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A Comparative Study On Cascade Reservoir Operation Models

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Abstract— Optimal utilization of available water resources becomes more urgent due to rapid growth in the world economy and population. In this sense, optimal operation of reservoirs plays a majour role. Using inflow records from May, 1982 to April, 1987, simulations are carried out for Qingjiang cascade reservoirs operation methods of HEC-ResSim, combined reservoir operation and conventional operation methods and results are compared. HEC-ResSim is very prominent in maintaining the desired pool water levels, also able to generate additional 199 GWh (2.39% improvement) electric energy and save 1688 Mm3 (19.46% reduction) of spill releases annually. Combined reservoir operation model is also capable to generate additional 186 GWh (2.23% improvement) electric energy and save 2730 Mm^3 (31.47% reduction) annually. Therefore, both cascade reservoir operation models can be used to enhance hydropower production and harness maximum water resources from cascade reservoirs instead of currently using conventional method.

Keywords — cascade reservoirs, hydropower generation, HEC-ResSim, conventional

I. INTRODUCTION

With the rapid development of world economy and population, the need for the optimum utilization of water resources has become more urgent than ever. Reservoirs are one of the most efficient measures for the integrated water resources development and management. By altering the spatial and temporal distribution of runoff, reservoirs serve for multi-purposes, such as flood control, hydropower generation, navigation, recreation, etc [1]. During the past few decades, various simulation and optimization models have been developed in order to support the decision-making process of the reservoir operation and reviewed by many authors [2-7]. However, it reveals that no general technique is available to grasp whole water resources optimally. Most of the reservoir systems in the world are still managed on fixed predefined operating rules based on the different simulation models. This is mainly due to institutional, rather than technological and mathematical limitations [8]. Simulation is a modeling technique that is used to approximate the behavior of a system on the computer, representing all the characteristics of the system largely by a mathematical or algebraic description [4]. In a pure simulation model, reservoir releases are determined by a set of predetermined operating rules. Through a series of simulation these rules can be modified and improved until model results are judged acceptable. On the other hand, optimization models involve allocating resources, developing stream flow regulation strategies and operating rules, and making real-time release decisions within the guidelines of the operating rules [6].

The earliest simulation model appearing in the literature seems to be the study performed by the U.S. Army Corps of Engineers in 1953 for the operational study of six reservoirs on the Missouri River [4]. Since then, simulation models have been widely used for planning and managing complex water resources systems. Among the wide range of simulation models, HEC-3 [9] and HEC-5 [10] models which were developed by U.S. Army Corps of Engineers can be considered as some of the best simulation models in the history. HEC-3 model is specific for reservoir system analysis for conservation purpose while HEC-5 is for simulation of flood control and conservation of systems. HEC-5 model has been updated as HEC-ResSim to include Windows-based graphical user interface by US Army Corps of Engineers for reservoir system simulation in 2003 [11]. Various optimization models based on linear programming (LP), nonlinear programming (NLP), dynamic programming (DP), genetic algorithms (GA), artificial neural network (ANN), etc., for reservoir operation are also very common in the academic literature [12-20]. Although various operation models based on simulation and optimization techniques are available, conventional operation chart is still widely used for deriving operation rules due to its concise and direct-viewing. The Qingjiang River cascade reservoir system in China is also opearted based on the conventional guide curves. However, it is only used in single reservoir operations, and cannot be used in the combine operation of cascade reservoirs. Therefore, poor storage distribution can be seen among cascade reservoirs, and much of flood water resources are wasted during the flooding season. The objective of this paper is to compare the HEC-ResSim Reservoir System Simulation model developed by the U.S. Army

Corps of Engineers [11] and the combined reservoir operation model [21] developed by the authors with the currently using conventional method in the Qingjiang cascade reservoirs.

II. MATERIALS AND METHODS

A. Qingjiang Cascade Reservoir System and Operation Plan

The Qingjiang basin is situated at southwest Hubei province in China and located between the east longitudes 108°35 ' ~ 111°35 ' and the north latitudes 29°33 ' ~ 30°50 ' in the subtropical area. It is mountainous and has multi karsts land form with basin area of 17600 km^2. Abundant rainfall is found in the basin and mean annual rainfall is approximately 1460 mm. Mean annual runoff depth is 876 mm and mean annual runoff is 423 m^3s^{-1}. Qingjiang River is one of the main tributaries of Yangtze River, and winding from west to east. The total length of the mainstream is 423 km with a hydraulic drop of 1430 m. Qingjiang River has a total exploitable hydropower potential of 3500 MW with annual output more than 10000 GWh. Along the Qingjiang River, a three-step cascade reservoir system is found from upstream to downstream namely, Shuibuya, Geheyan and Gaobazhou. Main objectives of this cascade reservoir system are power generation and flood control. Improving navigation and fisheries facilities are the other benefits. A diagram of Qingjiang basin with the cascade reservoir system is shown in Figure 1, and the basic physical parameters of three reservoirs are listed in Table 1.

