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Modeling dynamics and adaptation at operational and structural scales for the ex-ante economic evaluation of large dams in an African context

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ABSTRACT

Dams can produce electricity and ensure water security, but at the same time they radically alter the hydrological regime of rivers with significant consequences for the economic and environmental welfare of the region in which they are located. Cost-benefit analysis (CBA) is currently the most frequently used framework for the economic evaluations of dams. Changes at different time scales influence the economic appraisal of dams. However, change and adaptation at both the operational and the structural level are often not included in the CBA evaluation. Not including change and adaptation limits the realistic estimation of cost and benefits, and the appreciation of resilient solutions that offer satisfactory responses for a large set of future scenarios.

In this paper we consider the specific features of large dams in an African context, and identify methods for an economic evaluation that takes into account for change and adaptation at both the operational and the structural scales, as well as their interplay. These methods are then applied to the ex-ante evaluation of a system of existing dams on the Senegal River Valley. Results indicate the economic potential of the dams under changing conditions, for both adaptive and non-adaptive reservoir operation strategies.

1. Introduction

Large dams are strategic assets for the production of electricity and to ensure water security by storing water when it is most abundant and making it available when it is scarcer, and hence more valuable. Notwithstanding the service they provide, large dams are mega-projects [55] that often radically change the hydrological regime of a river, thereby affecting its economic and environmental conditions. Dams may be the focus of many controversial issues: the World Commission on Dams (WCD) [51] has been a milestone in a debate that it is still ongoing [2,12,21,47]. Understanding the effects of new dams and their role within the hydrological cycle, taking the costs and the benefits in economic, social, and environmental terms into account is a precondition to taking responsible and sustainable decisions [63].

Cost-benefit analysis (CBA) is the most frequently used method for the evaluation of economic impacts of dams in the academic literature [33], with a long history [8] of applications in the evaluation of the socio-economic feasibility of new projects. CBA evaluates policy interventions by comparing their negative and positive consequences using a common monetary metric to identify

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the net effects [40]. CBA considers the economic dimension of water uses, related to goods and services provided by water for which one is willing to pay [77].

The value of water is determined by the matching of supply and demand. In water systems, supply and demand are variable over time. Climatic variability, in particular, is especially pronounced in the case of many African rivers, whose hydrology is characterized by marked seasonality, interannual variation, and long periods of droughts [34,42]. Reservoirs can shift water availability over time. Water allocation decisions (i.e. releases from the reservoir) are taken at the operational level. Ex-ante economic evaluation of dams and their future operational management are closely intertwined: their operation depends on system characteristics, such as expected water availability, size and location of the dam; on the other hand, the economic yield of dams depends on how they are operated. Therefore, assessing a dams' costs and benefits cannot be separated from analyzing how the system is operated.

Dams have a very long expected lifetime, often spanning more than one generation. This raises different questions about the appropriate way to evaluate future costs and benefits: apart from the important and problematic selection of an appropriate discount factor [17,54,78], the meaningfulness of a CBA can be limited by the level of confidence that one has in the assumptions underlying the analysis. CBA, in fact, is based on a large set of assumptions that are not certain to hold for such a long period. Climate change, in particular, to which investment in dams is particularly sensitive, may radically alter water availability and its distribution over the year [70]. Under non-stationary conditions [45], using past data to quantify the operational variability, implicitly assuming stationary conditions [48], may be questionable. CBA guidelines suggest testing the robustness of results by performing a sensitivity analysis [53,61] with respect to the assumptions for which there is little confidence. This analysis, however, is limited to the final stage, and it is often regarded as secondary, both in time and importance, plus it is applied to relatively small changes in a few parameters.

Marginalist economics, in which CBA is rooted, focuses historically more on equilibria than on dynamics and change. As a consequence, change is generally overlooked in CBA. The non-marginal effects of new large dams on the African electric system and food markets call for the inclusion in the analysis of both exogenous and endogenous change. Much of the literature on CBA is in fact dedicated to the “empirical challenges” on how to give a market value to goods or services for which a market does not exist or it is not efficient [25,46]. Not considering the possible structural changes that affects dams or are triggered by dams can lead to poor decisions: it encourages overconfidence in strategies that fail if the future unfolds differently than expected [37,49].

Dams are long-term, almost irreversible, structural interventions. Conversely, their operational management, i.e. the step-by-step release strategy, is a non-structural measure that can be easily adapted to changing structural conditions. This adaptation capacity extends the number of scenarios in which dams can be economically sustainable. Adaptation to changing structural condition, however, must be analyzed at the interface of operational management, considering how the latter adapts, in the shorter term, to operational variability.

The aim of this paper is to identify methods able to take into account change and adaptation at both operational and structural level, and their interplay, for the ex-ante economic evaluation of large dams, specific to the African context. The usefulness of these proposed tool is demonstrated in an ex-ante CBA on an existing system of dams on the Senegal River, West Africa, where the net value of the dams is estimated under different hydrological conditions, corresponding to different levels of climate change.

The paper is organized as follows: in Section 2, we discuss how to evaluate alternatives projects by including variability, interaction, change, and adaptation at both the operational and the structural level. In Section 3 we demonstrate how the proposals presented in the paper can be used for the ex-ante economic evaluation of an existing system of dams on the Senegal River. Our results indicate the economic potential that a sustainable dam management can offer. In Section 4 we draw our conclusions.

2. Methodology

We differentiate between variability and change at two scales, that we define as “operational” and “structural”. Operational variability is the change, within a stationary condition. Operational variability, if boundary conditions have not changed, can be estimated from historical data. Structural change refers to the possible fundamental changes in behaviour of the system that may occur in the future, for which no data are available yet, only scenarios.

2.1. Operational variability

In ex-ante assessment of dams, the system being evaluated does not yet exist, consequently the analyst has to hypothesize how the system will be operated by defining its operational rules. In reservoir operation, the rules almost always depend on the reservoir water level, and often on the state of the hydrological and the electric system. Operational rules can be designed using either “optimization” and “simulation” methods [26,72]. In simulation methods, the analyst draws up some operational rules, selecting them by testing their effects in a simulation model. In optimization methods, the analyst defines the system objective and uses an optimization procedure, identifying operation rules as the output of this procedure. In CBA, the objective to be maximized is the welfare function.

