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Optimal Flood Control during La Niña Phenomenon using a Chain of Hydroelectric Reservoirs

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Abstract

This paper presents a flow control model applied on a chain of hydroelectric reservoirs to mitigate the impacts of floods. The objective function consists on maximizing the incomes of the generators subject to a set of equations that minimize the risk of floods downstream the reservoirs. The validation of the proposed model is performed using the technical parameters of two reservoirs operating in parallel in Colombia, south America. It was found that guaranteeing high levels of reliability in the flood control zone results in less profits for the generators. This model can be used to provide signals to the system planner and regulator to design proper incentives or compensations for those generators that are able to exercise flood control at the expense of lower profits.

Keywords*:* Flood control, multipurpose reservoirs, optimization.

INTRODUCTION

Weather phenomena such as *El Niño* and *La Niña* are characterized by irregularly periodic variations in winds and sea surface temperatures that cause raining lack and raining excess, respectively. These phenomena affect several tropical and subtropical countries causing droughts and floods. In this context, governments have developed strategies to mitigate the effects of *El Niño* and *La Niña*. Such strategies include building retaining walls and dams, improving drainage systems and adequate management of reservoirs for flood control.

There are several studies reported in the specialized literature regarding adequate management of reservoirs for flood control around the world. In [1] the authors analyze the ecological benefits of Longyangxia and Liujiaxia reservoirs on Yellow River in China making emphasis on flood control. In [2] an optimal operation scheme of reservoirs for flood control, based on real-time information and forecasts is proposed for the Three Gorges project. In [3] a flood control model is proposed for rainy seasons, applying a reliability and risk analysis based on the hydrological forecasts also for the Three Gorges project.

In Mozambique, flood control was proposed using a hydroelectric dam to mitigate social impacts. The authors modeled the trade-offs between hydropower generation and environmental flow scenarios [4]. In this context, the water availability for generating environmental flow and improving hydrological conditions is constrained by water demand for guaranteeing energy supply to electricity users. In Vietnam, the operation of a reservoir based on several guide curves was proposed for the Red River depending on the level of criticality [5]. In Malaysia, the operation of coordinated cascade reservoirs was proposed by means of guide curves, in order to maximize the annual storage potential [6]. In Canada, the flood control of a reservoir was approached considering the impact of the basin downstream of the hydropower plant due to discharges according to weather stations [7]. A state of the art describing several models and optimization techniques used for the optimal coordination and operation of reservoirs is presented in [8].

Colombia is a Latin American country largely affected by weather phenomena such as *El Niño* and *La Niña*. The effects of these phenomena tend to have a higher impact on the population with less economic resources that build their houses near river basins. This is further aggravated by the fact that nearly 70% of the electricity generation is provided by large hydropower plants [9].

The rainy season experienced in Colombia between 2010 and 2012, is considered by experts as the most devastating of the last 40 years and has been an important opportunity to reflect on the country's response capacity to natural disasters to which it is exposed. According to data from the Risk Management Department of the Ministry of the Interior and Justice, the 2010 rainy season was experienced in around 60% of the Colombian territory and more than 2.4 million people were affected [10]. In 2017, alerts were activated again for possible floods, since one third of the country's generation reservoirs had reached their maximum capacity [11]. This situation has generated concern in the public administration that aim to protect settlers, ranchers and farmers located downstream the generation plants. In this context, several studies have been conducted regarding the proper management of hydroelectric power plants in Colombia such as the ones reported in [9], [12] and [13].

This paper presents a mathematical model that allows the coordination of the operation of two reservoirs in parallel, in order to obtain an optimal balance between energy generation and flood control, avoiding unnecessary water discharges and monitoring a flood control zone downstream the reservoirs with the aim of minimizing the socio-environmental risks associated with floods. Several simulations were conducted using real data of two major reservoirs in Colombia for different hydrological conditions.

MATHEMATICAL MODELING

The objective function of the proposed model is given by equation (1), which seeks to maximize the profits of generators through energy sales. The objective function is composed of two terms, the first one corresponds to the maximization of income from energy sales and the second is a penalty for spilling water. In this case *m* and *n* correspond to the number of reservoirs and days, respectively. P_{ij} and G_{ij} are the average daily energy price and energy generated by reservoir *i* in day *j*, respectively. $V_{V_{ij}}$ is the volume of water spillage of reservoir *i* in day *j*; V_{Inu_j} is the volume of water above the maximum volume in the flood control zone (FCZ) in day j. $Pen_{v_{ij}}$ and Pen_{inu_j} are the penalization for spillage of reservoir *i* in day *j* and flood penalization in the FCZ in day *j*, respectively.

