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DERIVATION OF OPTIMAL JOINT OPERATING RULES FOR MULTI-PURPOSE MULTI-RESERVOIR WATER-SUPPLY BY SYSTEMS

BY SOON-THIAM KHU , XU WANG & QIAOFENG TAN

The derivation of joint operating policy is a challenging task for a multi-purpose multi-reservoir systems. The study proposed an aggregation-decomposition model to guide the joint operation of multi-purpose multi-reservoir systems, including: (1) an aggregated model based on the improved hedging rule (HR) to ensure the long-term water-supply operating benefit; (2) a decomposed model to allocate the limited release to individual reservoirs for the purpose of maximizing the total profit of the facing period; and (3) a double-layer simulation-based optimization model to obtain the optimal time-varying HRs using the non-dominated sorting genetic algorithm II, whose objectives were to minimize maximum water deficit and maximize water supply reliability.

The water-supply system of Li River in Guangxi Province, China, was selected for the case study. The results show that the operating policy proposed in this study is better than conventional operating rules and aggregated standard operating policy (SOP) for both water supply and hydropower generation due to the use of hedging mechanisms and effective coordination among multiple objectives.

What is the problem?

For a multi-reservoir water-supply system, the downstream water demand can be satisfied by any one or several reservoirs. In most cases, these reservoirs are operated independently without a joint operating rule. Meanwhile, reservoirs in China usually serve multiple purposes, such as flood control, hydropower generation, navigation, and recreation [1-2]. Therefore, the joint operating rule is expected to be able to coordinate not only individual reservoirs but also different water use purposes. Li River is a tributary of Xi River in the Pearl River Basin, which is located in the northeast of Guangxi Province of China. As shown in Fig. 1, the water-supply system of Li River consists of six reservoirs, including the Fuzikou Reservoir (FZK), Chuanjiang Reservoir (CJ), Xiaorongjiang Reservoir (XRJ), Qingshitan Reservoir (QST), Sianjiang Reservoir (SAJ) and Wulixia Reservoir (WLX). These reservoirs supply water for the 83 km reach from Guilin City to Yangshuo City (GL-YS), which is a famous tourist area in China. The highest priority is assigned to water supply. The water released is used to generate hydropower and then delivered to GL-YS. Although these reservoirs serve a common water supply objective, each reservoir releases according to its own operating rule curve predetermined in the design stage without considering the coordination of reservoirs. How to build a joint operation rule as well as coordinate multi-objective relationship is always a big challenge for the reservoir managers in Li River basin.

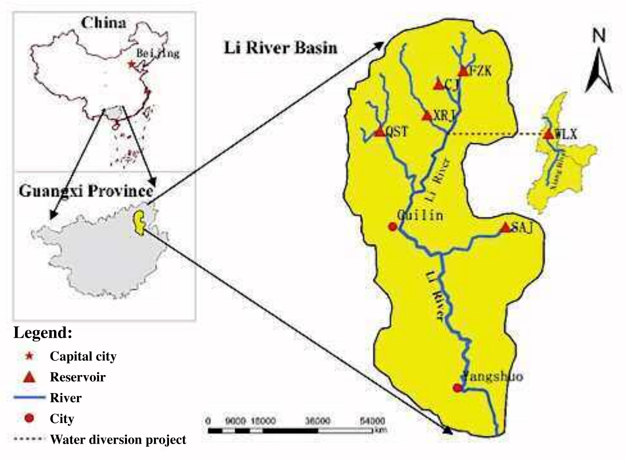

Figure 1. Location of Li River Basin in China

What kinds of reservoir operation rules were used to achieve joint operation?

To guide the multi-reservoir operation with joint water demand, the aggregation technique is used to simplify multi-reservoirs into a virtual reservoir and the type of corresponding operating rules is based on the hedging mechanism. Then a decomposition technique is used to guide the operation of each individual reservoir.

