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Application of adaptive time delay model in optimal control of a hydropower cascade

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Abstract

Small hydropower plants (SHP) are increasingly constructed in recent years as a substitution of the use of conventional energy materials such as wood and fossil fuel in remote rural regions. Besides new constructed plants, upgrading operational strategies of existed systems for increasing electricity productivity is also significant. Motivated by this issue, a combination of two techniques, simulation and optimization based on models is frequently used to improve the operation regimes of coordinated reservoir cascades. However, the application of a complex hydraulic model consumes a huge computation time. Hence, this paper proposes a replacement for the complex hydraulic model by an adaptive time delay (ATD) model. The cutting- edge point is that the ATD model is able to quickly predict the system dynamics both in simulation and optimization. This ATD model consists of only two parameters: time constant and time delay which are functions of unsteady flow and can be easily derived from complex hydraulic models (HECRAS, MIKE11), or from physical parameters of rivers (flow rate, roughness, bed slope, cross section). The integration of the ATD model into the simulation and optimization techniques will be demonstrated by a case study of a cascade of SHPs. In terms of optimization, a non-linear constrainted optimization algorithm is applied to improve electricity production to meet the scheduled demand.

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Keywords: small hydropower plant; water storage; adaptive time delay model; simulation; optimization

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1. Introduction

Over the past decade, a tendency for supplementing and replacing conventional fossil sources for electricity generation by renewable sources has been substantially exerted because of the scarcity and limitation of fossil energy. Although the natural replenishment of these sources for renewable electricity is well known, an efficient manner in using this energy is always essential. Hydropower is one of the viable option for sustainable energy production. However, operation and management of hydropower systems is a challenging issue for decision makers and operators. The reasons are conflicts among stakeholders (electricity, flood protection, agriculture, industry, and others) as well as the uncertain nature of reservoir inflow that adds considerably to complexity of the system [1-3]. Popular powerful techniques for hydropower analysis are simulation and optimization. Models represent the system attributes and predict the system responses under different conditions. A set of operating rules are developed and continuously improved in order to determine an acceptable release of reservoirs. On the other hand, the optimization that focuses on identifying optimal decision variables is based on mathematical formulation for maximizing or minimizing an objective function subject to constraints [4]. In fact, the optimization models for hydropower systems are applied for different operation period such as seasonal operation, daily, hourly, or event-based real-time regulation. Moreover, its applicability is not only for an individual hydropower plant, but also for cascade of hydropower plants that improves significantly electrical productivity. A large number of optimization approaches for dam optimal control exists, e.g., linear programming (LP), nonlinear programming (NLP), dynamic programming (DP), genetic algorithm (GA), and have been applied since years [5-9].

The paper introduces a new approach that combines an adaptive time delay model and reservoir model for simulation, and then applies nonlinear constrainted programming to achieve an optimal regulation for enhancing the electricity generation of a cascade of hydropower plants. The integration of adaptive time delay river dynamics into the optimization is considered as an innovation in this paper.

2. Methodology

The method consists of two components: simulation and optimization. In terms of simulation, the dynamic of system is shown by reservoir model and flow routing model (ATD). In which, the ATD model transfers the releases from upstream reservoir to downstream reservoir while reservoir model simulates behaviours of dams. Regarding optimization, nonlinear programming technique is applied to determine the best release of the cascade by which the electricity production will meet the objective. For illustration, a case study of a cascade with two hydropower plants is selected in order to compare an energy production of an optimized operation and existing operation. The objective of this study is to present a new method that may be applied to improve the electricity production of hydropower cascades. The system is a combination of an ATD model and a reservoir model and is presented in Fig. 1 and Equation 1, 2, and 3.

$$\frac{dV^u}{dt}=Q^u_{in}-Q^u_{out} \tag{1}$$

$$\begin{cases} T_c\dfrac{dq}{dt}+q(t)=Q^u_{out}(t) \\ Q^d_{in}(t)=q(t-T_d) \end{cases} \tag{2}$$

$$\frac{dV^d}{dt}=Q^d_{in}-Q^d_{out} \tag{3}$$

Where $Q^u_{in}(t)$ is inflow of upstream reservoir, $Q^u_{out}(t)$ is discharge of upstream reservoir, $Q^d_{in}(t)$ is inflow of downstream reservoir, is discharge of downstream reservoir, $V^u(t)$ is storage of upstream reservoir, $V^d(t)$ is storage of downstream reservoir, T_c is the time constant, T_d is the time delay.