The reservoirs operation is restricted by a set of constraints given by (2)-(7) in which lower indexes *min* and *max* indicate the minimum and maximum limits of the corresponding variable, respectively. Equations (2) indicates the limits of the volume of discharge of reservoir *i* (V_{G_i}) through the generation ducts. $V_{E_{ij}}$ corresponds to the total volume of reservoir *i* in day *j* and its limits are expressed in (3). Equation (4) indicates the volume limit in the FCZ in each time interval. This limit is set in such a way that floods are avoided in this zone. Equation (5) represents the volume balance of each reservoir taking into account inputs and outputs (see Figure 1). In this case V_{Q_i} is the volume of water provided by the basin of reservoir *i*. Equation (6) indicates the generation conversion factor where CF_i is the conversion factor of reservoir *i*; finally, equation (7) represents the total volume in the FCZ for day *j* (V_{FCZ_j}) where V_{Qext_j} is the volume of water provided by an external river in day *j*.

$$Max \sum_{j=1}^{m}\left(\sum_{i=1}^{n} P_{ij} * G_{ij} - V_{V_{ij}} * Pen_{v_{ij}}\right) - V_{Inu_j} * Pen_{inu_j} \quad (1)$$

Subject to

$$V_{G_{i_{min}}} \leq V_{G_i} \leq V_{G_{i_{máx}}} \quad (2)$$

$$V_{E_{i_{min}}} \leq V_{E_{ij}} \leq V_{E_{i_{máx}}} \quad (3)$$

$$V_{FCZ_j} - V_{Inu_j} \leq V_{ZC_{máx}} \quad (4)$$

$$V_{E_i} = V_{E_{ij-1}} + V_{Q_i} - V_{G_i} - V_{EF_i} - V_{V_i} \quad (5)$$

$$G_i = V_{G_i} * CF_i \quad (6)$$

$$V_{FCZ_j} = \sum_{i=1}^{n}\left(V_{G_{ij}} + V_{V_{ij}}\right) + V_{Qext_j} \quad (7)$$

Although the model proposed in (1)-(7) is generalized for any number of reservoirs, the analysis in this paper is performed for two reservoirs operating in parallel as illustrated in Figure 1. The parameters used in the simulations for reservoirs 1 and 2, labeled as R1 and R1, respectively are indicated in Table 1. For all simulations the maximum volume in the FCZ is considered to be 20 Mm3.

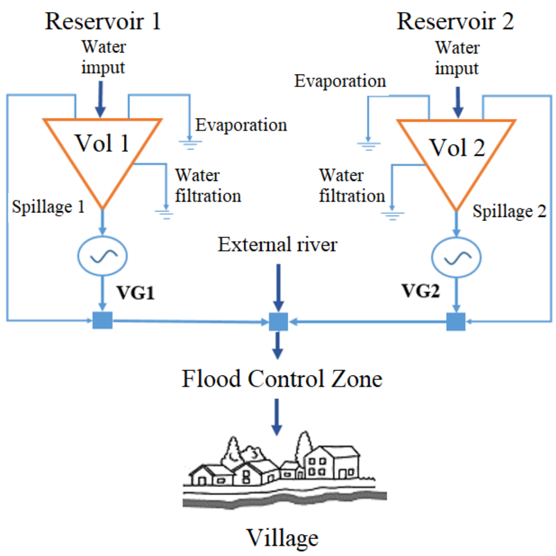

Figure 1. Illustration of water flows for two reservoirs operating in parallel

Table 1. Parameters used in simulations for reservoir 1 (R1) and reservoir 2 (R2).

Parameter	R1	R2
Minimum Volume (Mm3)	17.71	23.30
Maximum Volume (Mm3)	782.05	610.89
Conversion Factor (MW/Mm3/s)	2711.25	1945.89
Max discharge volume (Mm3/day)	10.62	12.33
Max discharge capacity (MWh/day)	28799	24000
Max spillage volume (Mm3/day)	362.88	864
Min discharge volume (Mm3/day)	0.53	0.12
Min generation capacity (MW)	60	10
Min generation capacity (MWh/day)	1439.67	239.34
Max generation capacity (MW)	1200	1000
Max generation capacity (MWh/day)	28800	24000

TEST AND RESULTS

Several tests were performed to show the applicability of the proposed model. Historical flow series of the rivers associated with the reservoirs and technical parameters reported by the generators to the National Dispatch Center (see Table 1) were used in all simulations. Four simulations were performed for a high hydrology scenario (see Table 2) activating and deactivating penalizations for spillage and flood control in the FCZ as indicated in Table 3.

