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Optimization Model of a Tandem Water Reservoir System Management

O. Ivanova, K. Neusipin, M. Ivanov, M. Schenone, L. Damiani, R. Revetria

***Abstract*— This paper presents a complex approach for modelling of a tandem reservoir systems for water drainage management. The model has been built over a segment of a river with a certain parameters of water inflow, water outflow, required power production and max possible flood occurrence. Then the segments may be replicated with specific parameters to simulate whole system of the river. The model has been optimized in order to obtain the water drainage operation policy with regards of current and expected water volumes in the reservoirs ratio, required power production revenue, and minimal flood occurrence. Model has been verified on a walk-through basis. The obtained results demonstrate good reliability disregards broad possible variations of the managed parameters and provide the optimal water drainage for minimum flood occurrence and desired power production revenue.**

***Index Terms*—Water drainage; Management; Simulation; Power production.**

I. Introduction

NOWADAYS, Nowadays, the life of a modern man could not be practically imagined without the use of electricity; we can even observe the constant growth of people demand in electricity. However, the resources in the most common sources of energy, such as oil, gas and coal, are rapidly decreasing; so, more often we start thinking the renewable alternatives thereof.

The energy of rivers, which is being employed by the hydroelectric power plants (HPP) for many years, still is considered to be one of the most thoroughly studied sources.

For a long time period and in many countries, gaining the maximum benefits from electricity generation remained the priority criterion in the management and control of the hydraulic structures. Such an approach demonstrated its inconsistency more than once, leading to serious problems.

Manuscript received July 16, 2017; revised August 10, 2017. Full names of authors are preferred in the author field, but are not required. Put a space between authors' initials.

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In order to improve the quality performance of an HPP system, the integrated approach is required to ensure the population safety and security at the tail-water areas, sufficient water level for navigation, provision of domestic and irrigation needs, minimum damage to flora and fauna, and, at the same time, maximum benefits deriving from electricity generation.

In the present paper, we will consider the task of optimizing the model of an integrated reservoir cascade management and control system.

II. Literature Review

Application of simulation and optimization techniques for determining the optimal operating policy for reservoirs is very important in water resources planning and management. There are many publications devoted to solving this issue using various simulation and optimization tools. Lap Tran et al. (2011) describe an economic optimization model for water management was developed to facilitate policy makers' decision making. The model includes the response of rice and fish yields to key factors including reservoir water levels, the timing and quantity of water release, and climatic conditions. The model accounts for variation in rainfall patterns, irrigation requirements, and the demand for low water levels during the fish harvest season. The optimization is performed to maximize profits in each of three production scenarios where the reservoirs water is used for: (1) only producing rice, (2) only producing fish, and (3) producing rice and fish. Fang et al (2014) propose a new storage allocation rule based on target storage curves using a developed simulation-optimization model. The model aims to alleviate water shortages in recipient regions by optimizing the key points of the water diversion curves, the hedging rule curves, and the target storage curves using the improved particle swarm optimization algorithm. Mayer and Muñoz-Hernandez (2009) describe integrated water resources optimization models to determine and maximize economic benefits of withdrawing water for various use categories. Optimization has been carried out to maximize economic benefits from agricultural water use, water used in aquaculture production, residential water use, industrial water use, hydroelectric power use, water allocated for ecosystem functioning, and recreational use, respectively. Belaineh, Peralta and Hughes (1999) present a simulation/optimization model that integrates linear reservoir decision rules, detailed simulations of stream/aquifer system flows, conjunctive use of surface and ground water, and delivery via branching

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canals to water users. The optimization module can perform two alternative functions: develop reservoir decision parameters that maximize conjunctive use of surface and ground water; or maximize total surface and ground water provided to users. Nishikawa (1998) formulated a model as a linear programming problem with monthly management periods and a total planning horizon of 5 years to minimize the cost of water supply while satisfying various physical and institutional constraints such as meeting water demand, maintaining minimum hydraulic heads at selected sites, and not exceeding water-delivery or pumping capacities. The decision variables are water deliveries from surface water and ground water. The state variables are hydraulic heads. Basic assumptions for all simulations are that the cost of water varies with source but is fixed over time, and only existing or planned city wells are considered; that is, the construction of new wells is not allowed.