The problem of how much water to withhold from immediately beneficial deliveries, retaining that water in storage, is known as ''hedging''[3]. The philosophy behind a hedging mechanism is that hedging is triggered to conserve water for future use when the reservoir water-supply capability falls into a specified range. For the widely used two-point HR, it consists of two parameters, namely the starting water availability *(SWA)* and ending water availability *(EWA)*. When water availability *(WA)* is between *SWA* and *EWA*, the HRs are triggered; Otherwise, SOP is used [4-5]. To adapt to the uneven-distributed runoff between months, time-varying HRs are used. Each month has its own HR. Meanwhile, considering the limited maximum damage depth constraints, another parameter called the damage depth index *(DDI)* is introduced into the HRs to control the acceptable level of damage. Correspondingly, there are two cases of HRs in month t: (1) Case I occurs when $0 \le (1-DDI_t)\cdot D_t \le SWA_t$ (Fig. 2(a)); while Case II occurs when $SWA_t < (1-DDI_t)\cdot D_t < D_t$ (Fig. 2(b)).

Case I:

$$R_t=\begin{cases} WA_t & \text{if } WA_t < SWA_t, \\ D_t+(SWA_t-D_t)\dfrac{WA_t-EWA_t}{SWA_t-EWA_t} & \text{if } SWA_t \le WA_t \le EWA_t, \\ D_t & \text{if } EWA_t \le WA_t < D_t+C, \\ WA_t-C & \text{if } WA_t \ge D_t+C. \end{cases} \quad (1)$$

Case II:

$$R_t=\begin{cases} WA_t & \text{if } WA_t < (1-DDI_t)D_t, \\ (1-DDI_t)D_t & \text{if } (1\text{-}DDI_t)D_t \le WA_t \le EWA_t-DDI_t\cdot D_t\dfrac{SWA_t-EWA_t}{SWA_t-D_t}, \\ D_t+(SWA_t-D_t)\dfrac{(WA_t-EWA_t)}{SWA_t-EWA_t} & \text{if } EWA_t\text{-}DDI_t\cdot D_t\dfrac{SWA_t-EWA_t}{SWA_t-D_t} \le WA_t < EWA_t, \\ D_t & \text{if } EWA_t \le WA_t < D_t+C, \\ WA_t-C & \text{if } WA_t \ge D_t+C. \end{cases} \quad (2)$$

where R_t is the total release of the aggregated reservoir at time t; SWA_t and EWA_t are the starting and ending water availability of the aggregated reservoir at time t; D_t is the water demand for the water-supply system at time t; and DDI_t is the damage depth index, indicating the rate that the water demand are not satisfied. The range of DDI_t is [0, 1], where $DDI_t=0$ indicates that no hedging is allowed and SOP is used to guide the operation, while $DDI_t=1$ indicates that no water is released. $C=\sum_{i=1}^{n} C_i$ is the total active capacity of all reservoirs.

How to coordinate multi-objective relationship?

The aggregation-decomposition technique is used to guide the joint operation of the multi-purpose multi-reservoir system, and a hierarchical multi-objective optimization model is proposed according to the priorities of different objectives. The outer optimal model based on the aggregation technique is used to decide the total release of the system, and thus the objectives with high priorities are considered in this model to ensure the long-term benefit of the primary operating task; while the inner optimal model based on the decomposition technique is used to allocate the limited total release to individual reservoirs to maximize the secondary objectives. For the reservoir operation problem in Li River Basin, the outer optimal model is used to ensure the priority of the water supply, the objective of which is to minimize maximum water deficit and maximize water supply reliability. This is a typical multi-objective optimization problem that can be solved using Non-domination Sorting Genetic Algorithm (NSGA-II). The inner optimal model is used to maximize the total profit of individual reservoirs for each period, which can be solve by (Genetic Algorithm) GA or Dynamic Programming (DP).

Reservoir joint operation for Li River water-supply system

To demonstrate the advantage of the proposed operating rules, the results of aggregated HRs are compared with those of aggregated SOP and conventional rules (CRs) in terms of the water supply reliability (WSR), maximum water deficit (MWD) and hydropower generation.

