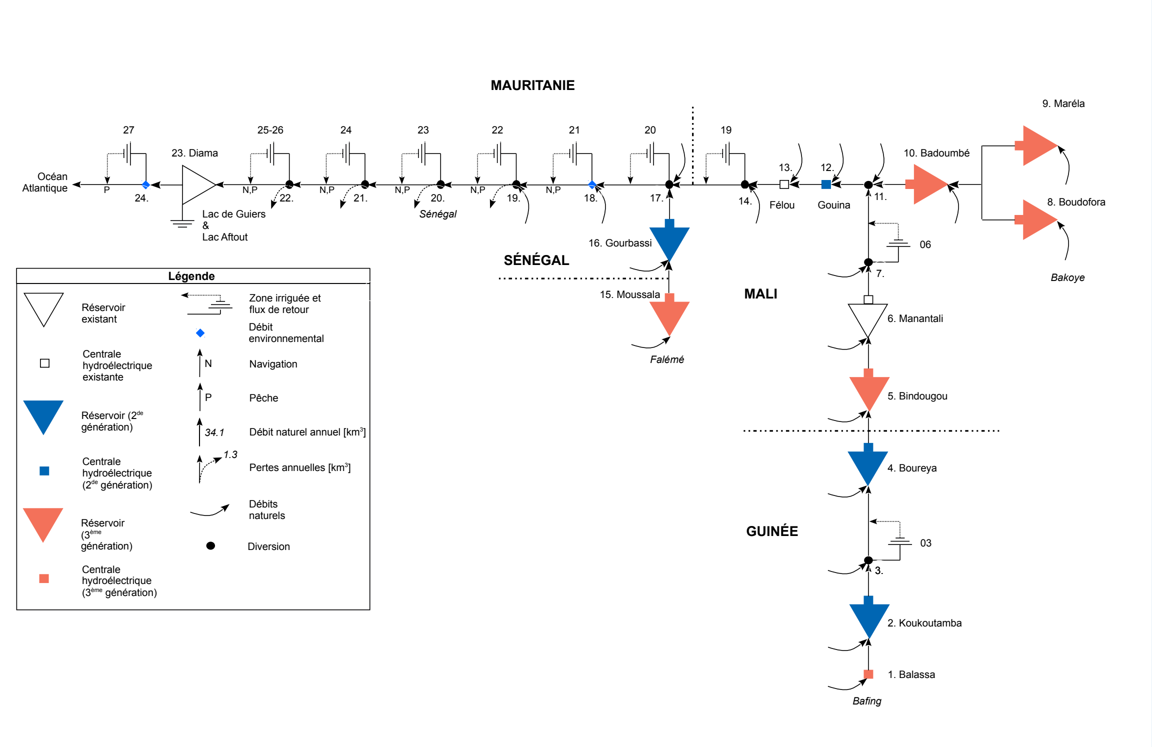
1. Water should be used where and when its user value is the greatest. For example, water withdrawals at a particular location and time should take place if the user value at that location and time is larger than the value of leaving the water in the river. This principle ensures that the allocation will be economically efficient and that basin-wide benefits will be maximized. In a transboundary river basin, this principle also favors countries with sound policies, i.e. policies that promote efficient uses and high productivity. Applying this principle to the Senegal River basin implies that multiple, multi-dimensional, trade-offs must be found between: (i) consumptive versus non-consumptive uses (e.g. irrigated agriculture versus hydropower), (ii) instream versus off-stream uses (e.g. fisheries versus irrigated agriculture), and (iii) immediate versus future uses (e.g. navigation versus storage).
2. Water should be stored in reservoirs upstream. Reservoirs store water when supply exceeds demand to make it available when demand is greater than supply. The ability to move water in time is the essential service offered by storage and, as such, this service can generate substantial basin-wide benefits in terms of energy generation, food production, flood control, and municipal and industrial water supply. However, associated to this service are the opportunity costs due to evaporation losses. Hence, to minimize the opportunity cost associated to evaporation, it is better to store water upstream where the hydro-climatic conditions are favorable, i.e. where evaporation losses are low.
3. Water for consumptive uses should be withdrawn downstream. This principle states that water should be diverted to consumptive uses after it has been used by non-consumptive uses. In the Senegal River basin where the dominant uses are irrigated agriculture and hydropower generation, it means that irrigated agriculture should be developed downstream of the hydropower facilities so as to leave as much water as possible for the production of energy. As a matter of fact, since hydropower generation is essentially a non-consumptive use, each unit of water flowing through a cascade of power stations will be used several times to produce energy.

