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Optimal Flood Control of a Hydroelectric Reservoir: a Genetic Algorithm Approach

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***Abstract*--Raining season in Colombia has caused negative effects on inhabitants, infrastructure and economy. Additionally, hard to predict weather phenomena such as "La Niña" have worsened the consequences of raining season. The Colombian electrical infrastructure has several hydropower reservoirs, which optimum management of resources such as minimization of water spilling and prevention of flooding downstream would decrease the negative impact of raining season on inhabitants. The aim of this paper is to describe a didactic exercise in which flood control of a hydroelectric reservoir is performed by a genetic algorithm with local search. The proposed modeling was applied to a Colombian hydropower plant during "La Niña" phenomenon. The results show the management of the hydraulic resources and the economic impact for a hydropower plant due to flood control.**

***Index Terms*—Genetic algorithms, local search, flood control, reservoir.**

I. Introduction

WEATHER phenomena in Colombia such as "El Niño" and "La Niña", characterized by raining lack and raining excess respectively, have caused negative effects on inhabitants, infrastructure and economy.

Colombia supplies its electric load with hydraulic, thermal and wind power plants. The installed power capacity in 2013 is about 13.690 MW and it is composed by 68% hydraulic, 31% thermal and 1% other technologies power plants. The hydraulic power plants are composed by 21 reservoirs for power plants witch capacity is greater than 20 MW with a total capacity volume of 11.200 Mm^3.[1]

In Colombia there is a regulated electricity market with a dispatch granted by economic merit. Electricity market promotes competition among all power plants[2]. During dry season the market must increase the thermal generation to meet the expected load, but during rainy season the market increases the hydropower generation to avoid overflowing reservoirs due to raining excess.

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The consequences for Colombia caused by "La Niña" phenomenon during years 2010 and 2011 were devastating to the population and the economy. The World Bank estimated the economic losses in 8.6 billion of Colombian pesos and 2.2 million of people affected[3]. Phenomena of this magnitude require actions to mitigate the impact on the population and the economy.

This paper presents a didactic exercise that illustrates flood control with a hydroelectric reservoir. The objective of the paper is to perform the management of the hydraulic resources and to evaluate the economic impact of a hydropower plant due to flood control over dense populated areas. A genetic algorithm combined with a local search was implemented in order to perform such control.

II. Mathematical Formulation

A Basic model of a hydropower plant is composed by a reservoir, an inflow and an outflow. A reservoir system can be used for many activities such as hydropower generation, water supply, irrigation, upstream and downstream flood control, ecological issues and navigation control [4][5][6]. Figure 1 shows a basic model of a hydropower plant.

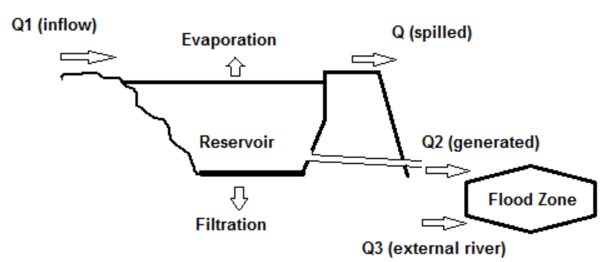

Figure 1. Basic model of a hydropower plant

Figure 1 depicts a reservoir system, with an inflow Q1, a reservoir, two outflows that represent water spill ($Q_{spilled}$) and water flow for hydropower generation (Q2), respectively, an external water flow (Q3), two imbalance flows (Evaporation and Filtration) and a flooding zone. In this case flood control is only necessary downstream and the reservoir is the main element for such control. The mass balance for a day of the reservoir system is shown in equation (1):

$$V(daily) = V_i + VQ_1 - VQ_2 - VQ_{spilled} - V_{Evap+filt} \quad (1)$$

Where:

V = Reservoir Volume at the end of the day.

V_i = Initial Volume at the beginning of the day.
VQ_1= Volume of Q_1 for a day.
VQ_2= Volume of Q_2 for a day.
$V_{Evap+filt}$= Volume of evaporation and filtration for a day.
$VQ_{spilled}$= Volume of $Q_{spilled}$ for a day.

In equation (1) only volumes VQ_2 and $VQ_{spilled}$ can be controlled by the reservoir. VQ_3 is an external flow that does not depend on the volume management of the dam. $V_{Evap+filt}$ is obtained with the average evaporation in the study zone and the average filtration in the reservoir for a day. Both values depend on the superficial area and the volume in the reservoir, respectively.

