International Conference on Hydroinformatics

2014

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Luciano Raso

Jean-Claude Bader

Marc Leblanc

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

DESIGNED OVERFLOW FOR FLOOD RECESSION AGRICULTURE AGAINST FLOW CONTROL FOR HYDROELECTRIC PRODUCTION IN AN AFRICAN CONTEXT

LUCIANO RASO (1), JEAN-CLAUDE BADER (2), MARC BLANC (2)
(1): UMR-GEAU, IRSTEA, 261, rue F.Breton, Montpellier, 34000, France
(2): UMR-GEAU, IRD, 261, rue F.Breton, Montpellier, 34000, France

. Manantali is a reservoir located in Mali, controlling about 50% of the total water flow of the Senegal River. Manantali is an annual reservoir, used to regulate the flow in the face of the extremely variable seasonal climate of the region, mainly for irrigated agricultural and hydropower purposes. The reservoir was built in 1987 and it has been operative for about 10 years now, exceeding the planned capacity of hydroelectric production and irrigable land surface.

. The economic benefits derived from the reservoir come at a price. Before the dam's construction, the annual flood was the basis of flood recession agriculture, practiced traditionally by the local populations downstream. Flood recession farming is based on natural irrigation and fertilization of the flood plain. Under the present management, flood recession agriculture is a secondary goal with respect to hydroelectric production and irrigation. These two objectives, in fact, require a more regular flow; therefore flow peaks are dumped in the reservoir. Annual floods are still produced, but they have been largely reduced. Moreover, the basin authority is evaluating the construction of different new reservoirs, which will enhance even further the controllability of the river flow.

. In this study we explore the possible optimal compromises among the conflicting objectives of flood recession agriculture against hydroelectric production and irrigation. Moreover, we examine how a better use of hydrological information can improve present reservoir management.

INTRODUCTION

Reservoirs are strategic assets to ensure water security, storing water when it is more abundant and making it available when it is scarcer, and then more precious. They can be used for many purposes, such as flood and drought protection, irrigation, and electricity production.
Reservoir operational management is a complex task [2]. Complexity arises from the presence of multiple reservoirs on the same basin, the need for balancing short and long-term effects, the

presence of relevant hydrological uncertainty, of multiple interests that must be coordinated and balanced, and of changing climatic conditions.

Reservoir construction continues in developing countries. Different African countries have recently built new reservoirs, and more are under evaluation [3]. These structures are intended to support the radical economic changes going on in Africa, as higher demand of electricity and irrigation, on top of traditional water uses, requires a more efficient use of water resources. However, new reservoirs change the existing hydrological regimes, affecting the interests of riparian communities. Understanding the effect of reservoirs, their role within the hydrological cycle, their cost and benefits in economic and environmental terms is a required condition to take responsible and sustainable decisions. Design of release policy, i.e. the rules according to which a reservoir is operated, has equivalent importance than the decision whether building the reservoir or not.

Manantali, a reservoir on the Senegal River, is a good representative of this continental trend. Manantali's present use is mainly energy production, and this has substantially altered the downstream conditions. The natural hydrological regime used to produce a major yearly flood that was used for flood recession agriculture. Flood recession agriculture is a type of agriculture based on cultivation on area where the flood brought water and sediments, fertilizing the land. The conflict between flood recession agriculture, which employed local population before the dam's construction, and energy production, which is mainly used in the urban areas, as the capitals of Senegal and Mali, is one of the main unresolved conflicts in this basin. Change of hydrological regime and suppression of the annual flood have not just a direct effect on agriculture; it breaks an ecological equilibrium with changes that are still under research.

Existing studies on optimal management for Manantali and its hydrological effects includes the SDAGE [3], and [1]. Even if these studies are a valid starting point, the SDAGE is limited by the monthly aggregation, and [1] by the way uncertainty is represented. The SDAGE uses in fact a monthly time step. In this basin, representing the hydrological process on a monthly base misses the fast dynamic of flood events, and average out much of the uncertainty. Research carried out by Bader et al [1] is more specific on the effect of energy production on flood production. However, this method builds up decision rules that, differently from SDP, do not explicitly consider the operational adaptivity.

This research aims at producing an investigation at a higher detail than that provided by the existing studies. For this purpose, we use a stochastic and adaptive control method at a finer time step. The final objective of this research is assessing how the optimal use of existing resources affect the two main conflicting objectives, and how gain due to better use of information can be distributed among the conflicting objectives.