Operating a reservoir system under uncertainty requires trade-offs between resource allocation over time: present benefits must be balanced against future, uncertain ones [11,67]. Including uncertainty when simulating operation is necessary to avoid the over-optimistic assumption of disposing of perfect information, which leads to overestimating the performance of the system [57]. At the operational level, decisions and uncertainty resolution are nested one after another: after each decision, new information becomes available and partially reduces uncertainty. This continuous alternation of decision and information provides a feedback mechanism, in which the release decisions can be adapted to the present conditions. The capacity of a reservoir to delay supply can be used to

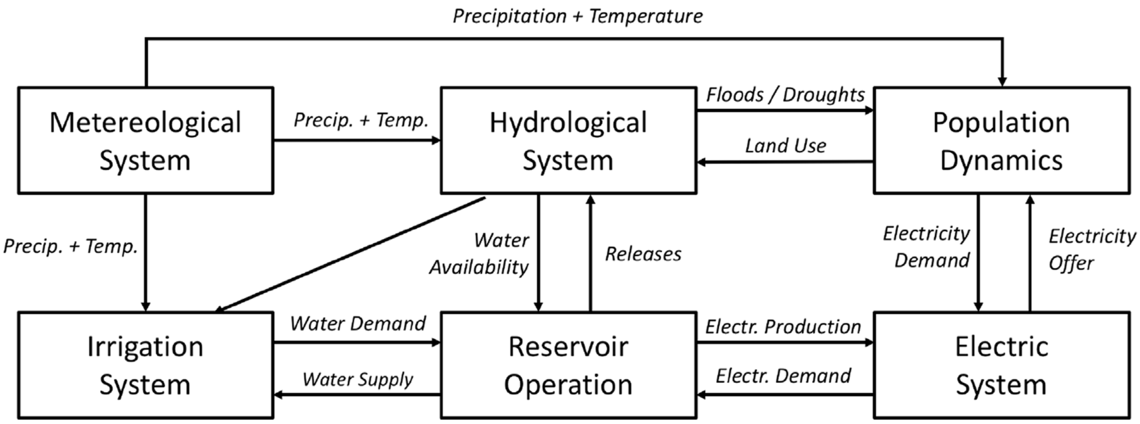

Fig. 1. Schema of the enlarged system dynamics. The boxes represent the sub-systems, and the arrows their main interactions.

hedge risk, resulting in an increased resilience to short-term variability of both demand and supply [27]. Multistage Stochastic Programming [64], which for long horizon is efficiently solved by Stochastic Dynamic Programming [6] can be used to include this adaptation mechanism in the optimization procedure. The use of a method derived from Stochastic Dynamic Programming is demonstrated in the Application section.

The selection of the simulation time-step should take into account the system dynamics and the relative short-term reservoir's capacity to adapt in the short-term. A long time-step aggregates, and hence disregards, hydro-economic processes that have a faster dynamics. In African rivers, in particular, the model should be able to reproduce the flood process [59]. Flooding is a relatively rapid process, so using a monthly time-step, which is often the case in strategic evaluations of dams [71], would neglect this process almost completely [58].

Some water uses, such as those with environmental objectives, transboundary water treaties, or pre-existing water rights, may have to be guaranteed. In this case the operational management of the dam must give higher priority to these objectives than to economic ones. The demand of these high priority water uses must be included in the simulation model. In the optimization procedure, higher priority water uses can be included in the operational rules as soft constraints, or high priority objectives [11], that have to be met before the economic ones.

2.2. Structural change

The system in which a dam will operate is a complex, adaptive one [39]. Ideally, the system model should include the representation of all the components that may change in the long term and will have a critical influence on the economic evaluation of dams. We consider that, in Africa, environmental and socio-economic change are two families of possible dynamics that can radically modify the economic benefits of new dams. Fig. 1 presents the components we consider should take priority in being included in the analysis and their relationships: meteorological and hydrological components can simulate environmental change, namely change in the hydro-climatic conditions of the system. Population dynamics and electric system components are intended to reproduce socio-economic changes.

The meteorological component is designed to represent precipitation and temperature patterns, and possible changes caused by climate change [31,32]. The hydrological system represents the availability of water in space and over time, considering all possible scenarios of change and long term effects, for example due to changes in land use or in the hydrological response [14]. The irrigation system component represents the crop-water production functions [26]. This component should include possible future irrigation strategies or future technologies [28]. The reservoir operation component simulates the operational management, including adaptation to changing condition. Adaptation occurs both at in the short term, to balance operational variability, and in the longer term, to ensure resilience in the face of structural change: operational rules are non-structural measures that can be adapted as soon as change is detected [60]. The population dynamics component reproduces how population growth and migration influence – and are influenced by – the demand for electricity and vulnerability to drought and flood events [22,41,44]. The electric system component is used to assess the value of electricity produced by the dam, also in relation with other sources of electricity, both on and off-grid [73], including possible changes in the energy mix driven by new technologies (solar and wind power, among others) [29], or new demands (use of electrical appliances and air-conditioning, for example) [30].

In enlarging the system boundary, most of the variables will move beyond the range of currently observed behaviour, therefore the enlarged system response is not predictable in the long term, introducing new, “deep” uncertainties. Deep uncertainties can be defined as uncertainties for which one can (incompletely) enumerate multiple possibilities for the system models, the probability distributions, and sets of values, without being able or willing to rank the possibilities in terms of how likely or plausible they are judged to be [76].

The policy analysis literature has produced a large set of approaches and methodologies to deal with the problem of deep uncertainties, such as robust decision making [23], assumption based policies [15], dynamic adaptive policy pathways [24], and decision scaling [10], among others. Rather than starting with predictions, these methods evaluate all the possible consequences of structural changes in order to identify the condition required to guarantee the success of the investment. When models are used in this type of analysis, the effects of a wide set of possible scenarios are explored through multiple runs of the system model [35] [38]. states that these methods are "catholic" regarding the measure of policy success, and their criteria can easily incorporate economic criteria, as in CBA.

CBA, used in combination with these methods, will include testing the robustness of the system to structural change, including the adaptation capacity beyond the observed variability. Considering a larger set of possible future conditions will help better appreciate resilient solutions that offer a portfolio of uses, that can hedge risk if, for example, one water use turns out to be less profitable than expected.

The hydro-economic model can be used to simulate the augmented resilience offered by adaptive operational rules, i.e. reservoir operational rules that adapt to change at the structural level [1]. Optimal operational rules are particularly advantageous in exploratory approaches: optimization methods can be used to simulate the capacity to adapt operational rules to changing structural conditions: when water is allocated according to a criterion of welfare function maximization, it is used where it is most valuable. For example: if a water use becomes more profitable, the operational rules adapt and allocate more water to that use, at the expense of relatively less profitable alternative uses.

3. Application

In this section we demonstrate the methodologies by using them for the ex-ante CBA of an existing system of reservoirs on the Senegal River. For this purpose, we use a system model designed to represent the main economic outputs of the system, and the socio-environmental constraints that must be met. The operational variability, the physical-institutional constraints, and their multiple interactions are taken into account by a dynamic system model. The model inputs are the current hydrological conditions, i.e. the water availability and its variability over time. The model outputs are the hydropower production, irrigated area, and irrigation discharge.

The system model has the following components: i) two hydrological sub-systems, i.e. the Upper Senegal River and the aggregated lateral contributions, ii) two reservoirs, i.e. Manantali and Diama, and iii) the irrigation-crop sub-system. These components are interconnected as shown in Fig. 2. Reservoir components are made of the continuity equation representing the mass balances and the reservoir physical and legal constraints on the reservoirs. The irrigation-crop model component represents rice growth as a function of water input over time: rice is in fact the crop planted in the irrigated district. The hydrological catchments are represented by a