The Equations 1 and 3 are the reservoir models that ensure mass balance of dams while the ATD model in Equation 2 transfers discharges from upstream reservoir to downstream reservoir through a river reach between two dams. This concept considers the dynamics of flow transfer in optimization that increase accuracy of the optimal result.

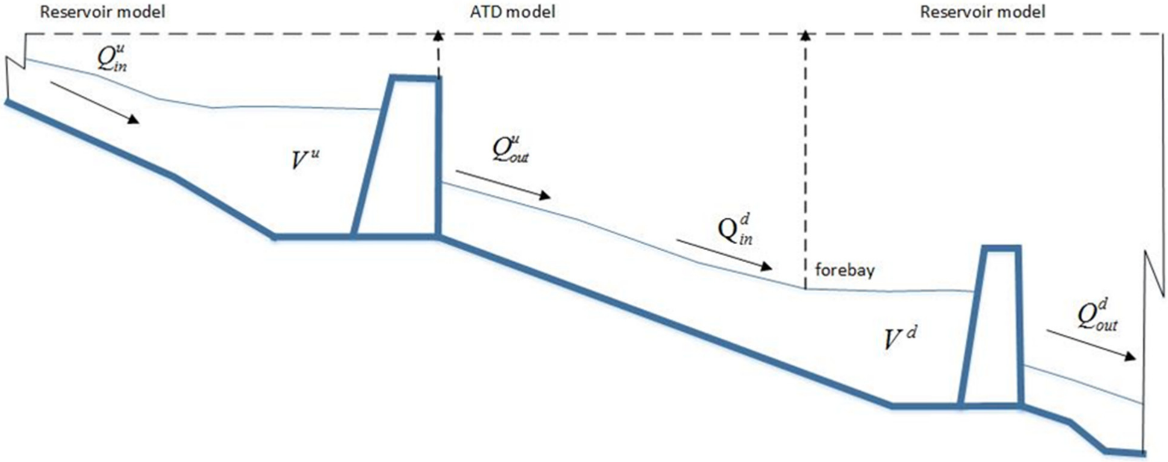

Fig. 1. Hydropower cascade

3. Case study

The study area is the Wuyang river, which is situated in the eastern part of Guizhou province in China and has a long and narrow basin. There are 16 hydropower stations constructed along the river mainstream. Among those stations, two reservoirs: Guanyinyan and Hongqi are selected in order to demonstrate the applicability of proposed method. In terms of Guanyinyan station, the dead water is 577 m while the flood checking water level is 600.5 m. The maximum release of turbine is approximately $70\,m^3/s$. Regarding Hongqi station, the dead water level is 499 m, the flood checking water level is about 521.7 m. In addition, the maximum discharge of turbine also reaches $70\,m^3/s$. The collected hourly data of flow rate, water level, and existing energy production for the month January, 2011 are used as input for this work. Both reservoirs are modelled by a continuity equation while the river reach between them is given by the ATD model. Optimization is implemented to improve energy productivity of the system to meet scheduled future demand.

3.1. Determination of parameters of ATD model

The ATD model is a simplified model of the existing complex hydraulic model which is built in a commercial software, HECRAS. According to the method already introduced in[10], the parameters T_c, T_d are derived by investigating the inflow and outflow of a river reach that is early computed by HECRAS. Nonlinear programming (NLP) technique is used as a tool to determine the parameters.

3.1.1. Derivation of characteristic hydrograph

The attributes of the watershed and river reach is accommodated in the characteristic hydrograph. This curve is obtained based on the method of [11, 12]. Data should be adequate to derive an accurate characteristic hydrograph. However, due to data shortage, one year data is used for deriving the characteristic hydrograph. Although this is a limitation, it is sufficient to show the applicability of the ATD model to optimization. Firstly, a data series that shows the river reach characteristics is illustrated in Fig. 2a. Secondly, the highest single peaked flood is selected as a typical hydrograph that is defined as in Fig. 2b by eliminating the complex parts of the hydrograph and adding the base flow. Thirdly, the hydrograph is normalized. After normalization, the duration of exceeding certain flood levels (98%, 95%…, 5 %.) are derived based on the collected data. Then, the hydrograph width at the defined flow level is calculated as the duration. This hydrograph width consists of 2 parts: one for the upward part and the other for downward part. Consequently, the durations and defined percentiles are used as coordinates for sketching the characteristic hydrograph in Fig. 2c. Finally, the designed flood hydrograph in Fig. 2d is derived corresponding the designed discharge from upstream reservoir, as 100 year flood event equivalent.