However, genetic algorithms (GA), due to evolution techniques, have become popular for solving optimization problems in various fields of science (Proletarsky and Neusipin, 2012). Particularly, this approach became widely used in water resources management. I.e. a simple optimization model for single and a cascade hydro-electricity reservoirs systems using GA was created by Asfaw and Saiedi (2011). The objective function was to minimize the difference between actual and installed generation capacity of plants. Devisree and Nowshaja (2014) use the genetic algorithm technique to evolve efficient pattern for water releases at multiobjective reservoir for maximizing annual power production and irrigation demands. Constraints include the release for power and turbine capacity, irrigation demand, storage continuity equation and reservoir storage restrictions. Fi-Jihn Chang and Li Chen (1998) have examined for function optimization and applied to the optimization of a flood control reservoir model two types of genetic algorithms, real-coded and binary-coded. Optimization has been carried out to reduce the outflow during the peak time and at the end of the flood to return the storage close to its initial value to reserve storage for the next flood coming. Hincal, Sakarya and Ger (2011) have explored the efficiency and effectiveness of genetic algorithm in optimization of three reservoirs in the Colorado River Storage with a simple optimization to maximize energy production. Another more complex combined simulation–genetic algorithm (GA) optimization model is developed to determine optimal reservoir operational rule curves of the Nam Oon Reservoir and Irrigation Project in Thailand was developed by Suiadee and Tingsanchali (2007). Both models operate in parallel over time with interactions through their solution procedure. The objective function was maximum net system benefit subject to given constraints for three scenarios of cultivated areas. Sadati et al. (2014) have developed an optimal irrigation water allocation using genetic algorithm under four weather conditions that were identified by combining the probability levels of rainfall, evapotranspiration and inflow. Moreover, two irrigation strategies, full irrigation and deficit irrigation were modeled under each weather condition. The Objective function maximizes the total farm income and is considered for the optimal operation of the reservoir and the irrigation of crops at any time interval during the irrigation season.

Thus, it may be seen that most of the papers aim usage of GA to do a simple optimization of one parameter either to minimize costs, or to maximize the revenue (of energy, production or whatsoever). This paper aims at a more complex optimization with several contradictory constraints.

III. Mathematical model

Simulation models are used to predict a system's response to a given design configuration with great accuracy and detail, and to identify the probable costs, benefits, and impacts of a project. That is, the simulation model predicts the outcome of a single, specified set of design or policy variables. In many situations the number of alternative designs is sufficiently large to preclude simulating each alternative and some other method is normally used to narrow the field of search. (Brooke et al, 1998).

In this paper, a reservoir cascade management and control system, which includes 3 reservoirs, was simulated; and its disposition is demonstrated in Fig. 1. According to such a scheme the Volga-Kama cascade is organized in Russia, where the Cheboksary and Nizhnekamsk reservoirs could be considered as the A and B reservoirs, while the Kuibyshev reservoir – as the C reservoir. The A, B and C dams appear to be the Cheboksary, Nizhnekamsk and Zhiguly HPPs, respectively.

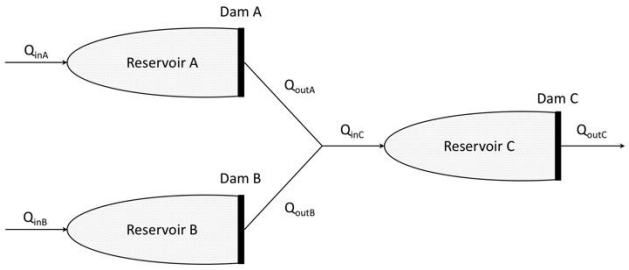

Fig.1: Tandem reservoir system model.