B. Conventional Operation Plan

In the original design, Qingjiang reservoirs use predefined guide rules based on the conventional method for instructing reservoir releases. However, hydropower plants are considered independently in the operation process. Therefore, it is impossible to realize better storage distribution among cascade reservoirs and does not display the overall power generation performance. The individual conventional operation charts of Shuibuya and Geheyan reservoirs are shown in Figures 2 and 3, respectively. According to the Shuibuya reservoir conventional operation chart, the whole storage space is divided into five operational zones. Accordingly, following generation parameters are used in the operation process. When the reservoir water level is between upper and lower basic guide curves, the hydropower plant is working under its firm capacity (310 MW). If the water level falls into operation zone ③, which is between upper basic guide curve and 800 MW guide curve, the power plant capacity is 800 MW. If the reservoir water level lies in the operational zone ②, the power plant capacity is 1600 MW which is same to the installed capacity. When the reservoir's water level rises to flood prevention limit or enters into the flood prevention zone, the reservoir adjusts according to designed flood control rules and power plant works under the installed capacity (1600 MW). If the water level falls below the lower basic guide curve, the power plant capacity is 250 MW.

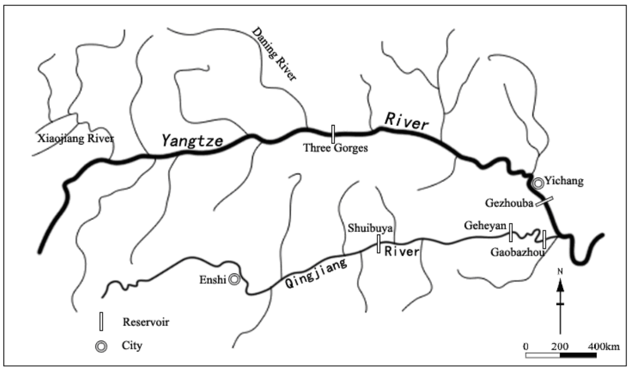


Figure 1: The Qingjiang basin with cascade reservoir system

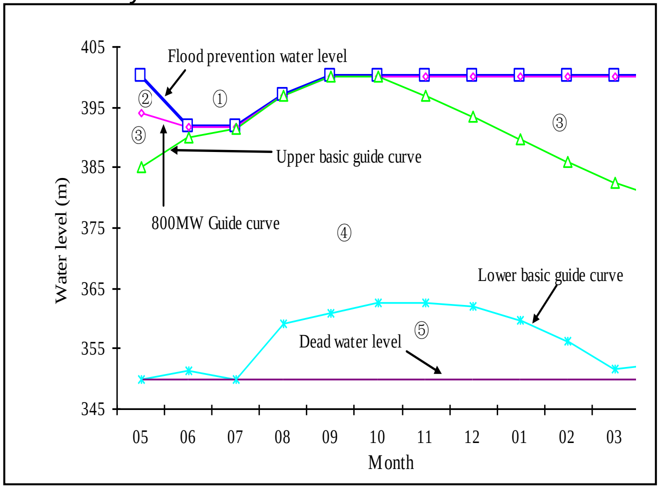


Figure 2: Conventional operation chart of Shuibuya reservoir

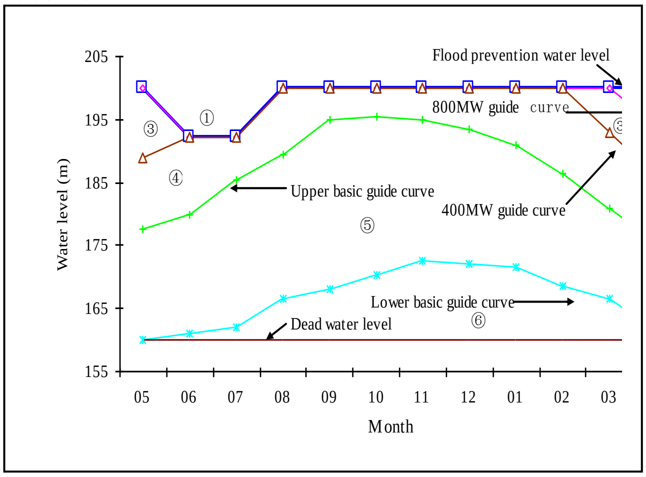


Figure 3: Conventional operation chart of Shuibuya reservoir

Table 1: Basic physical parameters of the Qingjiang cascade reservoirs

Reservoir	**Normal pool level （m）**	**Flood prevention water level （m）**	**Dead water level （m）**	**Total storage （108m^3）**	**Dead storage （108m^3）**	**Installed capacity （MW）**	**Firm Capacity （MW）**	**Regulation ability**
Shuibuya	400	391.8	350	43.45	19.41	1600	310	Multiyear
Geheyan	200	193.6	160	31.2	16.42	1200	241.5	Annual
Gaobazhou	80	78.5	78	3.56	3.05	270	77.3	Daily

Six operational zones are found in the Geheyan reservoir conventional operation chart as shown in Figure 3. When the reservoir water levels are in different operational zones, respective generation parameters of the Geheyan reservoir are shown in Table 2. If the water level rises to flood prevention limit or into the flood prevention zone, the reservoir is adjusted according to designed flood control rules, and the power plant works under the installed capacity (1200 MW). Gaobazhou is a very small reservoir comparing to Shuibuya and Geheyan reservoirs. Its effective storage capacity, installed power generation ability, and flood regulation ability are conspicuously smaller than the other two reservoirs. The hydraulic head is also less. Therefore, it is operated as daily run-off-river hydropower plant and the water level is retained at 78.5 m elevation at all the times.