TEST CASE

Manantali is an annual reservoir located in Mali, along the Senegal River, controlling about *50%* of the total water flow on this river. Its benefits are shared among Mali, Mauritania, and Senegal. These three countries participate with Guinea to the Organization for the Valorization of Senegal River (OMVS) project. Manantali reservoir volume is 12 x E9 m^3 and its installed capacity is 205 MW. The inflow is extremely variable, following the tropical raining seasonality. Most of the water falls in the upper part of the basin during the rainy season, in July-October [5]. Figure 1 displays the inflow to Manantali for different years. The

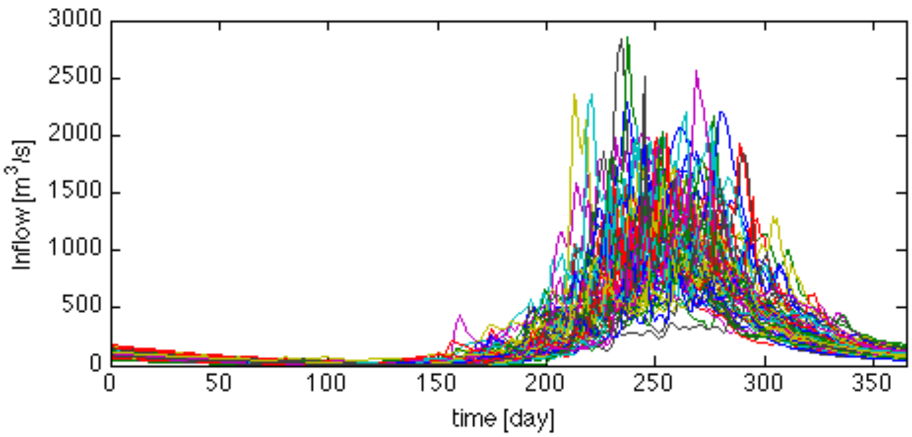

Figure 1. Observed inflow at Manantali, from 1st January 1950 to 31st December 2013.

hydrological signature is characterized by an extremely seasonal variability between the dry season, in January-June, and the raining one, in July-December.
Manantali is mainly managed for hydropower purposes, with positive effects on water availability for irrigation, which will become a more important objective in the near future [3]. Operating the reservoir for hydroelectric production reduces the annual river variability, enhancing also irrigation agriculture and navigation. The release strategy is decided before the rainy season, and the operational release decision is taken at daily base. The average inflow is 270 m^3/s and the average residence time is 1.4 years. Manantali was completed in 1987 and started to produce electricity in 2002, exceeding the planned capacity of hydroelectric production and irrigable land surface.
Manantali operation was originally designed to satisfy different rival objectives: energy production and low-flow augmentation on one hand; flood support on the other. These two macro-objectives are in conflict, because flood support requires spilling part of the water that can be, otherwise, be used for energy production.

Notwithstanding the original intentions, analysis of actual reservoir operation in the last years, when the reservoir was fully operative, shows that the riparian interests received less priority than energy production. The reservoir has reduced the floods intensity and frequency.
There are other environmental and ecological issues linked to the alteration of the natural hydrological regime that presently are only partially known, and require further investigation. Therefore, this analysis is limited to the economic aspects. Nonetheless, we recognize the possible presence of environmental-ecological consequences of hydrological regime change, caused by the rupture of existing natural equilibriums.

RESEARCH OBJECTIVE AND METHOD

This study aims at providing a detailed analysis of Manantali reservoir achievable goals, explore different optimal trade-off between the flood recession agriculture and the energy production, assess the existing conflict between old and present water use and the evaluating the role of uncertainty and adaptivity.
We will employ Stochastic Dual Dynamic Programming (SDDP) [7] at a daily time step. SDDP is an evolution of classic Stochastic Dynamic Programming (SDP). SDP is an off-line optimal

control method to define optimal rules under uncertainty. In the water management contest, SDP has been typically used to define release rules for reservoirs. Differently from its predecessor, SDDP does not suffer of the so-called curse of dimensionality, which means that the computational complexity grows exponentially with the number of variables. SDDP allows us to use a finer time frequency, include in the model the spatial variability of hydrological process and the routing along the downstream river.
SDDP has been recently extensively analyzed by [6], and it is now accepted as a valid approximation of the original SDP. In SDDP, the cost-to-go function is approximated by hyperplanes representing Bender's cuts of a convex function. For this reason, the "time step" problem must be convex. We will use linear model and linear objective function, to ensure the linearity of the problem, thus its convexity. SDDP requires the complete modeling of the physical system by state transition representation.

Phisical Model
The physical model is made of a semi-lumped hydrological model, a reservoir model, and a hydraulic routing model.

The hydrological model is designed to statistically reproduce the hydrological process and its uncertainty. SDDP requires model linearity, but allows parameter to be time-variant and residual to have any distribution. Then the hydrological process is represented by a periodic linear autoregressive model with log-normal residuals. The autoregressive model is calibrated on the standardized logarithm of inflow signal, $y_t=[log(q_t)-\mu_t]/\sigma_t$, where μ_t and σ_t are periodic mean and average of $log(q_t)$. To have an autoregressive model on q_t, the autoregressive model identified on y_t is transformed in an autoregressive model on q_t by linearization on the climatic average value for that day. In this transformation, residuals become log-normal distributed. This ensures the non-negativeness of discharge values and a better representation of the hydrological process. The hydrological process is modeled at two locations: Bafing and the aggregated lateral inflow, from Oualia and Kidira. Spatial correlation is included.