For each of the reservoirs, the following indicators were specified: input flow, hydrodynamic and geometric characteristics, electricity generation and agriculture demands. Besides, for each section of the river network the largest peak discharge was determined, which exceed was assumed to be the flood event.

Each reservoir was operating according to the scheme shown in Fig. 2. Thus, the reservoir received a total flow of different affluxes varying in origin and nature. In addition, the precipitation falling over the reservoir bowl and the groundwater, which could be either positive, or negative depending on the direction of filtration, were separately taken into account. The reservoir filling process was described in detail in the previous work currently in press and is based on a methodology based on SD as in Briano et al. (2009). Besides, the model describes the evaporation process, which could pass to the condensation process depending on the difference between the values of the water vapor pressure. Irreversible water consumption is going to meet the agricultural and domestic needs. The tail-water receives the flow that consists of water passing through the turbines and bypass, which is employed in order to avoid the

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reservoir bowl overflow.

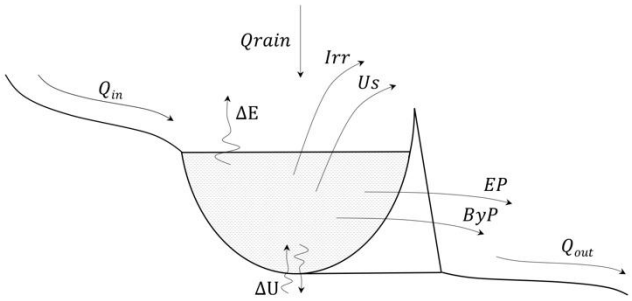

Fig.2: Reservoir model.

The basic equation to describe the reservoir operation process appears to be the balance equation given below:

$$Q_{in} = \Delta E \pm \Delta U + Irr + Us + EP + ByP \quad (1)$$

Q_{in} – incoming flow
ΔE – evaporation
ΔU – underground water (could be positive or negative)
Irr – water, spent for irrigation
Us – water for household usage
EP – discharge for energy production
ByP – discharge through bypass
Q_{out} – discharge from reservoir

IV. Application to a River System

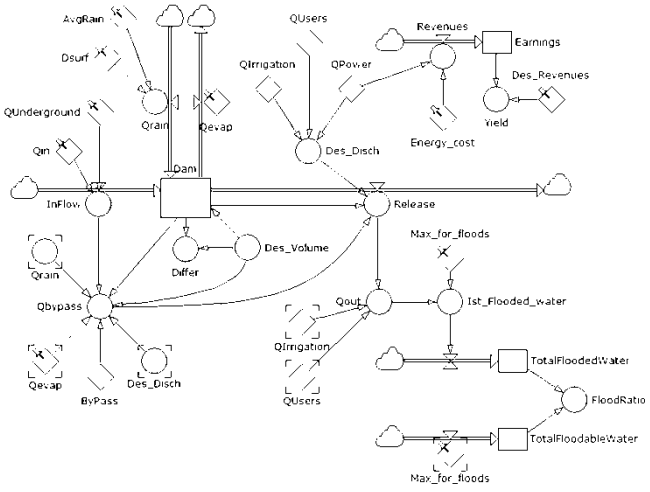

Fig.3: Dynamic model.

Fig. 3 shows the scheme of a separate reservoir operation dynamic model. The reservoir incoming flow indicated in the InFlow chart consists of the surface waters influx from the upstream pool; it could include streamflow, rainfall runoff, etc., and is set in the form of the flow and groundwater hydrograph. In addition, the model includes a possibility of receiving rain precipitation falling directly over the reservoir. It is marked as Qrain in the scheme and is calculated in accordance with the following formula:

$$Q_{rain} = Dsurf * AvgRain \quad (2)$$

where Dsurf is the water catchment surface area;

AvgRain is the amount of precipitation per area unit and per time unit.