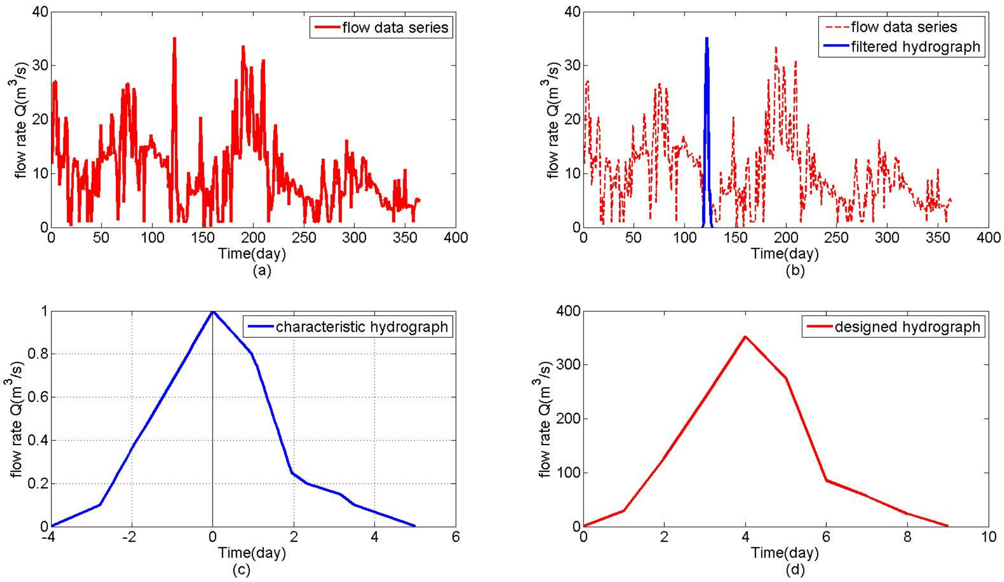

Fig. 2. Procedure for deriving characteristic hydrograph

3.1.2. Model parameter estimation

Before computing the ATD model from the HECRAS model, it is ensured that the HECRAS model of the studied river reach is earlier calibrated and validated. The designed flood hydrograph is used to generate outflow based on this model. Afterwards, the input, output and travel time obtained from HECRAS will be used to derive ATD model based on NLP. The optimization problem of the system is presented in Equation 4.

$$\min \sum_{i=1}^{n} \left(Q^{i}_{HEC} - Q^{i}_{ATD}(T_c, T_d) \right)^2 \tag{4}$$

Subject to

$$\begin{aligned} &T_c = \alpha T_{HEC} ; T_d = \beta T_{HEC} \\ &\alpha + \beta \le 1 \\ &\alpha >, \beta > 0 \\ &\alpha_o = \beta_o = 0.5 \end{aligned} \tag{5}$$

Where Q_{HEC} is the outflow generated by HECRAS, $Q_{ATD}(T_c, T_d)$ is the outflow derived by ATD model, T_c is the time constant, T_d is the time delay, T_{HEC} is travel time derived from HECRAS, α , β are coefficients defined from NLP.

The result is presented in Fig. 3a where the Q_{HEC} and Q_{ATD} are almost identical as illustrated by the values in Table 1. The calibration reaches a very good result with NSE= 0.999 and PBIAS =-0.70, while the validation results for a whole data series in Fig. 4 show an acceptable accuracy with NSE=0.87 and PBIAS=-3.65. The coefficients for extracting T_c and T_d from T_{HEC}, α and β are 0.378 and 0.01, respectively. The curves of time constant and time delay versus discharge are also illustrated in Fig. 3a, 3b. These curves are then used by ATD model to estimate the inflow of downstream reservoir by linear interpolation.