The reservoir is modeled by the continuity equation

$$v_{t+i} = \mathrm{v}_t + \Delta t \cdot \left(q_t^{Bafing} - r_t - s_t - e_t \right) \tag{1}$$

Where v is the volume, r the release, s the spillage, e the evaporation from the reservoir.
For water level between 185 and 210 m, in which the reservoir is normally operated, the reservoir can be assumed cylindrical. The evaporation, at this preliminary stage, is neglected.
Release and spillage are the controllable variables, constrained between zero and maximum release, r_{max}, and maximum spillage, s_{max}. Maximum release and maximum spillage depend on the water level. The water level is univocally related to the volume, therefore the constraint on maximum release through turbines and bottom outlet can be defined by different linear cuts as in Equations (2), maintaining the linearity of the optimization problem. In Equation (2), $[a_i, b_i]$ define the n linear cuts for the maximum release and spillage from the bottom outlet.

$$\begin{aligned} &0 \le r_t \le a_j \cdot v_t + b_j \quad \forall j = 1,\ldots,n_r \\ &0 \le s_t \le a_j \cdot v_t + b_j \quad \forall j = k+1,\ldots,n \end{aligned} \tag{2}$$

The reservoir has also surface spillways, but these are neglected, and then the total spillage capacity is underestimated. Underestimating the spillage capacity produces conservative policies that not to jeopardize the dam safety.

Neglecting the propagation delay, we will model the hydraulic routing by a simple mass balance.

$$g_t^{Bakel} = r_t + s_t + q_t^{Kidira} + q_t^{Oualia} \tag{3}$$

Objective Function

System objectives are energy production and flood production. The cumulative objectives are made up of the sum of daily objectives. Daily energy production is proportional to the product of hydraulic head into discharge.

$$P_t = c \cdot \Delta h_t \cdot r_t \tag{4}$$

where c is a multiplying factor, proportional to gravity, water density, and turbine efficiency. the hydraulic head, Δh, is the difference between the water level in the reservoir and downstream, but the latter changes much less than the first and will be considered constant. Water level in the reservoir is linked to the volume via the storage curve. When the water level is within its operational band, the reservoir can be considered cylindrical. In this case water level is directly proportional the water volume. Even after these simplifications, Equation (5) is a hyperbolic paraboloid on v and r, which is a non-convex function. Nonetheless, it can be linearized with a Taylor expansion on an average or other relevant point, (h_0,r_0). Then, the only required parameter is the ratio between the two slopes at that point, $k_S=\Delta r(h_0,r_0)/\Delta v(h_0,r_0)$, and the energy production objective becomes becoming a linear optimization in two variables, as in Equation (5), in which the importance of maintaining a high hydraulic jump depends on its relation with the average discharge, i.e. on some characteristic of the reservoir.

$$g_t^E = r_t + k_S \cdot v_t \tag{5}$$

The flood production objective is met when an excess of water overflow on the floodplain. Benefit of flood can be considered proportional to the flooded surface at Bakel, and flood surface at Bakel depends on the water level.

$$Flood_t = f\left(q_t^{Bakel}\right) \tag{6}$$

Equation (6) expresses the relationships between flow and flooded area. This relationship is difficult to include in the optimization, for the presence of a threshold and other non-linearities. Therefore we will use a simplified operational indicator considering the benefit proportional to the flow at Bakel for the period that the flood is expected, i.e. August-September. The daily flood production indicator, g_t^F, active in August-September only, is defined in Equation (7).

$$g_t^F = q_t^{Bakel} \tag{7}$$

Table 1. Synthetic Table of results, per scenario and objective

Configuration	Energy [TWh/year]	Flood [10^9 m^3/year]	Manantali contribution to flood [%]
E	1.12	3.9	60%
F1	1.11	4.1	62%
F2	1.06	4.5	65%

The aggregated objective is made of the weighted sum of g^E and g^F. Different optimal compromises between the two objectives can be found by varying their weights.

RESULTS

We show here some preliminary results. We analyze the effects of optimal decision rules obtained with SDDP for three configurations: one optimizes electricity production only, other two are a more balanced compromises between flood and energy production. The first is called configuration E, the latter are F1 and F2. The importance of electricity production - flood production objectives is: 100%-0% in E, 85%-15% in F1, and 70%-30% in F2. The optimal decision rules and the simulation results are obtained using the observed discharge from 1st January 1950 to 31st December 1970. In this simulation we did not include a safety constraint that obliges the operator to spill water when the water level in the reservoir exceeds 208m, therefore the results overestimate the maximum performance that the reservoir can produce.