The model also considers water evaporation from the reservoir surface; in the scheme this flow is designated as Qevap and could be calculated as:

$$Q_{evap} = W * D_{surf}, \quad (3)$$

where W is the evaporation rate.

Empirical formulas were most widely used in assessing evaporation from unexplored lakes and reservoirs; such formulas were based on using the standard observations data obtained from a network of meteorological stations located on land accompanied by subsequent recalculation of hydrometeorological elements for the water surface conditions. Among such formulas, the SHI one became extremely popular, when assessing evaporation from water basins during warm periods:

$$E = 0{,}14n(e_0 - e_2)(1 + 0{,}72v_2) \quad (4)$$

where n is the calculation period;

e0 is the average value of the maximum water vapor pressure above the water surface determined from the water surface temperature (mbar);

e2 is the average value of the water vapor pressure (absolute air humidity) above the water basin at a height of 2 m (mbar);

v2 is the average daily wind speed (m/sec).

Comparison of the daily evaporation amounts calculated in accordance with this formula with the measured amounts demonstrated that the average error constituted 13.5% and in 75% of cases it did not exceed 8 - 10%. The maximum error values reached 25 - 30%, they were referred to the arid regions and were bearing a negative mark.

As evaporation is offering relatively small contribution to the overall water exchange in the reservoir, the error would produce a very insignificant effect upon the result, which allows us to adopt this formula for further calculation.

The initial water level in the reservoir is equal to the normal headwater level (NHL), which appears to be the desired level and is set in Des_Volume. The difference between the available and expected volumes of water in relation to the expected volume in Differ element is calculated using the following formula:

$$Differ = \frac{|Dam - Des_Volume|}{Des_Volume} \quad (5)$$

Water discharge from the reservoir occurs only, when the required water volume in the reservoir is available and is calculated in the Release element according to the following condition:

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$$MIN\left(\frac{Dam}{Timestep}, QPower + QIrrigation + QUsers + Qbypass\right) \quad (6)$$

where QPower is the water flow directed to the electricity production;

QIrrigation is the water flow spent to meet the agricultural needs;

QUsers is the water flow consumed for domestic needs;

Qbypass is the water flow discharged to the downstream bypassing the turbines.

QIrrigation, QUsers and QPower values are defined as a range of values that cover the needs of water consumption.

The revenue resulting from the electricity production is calculated in the Revenues element; and it further stored in the Earnings element:

$$Revenues = EnergyCost * QPower \quad (7)$$

where EnergyCost is the cost of electricity produced from the 1 m3/sec flow.

As of today, we do not possess efficient and economical methods for storing the generated electricity, that is why, we limit the production to a certain value indicated in the Des_Revenues element. In the Yield element, we constantly compare the revenue derived from the generated electricity with the expected income:

$$Yield = \frac{Earnings}{Des_Revenues} \quad (8)$$

where Earnings is the received profit;

Des_Revenues is the expected income.

In case the water inflow into the reservoir proves to be so great that after covering all the needs there still a remaining surplus, which accumulation leads to exceeding the permissible level, an emergency discharge passing by the turbines shall be involved, i.e. the bypass. Below you could find the formula illustrating the said condition:

$$if\ (Dam \geq DesVolume, (InFlow + Qrain - Qevap - QIrrigation - QUsers - QPower) + ByPass) \quad (9)$$

The water flow passing to the tail-water is calculated in the Qout element using the following formula:

$$Qout = Release - QUsers - QIrrigation \quad (10)$$

In this work above, we stated that the safety and security criterion should become one of the criteria required for the reservoir integrated management and control, that is why, we introduced the Ist_Flooded_water element in this scheme, which determines the amount of water that left the channel. It works according to the following condition:

$$MAX(0, Qout - Max_for_floods) \quad (11)$$

where Max_for_floods is the maximum permissible water flow in the channel that does not cause damage to the environment.