Table 1. Result of estimating parameters of ATD model

Criteria	Calibration	Validation	α	β
NSE	0.99	0.87	0.378	0.01
PBIAS	-0.70	-3.65		

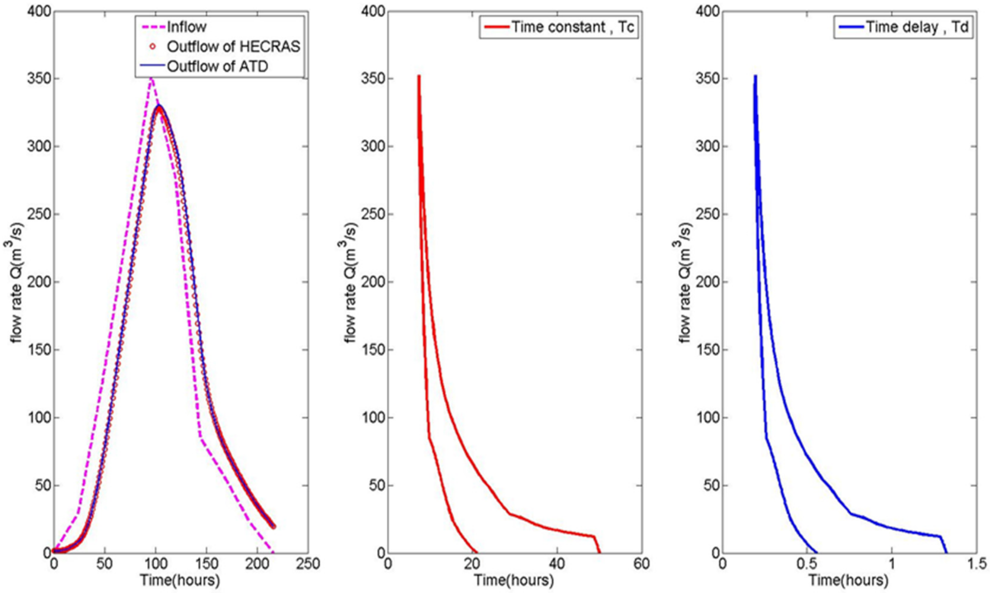

Fig 3. Time constant and time delay derived from HECRAS model

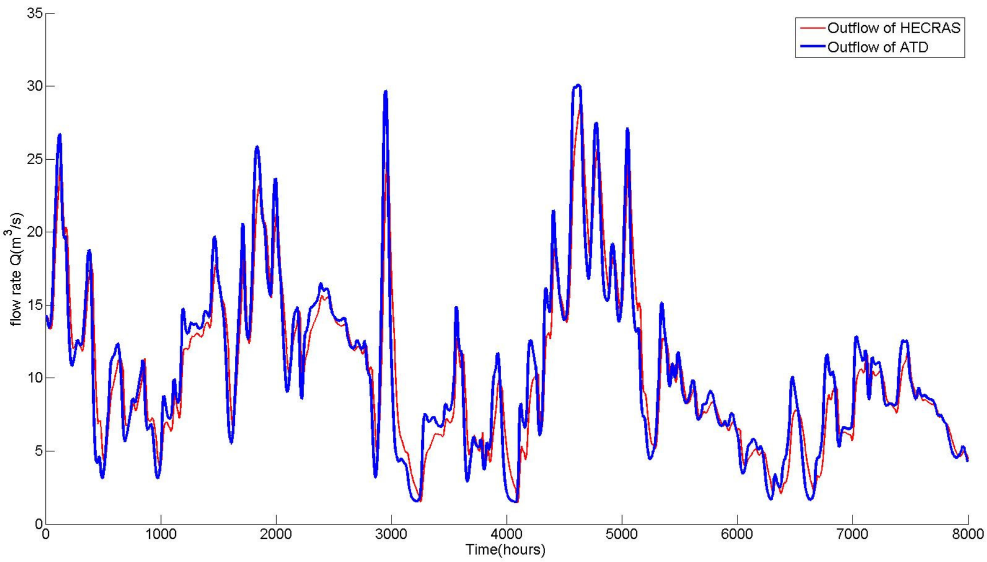

Fig 4. Validation of ATD model for a data series of flood event

4. Optimal control for hydropower cascade

The purpose of this research is to test the applicability of the ATD model in a real nonlinear constrainted optimization set up in order to improve electricity production of a hydropower cascade. Hourly data is used in the optimization to derive hourly operational releases of the reservoirs.

4.1. Formulation of power generation

The energy generation in a time period T is calculated as in Equation 6

$$E=\sum_{t=1}^{T} P_t \Delta t, P_t=\sum_{i=1}^{N} \rho g \mu H Q \tag{6}$$

Where E is the energy generated in a duration Δt ; P_t is the power generation; ρ is the density of water; g is the gravitational acceleration; H is the water head; Q is the turbines discharge; η is the overall efficiency of hydropower plant.