Table 2. Parameters for a high hydrology scenario

Parameter	Value
Average water flow reservoir 1 (m3/s)	258.86
Initial volume reservoir 1 (%)	50%
Maximum generation capacity reservoir 1 (GWh/day)	28.8
Average water flow reservoir 2 (m3/s)	305.73
Initial volume reservoir 2 (%)	50%
Maximum generation capacity reservoir 2 (GWh/day)	24
Average water flow from external river (m3/s)	0.4

Table 3. Active (ON) and inactive (OFF) penalizations for different simulations

Simulation	Spillage		Flood	
	ON	OFF	ON	OFF
1	x		x	
2	x			x
3		x	x	
4		x		x

Figure 1 and Figure 2 show the behavior of the energy generated in GWh / day for reservoirs 1 and 2, respectively. It is observed that when the penalties for spillage and flooding in the FCZ are active (simulations 1 and 3, respectively), the energy generated through reservoir 1 is reduced to adjust the maximum volume limit permitted in the FCZ.

Note that generation in reservoir 1 reduces in the days in which the average energy market price is lower and increases when the price increases. The direct proportionality between the average energy market price and the energy generated by the reservoir guarantees the maximization of the generator's income, while the restrictions for flood control in the FCZ are met.

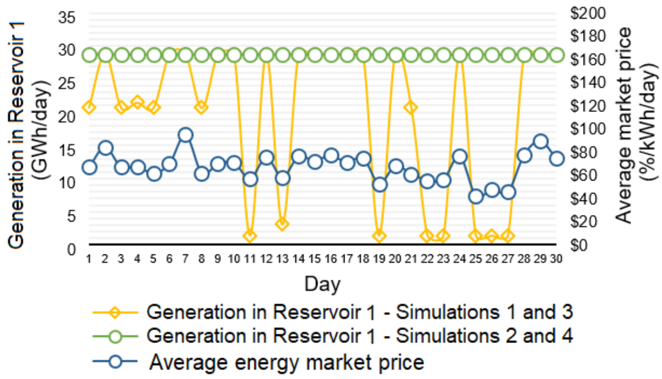

Figure 2. Generation of reservoir 1. High hydrology.

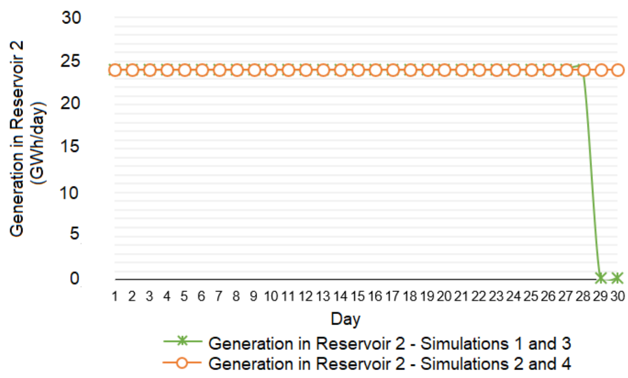

Figure 3. Generation of reservoir 2. High hydrology.

Reservoir 2 operates almost all the time at nominal capacity (see Figure 3), due to the fact that its storage capacity is lower than that of reservoir 1; therefore, the model forces the generator to produce the greatest amount of energy so as not to violate the restrictions for maximum storage capacity.

Figure 4 and Figure 5 show how the level of the reservoirs increases. Note that the volume of reservoir 1 increases for those simulations in which flooding of the FCZ is penalized (simulations 1 and 3). On the other hand, the volume of reservoir 2 is quite similar in the four simulations.

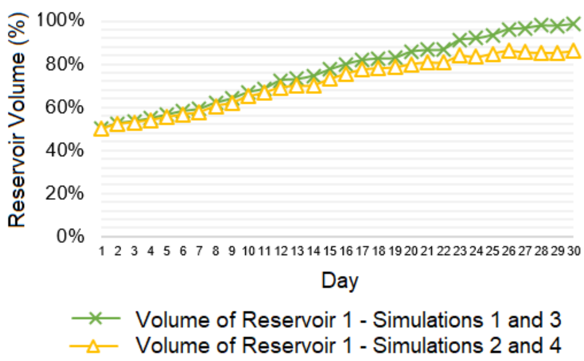

Figure 4. Volume of reservoir 1. High hydrology.