Normalization of the value of the aggregate volume of water released to the flood plain is performed in the FloodRatio element:

$$FloodRatio = \frac{TotalFloodedWater}{TotalFlodableWater} \quad (12)$$

TotalFloodedWater is the total amount of water that went beyond the channel (gone to flood) covering the entire period of time;

TotalFlodableWater is the estimated aggregated critical amount of water in the channel covering the entire period of time, which excess leads to floods.

A. Model optimization

Optimization models provide a means of reducing the number of alternatives which need to be simulated in detail, i.e., screening them. These models search the space of possible design variable values and identify an optimal design and/or operating policy for a given system design objective and set of constraints (Loucks, Stedinger and Haith, 1981).

At the given stage of the model construction, the dam management and control process optimization is carried out following the 3 criteria: maintaining the normal headwater level in the reservoir, increasing profits from electricity generation and minimizing floods.

1) Maintaining the normal headwater level in the reservoir to avoid the bowl overflowing (and, as a consequence, collapse of the dam) and shallowing, which could lead to the disruption of the household and agricultural supply operation, local biocenosis, etc. In the given model, this condition is presented as minimizing the difference between the expected and available water levels in the reservoir:

$$Differ = \frac{Dam - Des_Volume}{Des_Volume} \rightarrow min \quad (13)$$

2) At the present stage, our model does not include a system of electricity consumption and storage, that is why, our task is to generate the greatest income, and the value of the expected profit is used for the normalization purpose:

$$Yield = \frac{Earning}{DesRevenues} \rightarrow max \quad (14)$$

3) The task of minimizing floods under this model is solved by limiting the discharged flow from the reservoir:

$$FloodRatio = \frac{TotalFloodedWater}{TotalFloodableWater} = \frac{Qout - Max_for_floods}{Max_for_floods} = \frac{Qout}{Max_for_floods} - 1 \rightarrow min \quad (15)$$

4 parameters are set in the model, by varying which in the given range of satisfying values, we could find the optimal solution:

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1) Domestic needs expenditures
2) Agricultural needs expenditures
3) Electricity generation flow
4) Bypass flow

B Sensitivity analysis

In order to analyze how sensitive the developed model is to variations in the assumptions that were made for it a sensitivity analysis has been carried out. It allows to understand what assumptions have the highest influence on the model. Among various assumptions have been selected any inflows from balance equation (1), such as incoming flow, evaporation, underground water, irrigation discharge, household water, discharge for energy production, discharge through bypass, discharge from reservoir. To perform the sensitivity analysis any of these may be set within a fixed, normal, truncated normal, uniform, triangular or exponential distribution with an expected value and a standard deviation.

The possible decisions are set in a way to fulfill all requirements for all stakeholders of the river systems, i.e. minimum possible and maximum water supplied for household usage, power production, irrigation and water bypass.

The chosen objectives assure high performance of the systems and were chosen according to the equations 13-15. For objectives estimation a confidence level calculation was chosen. In this case a percentage of runs fulfilling each objective's target is calculated. This percentage is in turn compared to the confidence level for the objective, and a deviation is calculated.

The sensitivity analysis is performed as a combination of the optimization (evolutionary search) method and the risk analysis (Latin Hypercube) method to find the optimal decisions. As a result, optimized values for FloodRatio, Yield, and Differ is calculated for a given range of various assumptions.

Repeating the abovementioned procedure for various possible inflow ranges results in a thorough walk-through model verification.

V. Results

The developed model allowed to perform determining the optimal operating policy for a system of reservoirs from the point of view of water resources planning and management. In particular, it was performed model optimisation, and walk-through validation. It resulted in a number of runs with various input data relevant for different modelled water systems with an outcome of a preferable system management.