The hydro-economic model of the Senegal River basin

The hydro-economic model of the Senegal River basin considers both the hydrologic and economic aspects associated with water uses and solves the water allocation problem by balancing the three principles discussed above. The allocation problem is solved for various scenarios representing different alternative levels of water resources' commitment in the basin (development scenarios), and alternative allocation policies between competing uses (management scenarios).

The model typically seeks to maximize basin-wide expected net benefits from hydropower generation and irrigated agriculture taking into account navigation, municipal and industrial uses, and the artificial flood as constraints. The model also captures the variability of the hydro-climatic conditions in the region, therefore, providing statistical distributions of the results. The optimization problem is solved on a monthly time step and the optimal allocation policies are then simulated over the historical flow records. Figure 2 displays how the Senegal River basin is schematized in the hydro-economic model.

Figure 2. Schematization of the Senegal River basin



The hydro-economic model has been used to determine allocation policies for three levels of development of the basin:

- the first level corresponds to the current situation (Baseline scenario);
- the second level represents an intermediate development of the basin with about 250 000 ha under irrigation and the second-generation power plants as listed in SDAGE[1] are online. This is the expected level of development around 2030;
- the third level assumes that the third-generation power plants as listed in SDAGE are operational and that 402 000 ha are irrigated (revised PARACI[2]). It gives an indication of the basin's commitment by the middle of the century.

In terms of water resources allocation, the management scenarios are used to investigate the consequences of alternative priorities given to the main economic sectors: agriculture-fisheries (Food security scenario) versus energy-navigation (Energy security scenario). Considering the importance of the artificial flood for fisheries and irrigated agriculture, allocation policies prioritizing the production of food imply the re-operation of the reservoirs and the implementation of managed flood releases.

To highlight the trade-offs in the Senegal River basin, two management scenarios are proposed:

- Food Security: This scenario emphasizes the production of food through irrigated agriculture and fisheries. To achieve this, the scenario assumes that the artificial flood is still implemented to ensure flood recession agriculture over 53 000 ha in the lower Senegal River basin.
- Energy: This scenario is similar to the Food Security one, except that the allocation priority is now given to the production of hydroelectricity and, consequently, the artificial flood is not implemented.
- Low Flood Extent: This is a variant of the Food security scenario with a smaller artificial flood: average area of 53 000 ha but only 28 000 ha are guaranteed 95 percent of the time. This scenario aims at striking a balance between the two extreme scenarios (Food versus Energy security).
- Navigation: In this variant of the Energy security scenario, the reservoirs are operated so as to minimize the deficit with respect to the target flow for navigation purposes.