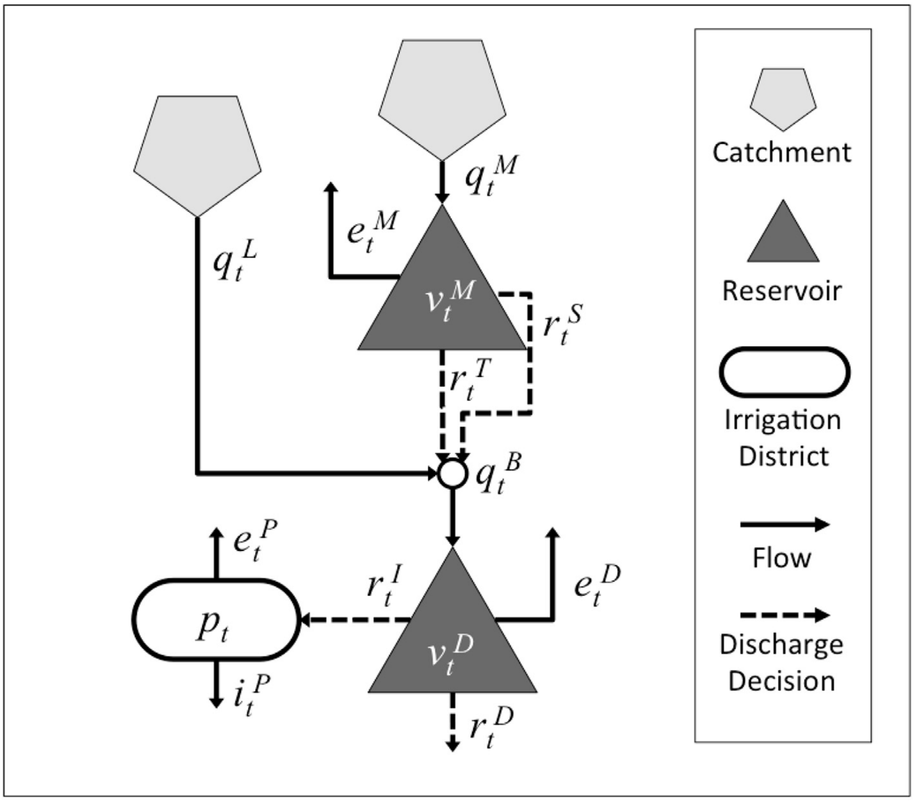

Fig. 2. System model scheme, including components and main variables.

stochastic model that reproduces interannual variability, uncertainty in the streamflow process over the hydrological year, and correlation among catchments. The operational management of the reservoirs is assumed to be centralized. Hydrological uncertainty, especially at the seasonal scale, poses a challenge to the design of efficient operational rules [56], which are defined by use of Stochastic Dual Dynamic Programming [65], a method derived from classic Stochastic Dynamic Programming [69] whose applicability extends to larger systems but it requires the time-step optimization problem to be convex. All model components are further detailed in Appendix B.

In the CBA, costs include all the initial investment plus operation and maintenance costs. Benefits include hydropower and irrigation production only. The model represents uncertainties in two forms: at operational level, we estimated the hydrological variability from past observed discharge; at structural level, we consider the possible reduction in water availability due to climate change.

In the rest of this section we first present the system under analysis, then describe the main features of the CBA, i.e. how costs and benefits, socio-economic constraints, and effects of climate change and adaptation are included in the analysis. Finally, we show the results of the analysis and a discussion on its main assumptions.

3.1. Senegal River

The Senegal River is 1,790 *km* long; it is the second longest river in West Africa. The river flow regime depends mostly on the rainfall in the upper basin in Guinea. The river inflow is extremely variable, reflecting the seasonality of tropical rainfall. Every year, under the natural regime, and when the discharge is sufficiently high, water spills into the valley floodplain, facilitating flood recession agriculture. Flood recession agriculture is a profitable production system for farmers that does not require any purchased inputs: every time the floodplain is inundated by the flood, vast areas are systematically sown with sorghum. Apart from agricultural production, the flood provides the conditions required for forested ecosystems, livestock breeding, fish reproduction, and groundwater recharge.

In 1972 Senegal, Mauritania, and Mali created the Organisation for the Development of the Senegal River, OMVS (Organisation pour la Mise en Valeur du fleuve Sénégal), the river water authority, with a mandate to ensure food security, energy production, and harmony among all riparian users. The OMVS has gradually embraced the principles of Integrated Water Resources Management, in which water allocation decisions are based on economic, social, technical and political factors, in accordance with stakeholders' interests [19]. Construction of new dams is among OVMS's tasks. The hydraulic conditions of the river offers a good potential for dams [13,36,74]. Plans for development, if implemented extensively, could lead to the damming of all river tributaries (see Fig. 3). Presently, however, only three reservoirs are fully operational: Manantali and Felou, in Mali, and Diama, close to the river delta. As we do not dispose of sufficient information on Felou dam, our analysis only concerns Manantali and Diama dams. For these dams, an ex-post evaluation already exists [16]: despite some limitations, the whole project is considered a successful integration project [20].

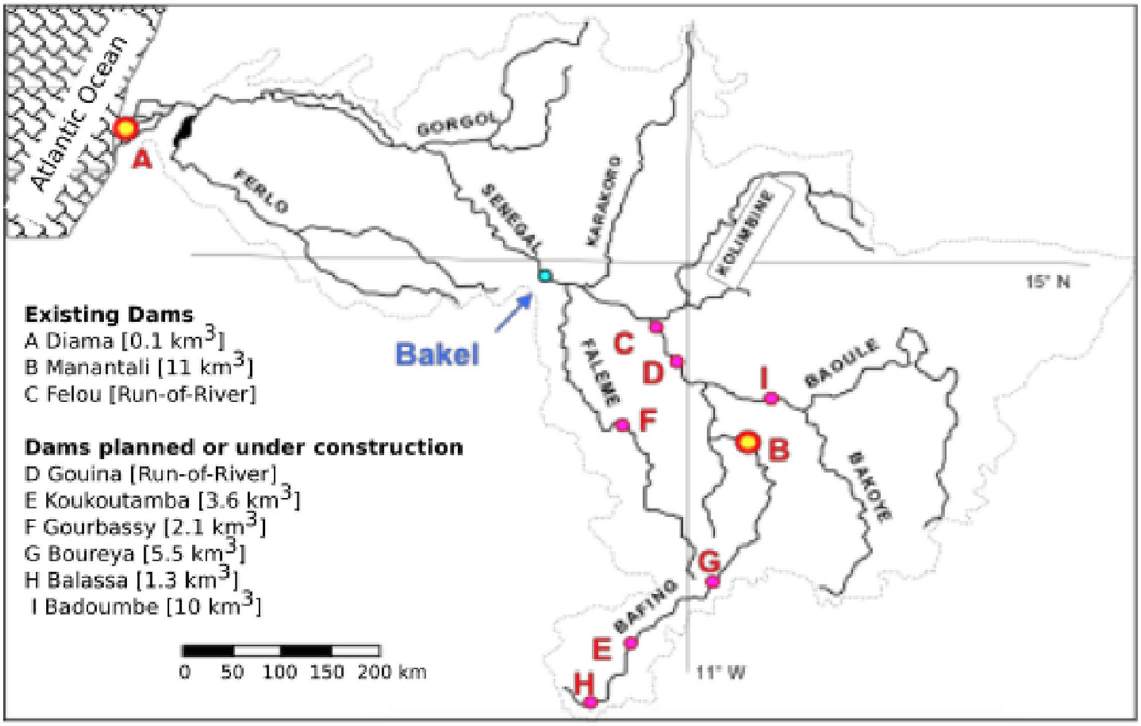

Fig. 3. Map Senegal River, existing and planned dams.