Table 2: Generation Parameters of the Geheyan Reservoir Conventional Operation Chart.

Operational zone	Area	Generation capacity (MW)
①	Above the flood prevention water level	1,200.0
②	Flood prevention water level ~ 800MW guide curve	1,200.0
③	800MW guide curve ~ 400MW guide curve	800.0
④	400MW guide curve ~ Upper basic guide curve	400.0
⑤	Upper basic guide curve ~ Lower basic guide curve	241.5
⑥	Below the lower basic guide curve	73.0

C. HEC-ResSim Model

HEC-ResSim is a computer based simulation model which can be used to simulate reservoir system operations. It is comprised of a Windows-based Graphical User Interface (GUI). In addition, it has capability of data storage and management and graphics and reporting facilities. The Data Storage System, HEC-DSS is used for storage and retrieval of input and output time-series data.

HEC-ResSim model offers three basic separate sets of functions called modules that provide access to specific types of data within a watershed. These modules are watershed setup, reservoir network and simulation. Each module has a unique purpose and associated set of functions accessible through menus, toolbars and schematic elements. The purpose of watershed setup module is to provide a common framework for watershed creation and definition among different modeling applications. A watershed is associated with a geographical region for which multiple models and area coverage can be configured. A watershed may include all of the streams, projects (eg., reservoirs, levees), gage locations, impact areas, time-series locations and hydrologic and hydraulic data for specific area. After creating a new watershed, it has the ability to import maps from external sources, specify the units of measuring, add layers containing additional information about the watershed and configure elements. Moreover, it has the ability of adding projects and time-series icons within the watershed module. The purpose of the reservoir network module is to isolate the development of the reservoir model from the output analysis. Using the configurations that are created in the watershed setup module as a template, the reservoir network can be created. Here, it can build river schematic, describe the physical and operational elements of the reservoir model and develop the alternatives that require analyzing. Furthermore, it can add routing reaches and other network elements to complete the connectivity of network schematic. Once the network schematic is completed, physical and operational data can be defined. Also, alternatives can be created that specify the reservoir network, operation sets, initial condition and data storage system path names. HEC-ResSim model has the ability of defining reservoir systems for storage balancing between tandem reservoirs and reservoirs in parallel. The purpose of the simulation module is to isolate output analysis from the model development process. Once the reservoir model is completed and alternatives have been defined, the simulation model is used to configure the simulation. The computations are performed and results are viewed within the simulation module. Results of the simulation can be viewed as plots and tabular form. Additionally, numbers of summery reports are available after simulation is performed. These different kinds of results can be used to derive or refine operation rules and further analyzing [11].

D. Combined Reservoir Operation Model

The newly developed combined reservoir operation model [21] consists of three components. (1) Combined guide curves (2) storage distribution and (3) optimization.

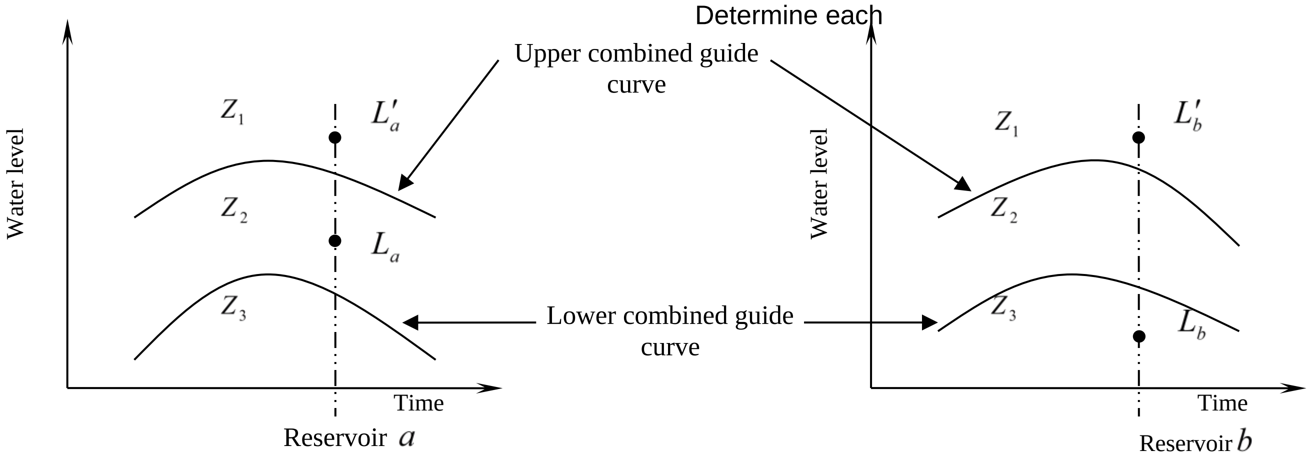


Figure 4: Combined reservoir operation chart for a hypothetical cascade

- Combined Guide Curves

The total generation capacity of the cascade reservoirs is determined by the combined guide curves in the combined reservoir operation chart. It is determined according to the current water level of each reservoir in the combined reservoir operation chart with particular judging rules. The combined reservoir operation chart for a hypothetical cascade with two reservoirs is shown in Figure 4.