Table 1 shows the results of the three rules in the training and testing periods. The selected aggregated HRs could improve the two water-supply objectives of CRs, and decrease the MWD of the aggregated SOP significantly by slightly sacrificing WSR in both the training and testing periods. In addition, the total annual power generation of the reservoir system is improved by the aggregated HRs in both periods. The power generation obtained by the aggregated HRs is always higher than that obtained by the aggregated SOP; and the power generation obtained by the aggregation-decomposition model (aggregated HRs or SOP) is higher than that obtained by CRs for all reservoirs except for XRJ and SAJ. Fig. 3(a)-(b) show the monthly average storage and output process of the aggregated reservoir. Fig. 3(a) clearly shows that the storage of the aggregated HRs is always greater than

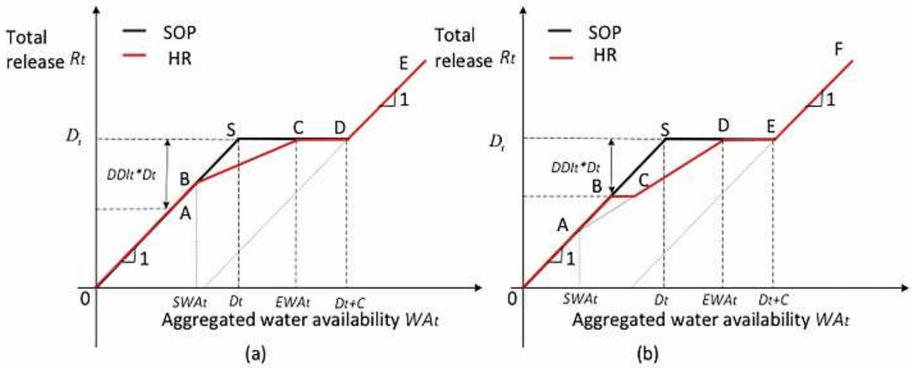

Figure 2. Improved HRs of aggregated reservoir considering the damage depth: (a) case I; (b) case II

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***Qiaofeng Tan*, PhD student from Sichuan University. She has been engaged in joint operation of cascade reservoirs, optimization and utilization of basin water resources, and high efficiency solution algorithms.**

that of the aggregated SOP and CRs due to the use of hedging mechanism which could retain water for future use. Generally speaking, the more the water is stored in reservoirs, the more the hydropower may be generated in the future because of the higher water head. Thus, the output of the aggregated HRs is higher than that of other schemes in most months (see Fig.3(b)).

In conclusion, the aggregated HRs are superior to the other two rules for both water supply and hydropower generation because of the use of the hedging mechanism and the optimal water allocation of the release among reservoirs. ■

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Option		Training period CRs	 Aggregated SOP	 Aggregated HRs	Testing period CRs	 Aggregated SOP	 Aggregated HRs
Water supply reliability(%)		91.04	98.95	95.00	91.23	98.68	94.30
Maximum water deficit (m3/s)		30.98	39.28	8.23	31.21	41.04	9.89
Annual power generation (10^8 kw.h)	FZK	0.4931	0.5305	0.5382	0.4935	0.5355	0.5378
	CJ	0.2631	0.2673	0.2692	0.2632	0.2662	0.2684
	XRJ	0.6414	0.5928	0.5980	0.6399	0.5939	0.5965
	WLX	0.2622	0.2806	0.2830	0.2610	0.2790	0.2794
	QST	0.6568	0.6673	0.6680	0.6570	0.6650	0.6717
	SAJ	0.2322	0.2135	0.2180	0.2340	0.2130	0.2172
	System total	2.5488	2.5520	2.5744	2.5486	2.5526	2.5710

Table 1. Comparison of operation results of different operation rules

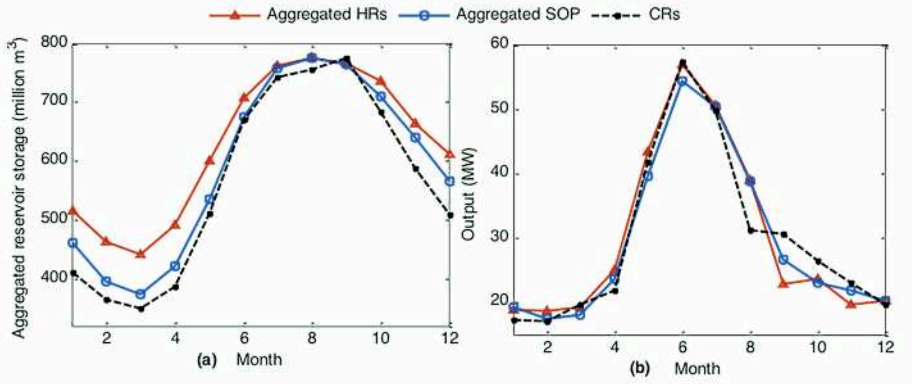

Figure 3. Monthly average operating process of the aggregated reservoir: (a) storage; (b) output