The Equations 7 and 8 are used to define downstream tailwater level for Guanyinyan and Hongqi stations

$$Z_{tw}=133.8542+0.7766Z_{fb}+6.0482Q^{0.1376} \tag{7}$$

$$Z_{tw}=-177.0298+1.3793Z_{fb}+5.8354Q^{0.0235} \tag{8}$$

Where Z_{tw} is the downstream tail water level of hydropower station; Z_{fb} is the forebay level of the downstream reservoir; Q is the discharge toward downstream of the reservoirs.

To simplify the optimization task, assumptions are made as listed below:

- Overall efficiency of hydropower plants are assigned as 0.9 for both reservoirs;
- The hourly data is used to implement optimal operation;
- Environmental flow and other downstream demand of flow are not taken into account in this study;
- Evaporation from reservoirs is not considered;
- Tail water is defined as function forebay water level of downstream reservoir and discharge of upstream reservoir presented in Equation 7 and 8;
- Release from an upstream reservoirs will be transferred to downstream by ATD model;
- The optimal flow rate through turbines is calculated by considering the discharge capacity of turbines;
- The 40-day data of power capacity will be optimized and compared to current energy production;
- Spill is not considered.

4.2. Objective function and constraints

Equation 7 expresses the objective function which will be optimized to improve electricity production.

$$\min\sum_{i=1}^{n}\sum_{j=1}^{m}(E_{d,i,j}-E_{o,i,j})^2 \tag{9}$$

Subject to the constraints:

- Water balance of dam:

$$V_{i,j} = V_{i,j-1} + \left(I_{i,j} - Q_{i,j}\right)\Delta t \tag{10}$$

- Limitation of reservoir water level, outflow as:

$$ZD_{i,j}<Z_{i,j}<ZF_{i,j} \tag{11}$$

$$Qmin_{i,j} \le Q_{i,j} \le Qmax_{i,j} \tag{12}$$

Where n is number of dams; m number of hour; $E_{d,i,j}$ is the total energy demand of reservoir i at hour j; $E_{o,i,j}$ is the sum of optimal energy of reservoir i at hour j; $V_{i,j}$ storage of reservoir i at hour j; $I_{i,j}$ inflow to reservoir i at hour j is determined by ATD model; $Q_{i,j}$ is the outflow through turbine of reservoir i at hour j; Δt is the time interval; $Z_{i,j}$ is the water level of reservoir i at hour j; $ZD_{i,j}$ is the dead water level of reservoir i at hour j; $ZF_{i,j}$ is the flood warning water level of reservoir i at hour j; $Qmin_{i,j}$ is the minimum flow through turbine i an hour j; $Qmax_{i,j}$ is the maximum flow through turbine i at hour j.

4.3. Results

The reservoir system Guanyinyan and Hongqi is optimized for 40 days and the optimized energy is compared to current energy production. As shown in Fig. 5, the scheduled electricity generation (dotted blue line) is almost coincides with the optimal energy production that demonstrates the optimized system meet the expectation. On the other hand, the green solid line illustrates current energy production of the cascade before optimization. Table 2 presents accumulated power generation of the cascade. The totally current energy production is 845.80$10^4$Kwh in which Guanyinyan and Hongqi reservoir accounts for 380.91$10^4$Kwh and 464.89 10^4Kwh respectively. After the system is optimized, the Guanyinyan produces 495.18$10^4$Kwh, whereas the production of Hongqi rises to 604.36 10^4Kwh. The total optimal energy of the system reaches 1099.50 10^4Kwh so that it satisfies the scheduled production.

Table 2. Accumulative electricity generation of the cascade

No	Wuyang hydropower cascade		Total E(10^4Kwh)
	Guanyinyan	Hongqi	
Current energy	380.91	464.89	845.80
Optimal energy	495.18	604.36	1099.5