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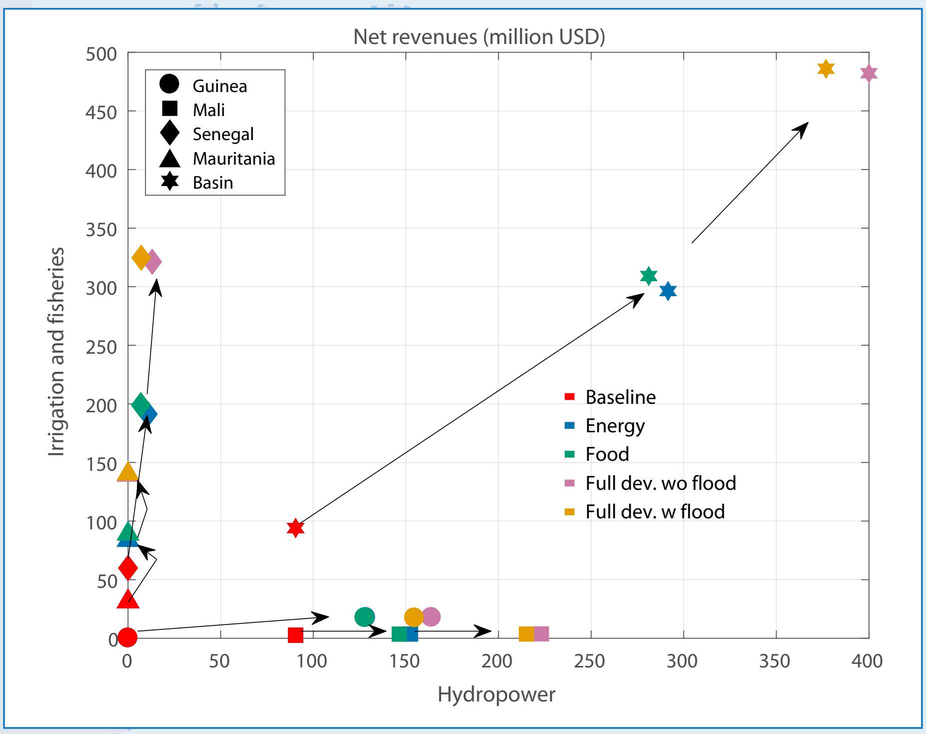
[1] OMVS, 2011. SDAGE du Fleuve Sénégal – Schéma Directeur. Préparé par CSE-CG-SCP

[2] OMVS, 2017. Plan d'action régional pour l'amélioration des cultures irriguées dans le bassin du fleuve Sénégal. Préparé par FAO

Main results

The Senegal River basin is a largely untapped resource where significant economic benefits can be expected. As shown in Figure 3, in the food sector, a threefold increase with respect to the current situation is possible, while a fourfold increase in energy production could be achieved if all hydropower projects, second and third generation, were on-line (full development scenario). The distribution of those benefits among the riparian countries follows closely their natural endowments: upstream countries (Mali and Guinea) have natural endowments favorable to the production of hydroelectricity and storage, whereas Mauritania and Senegal have the right topography and soils for irrigated agriculture.

Figure 3. Average annual net revenues



The box-whisker plots (Figure 4 and Figure 5) show the simulated annual energy production values and the recession agriculture cultivated areas for the three different levels of development. The simulations were carried out over 56-year-long monthly streamflow records. These charts present a box containing the 50 percent of the simulated data, the red band inside the box is the median (second quartile), and each dot represents an annual value. Figure 4 shows that the implementation of the artificial flood reduces the power output by 7 percent in the intermediate level of development (Energy versus Food) and 6 percent in the full-development scenario (Full development without flood versus Full development with flood).

In contrary, Figure 5 shows a significant reduction of the extent of flood recession agriculture, when the management scenario does not include the artificial flood. Although the 4.5 km^3

flood pulse in September guarantees recession agriculture with a reliability exceeding 95 percent, it automatically reduces the availability of water during the rest of the year, therefore affecting the irrigation schemes with high water demands during the dry season.