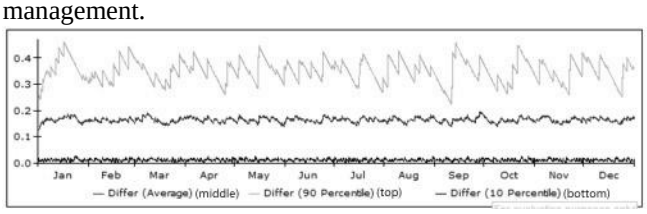

Fig. 4. Optimized operation policy for the water management in reservoir system for low rain period.

For this a set of criteria is evaluated and presented their optimal values range. The model provides us with a range of values for a Differ ratio, that describes the current and expected water volume in the reservoirs, Yield ratio that describes the power production revenue, and FloodRatio that characterizes flood occurrence. Each of these values are provided as a range with an average, confidence interval and percentiles (5, 10, 25, 75, 90 or 95%) upon demand. Modelling term can be selected from a range of 1 to 25 years. Fig. 4 and 5 present results of one of such runs with a certain given inflow that correspond to a low rain period. The incoming flow was set to 6000 m3/s with standard deviation 4000 m3/s, lower minimum 1000 m3/s and maximum limit 14000 m3/s. The underground flow was set to 500 m3/s with standard deviation 400 m3/s, and maximum limit 1500 m3/s.

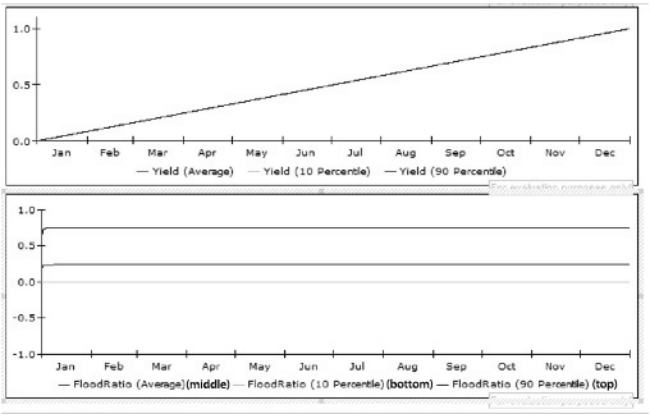

Fig. 5. Obtained reservoir system operation objectives at optimal water management policy for low rain period.

In order to simulate a system of several reservoirs a model presented on Fig. 3 was continuously repeated to achieve the required number of segments in the river with specific parameters for each segment until the necessary number of segments was reached. It may be seen that with the suggested operation policy provided at Fig. 4 the flood will not occur in the area at any case as the Flood ratio will not exceed one, while the revenue from power production (Yield) will achieve its maximum possible value within one year (Fig. 5).

If the inflows are changed to the values that characterize heavy rain period (see Fig. 6), even the optimal operation policy will result in the high flood probability. The incoming flow was set to 16000 m3/s with standard deviation 5000 m3/s, lower minimum 1000 m3/s and maximum limit 25000 m3/s. The underground flow was set to 2000 m3/s with standard deviation 100 m3/s, and maximum limit 6000 m3/s. The evaporation was set to 2000 m3/s with standard deviation 200 m3/s, and maximum limit 4000 m3/s.

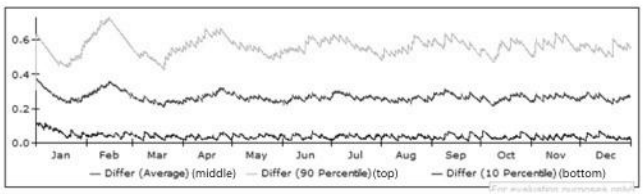

Fig. 6. Optimized operation policy for the water management in reservoir system for heavy rain period.

The results are presented on Fig. 7. It may be seen that the probability of flood non-occurrence is less than 15%.

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However, this would be the flood with the lowest possible water level increase and, hence, damages incurred. Meanwhile, the power production remains to maintain at its optimal value.