It is similar to conventional operation charts, and mainly consists of different guide curves and corresponding operational zones. Accordingly, upper and lower combined guide curves of each individual operation chart divide the whole storage space into three operational zones, named higher capacity zone (Z_1), firm capacity zone (Z_2) and lower capacity zone (Z_3). The combined guide curves have particular features relative to conventional operation charts. Those reflect the total generation capacity of the cascade reservoir system in every time interval and do not mention the individual reservoir generation capacity. However, guide curves in the conventional operation chart correspond to individual reservoir generation capacity. The combined guide curves display the relationship between reservoir water level and the total generation capacity of the reservoir system through each reservoir operation charts. When water levels are in higher capacity zone, firm capacity zone and lower capacity zone, corresponding total generation capacities of the cascade are N_1, N_2 and N_3, respectively ($N_1 > N_2 > N_3$). Another unique feature of the combined guide curve is that it demonstrates the optimized power generation capacity and better storage distribution among cascade reservoirs.

There are three steps in using the combined reservoir operation chart. (1) Obtain the current water levels of each reservoir in the cascade. (2) Compare each reservoir water level and decide the total generation capacity of the cascade (here, some empirical judging rules were introduced for determining the total generation capacity). (3) Determine each reservoir's hydro power demand according to the total generation capacity using the storage effectiveness index (SEI) method [22] and establish better storage distribution among cascade reservoirs.

- Judging rules

Rule 1: "If the water levels of every reservoir are in the same operational zone, the cascade total generation capacity would be the same as individual generation capacities in the corresponding operation zone". As an example, at the current time *t*, water levels of reservoirs *a* and *b* in Figure 4 are L_a' and L_b' respectively. The corresponding generation capacities are N_1 in both cases. Since both water levels are in the same operation zone Z_1, N_1 is considered as the total generation capacity of the cascade.

Rule 2: If water levels of each reservoir are in different operational zones, the judging rule becomes complex than the above. The principle in such a case, water levels of each reservoir should be in the same operational zone or as close as possible after releases are made at the current time-step. This is achieved by releasing water for power generation from the reservoir which has highest total generation capacity at the current time while other reservoirs reduce or stop their releases. As an example, if water levels of two reservoirs in Figure 4 are L_a and L_b which are in different operational zones, corresponding total generation capacities are N_2 and N_3, respectively ($N_2 > N_3$). In this case, reservoir *a* undertakes the main role in power generation by increasing its generation rate while reservoir *b* reduces its generation rate to push water levels into the same operational zone. Main steps of this rule can be summarized as follows.

"First assume N_2 as the cascade total generation capacity and undertake power generation to push each reservoir's water level into the same operation zone or as close as possible at the end of the current time-step. Second, when water level of each reservoir comes into the same operational zone, releases are made according to storage effectiveness index for better storage distribution among cascade reservoirs".

During the first step it should avoid increasing the reservoir *b*'s generation rate more than the total generation capacity of the cascade, N_2. If the actual generation rate, N_t is smaller than N_3 during the computing time interval, then decide N_3 as the total generation capacity of the cascade. If water levels are still in different operation zones after the estimation and also actual generation rate, N_t is less than N_2 and larger than N_3 ($N_2 > N_t > N_3$). Then the total generation capacity of the cascade is considered as N_t. It is neither N_2 nor N_3.

- Storage Distribution

Storage effectiveness index (SEI) developed by U.S. Army Corps of Engineers [22] is used to achieve better storage distribution among cascade reservoirs. SEI is one of the decision making rules in the reservoir system operation for maximizing firm hydropower production. For each reservoir in the cascade, a "SEI" is calculated for each time-step, using forecast inflow and power demands for the current time-step and remaining time-steps. In the release process, it is accomplished according to the magnitude sequence of SEI values of each reservoir. The reservoir with lowest SEI value is drawn down first during the release season and, vice versa during the refill season or period. Here, the refill season is defined as the season when system inflows exceed the needs to meet hydropower production demands.

Assuming all flow can be utilized through turbines for power generation, the energy shortage for the current time step, E_q is computed by

$$E_q = E_x - \sum_{i=1}^{N} 9.8 \eta_i I_i H_i \Delta t \qquad (1)$$

Where E_x is the energy requirement for the current time-step; *i* is the reservoir index; *N* is the total number of reservoirs in the cascade; ηi is the turbine efficiency of reservoir *i*; I_i is the inflow to reservoir *i* during the current time-step; H_i is the hydropower head as a function of reservoir storage of reservoir *i* and Δt is the computing time-step.

The drawdown storage of reservoir *i* for power generation, ΔS_i is expressed by,

$$\Delta S_i = E_q / (9.8 \eta_i H_i) \qquad (2)$$

The drawdown period power loss, E_i due to drawdown of reservoir *i* by ΔS_i is expressed by;

$$E_i = 9.8 \eta_i (W_{oi} + W_{qi}) H_i (S_i - \Delta S_i) \qquad (3)$$

Where W_{oi} is the cumulative outflow capacity of upstream reservoir *i* during the remainder of the drawdown season; W_{qi} is the cumulative inflow capacity of upstream reservoir *i* during the remainder of the drawdown season; S_i is the current reservoir storage of reservoir *i*.