Figure 4. Annual energy production for different levels of development

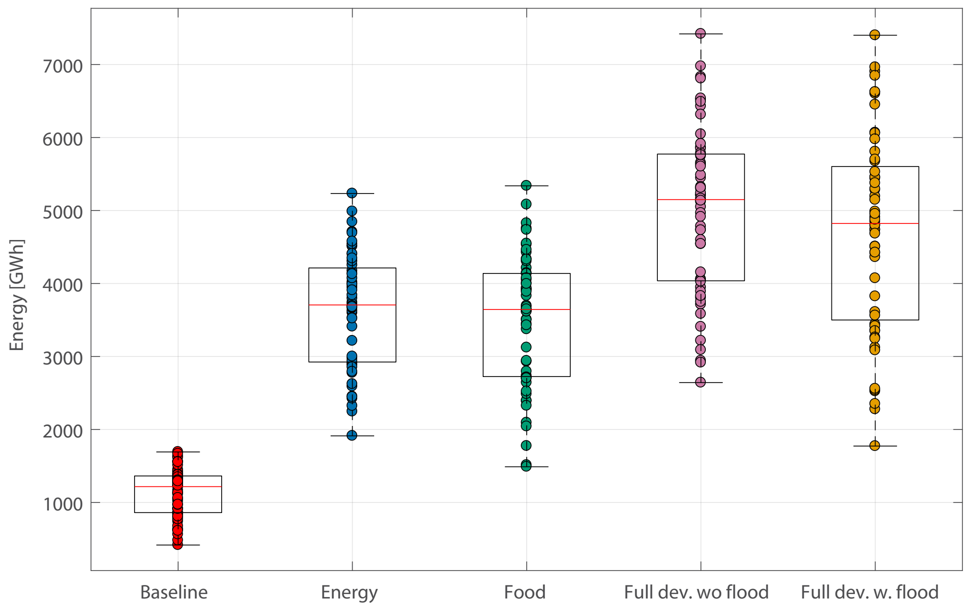