3.2. Cost benefit analysis

We chose to perform a "narrow" CBA [62], i.e. our analysis is limited to the economic services. In this analysis, energy production and irrigation, in particular rice production, are included as the main economic uses of the water. As a synthetic index, we selected the net present value because of the advantages it offers over other indexes [61]. The net value NV of the project is the difference between overall benefits B and overall costs C. Overall costs and overall benefits are calculated as in Equations (1) and (2).

$$B = \sum_{y=0}^{N} \frac{B_y}{(1+r)^y} \tag{1}$$

$$C = C_i + \sum_{y=0}^{N} \frac{C_y}{(1+r)^y} \tag{2}$$

In Equations (1) and (2), C_i are the initial investments costs, C_y the yearly operation and maintenance costs, and B_y the yearly benefits, y is the year index, N is the project horizon in years, set at 30 years, and r the discount factor, set at 10%. The yearly benefits and costs B_y, C_y are stochastic variables with mean $\mathbb{E}(B_y)$, $\mathbb{E}(C_y)$ and variance $VAR(B_y)$, $VAR(C_y)$. Assuming quasi-stationarity of B_y and C_y, i.e. there are no long-term trends in the series of benefits and costs, and independences among yearly benefits, the yearly benefits and costs over the project horizon are distributed as in Equation (3), which is obtained by applying the property of sum of stochastic variables.

$$B \sim \mathcal{N}(\mathbb{E}(B_y), VAR(B_y))\cdot D \tag{3}$$

$$C \sim C_i + \mathcal{N}(\mathbb{E}(C_y), VAR(C_y))\cdot D \tag{4}$$

where $D = \sum_{y=0}^{N} \frac{1}{(1+r)^y}$.

The initial investment costs for the entire project (i.e. C_i) are 413 billion West African Francs (French acronym, CFA), distributed as follows: 135 billion CFA for Manantali, 36 billion CFA for Diama, 205 billion CFA for hydropower plant and transmission lines, and 37 billion CFA for other complementary measures and analysis [20]. Strong evidence shows that the cost of large infrastructural projects is systematically underestimated [18], also in case of large dams [68] [2]. suggest adjusting ex-ante cost estimation by using a correction factor, calculated based on similar past projects. In absence of any other information that justifies a different value, we use a correction factor of between 0% and 50%. The latter value corresponds to the average overrun for the construction of dams in Africa. This stochastic correction factor is included in the CBA to estimate the uncertainty about the cost of initial investments.

The sum of yearly operation and maintenance costs and yearly benefits for electricity production and irrigation make up the total yearly operation and maintenance costs and the total yearly benefits, i.e. C_y and B_y, such that

$$B_y = B_y^E + B_y^I$$

$$C_y = C_y^E + C_y^I.$$

Operation and maintenance costs and yearly benefits for electricity production E and irrigation I, defined in Appendix A, can be calculated from the output of the simulation model.

The economic effects of flood support and drinking water supply are not sufficiently known, hence these two water uses are not included in the CBA. Even if not economically evaluated, drinking water and flood support are included in the reservoir management as high priority objectives, i.e. considered as constraints to the reservoirs operation.

Fulfilling the flood support objective would require the production of 45.000 ha of cultivated land each year. The relationship between the discharge trajectory and the flood surface has been clearly established [3] but, being non-convex, it cannot be used in the optimization procedure used in the analysis. The flood support objective is therefore included by a simplified criterion: minimizing the difference between the discharge and the historically observed discharge under natural conditions, i.e. without the effects of dams. The rationale behind this modeling choice is that reproducing natural discharge is beneficial for the flood support. Effects are then quantified by considering the volume of water whose discharge is larger than the flood threshold, above which water is considered to spill into the flood plain. Drinking water objective requires maintaining discharge higher than demand, set at $10 m^3/s$, at Bakel [4].

3.3. Response to climate change

Climate change has been already detected in this region [52]. Moreover, climate studies from the combined used of regional climate models and hydrological models [43] shows that the impact on water availability and time-space distribution in the Senegal Basin is expected to decrease in most of the upper basin.

The analysis of structural change explores possible scenarios of climate change. We performed a "stress test" [9] of the system to evaluate how the system will respond to a reduction in water availability. The inflow series was reduced by a multiplicative factor to represent variation in discharge for three scenarios: stationary condition (no change), moderate climate change (−15%), and severe climate change (−30%).

The system was tested under adaptive and non-adaptive policies. In adaptive policies, the system adapts the release strategy to the

Table 1
CBA Results in the flood support case: Net value of the Diama + Manantali project, for different scenarios of Climate Change (CC), in the case of adaptation and non-adaptation to climate change. The range includes the uncertainty on initial investment and the climate variability. Moderate and severe climate change scenarios correspond to a reduction in water availability of 15% and 30%, respectively.

Net value [10e4 MM CFA]	Adaptation to CC	Non-Adaptation to CC
Stationarity	34–90	34–90
Moderate CC	30–75	12–62
Severe CC	6–45	−6–37

structural change, i.e. the new hydrological conditions. In non-adaptive policies, the release strategy does not adapt to the structural change. Performances of non-adaptive policies correspond to what one would have estimated using a CBA approach, in which structural change is not taken into account. When non-adaptive policies are evaluated under changing structural conditions, their performance is a benchmark with which the performances of adaptive policies can be compared: the mark-up that adaptive policies offer indicates the added value of including adaptation.

3.4. Results

Table 1 summarizes the results of the CBA. Climatic variability is reported by the range around the average plus–minus the standard deviation, corresponding to about the 70% of cases. The uncertainty on investment costs is included in the estimation of the net value. Climate change is reported by showing results for the three scenarios.

The results in Table 1 reveal a considerable difference between the lowest and the highest estimates. This is true for all the change and adaptation scenarios. This difference is mostly driven by the notable climatic variability of this river. The comparison between the scenarios of adaptation and non-adaptation to climate change highlight the importance of including the adaptation capacity: when the reservoir operation adapts to new structural conditions, i.e. the "Adaptation to CC" column, the loss due to climate change is mitigated, resulting in a positive net value for all climate change scenarios. When the reservoir operation does not adapt to new structural conditions, i.e. the "Non-Adaptation to CC" column, the reduction of water availability is not counterbalanced by an appropriate reservoir operational management, resulting in a bigger drop in performance that, in the Severe CC scenario, may result in a negative net value.

Table 2 presents some details of results for the stationary case. The results in Table 2 show that the net benefits from electricity and irrigation are comparable, and that variation in the benefits from irrigation is higher than in those from electricity. Considering that irrigation variability is related to climatic variability, the results can be interpreted as an indication of the low resilience of the irrigation sector to climate. In the stationary case, the benefits from electricity production range between 420 and 900 $GWh/year$. This range corresponds to other CBA estimations: the higher value in corresponds to the initial CBA estimates [50], a posteriori considered to be over-optimistic and not feasible under present climate conditions. The lower value corresponds to other CBA estimates [20]. We do not have details on how these estimations were made.

The marked variability of rice production has important consequences for food security. Dry years can result in the loss of the crop, with catastrophic consequences for regional stability. In this simulation, however, we consider that the system is operated as if the decision maker is risk-neutral. In practice, it is usually preferable to avoid large variability. In this case, a Risk-Benefit Analysis (RBA) could be conducted. In RBA, risk aversion is taken into account by including risk as a cost [66].