The storage effectiveness index of reservoir *i*, SEI_i is calculated by

$$SEI_i = E_i / E_q \qquad (4)$$

The SEI method is used with the proposed combined operation chart as following,

(1) If the water levels of every reservoir are in the same operational zone, the SEI method is directly used to achieve better storage distribution among cascade reservoirs. The sequence of release is the same with SEI of each reservoir from small to large during the drawdown period, and vice versa during the reservoir refill period.

(2) If the water level of each reservoir is in different operational zones, the reservoir with highest total generation capacity supplies water for power production first. Other reservoirs reduce or stop their releases for bringing the water level of each reservoir into the same operational zone. When the water levels of each reservoir come into the same operational zone, the SEI method is used to determine storage distribution among cascade reservoirs as mentioned above.

- Optimization

Particle Swarm Optimization (PSO) algorithm is used for the optimization purpose of the combined reservoir operation model. It is a population based stochastic optimization technique proposed by Kennedy and Eberhart [23].

Assume the population (swarm) is made up of *m* particles and *n* dimensional searching space. It means, particle *i* has *n* dimensional velocity vectors in the searching space. If x_i is the current position of the particle *i* in the swarm, $\{x_i = x_{i1}, xi_2, \ldots, x_{im}, i=1,2\ldots m\}$ the best position where particle *i* has encountered during its flight is P_i $\{P_i = (P_{i1}, P_{i2}, \ldots, P_{im})\}$ and it is called P_{best}. The global optimized position where particle has encountered, when the particle takes all the population as its topological neighbors, is P_g $\{P_g = (Pg1, P_{g2}, \ldots, P_{gm})\}$ and it is called G_{best}. v_i is the current velocity of particle *i* during the search in *n* dimensional searching space $\{v_i = v_{i1}, v_{i2}, \ldots, v_{in})\}$. Modified velocity, x_{ij}^{k+1} of particle *i* can be written as,

$$x_{ij}^{k+1} = x_{ij}^{k} + v_{ij}^{k+1} \qquad (5)$$

$$v_{ij}^{k+1} = w v_{ij}^{k} + c_1 r_1 [p_{ij} - x_{ij}^{k}] + c_2 r_2 [p_{gj} - x_{ij}^{k}] \qquad (6)$$

Where *w* is a parameter called "inertia", $v_{ij} = \varepsilon\ [-v_{max}, v_{max}]$, v_{max}, is a constant; c_1 and c_2 are accelerated velocity constants which push particle to P_{best} and G_{best}; r_1 and r_2 are stochastic constants in the interval of (0,1).

- Guide curve establishment

Each particle *i* in the particle swarm algorithm represents a specific position, x_i in the combined reservoir operation chart. When all these particle positions, ($x_{i1}, x_{i2}, \ldots, x_{in}$) are connected together from beginning to end, it represents guide curves of each reservoir in the combined reservoir operation chart.

The particle dimension of this problem can be written as,

$$n = T \times L \qquad (7)$$

Where n is particle dimension; T is the total number of time periods in the year; and L is the total number of guide curves in all reservoirs.

During the solution process, particles carry on optimization using single guide curve as the basic unit, because we assume a guide curve is made up of current position of connected particles. The location of guide curve changes as particles move to their best positions.

- Objective function and constraints

If all hydropower plants meet the required water supply and initial power supply, the objective is to generate maximum power from the whole system, i.e.,

$$\max \quad f = \sum_{t=1}^{T}\sum_{i=1}^{N} 9.8 C_{i,t}\eta_i H_{i,t} Q_{i,t}\,\Delta t \qquad (8)$$

$$t = 1,2,\cdots,T \quad i = 1,2,\cdots,N$$

Where t is the computation time interval index; T is the total number of computation time intervals; $Q_{i,t}$ is the flow rate use for power generation of reservoir i during the time interval t; $C_{i,t}$ is the price for the electricity of reservoir i during the time interval t; $H_{i,t}$ is the hydropower head of reservoir i during the time interval t; and other notations have same meaning with above.

subject to,

$$V_{i,t+1} = V_{i,t} + (I_{i,t} - q_{i,t})\Delta t \qquad (9)$$

$$I_{i+1,t} = q_{i,t} + IB_{i,t} \qquad (10)$$

$$q_{i,\min} \le q_{i,t} \le q_{i,\max} \qquad (11)$$

$$N_f \le \sum_{i=1}^{N} N_{i,t} \le \sum_{i=1}^{N} NT_i \qquad (12)$$

Where $v_{i,t}$ is the storage of reservoir i at the beginning of the time interval t; $I_{i,t}$ is the inflow to reservoir i during the time interval t; $q_{i,t}$ is the outflow of reservoir i during the time interval t; $IB_{i,t}$ is the inflow between reservoir i and $i+1$ during the time interval t; $q_{i\ \min}$ is the minimum discharge capacity of reservoir i for down stream ecological requirements; $q_{i\ \max}$ is the maximum discharge capacity of reservoir i and it is limited by the down stream flood prevention limitations; N_f is the firm capacity of the cascade reservoir system; NT_i is the maximum generation capacity of reservoir i; and $N_{i,t}$ is the generation capacity of reservoir i during the time interval t.