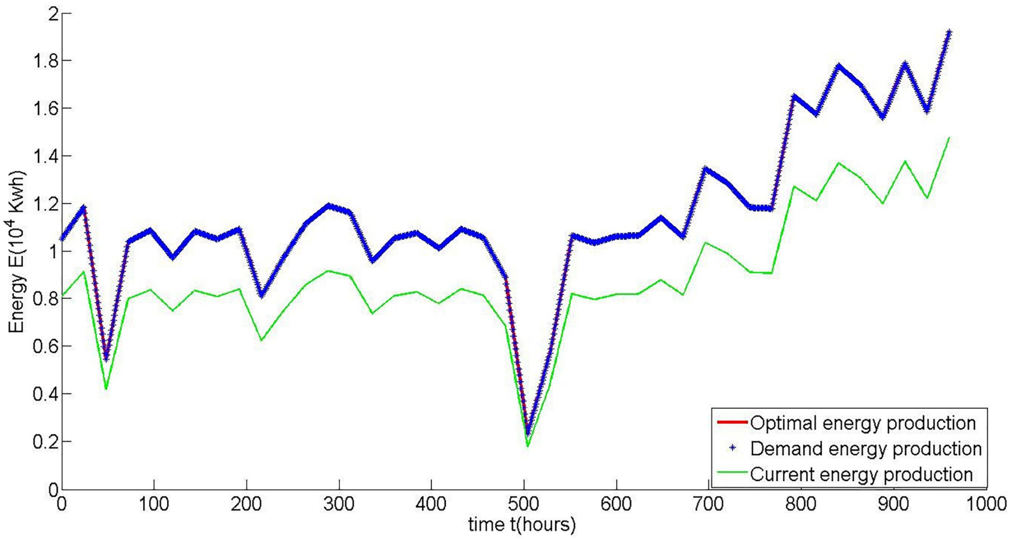

Fig. 5. Result of energy optimization of the cascade

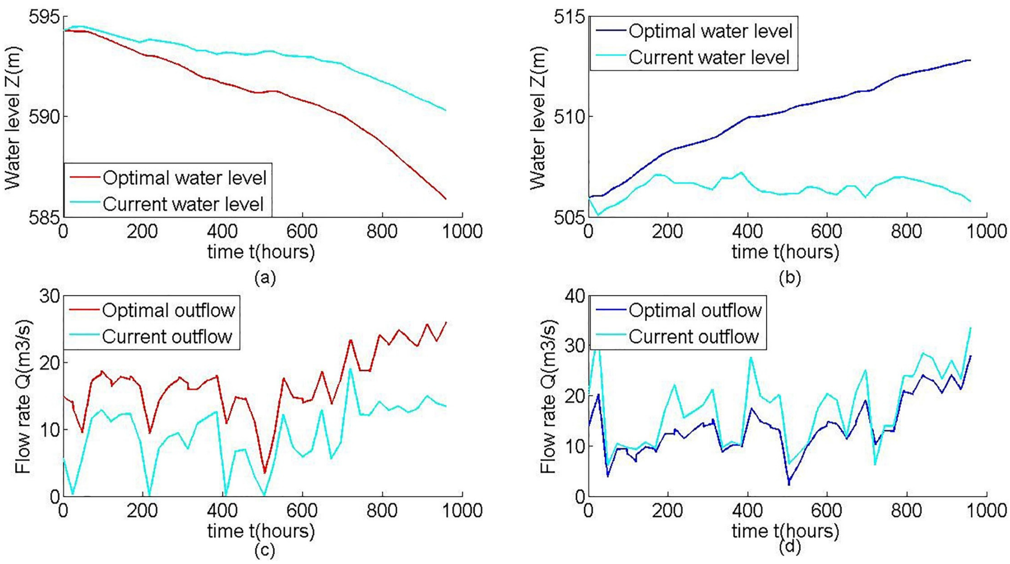

Fig. 6. Optimal operation rules of the cascade

To reach the scheduled energy production, new operating rules for the cascade have been derived and presented in Fig. 6. The cyan curves show current water level and flow rate through turbines of both reservoirs. The red curves present the optimal water level and discharge of Guanyinyan reservoirs whilst the blue ones illustrate for Hongqi reservoir. According to Fig. 6a and 6c, the Guanyinyan dam releases more water to increase electricity production and inflow for Hongqi so that the water level in the dam goes down. The different circumstance happens for Hongqi reservoir as shown in Fig. 6b and 6d. The release from Guanyinyan and intermediate flow are stored whereas the outflow for turbines has not significantly changed in comparison with current situation. However, the energy production also goes up due to the risen water head. Therefore, the power production of a whole system increases as expected.

5. Conclusions

This paper introduced a new approach that utilizes an ATD model in the optimization procedure of a hydropower cascade. The advancement is that the system dynamics are considered during the optimization process. The method has been applied to a two reservoir system with promising results.

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