The system shown in Figure 1 must account for the constraints represented in equations (2)-(5):

$$VQ_{2\ min} \leq VQ_2 \leq VQ_{2\ max} \ (2)$$
$$V_{min} \leq V \leq V_{max} \ (3)$$
$$Q_{Floodzone} = Q_2 + Q_3 + Q_{spilled} \ (4)$$
$$Q_{Flood\ zone} \leq Q_{Max\_Flood\_zone} \ (5)$$

Equation (2) stands for the minimum and maximum limits of water flow due to hydropower generation; equation (3) represents the limits of the reservoir's net volume; equation (4) stands for the balance of water inflow in the flood zone and equation (5) allows performing flood control by limiting the water inflow in the flood zone. In this case $Q_{Max\_Flood\_zone}$ is the maximum flow level that can pass through the populated area without causing inundation.

III. Genetic Algorithm Structure

A Genetic Algorithm (GA) is a metaheuristic technique inspired in the natural process of evolution. The GA is started with a set of randomly generated solutions. This set of solutions is also called population. Every individual of the population is represented by a string of binary numbers (known as chromosome). Solutions from one population are taken and used to form a new population. For this, the individuals must go through a set of steps known as selection, recombination and mutation.

In the selection process the fittest individuals are chosen to generate new individuals. Such selection is performed by tournament. Then, new individuals are created by a process called recombination. In this step two strings are combined in a randomly selected point to generate two new individuals (offspring). Once the offspring is generated the new solutions must go through the mutation step. In this step a small change in the string (changing one to zero or vice versa) is performed with a given probability. In addition to the common GA operators a local search was implemented. The local search is performed in every iteration in order to find better solutions and escape from locally optimal solutions. The main objective is to find the optimal dispatch for every day in Mm^3 avoiding spill flow and downstream flooding through penalties in the objective function. The algorithm structure is shown in Figure 2.

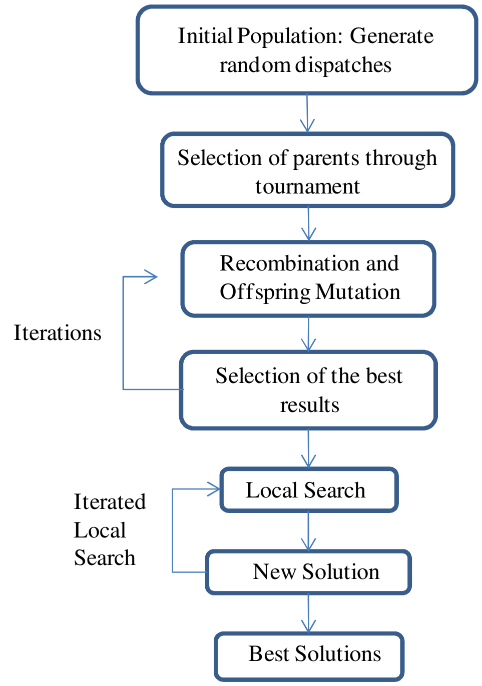

Figure 2.Genetic Algorithm Structure

The Genetic Algorithm uses as objective function the monetary profit maximization of the hydropower plant. The algorithm was implemented for modeling a deterministic case.

IV. Study Case

A Colombian hydropower plant was taken to evaluate the performance of the GA illustrated in Figure 2. The principal characteristics of the plant are shown in Table 1.

TABLE I
Principal characteristics of the hydropower plant [1]

Description	Value
Maximum Reservoir Volume [Mm3]	1863,54
Minimum Reservoir Volume [Mm3]	358,97
Maximum Volume by Power Generation for a day [Mm3]	60,48
Minimum Volume by Power Generation for a day [Mm3]	6,48
Maximum Reservoir Height [m.o.s.l]	130,5
Maximum Volume of discharge by controlled spilling for a day [Mm3]	820,8
Total Reservoir Area [Km2]	77

Figure 3 shows the real situation in the year 2010 during the phenomenon of “La Niña” in Colombia, when the hydropower plant lost its ability to perform water control using its spiller and the capacity for performing flood control[7].