Considering constraints of the electric power system of Qingjiang cascade hydropower plants, the adjusted objective function for particle swarm algorithm optimization can be written as,

$$\max \quad F = \sum_{t=1}^{T}[\sum_{i=1}^{N} C_{i,t}N_{i,t} + \alpha(\sum_{i=1}^{N} N_{i,t} - N_f)^{\beta}]\Delta t \qquad (13)$$

where α and β are penalty for electric power system constraints; if $\sum_{i=1}^{N} N_{i,t} \ge N_f$ then $\alpha=0$, otherwise $\alpha>0$. Other notations have same meanings as previously introduced.

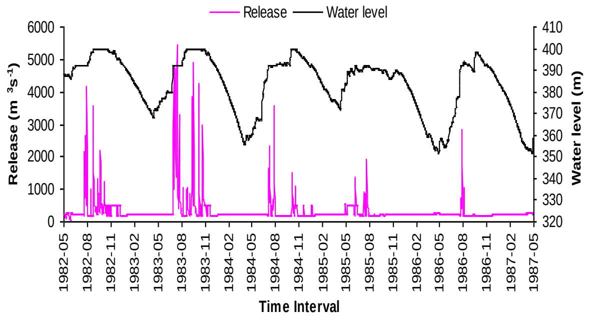
III. SIMULATION RESULTS AND DISCUSSION

Considering previous inflow records of Qingjiang cascade reservoirs from 1955 to 2005, five consecutive years were selected (from 1st May, 1982 to 30th April, 1987) for simulation studies. The first two years were wet years, third year was a normal year and last two years were dry years. These five years represent different hydrological characteristics and release patterns, hence more appropriate for analysis purposes. Qingjiang cascade reservoir system has been successfully applied to the HEC-ResSim model and a 3-hour simulation was performed to the above selected period. Similarly, parallel simulations were also done with the combined reservoir operation model and the conventional method. All the physical and operational conditions were very similar in three simulations.

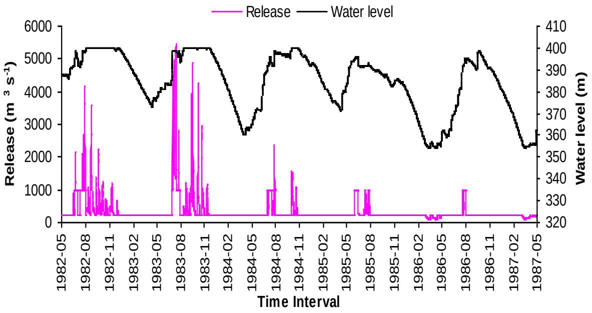
A. Pool Water Levels and Releases

- Shuibuya reservoir

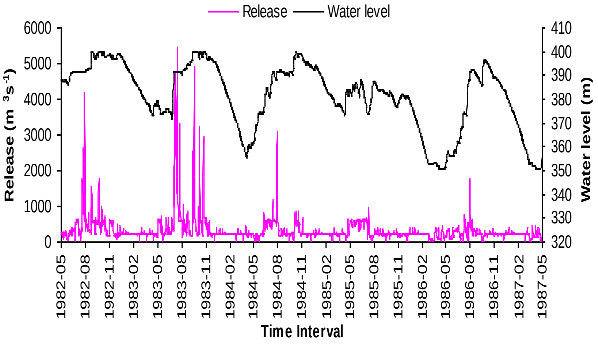
Resulted pool water levels and total releases of Shuibuya reservoir from three methods are shown in Figure 5. Accordingly, all the methods show an annual cyclic modulation phenomenon of the pool water level. Comparing with the conventional method pool water level, both HEC-ResSim and combined reservoir operation models show slight variations at some instances. HEC-ResSim model shows a clear difference during the peak flooding seasons (from 1st June to 31st July) and endmost dry years. Combined reservoir operation method shows a clear difference in the first dry year. The resulted average pool water level of the Shuibuya reservoir from the combined reservoir operation model is 381.5 m and it is less than the conventional average pool water level of 383.4 m. From the starting of simulations on 1st May, 1982 all the methods raise the pool water level by maintaining minimum releases (230 $m^3\ s^{-1}$) and reached to the conservation elevation with the onset of peak flooding season. Up to that, the pool water levels resulted from three methods are very similar and the main deviation is occurred during the peak flooding season. Conventional and combined reservoir operation methods maintain the pool water level at the conservation elevation (391.8 m) by spilling excess water while HEC-ResSim allows to rise the pool water level above the conservation elevation. HEC-ResSim offers priority for releasing excess water to the reservoir that is farthest above the desired storage in cascade reservoirs simulation. In this case, priority is given to Geheyan reservoir as Shuibuya has more space for excess water. Anyway, it does not allow to rise the pool water level more than 400 m elevation which will be threaten to the dam, when pool water level reaches to 400 m elevation it activates the dam controlled outlet and release excess water. After escaping the threat of rising pool water level, HEC-ResSim maintains releases at maximum capacity through power plants (1000 $m^3 s^{-1}$) by arresting the releases through spill gates. This phenomenon is common in all flooding seasons of the whole analyzed period. During the peak flooding period the water levels resulted from combined operation method and conventional method are similar. However, total releases of combined reservoir operation method are comparatively less than the conventional method due to the combined operation of Shuibuya and Geheyan reservoirs. During the non-flooding season water levels resulted from three methods are very similar. The other difference is occurred at the end of dry years due to different release mechanisms of three methods when the pool water level reaches to the dead storage level.