Table 1 shows the results aggregated by sub-objective for each configuration, where the flood indicator consider the cumulated water when q_{bakel}>1500 m^3/s. These preliminary results show that the conflict is much reduced when the system is optimized. Indicators show in fact high values for all three configurations. Moreover, passing from E to F2, the loss in electricity is relatively small. The contribution of Manantali to the flood is also particularly high.

Figure 2 shows more detailed simulation results, for year 19. In figure 2, Plot 1 (above) shows the water volume on time, and plot 2 (below) shows the inflow and outflow for the same period. Figure 2 shows that the water level is kept high until day 85. From that time on, the controller lowers the water level in expectation of the high flow event. After the high flow event is realized, and the inflow is known, the controller re-adjust the system to bring rapidly up the water level. Figure 2 show also that the flood process is fast. Discharge changes at a time scale faster than the month. For this reason, daily information and adaptation is important. Uncertainty plays a relevant role, for the amount of water is not known before the beginning of the wet season. Going on in time its amount becomes more and more certain. Information enters the system day by day. At the same time, decisions of resource allocation must also be taken at a daily base, and the evolution of uncertainty and decision must be properly modeled.

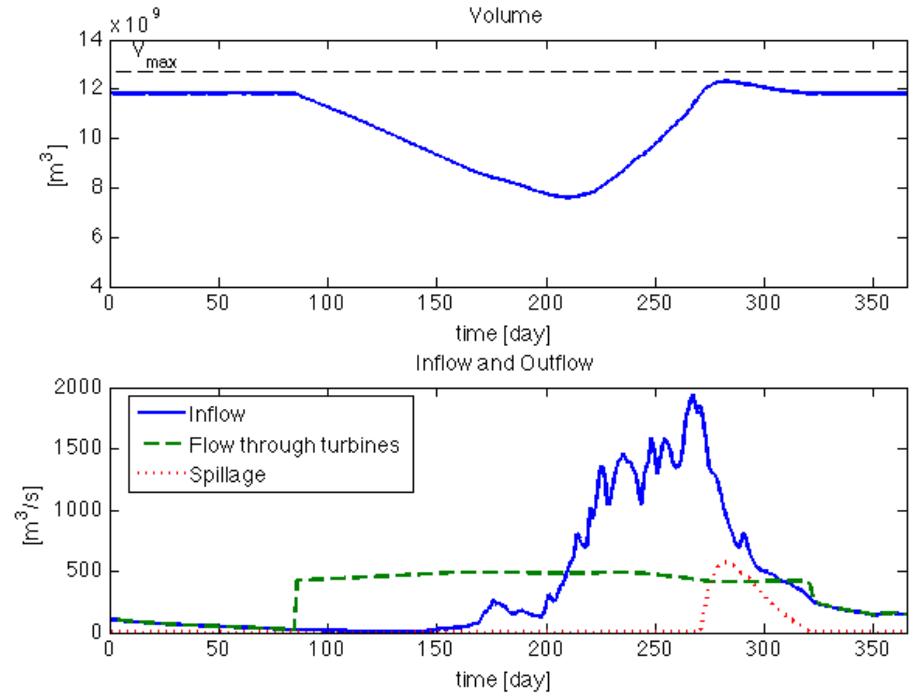

Figure 2. Simulation results from 1st January 1963 to 31st December 1963. Plot 1: Reservoir volume on time. Plot2: Inflow and outflow from and to the reservoir. The outflow is divided into release trough turbines and spillage.

CONCLUSIONS

Manantali is a reservoir on the Senegal River that has mainly been used for energy production. Its operation has deeply changed the hydrological regime, dramatically reducing the annual flood that the local population used to use for flood recession agriculture. We explored the presence of systematic conflict between energy and flood production. Showing three possible trade-offs, to understand the costs of trade-offs, and whether a better management can

For this purpose, we used Stochastic Dual Dynamic Programming at a daily time step. We stressed the importance of selecting the proper decision time-scale, and the correct inclusion of uncertainty and its reduction.

Results show that optimization techniques can largely contribute to both energy and flood production. There is indeed a systematic conflict between the two objectives. However, if operated in an optimal way, the reservoir can offer satisfactory management for both the objectives.

The Senegal River faces rapid changes. Different development plans are under evaluation, such as the construction of new reservoirs, and the development of agro-business. More reservoirs will make the flow even more controllable, and new water demand will make the management even more complex. Understanding the ongoing processes and the system limits is extremely important, which justifies this research and requires even more research on this basin.

ACKNOWLEDGMENTS

We are grateful to Prof. Amaury Tilmant, from Laval University, for the SDDP code. This research is completely funded by AXA post-doc research fellowship.

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