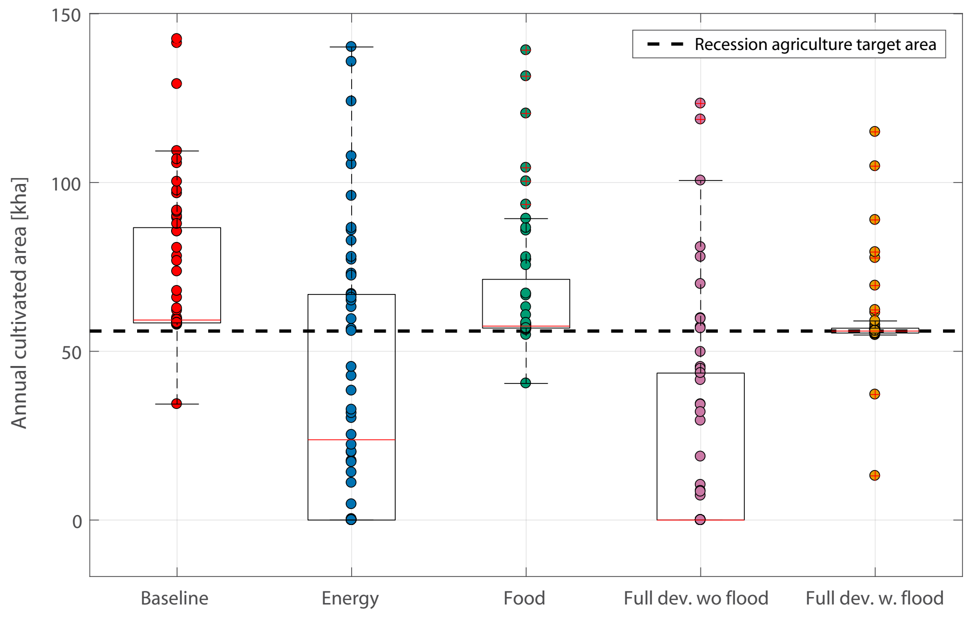
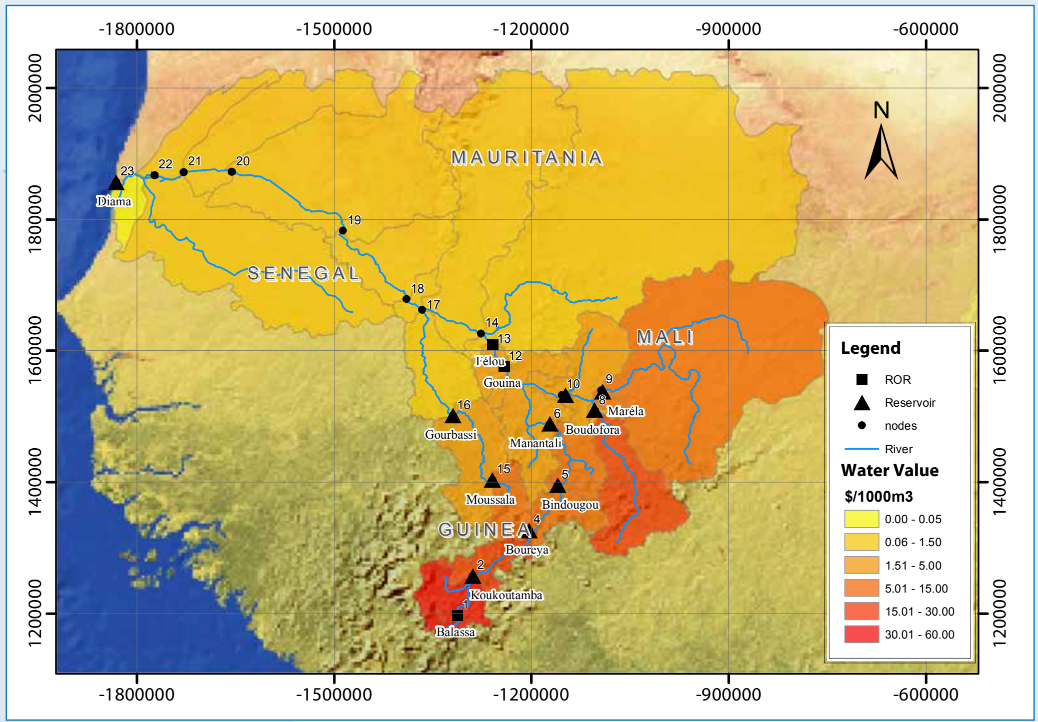