a. Conventional method



b. HEC-ResSim method

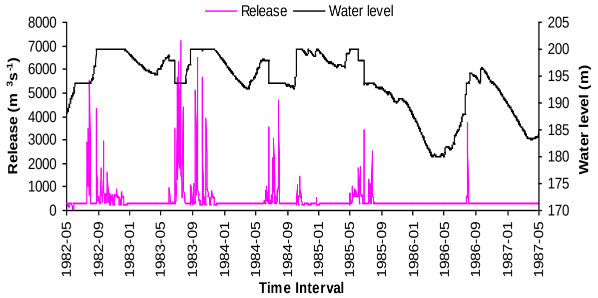


c. Combined reservoir operation method

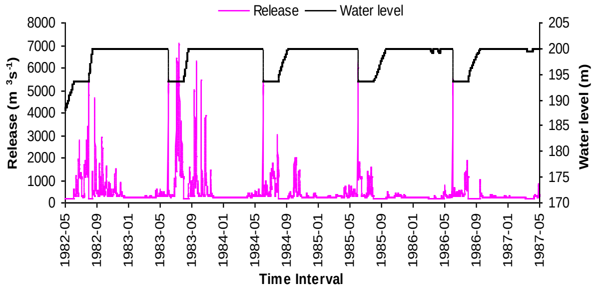
Figure 5: Releases and pool water levels of Shuibuya reservoir from May, 1982 to May 1987.

- Geheyan reservoir

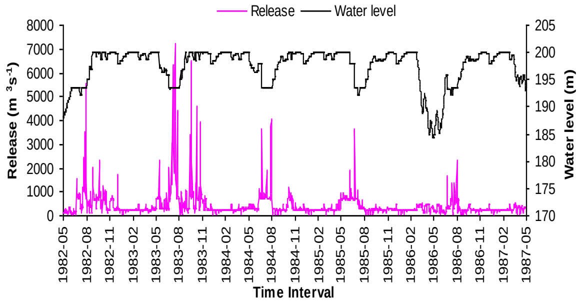
Cascade simulation results of pool water levels and total releases for Geheyan reservoir from three methods are shown in Figure 6. Accordingly, prominent differences can be seen in the Geheyan reservoir water levels. HEC-ResSim is very prominent in maintaining



a. Conventional method



b. HEC-ResSim method

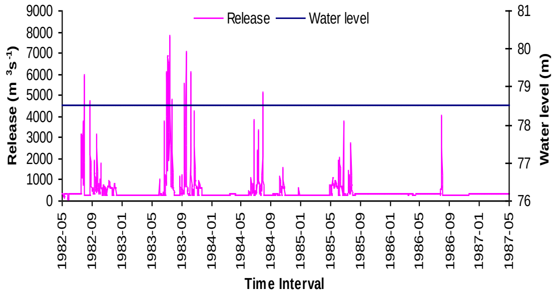


c. Combined reservoir operation method

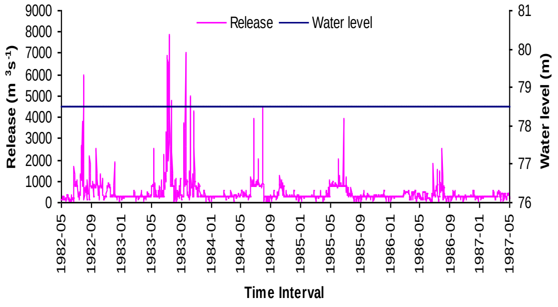
Figure 6: Releases and pool water levels of Geheyan reservoir from May, 1982 to May 1987.

the desired pool water level. During the whole analyzed period HEC-ResSim is capable to maintain the pool water level at the conservation elevation. Combined reservoir operation model also has the ability of raising the Geheyan reservoir water level prominently. However, a slight variation can be seen with the time. The resulted average pool water level of the Geheyan reservoir from the combined reservoir operation model is 197.5 m and it is significantly higher than the conventional average pool water level, which is 193.8 m. At the end of dry years, water levels of combined reservoir operation and conventional methods are clearly dissimilar than the HEC-ResSim method. However, HEC-ResSim maintains the pool water level at the conservation elevation. These differences are occurred due to dissimilar release process of the Shuibuya reservoir during the mean time.

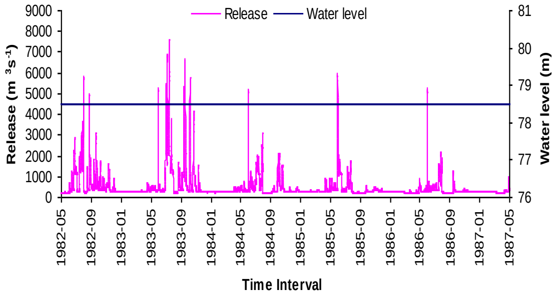
- Gaobazhou reservoir



a. Conventional method



b. HEC-ResSim method



c. Combined reservoir operation method

Figure 7: Releases and pool water levels of Gaobazhou reservoir from May, 1982 to May 1987.