CO-OPTED COUNCIL MEMBERS

IAHR would like to welcome the new co-opted Council Members for the term 2017-2019

Dr. Damien Violeau
Senior Scientist, Laboratoire National d'Hydraulique et Environnement, EDF R&D
FRANCE

Damien Violeau has been working since 1997 at the Laboratoire National d'Hydraulique et Environnement of EDF R&D, where he was appointed Senior Scientist in 2013. He is also involved in the Laboratoire d'Hydraulique Saint-Venant, created in 2006. His main activities are the development of the Smoothed Particle Hydrodynamics (SPH) numerical method and the design of coastal waterworks, with an additional contribution to turbulent processes in the environment. He compiled his work on Theoretical fluid mechanics, SPH and its application to waterworks in a 600+ page book published by Oxford University Press in 2012. Besides his research activities, he developed a long and fruitful teaching experience, as lecturer in several engineering colleges in France, in particular Ecole des Ponts ParisTech, where he has been teaching Fluid Mechanics since 1998. Damien was introduced to IAHR in 2003, first as a member of the Hydroinformatics Section, then as a member of the Maritime Section (now Committee on Coastal and Maritime Hydraulics) where he was secretary from 2006 to 2007. He participated to the Biennial congresses since then, as well as many other IAHR congresses, as speaker, chairman and organizer of special sessions. He is also a regular reviewer of JHR, and was appointed Associate Editor in January 2015. He was co-opted member of the Council in 2013 and participated to the Council meeting in Porto that year. Since then, he started to think about the way to improve the links between Industry and Academia in IAHR. He also built a new YPN, the Paris IAHR YPN, officially started at the end of 2014; he is the YPN advisor.
Damien has also been member of ERCOFTAC and is member of the French Hydro Society (SHF). In 2005, he created the SPH European Research Interest Community which he chaired until 2009.

Hajime Nakagawa
Professor of Disaster Prevention Research Institute and Director
Kyoto University
JAPAN

Hajime Nakagawa is the Professor and the Director of the Disaster Prevention Research Institute (DPRI) of Kyoto University and is also the Director of the Ujigawa Hydraulics Laboratory attached to DPRI. He currently serves as the Secretary General of the Japan Chapter of IAHR. He has been involved in development of hazard maps for overland flood flow and debris for the prevention and mitigation from the water and sediment related disasters. He also currently serves as a Vice-President of World Association for Sedimentation and Erosion Research (WASER).

Nor Azazi Zakaria
Director and Founder of River Engineering and Urban Drainage Research Centre (REDAC)
Director of Engineering Campus, University Sains Malaysia
Professor of Civil Engineering
IAHR-APD Executive Committee
Scientific Expert Panel for Prime Minister's Science Advisor
Professional Congress Organiser of 37th IAHR World Congress
MALAYSIA

Nor Azazi has served in Universiti Sains Malaysia (USM) since 1994. He then established the River Engineering and Urban Drainage Research Centre (REDAC) in 2001 and has since remained as the Director. REDAC is the first research centre in USM Engineering Campus accorded as the Higher Institution Centre of Excellence (HICoE) in Service Thrust on Stormwater Management niche area.
Nor Azazi's main research interests are Sustainable Urban Drainage Systems and River Management. He is the leading researcher in the innovation of Bio-ecological Drainage System (BIOECODS), and is now an established figure in the field of stormwater management at national and international level. He is the Executive Committee for Malaysian National Committee on Irrigation and Drainage (MANCID) and Malaysia Stormwater Organization (MSO), as well as IAHR APD.