Flood support presents an extremely large variability. This variability, however, occurs both when dams are present and under natural conditions, and can therefore not be attributed to the presence of the dams. Dams cause instead a small loss of flood support that we considered acceptable. The drinking water objective, not included in the economic analysis, benefits from the presence of the dams. A dam can help ensure almost constant availability of water that can be used for drinking.

The economic sustainability of Manantali only suggests the practicability of an adaptive policy [75], where Manantali is

Table 2
CBA results in the scenario considering climate stationarity and flood support, including net benefit per sector (i.e. benefit less operation costs) and non-economic effects.

Stationary conditions	No Dams	Manantali	Manantali + Diama
Initial Costs [10e+4 MM CFA]	0	38–56	41–62
Variable Net Benefits [10e+4 MM CFA/year]			
Electricity	0	3.7–7.9	3.5–7.5
Irrigation	0	0	2.2–9.9
Non-Economic Effects:			
Flood Support [km^3/year]	0.05–8.7	0.3–6.5	0.3–6.7
Drinking Water [days/year]	180–240	360–364	360–364

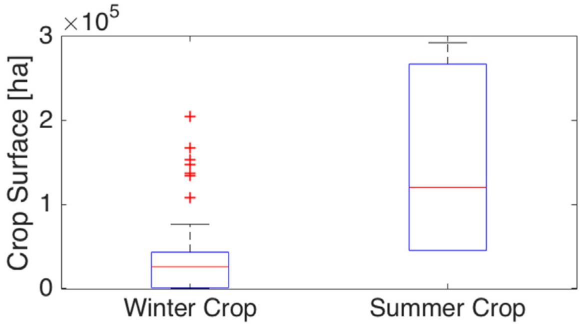

Fig. 4. Crop surface per season, box-plots. Scenario considering climate stationarity and flood support constraint, case of Manantali + Diama.

constructed first and the decision about the construction of Diama is postponed. An adaptive plan in two stages has some advantages over the simultaneous construction of all infrastructures: it makes it possible to test the assumptions underlying the policy, to evaluate the initial investment, to develop new valuable knowledge and to gain experience.

The irrigation variability is heterogeneously distributed among cropping seasons. Fig. 4 shows that most of the income is concentrated in the wet season. These results are in line with the estimation in the SDAGE [50], which consider a crop surface of $2{,}5 \times 10e + 5$ ha in the wet season and a crop surface of $0.5 \times 10e + 5$ ha in the dry season. In Fig. 4, the presence of many outliers, defined as data-points falling outside the 97.5% range, indicate the long tail of the crop distribution in the dry season.

Fig. 5 highlights the cost of flood support, showing irrigation and electricity benefits for two cases: reservoir operation with and without flood support as a constraint. A significant drop in both irrigation and electricity benefits can be observed. Not knowing the benefits of flood support, nor the long term effects of not producing a flood, a reservoir operation designed without flood support is not an option at the moment. Further research into the effects of floods, would, however, advance our understanding of the flood recession agriculture process. This information could then be used to calibrate better flood support, resulting in more efficient use of water.

Fig. 6 shows the system response to climate change. The figure includes some details of the stress test when water availability is reduced due to climate change. The benefit of both electricity and irrigation decreases with a decline in water availability. Nonetheless, in most of the cases, climatic variability is much greater than the reduction due to climate change. If climate change is not taken into account, and the system is operated like in non-adaptive policies, energy production decreases, and irrigation production becomes more erratic. Adaptive system operation limits the negative impacts of climate change. Concerning electricity production, adaptive operation limits the loss in production. This is achieved by adapting the drawing down of the reservoir, hence maintaining a higher water head. Concerning irrigation, adaptive policies reduce production variability. This is achieved by adapting the irrigated area to the new conditions.

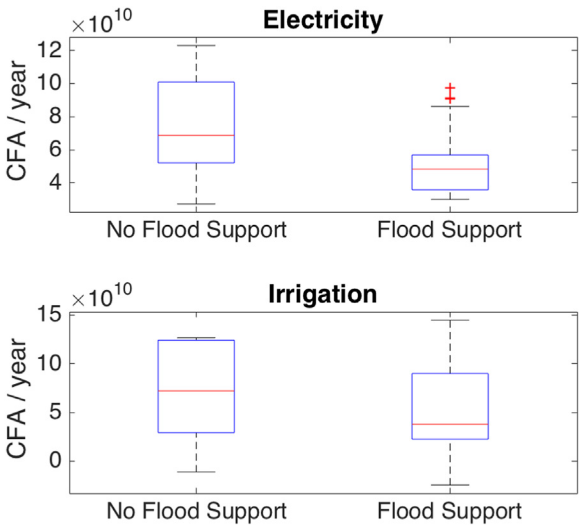

Fig. 5. Influence of flood support on net yearly benefit (i.e. yearly benefit less operation costs) from irrigation and electricity, box-plots. Scenario considering climate stationarity, case of Manantali + Diama.

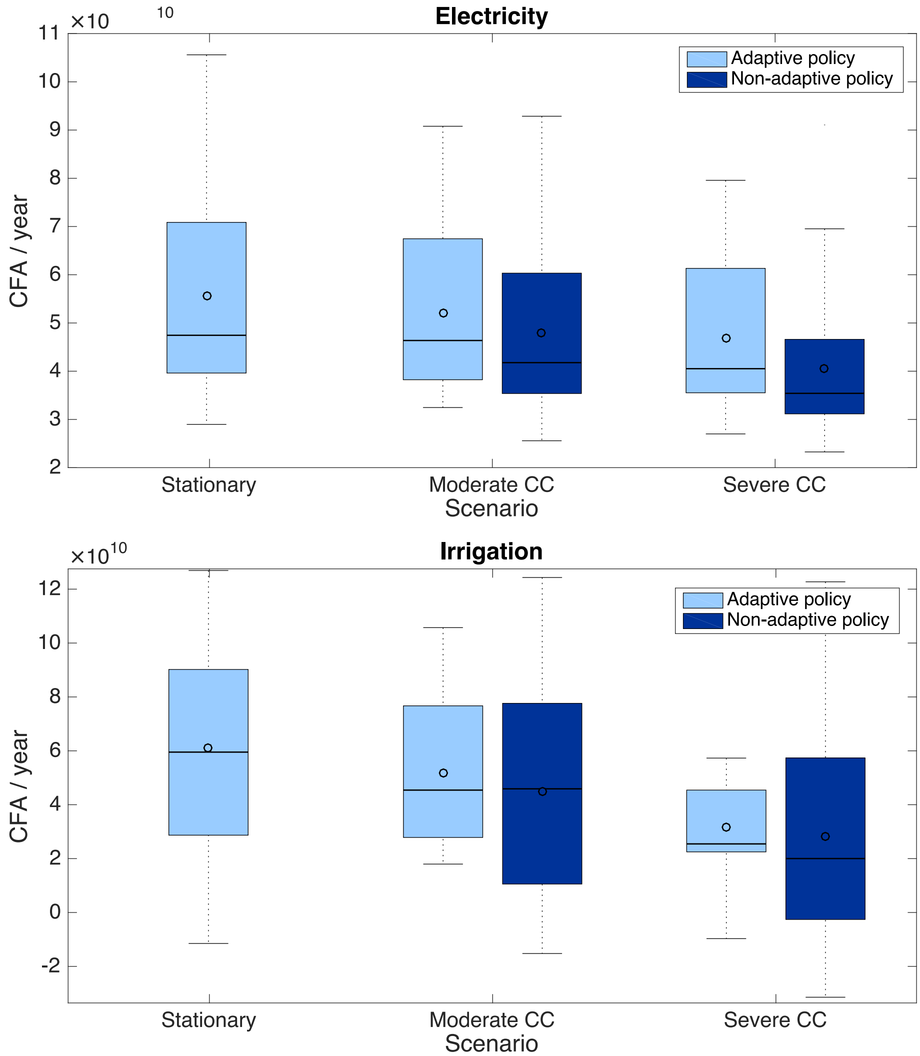

Fig. 6. Stress test: Net yearly benefit (i.e. yearly benefit less operation costs) for irrigation and electricity, for different scenarios of climate change, box-plots. Scenario with flood support, case of Manantali + Diama.