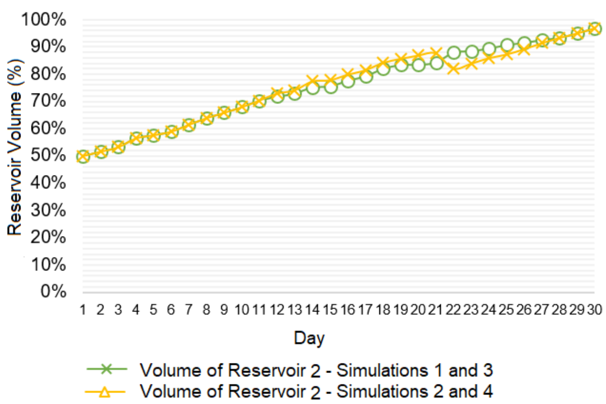

Figure 5. Volume of reservoir 2. High hydrology.

Figure 6 illustrates the spillage volume of reservoirs 1 and 2. Note that reservoir 2 spills water in day 21 which coincides with a small reduction in its volume as indicated in Figure 5.

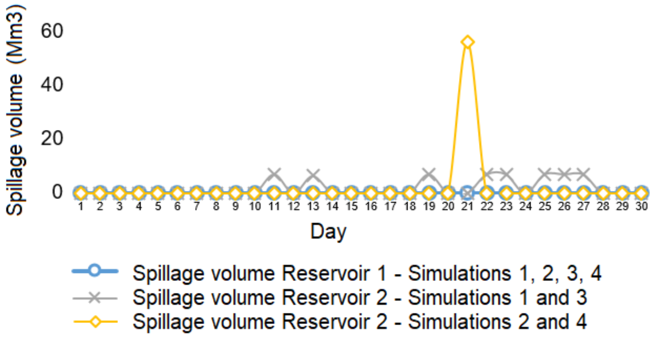

Figure 6. Spillage volume of reservoirs 1 and 2

Figure 7 indicates the water volume in the FCZ for all simulations. Note that in simulations 2 and 4 when no penalization is applied for flood control, the water flow in the FCZ largely exceeds its maximum in day 21.

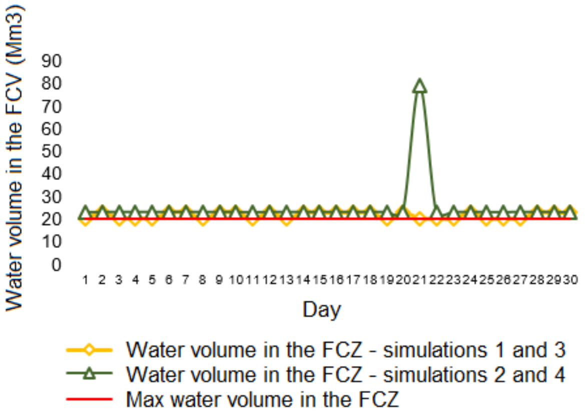

Figure 7. Water volume in the FCZ

Reliability in the FCZ is plotted in Figure 8. It can be seen that in none of the cases is it possible to obtain 100% reliability. This is because the simulated scenario considers the greater historical flows in the reservoirs analyzed. However unlikely, this scenario shows that keeping a high relativity in the FCZ (between 80 and 100%) is doable if a proper penalization is applied for flood control.

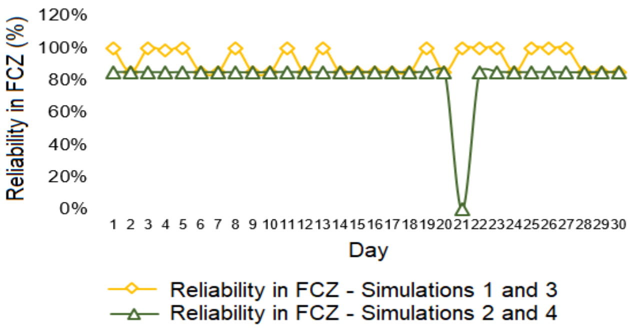

Figure 8. Reliability in the FCZ

Total incomes for energy sales for both reservoirs are depicted in Figure 9. Note that guaranteeing a high reliability in the FCZ represents an important reduction in income for both reservoirs. This result can be used as a sing for regulators when designing proper strategies to incentive generator able to provide flood control.