Figure 5. Annual cultivated area (recession agriculture) for different levels of development



In fact, when considering the total annual irrigated agriculture (including recession agriculture), results show that for the intermediate level of development, 255 000 ha can be supplied with a reliability of 90 percent, while for the full level of development, 402 000 ha are supplied with a 85 percent reliability. Management scenarios without the artificial flood, while compromising recession agriculture, are characterized by a high supply reliability of irrigation water (> 98 percent).

Figure 6. Marginal value of water – Full development scenario

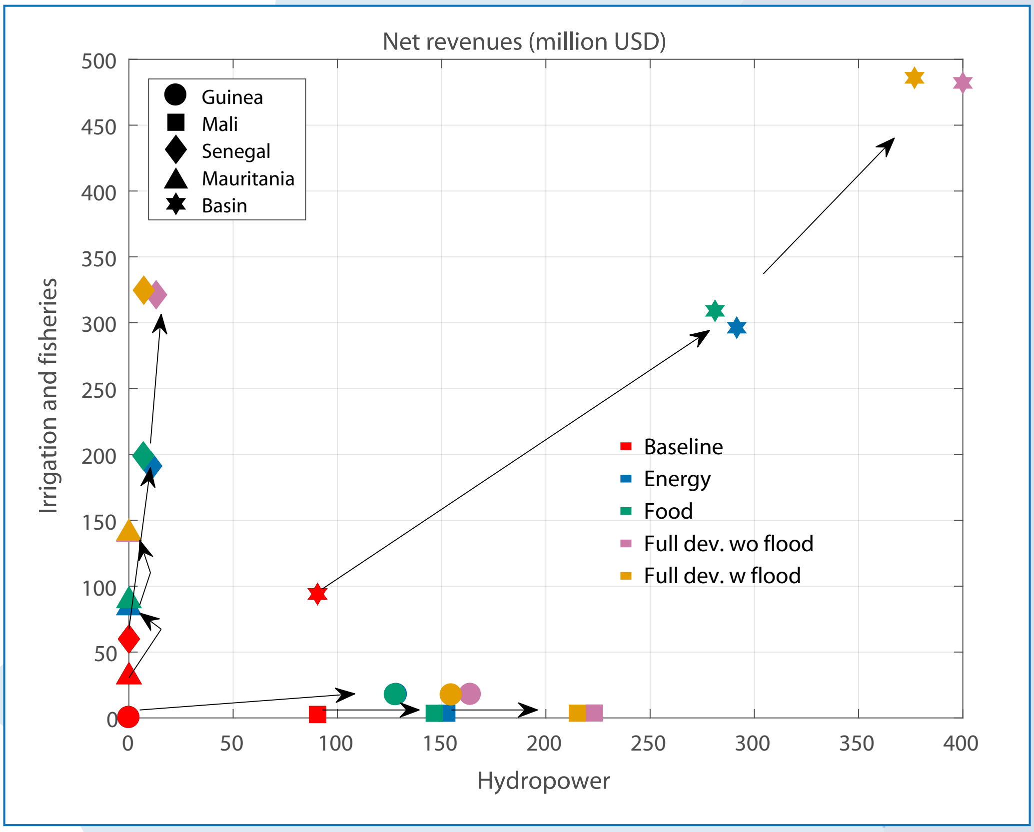


The examination of the map showing the value of water to users reveals the important role played by the Bafing sub-basin. This sub-basin accounts for 90 percent of the economic value of storage services and up to 61 percent in terms of hydropower generation. The floodplain, shared between Senegal and Mauritania, on the other hand, is responsible for more than 90 percent of the production of food through fisheries and irrigated agriculture.

The analysis of the trade-off relationship between the main competing uses confirms the existence of the two coalitions: food production versus hydropower-navigation. Four performance indicators, one per economic sector, are considered:

- Flood recession agriculture: This is the relative satisfaction level with respect to the Food security scenario.
- Energy: This is the relative satisfaction level with respect to the energy output that the system can generate with the Energy security scenario, which, by definition, is an upper bound.
- Navigation: This is the relative satisfaction level with respect to the best conditions for navigation that the system can guarantee under the Navigation scenario.
- Fisheries: This is the relative satisfaction level with respect to the Baseline scenario (variant without the artificial flood).

Figure 7. Trade-offs between competing objectives



Using the above indicators shows that of the two main coalitions of objectives, the one dealing with food production (irrigation and fisheries) is much more vulnerable to changes in: (i) allocation policies and (ii) hydro-climatic conditions. On Figure 8, the thick lines correspond to the average performance of a particular scenario, while the thin lines give an indication of the year-to-year variability.

Conclusions

The performance of the Senegal River system can be significantly improved through the coordinated operation of the multi-reservoir system. The reasons are to be found in the high space and time variabilities that characterize river discharges throughout the basin, and in the artificial flood that is needed to sustain riverine ecosystems, fisheries and flood recession agriculture. In the hydropower sector only, the modelling efforts have shown that significant gains (from 5 percent to 30 percent) can be expected depending on the power plant and the level of development of the basin.

In the future, as water resources in the basin will be increasingly committed, there will be a need to balance the competing interests between food production and energy generation, especially if the artificial flood were to be maintained. In that case, the planning, design and sequencing of investment in large hydraulic infrastructure projects will be critical in order to minimize the opportunity cost of the flood.

If the riparian states were to forgo the artificial flood, the need for coordination is less acute and there is considerable room for development before tensions would arise between two sectors (irrigated agriculture and navigation). However, giving up on the artificial flood would damage riverine and aquatic ecosystems, and negatively impact traditional fisheries in the floodplain.

The performance of long-lived development projects like hydraulic infrastructures should be tested against the likely states of the basin extending over their life-span. Clearly, third generation power plants and further extensions of irrigated agriculture will influence the state of the Senegal River basin in the decades to come. Moreover, the performance of those projects should also be assessed against a changing climate since it will also influence the state of the basin. Furthermore, those projects are still designed in a piecemeal fashion as there is no feedback loop between the feasibility studies and the basin-wide simulation model. Consequently, each project seems to be designed individually, and in the case of reservoirs, the operating rules ignore potential synergies with other existing/planned infrastructures.