3.5. Limitations

The analysis has several limitations that need to be clearly indicated. Here, we list some of the relevant elements this CBA does not consider, without claiming to be exhaustive: all other modeling choices can be inferred by analyzing the system model.

We do not have sufficient information to include in the CBA the other relevant components from Fig. 1, namely: population dynamics, the energy system, and meteorological components. This is a major limitation of this analysis. Future research will expand the system boundaries to include all the key components included in Fig. 1.

The analysis does not include the indirect effects on secondary markets and on changes in demand. The benefit of navigation and the cost of alternative land use is not considered, in fact assuming that navigation will not be practiced and that land availability for irrigation is not a limiting factor. We use a mono-culture irrigation production function, only considering rice, de facto limiting the capacity to represent the real adaptation capacity of the agricultural system. The estimation of the price of electricity does not consider different uses, hence different values, for different seasons. We consider only aggregated production: the cost due to an irregular electricity supply is not taken into account. The value of electricity does not include the opportunity cost offered by other renewable energy sources. The irrigation model is largely simplified and its uncertainty is not represented. The cost of labour, like many other variables, is considered to be fixed, whereas in practice, it depends on the dynamics of development that are partially exogenous, partially influenced by the presence of the dams. All dynamics faster than the model time step, i.e. one week, are excluded. Hydrological dynamics lasting more than one year, such as the Hurst effect [34], are not included in the reservoir operation. The effect of climate change on water availability is represented by rescaling the hydrological inflow by a multiplicative factor, hence reducing the total amount of available water, but not considering other possible changes in the hydrograph.

4. Conclusions

In this paper we indicated how the ex-ante economic evaluation of large dams, specific to the African context, can benefit from the use of methods that take into account change and adaptation at both the operational and the structural level, and their interplay. We applied these methods in a Cost-Benefit Analysis (CBA) of an existing system of dams on the Senegal River, in which we used an exploratory approach to map the net value of the projects under different conditions that may change in the future. The exploratory analysis is limited, in this case, to changing water availability due to climate change.

Marginalist economics, in which CBA is rooted, focuses historically more on equilibria than on dynamics and change. As a consequence, change is generally overlooked in CBA. Nonetheless, for the economic appraisal of large dams, we suggest that approaches that consider system dynamics under uncertainty and their capacity for adaptation are more appropriate than detailed but static deterministic procedures. Dams do in fact have non-marginal impacts, and are dependent on external climatic conditions that are currently undergoing a rapid and structural change. In our analysis we show how overlooking the fact that water availability may change in the future can have negative consequences for the economic performances of dams. Our results shows how including adaptation (adaptive policies, in the test-case) at the structural scale can help mitigate these negative consequences, compared with the case in which adaptation is not included (non-adaptive policies). The mitigation of the negative consequences of climate change in this specific test case is, however, not particularly remarkable if compared to the operational variability of the hydrological system.

The economic appraisal of a dam cannot be separated from how it will be managed at the operational level, i.e. from the design of its operational rules. In the application, the operational rules were designed using SDDP, a stochastic dynamic programming method. Using SDDP, operational rules can be directly defined from the system model and the system objective, which, in the case of CBA, is the welfare function. This is particularly advantageous in exploratory approaches: optimization methods can be used to redesign operational rules according to changing structural conditions, hence simulating a system capable of adapting at both structural and operational level. In the CBA, we redesigned the reservoir operational rules for all water availability scenarios. The analysis shows a limited drop in performances for hydropower and more variability for irrigation.

The CBA reveals the potential for economic exploitation on the Senegal River, made possible by the presence of new dams, without excessively affecting the environmental conditions of the river. The dynamic model of the system enabled the representation of main hydro-economic processes related to the dams and their impacts, including flood support. The analysis shows how, thanks to their adaptive operational management, the dams are able to partially hedge the natural variability of the Senegal River. Despite this hedging effect, some interannual variability, explicitly communicated in the CBA results, is necessarily present.

The CBA was based on a large set of assumptions and simplifications, that we have clearly underlined. Despite our intention, and the effort invested, to extend what can be considered as dynamic, important variables were assumed to be static: this is likely the main limitation of this analysis, if not of CBA in general. A more realistic estimation would need to extend the system boundaries to enlarge the set of variables that are dynamic. In the African socio-economic and environmental context, we identified some subsystems as key components that will have to be integrated in the CBA. Beyond the reservoir dynamics and its operation, these are: i) the meterological system, ii) the hydrological system, iii) population dynamics, iv) the irrigation system, and v) the electric system. Extending the whole system, however, requires modeling processes that are not completely understood (and consequently not yet predictable), thereby increasing the need for – and the importance of – an exploratory approach, robust decision making, and adaptation. Research in the near future will fill this gap, thereby expanding the system boundaries to include all the key components.

Appendix A. Operational costs and benefits

Yearly operational costs and benefits are defined in Equations (A.1-A.4).

$$B_y^E = p_E \cdot \sum_{t=1}^{h} E_t \tag{A.1}$$

$$C_y^E = c_E^f + \sum_{t=1}^{h} c_E^v \cdot E_t \tag{A.2}$$

$$B_y^I = \sum_{s=dry}^{wet} c_Y \cdot c_R \cdot p_{t_h} \tag{A.3}$$

$$C_y^I = \sum_{s=dry}^{wet} \left[c_S \cdot p_{t_S} + \sum_{t=t_s}^{t_h} \left(c_I \cdot r_I + c_M \cdot p_{t_h} \right) \right] \tag{A.4}$$

In Equations (A.1-A.4), B_y^E and C_y^E are the yearly benefits and the yearly operation and maintenance costs for electricity, and B_y^I and C_y^I are the yearly benefits and the yearly operation and maintenance costs for irrigation.

In Equation (A.1), The yearly benefits from electricity is the product of the value of electricity, p_E, into the sum hydropower production, E_t, on that year. The time-step hydropower production, defined in Equation (B.3), is calculated from the model simulation. The value of hydro-electricity p^E is defined using the alternative cost technique, where the value of hydropower is equivalent as the cost savings of compared with the next less expensive energy production alternative [26]. For this purpose, we consider the average opportunity cost of thermal energy in West Africa (105 CFA/kWh), considering a balanced mix of gas (70 CFA/kWh) and diesel (140 CFA/kWh). In Equation (A.2), the variable operational cost of hydropower, c_E^v is 20 CFA/KWh, and c_E^f the fixed maintenance costs, assumed zero, as in Ref. [50].