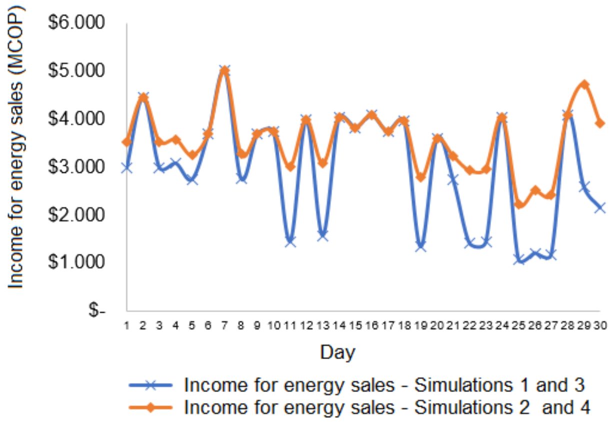

Figure 9. Total income from energy sales.

CONCLUSIONS

This paper presented a mathematical model for flood control applied to two reservoirs operating in parallel. The objective function considered in the study is the maximization of incomes obtained from energy sales for both reservoirs. Nevertheless, generators are penalized for spillage and for exceeding a given water volume in a flood control zone. Different simulations were performed for a high hydrology scenario activating and deactivating both penalizations. It was found that reliability in the flood control zone increases significantly when the corresponding penalty is considered. However, due to the high hydrology it is not possible to guarantee a 100% reliability in the flood control zone in all the time horizon. It was also found that high levels of reliability in the flood control zone are aligned with less income to generator owners due to energy sales of the reservoirs. This conflict of interests needs further and deeper analyses by generator and regulators in order to device proper strategies to incentive generators to exercise flood control when needed.

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REFERENCES

[1] H. Du y Z. Zhang, «Longyangxia and Liujiaxia Reservoirs Ecology Flood Compensation Benefits», IEEE 2012 World Autom. Congr., pp. 1-5, 2012.

[2] L. Guohua, W. Guoli, y X. Shufeng, «A Multi-reservoir Flood Operating System Based on Fuzzy Messages», 2009 Sixth Int. Conf. Fuzzy Syst. Knowl. Discov., pp. 22-28, 2009.

[3] X. Dong, J. Liu, Y. Li, H. Bo, y X. Deng, «Dynamic Application and Risk Analysis of Flood Control Water Level to the Three Gorges Reservoir by Utilizing Mid-Term Inflow Forecasts», Power Energy Eng. Conf. (APPEEC), 2010 Asia-Pacific, pp. 1-5, 2010

[4] R. Beilfuss, «Modelling trade-offs between hydropower generation and environmental flow scenarios: a case study of the Lower Zambezi River Basin, Mozambique», Int. J. River Basin Manag., vol. 8, n.o 3-4, pp. 331-347, 2010.

[5] L. Le Ngo, «Optimising reservoir operation. A case study of the Hoa Binh reservoir, Vietnam», Technical University of Denmark, 2006.

[6] T. Asfaw, K. Yusof, y A. Hashim, «Parameters Estimation and Rule Curve Development of Cascade Hydropower Reservoirs», Natl. Postgrad. Conf. (NPC), 2011, 2011.

[7] C. Fortier, A. Assani, M. Mesfioui, y A. Roy, «Comparison of The Interannual and Interdecadal Variability of Heavy Flood Characteristics Upstream and Downstream from Dams in Inversed Hydrologic Regime: Case Study of Matawin River (Québec, Canada) », River Res. Appl., vol. 27, n.o 10, pp. 1277-1289, 2011.

[9] V. H. Bedoya y J. López, «Optimal Flood Control with a Hydroelectric Reservoir: a Colombian Case Study», Transm. Distrib. Conf. Expo. - Lat. Am. (PES T&D-LA), 2014 IEEE PES, 2014.

[10] Organización Panamericana de la Salud, «El fenómeno de La Niña hizo estragos en Colombia», Disasters: Preparedness and Mitigation in the Americas, pp. 6-7, 2011.

[11] Economía y Negocios El Tiempo, «El 30,4 % de los embalses del país está al tope, según firma XM», 15 de mayo 2017, 2017. [En línea]. Disponible en: http://www.eltiempo.com/economia/sectores/embalses-en-colombia-estan-llenos-por-temporada-de-lluvias-88476.

[12] S. F. Rodríguez-Corso, «Simulación dinámica de inundaciones asumiendo un estado crítico de máxima escorrentía, bajo cinco periodos de retorno, en la Quebrada la Viergen del Municipio de San José de Miranda-Santander», Rev. UIS Ingenierías vol. 17, no. 1, pp. 251-270, Ene. 2018.

[13] D. M. Rey, J. del C. Zambrano, «Estudio de la respuesta hidrológica en la cuenca urbana de montaña San Luis-Palogrande. Rev. UIS Ingenierías vol. 17, no. 1, pp. 115-126, Ene. 2018.