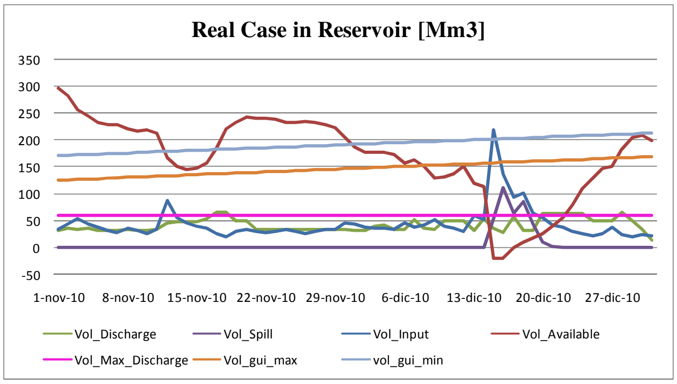

Figure 3. Real Case year 2010

Figure 3 shows the available reservoir's volume for two months. *Vol_gui_min* and *Vol_gui_max* are the minimum and maximum rule curves for reservoir operation respectively. In figure 3 *Vol_gui_max* is located below *Vol_gui_min* because both values were obtained for the available reservoir's volume. The rule curves are an indicative signal to the reservoir operation in real time. The *Vol_Input* curve is the real input of water flow obtained for a day. *Vol_Discharge* curve is the real water flow discharged by power generation for a day. *Vol_Spill* is the real water flow discharge by spilling for a day.

The rule curves have multiple purposes for the reservoir operation constrained by the environmental license[8]. The minimum rule curve has several environment objectives to achieve such as: maintaining the historical river level to avoid severe changes in the ecosystem, supply the aqueducts and maintaining the river navigability. The maximum rule curve is the one that is responsible for downstream flood control. Figure 3 shows that the upper and lower rule curves are very close, which results in a small operation margin for the reservoir.

During the months of November and December, the reservoir was operating in the vicinity of the range between both rule curves, but the operation strategy was not enough to dam the inflow. The importance to maintain the control of the inflow is to avoid uncontrollable downstream over flows that can affect populated areas.

The model performed by the algorithm proposes an external variable to complement the reservoir system for flood control. That variable must contain the information about the external input water flow to the flood zone as shown in Figure 1 (Q_3). The model contains the same variables, parameters and rule curves as the real case, additional is included VQ_3 curve.

The Genetic Algorithm uses as objective function the monetary profit maximization of the hydropower plant. The algorithm penalizes the objective function when there are the following deviations:

- Reservoir operation out of the rule curves range.
- Spilling of water.
- Flood in flood zone control (populated area to be protected).

The objective function is shown in equation (7)

$$Max \sum_{i=1}^{N\_days} \begin{pmatrix} C_i * CF_i * Vol\_Discharge_i - Vol\_spill_i * Pen\_spill \\ -Vol\_curve_i * pen\_curve - Vol_{flood_i} * pen\_flood \end{pmatrix} \quad (7)$$

Where:

C_i= Cost of the Energy [COP/GWhD]
CF_i= Factor of conversion [GWhD/Mm^3]
Pen_spill= Penalty for spill water [COP/Mm^3]
Pen_curve= Penalty for each Mm^3 outrange of the rule curves [COP/Mm^3]
Pen_flood= Penalty for flood in the flood zone control [COP/Mm^3]
COP= Colombian Pesos.

Figure 4 shows the results obtained using the proposed model. The available volume is located out of the rule curves range due to the fact that the reservoir is preparing its capacity to avoid spilling. It is worth to mention that the rule curves are only a guide for the reservoir operation, they are not obligatory to be followed by the hydropower plant. That means, that the rule curves do not represent a real physical constrain for the reservoir system, rather, the rule curves are just a guide.

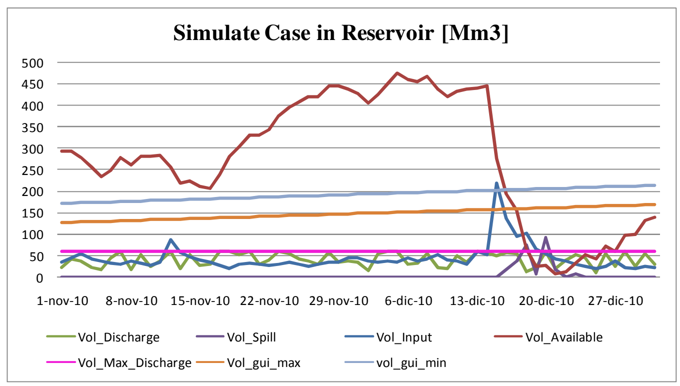

Figure 4. Simulated Case avoiding spill flow

The phenomenon of "La Niña" in Colombia produces raining excess in much of the country[9][10], for that reason, the reservoir systems must be prepared in advance for severe changes in the pattern of the input water flow. Figure 4 shows that the available volume is not located into the range between the rule curves.