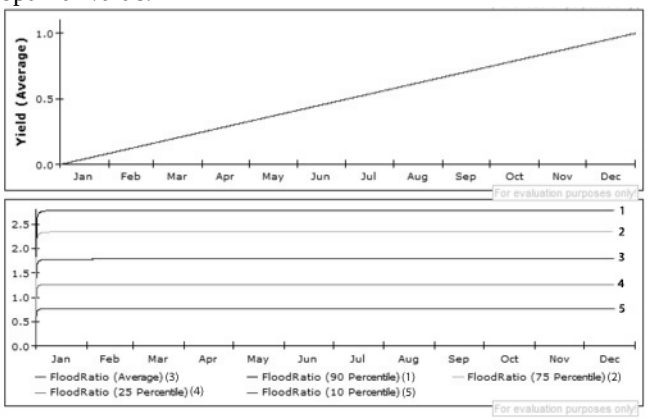

Fig. 7. Obtained reservoir system operation objectives at optimal water management policy for heavy rain period.

Furthermore, the inflow values were set for an average range, that corresponds to the moderate weather conditions (see Fig. 8). The incoming flow was set to 9000 m3/s with standard deviation 5000 m3/s, lower minimum 1000 m3/s and maximum limit 19000 m3/s. The underground flow was set to 1000 m3/s with standard deviation 500 m3/s, and maximum limit 3000 m3/s. The evaporation was set to 400 m3/s with standard deviation 100 m3/s, and maximum limit 1000 m3/s.

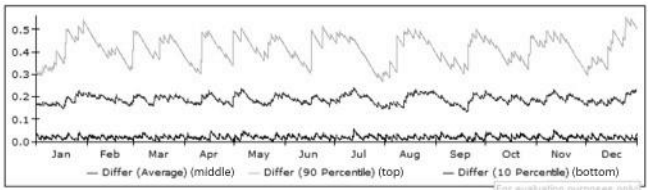

Fig. 8. Optimized operation policy for the water management in reservoir system for moderate rain period.

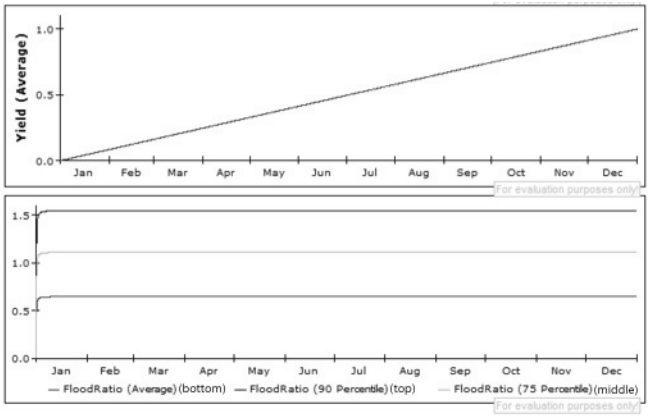

Fig. 9. Obtained reservoir system operation objectives at optimal water management policy for moderate rain period.

This resulted in a FloodRatio average close to 0,65. And only 70 percentile of floods has exceeded the critical value and resulted in flood event. Power production has also remained to maintain at its optimal value. Results were obtained after an extensive simulation campaign based on the minimization of the experimental errors as in Cassettari et al. (2009).

VI. Conclusions

The proposed model allows to perform simulation of water drainage policy for a tandem of reservoirs at the complex river system. This model has been verified on a walk-through basis. It resulted in high reliability disregards broad possible variations of the managed parameters: in all cases it has produced a stable result, that was consisting of an optimal water reservoir operation policy with the desired criteria set before, such as ratio of current and expected water volume in the reservoirs, highest possible power production revenue, and minimal possible flood occurrence.

However, in the future developments this model will be thoroughly verified for its sustainability and the data obtained will be compared to the real data of various water systems with the help of RSM as in Cassettari et al. (2013).

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