Pool water levels and total releases of Gaobazhou reservoir from three methods are shown in Figure7. Accordingly, all the methods similarly maintain the pool water level at conservation elevation during the whole analyzed period by regulating the inflow equal to the outflow. However, prominent dissimilarities can be seen in outflows in some instances. HEC-ResSim shows prominent disparity at the beginning of peak flooding period. On that occasion total releases from HEC-ResSim are conspicuously higher than the conventional and combined operation methods and it is due to higher releases of the Geheyan reservoir at the same time. During the rest of the peak flooding period, slight variations are caused due to different outflow pattern of the Geheyan reservoir as Gaobazhou maintains outflow equal to inflow. Though the release pattern of the combined operation method is somewhat similar to the conventional method, releases are significantly lower than the conventional method.

B. Power Generation and Spill Releases

Simulation results of annual power generation and spill releases from three methods are summarized in Table 3. Flood water resources utilization of three reservoirs with the total cascade is also shown in the same table. Accordingly, HEC-ResSim model can generate additional 171 and 29 GWh annually from Shuibuya and Gaobazhou hydropower plants, respectively. However, Geheyan power plant shows 1 GWh reduction than the conventional method. The reduction rate is 0.03% and comparing with the Shuibuya and Gaobazhou reservoirs, it is a minute reduction and can be neglected. Although the Gaobazhou reservoir is being paid little attention in this simulation, since it is using as daily run-of-river hydropower plant, it shows conspicuous increment in power generation. The increment of the whole cascade power generation is 199 GWh and it is a 2.39% improvement over the conventional method which is the original design. Therefore, a great improvement of power generation can be achieved by using the HEC-ResSim model as an operation tool for the Qingjiang cascadereservoirs. The combined reservoir operation model shows higher power generation results over the conventional method in all these reservoirs. The cascade total power generation increment from the combined reservoir operation model is 186 GWh and it is 2.23% improvement over the conventional method.

Simulation results show that the HEC-ResSim model is capable to reduce annual spill releases of all three reservoirs by varying degrees. The whole cascade annual spill reduction is 1688 Mm^3 and it is 19.46% reduction to the conventional method. Combined reservoir operation model is also very prominent in spill release reduction. Similar to the HEC-ResSim model, the combined reservoir operation model also reduces spill releases of all three reservoirs. The total spill release reduction from the combined reservoir operation model is 2730 Mm^3

and it is 31.47% to the conventional method. Likewise, HEC-ResSim model achieves 4% and combined reservoir operation model achieves 6.5% increment in flood water resources utilization in Qingjiang cascade reservoirs operation, annually.

Table 3. Simulation Results of Conventional, HEC-ResSim and Combined Reservoir Operation Methods During May, 1982 to May, 1987 for Qingjiang Cascade Reservoirs.

Parameter	**Operation method**	**Reservoir**			**Total**
		Shuibuya	**Geheyan**	**Gaobazhou**	
Annual electricity generation (GWh)	Conventional	4081	3345	923	8349
	HEC-ResSim	4252	3344	952	8548
	Increment of generation	171	-1	29	199
	Increasing rate (%)	4.19	-0.03	3.14	2.39
	Combined operation	4241	3368	926	8535
	Increment of generation	160	23	3	186
	Increasing rate (%)	3.92	0.69	0.32	2.23
Annual spill release (Mm^3)	Conventional	1839	2674	4163	8676
	HEC-ResSim	1275	2354	3359	6988
	Reduced spillage	564	320	804	1688
	Reducing rate (%)	30.67	11.97	19.31	19.46
	Combined operation	779	1883	3284	5946
	Reduced spillage	1060	791	879	2730
	Reducing rate (%)	57.64	29.58	21.11	31.47
Flood water resources utilization (%)	Conventional	83.50	81.64	73.63	79.10
	HEC-ResSim	88.51	83.80	78.67	83.11
	Combined operation	92.98	87.04	79.15	85.63

In comparison of HEC-ResSim and combined reservoir operation methods, HEC-ResSim model is capable to generate additional 13 GWh electric energy, annually. However, the spill release reduction of combined reservoir operation model is significantly higher than the HEC-ResSim model and it is 1042 Mm^3 during the analyzed period. Therefore, combined reservoir operation model achieves 2.5% increment in flood water resources utilization over the HEC-ResSim model.

IV. CONCLUSIONS

Both newly introduced HEC-ResSim and combined reservoir operation models are capable to generate considerable amount of extra electricity and reduce spill release from the Qingjiang cascade reservoirs. The annual power generation increments from HEC-ResSim and combined reservoir operation models are 199 GWh (2.39%) and 186 GWh (2.23%), respectively. Combined reservoir operation model is fantastic in reducing spill releases by 2730 Mm^3 (31.47% reduction) annually. The spill release reduction from the HEC-ResSim model is 1688 Mm^3 (19.46% reduction). Therefore, both new methods can be used to enhance hydropower production and harness maximum water resources from the Qingjiang cascade reservoirs instead of currently using conventional method.

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