During the phenomenon of "La Niña", flood control must be a priority for the reservoir system. In the case study, the volume VQ_3 is not controlled by the reservoir, but the volumes VQ_2 and VQ_{spill} are the complement for the $Q_{Flood\ Zone}$ as shownin equation (8).

$$VQ_{Flood\ zone} = VQ_2 + VQ_{spill} + VQ_3 \quad (8)$$

Figure 5 shows the situation when the reservoir is controlling $VQ_2$and VQ_{spill} for avoiding flood in the study zone.

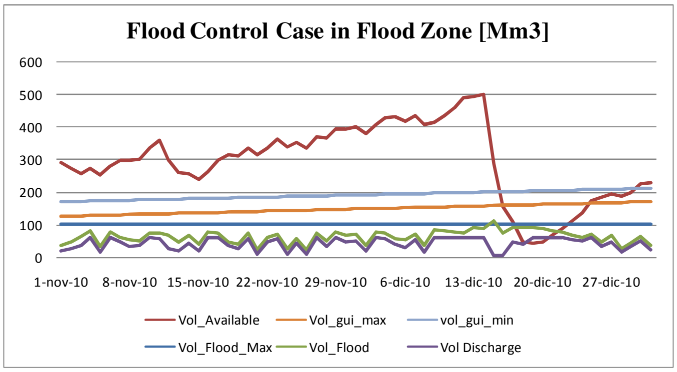

Figure 5.Flood control in the flood control zone

Vol_Flood_Max is the maximum volume allowed in the zone of flood control for a day, and *Vol_Flood* is the flow in such zone. Figure 5 shows that the reservoir discharge depends on the flow by the flood zone.

The model associates a cost to the reservoir operation for the monetary profit maximization. Figure 6 shows the percentage of benefit received by the hydropower plant with and without external variables to flood control.

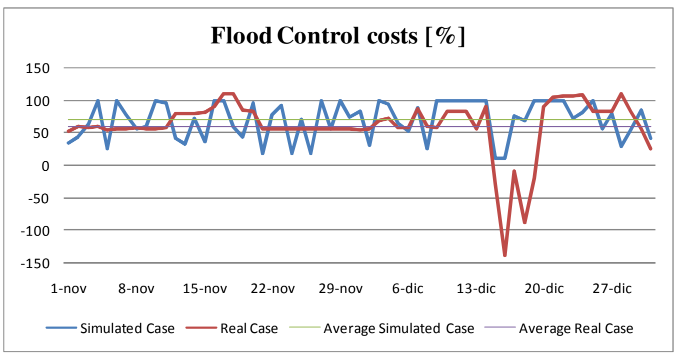

Figure 6. Flood control costs.

In the real case the cost was impacted by the spilling as a lost opportunity to generate electric power. The flood control produces a variation around the range between the rule curves, for that reason, the profit is not uniform. However, in the long term the averages are similar, but certainly it could not be said if the profit for both cases would be the same. It poses a new challenge regarding which economic approach model to follow in case the profit of the power plant is lower due to flood control. In order to turn the flood control as an economically feasible option, the economic benefit value generated by the plant when it is controlling floods should be estimated as the economic value of the avoided losses and damages.

V. Conclusions

The phenomenon of "La Niña" in Colombia produces raining excess in much of the country, for that reason, the reservoir systems must be prepared to perform changes in the pattern of the input water flow.

This study shows that food control during the phenomenon of "La Niña" is feasible, and could be implemented in the near future. Several benefits could be achieved by flood control, the main of which is the protection of the downstream population.

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This work is the initial effort of an ambitious project that aims to develop hydro-meteorological models able to predict and give operational tools to face the phenomenon of "La Niña" in Colombia. Such models would be used in order to mitigate negative effects in infrastructure and inhabitants without causing a major impact on the economic performance of the Colombian energy market.

VI. References

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VII. Biographies

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