In Equations (A.3-A.4), s is the index for the season, which can be either dry (from January to June) or wet (from July to October), p_t and r_t^I, are the irrigated surface and irrigated discharge at each time-step, whose values are identified from the model simulation, c_S are the specific sowing costs [CFA/ha], c_I the specific irrigation costs [CFA/m^3s^{-1}], c_M are the specific operation and maintenance costs per time-step [CFA/ha], and $c_Y \times c_R$ is the product of crop yield into the rice price. All parameters values depend on the type of irrigation technology used. Their value, defined in Appendix C, are derived from Ref. [50]. The irrigation cost is considered zero, assuming irrigation by gravity. The net irrigation benefits is the sum of harvest revenue less sowing, irrigation, and maintenance costs. The benefits of irrigation are defined by the revenues from rice production. The value of specific value and operational costs are defined according to the [50], and reported in Appendix C.

Appendix B. Model components

B.1. Reservoirs

Reservoir models are made of the continuity equation representing the mass balance and the reservoir physical-legal constraints. Equation (B.1) represents the Manantali reservoir model.

$$v_t^M = v_{t-1}^M + \Delta t \cdot (q_t^M - r_t^T - r_t^S - e_t^M) \tag{B.1}$$

In Equation (B.1), v_t^M is the reservoir volume, Δt the simulation time-step, q_t^M the inflow to the reservoir, coming from the Bafing tributary, upstream of the reservoir, r_t^T and r_t^S are the controlled release through turbines and spillways, and e_t^M the evaporation from the reservoir. Volume and releases are constrained as in Equation (B.2): volume is limited between a lower and an upper boundary. Constraints on maximum releases are due to physical constraints. The minimum spillage constraint is related to obligation intended to ensure dam safety. All constraints depend on the reservoir water level. The water level is univocally related to the volume, therefore the constraint on maximum release through turbines and bottom outlet can be related to the reservoir volume. R-functions relate maximum and minimum discharge to the reservoir volume. Detail of this constraints are given in Appendix B.1.1. Evaporation e_t^S is the specific potential evaporation e_t^S into the reservoir surface S^M. The reservoir surface is considered constant.

$$v_{\min}^M \le v_t^M \le v_{\max}^M \tag{B.2a}$$

$$0 \le r_t^T \le R^T(v_t^M) \tag{B.2b}$$

$$R^L(v_t^M) \le r_t^S \le R^S(v_t^M) \tag{B.2c}$$

$$e_t^M = e_t^S \cdot S^M \tag{B.2d}$$

Equation (B.3) represents the hydropower function.

$$E_t = \eta \cdot \Delta t \cdot \Delta h_t \cdot r_t^T \tag{B.3}$$

where energy at each time step is the product of hydraulic head Δh_t, discharge through turbines, the simulation time-step, and the conversion factor η, defined in Appendix C. We use this function within an optimization procedure that requires the problem to be convex. Therefore Equation (B.3), which is concave, must be linearized as in Ref. [58].

Diama mass balance is modeled as in Equation (B.4).

$$v_t^D = v_{t-1}^D + \Delta t(q_t^B - r_t^I - r_t^D - e_t^D) \tag{B.4}$$

In Equation (B.4), v_t^D is the reservoir volume, q_t^B the inflow to the reservoir, r_t^I the withdrawal for irrigation, r_t^D the release to the see, considered here as unconstrained, and e_t^D the reservoir evaporation. Diama is much smaller than Manantali, therefore its reservoir volume is considered to be zero. In this case the mass balance of Equation (B.4) is preserved, but the reservoir dynamic is neglected. The maximum release to the see is limited by physical constrains, depending on the reservoir volume according to function R_D. Evaporation is the product of specific evaporation e_t^S into the reservoir surface S^D, considered constant.

$$0 \le r_t^D \le R^D \tag{B.5a}$$

$$e_t^D = e_t^S \cdot S^D \tag{B.5b}$$

B.1.1. Releases constraints

Release are constrained between zero and a value function of volume R, depending on the reservoir physical structure. The R-functions are implemented in SDDP by linear cuts. Constraint functions are defined by pairs of points in $[r_i^{\max}, v_i]$. Functions R are approximated by line passing through two consecutive pairs.

$$r_t \ge 0 \tag{B.6a}$$

$$r_t + a_i \cdot v_t \leq b_i \tag{B.6b}$$

Spillage almost never occurs for low volumes, therefore the cut for the maximum spillage is realized by selecting two points close to the normal operational point, considered at $v_{\max}^M$. The legal requirement for dam safety requires a minimal release when volume exceeds v_{legal}^M. This constraints is implemented by an additional linear cut (Fig. B.8).

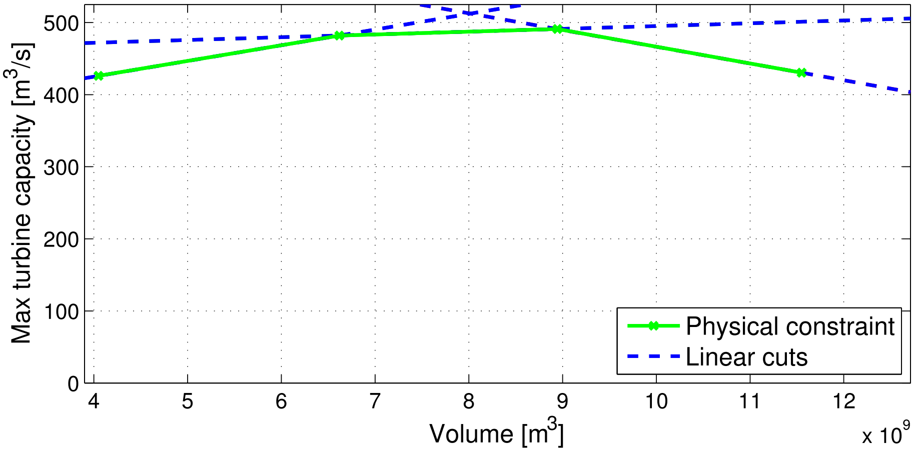

Fig. B.7. Release through turbine constraint, Manantali reservoir.

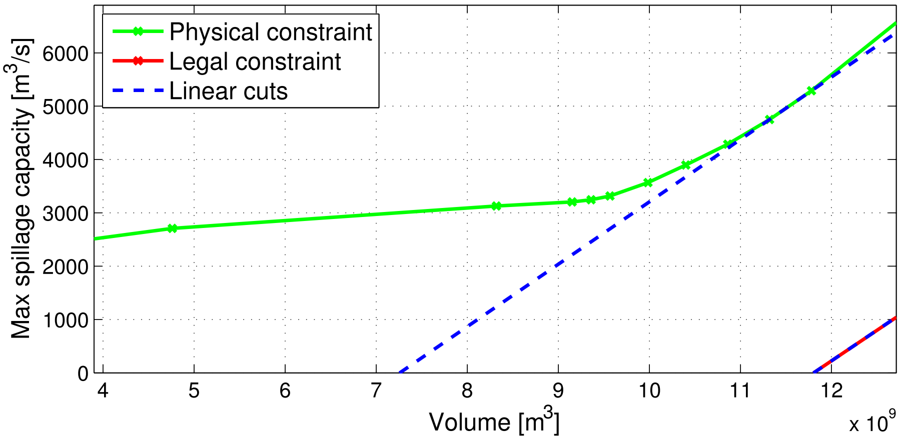

Fig. B.8. Release through spillways constraint, Manantali reservoir.

B.2. Irrigation-crop model

The Irrigation-crop model considers the possibility to cultivated rice only. We consider two irrigation cycles per year. Starting in January and June. Each irrigation cycle lasts 14 weeks (i.e. about 100 days).

Equation (B.7) represents the dynamic of the irrigated surface: Irrigation happens from $t = t_s$, sowing time, to $t = t_h$ harvest time. At sowing time, t_s, the decision of irrigated surface, p_s is taken. In this experiment, decision over p_s is taken by the optimization procedure according to the criteria of maximum expected net revenues from irrigation. The area must be irrigated for the entire period, until the harvest time, t_h.

$$p_t = \begin{cases} p_s & \text{at } t = t_s \text{ (Sowing Instant)} \\ p_{t-1} - L_t & \text{at } t_s < t \leq t_h \text{ (Crop Period)} \\ 0 & \text{otherwise} \end{cases} \tag{B.7}$$

In case of water deficit, irrigated surface decreases. L_t lost surface is proportional to the part of surface that is non-irrigated. Equation (B.8a) defines surface loss in function of the water provided, where d_t is the specific water demand, i.e. volume of water demand per surface. Specific water demand d_t is the sum of i) evapotranspiration ii) percolation, iii) other losses. Withdrawal for irrigation r_t^I is limited by the maximum water demand at that instant $r_{\max,t}^I$, as in Inequalities (B.8b). The maximum water demand is defined as in Equation (B.8c). In case of water shortage, the irrigation demand is reduced and adapted to the new irrigated surface, p_t for all the following instants, until harvest time.

$$L_t = p_{t-1} - \frac{r_t^I}{d_t} \tag{B.8a}$$

$$0 \le r_t^I \le r_{\max,t}^I \tag{B.8b}$$

$$r_{\max,t}^I = d_t \cdot p_{t-1} \tag{B.8c}$$

B.3. Inflow and hydraulic transfers

Streamflow processes are represented by a stochastic model, able to reproduce the interannual variability in water availability, and the uncertainty within the hydrological year.

$$[q_t^M, q_t^L] = \mathscr{M}_t(q_{t-1}^M, q_{t-1}^L, \varepsilon_t) \tag{B.9}$$

Model $\mathscr{M}$ is a yearly-cyclostationary multiplicative autoregressive model, identified on historical discharge data from 1950 to 2010, as described in Ref. [58], at the weekly scale. The model is multivariate and contains a correlation factor in the random variable ε_t in order to reproduce the correlation among subcatchments as present in the data.

Discharge at Bakel is the sum of total discharge from the reservoir and lateral inflow, with a time step delay (=1 week), as in Equation (B.10). Lateral inflow between the upstream stations and Bakel is neglected.

$$q_t^B = q_{t-1}^L + r_{t-1}^R + r_{t-1}^S \tag{B.10}$$

B.4. Reservoir operational rules

Water availability on the Senegal river is extremely variable, both within and among hydrological years, and largely uncertain. Despite the uncertainty, the system operation can be designed to adapt to climatic uncertainty: at each step, new information becomes available and partially reduces uncertainty. Optimal system operation can be framed as a Multistage Stochastic Programming problem [7,65], which, for long horizon, is conveniently solved by Stochastic Dynamic Programming (SDP) [5]. Equation (B.11) represents the Bellman equation.

$$H_t(v_t, p_t, q_t) = \max_{\mathscr{D}} \left\{ h_t(\cdot) + \mathop{\mathbb{E}}_{q_t^M, q_t^L}[H_{t+1}(v_t, p_t, q_t)] \right\} \tag{B.11}$$

In Equation (B.11), h_t is the step cost-benefit function, H is the cost-to-go function, that sums up all future costs and benefits. The step function h_t contains the i) electricity revenues, ii) irrigation costs and revenues, and iii) other operational constraints, as flood support and minimum discharge. The Bellman equation is used to define an optimal control strategy, i.e. a rule that gives the optimal set of decision $\mathscr{D}$ given the present state of the system. The set of decisions is made up of variables r_t^T, r_t^S, r_t^D, r_t^I, p_s, i.e. all releases and withdrawal for irrigation at each time steps, and irrigated surface at the beginning of each crop seasons. The system state, on which the decision is based, is made of reservoir volume, irrigated surface, and river discharge. The inclusion of the latter means that hydrological conditions of the catchment are taken into account in the reservoir operational management.

Appendix C. Main variables and values

C_i	Initial Investment Costs [CFA]
B_y	Yearly benefits, Total [CFA]
C_y	Yearly costs, Total [CFA]
B_y^E	Yearly benefits, Electricity [CFA]
B_y^I	Yearly benefits, Irrigation [CFA]
C_y^E	Yearly operation costs, Electricity [CFA]
C_y^I	Yearly operation cost, Irrigation [CFA]
r	Discount factor [10%]
q_t^M	Inflow to Manantali, i.e. discharge at Soukoutali [m^3/s]
q_t^L	Lateral inflow, sum of discharge of Bakoye (Oualia station) and Faleme tributaries (Gourbassi station) [m^3/s]
v_t^M	volume at Manantali [m^3]
r_t^T	Release through Turbines at Manantali [m^3/s]
r_t^S	Release through Spillways at Manantali [m^3/s]
q_t^B	Discharge at Bakel [m^3/s]
e_t^S	Specific evaporation [m/s]

e_t^M	Evaporation from Manantali $[m^3/s]$
q_t^B	Discharge at Bakel $[m^3/s]$
v_t^D	volume at Diama $[m^3]$
e_t^D	Evaporation from Diama $[m^3/s]$
r_t^D	Release to the see $[m^3/s]$
r_t^I	Irrigation withdrawal $[m^3/s]$
p_t	Irrigated surface $[m^2]$
i_t^P	Infiltration $[m]$
e_t^P	Evaporation $[m]$
η	Conversion in Equation (B.3) $[1000 kg/m^3 \cdot 9.81 m/s^2 \cdot 0.9 \cdot 10^{-6} MW/W \cdot 2.78 \cdot 10^{-4} h/s]$
Δt	Simulation time-step [7 days = 604800 s]
p_E	Value of hydropower [105 CFA/KWh]
c_E^v	Hydropower, variable operation costs [20 CFA/KWh]
d_t	Rice, water specific demand [10 mm/day = 1.157 $\cdot 10^{-7} m/s$]
c_S	Rice, sowing specific cost [300.000 CFA/ha = 30 CFA/m^2]
c_M	Rice, maint. spec. cost [100 $CFA/(ha \cdot day) \cdot \Delta t$ = 7.0 $\cdot 10^{-2} CFA/m^2$]
c_I	Irrigation specific cost [0 $CFA/day \cdot (m^3/s)$]
c_Y	Rice, yield [5 Ton/ha]
c_R	Rice, price [125.000 CFA/Ton]
$\bar{q}^B$	Floodplain threshold [1300 m^3/s]
$\bar{q}^D$	Drinking water, demand [$10 m^3/s$]

Appendix D. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.wre.2018.08.001.

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