Allocating water storage of multiple reservoirs to enhance empty flushing

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Abstract

The development of Nan-Hau Second Reservoir is currently at the stage of feasibility planning. It aims to provide adequate water to enhance hydraulic flushing of the existing downstream Nan-Hau Reservoir, to allow the entire tandem reservoir system advancing toward sustainable utilization. This paper studies the joint operation strategy of both reservoirs for steady water supply and optimal schedules of empty flushing. The joint operating rule curves are derived to enhance reservoir desilting by empty flushing while ensure achieving specific firm yield of water supply.

Keywords: reservoir desilting, empty flushing, water supply, joint operation of multiple reservoirs

1 Introduction

Nan-Hau (NH) Reservoir is situated on the Hoku Creek, a tributary of the Tsengwen River in southern Taiwan. It stores the surplus streamflow from the Hoku Creek and the trans-basin diverted water from the adjacent ChiSan Creek to jointly supply the public demands of Tainan and Kaoshiung districts. The current yield of public water supply by NH Reservoir is 0.5 million m^3/day. The original designed capacity of NH reservoir was approximately 158 million m^3, and it has currently declined to 96.89 million m^3, due to the severe sedimentation primarily contributed by Typhoons Kalmaeigi in 2008 and Morakot in 2009.

In order to alleviate the sedimentation problem, a sluicing tunnel is currently constructed in the impounding area of NH Reservoir to enhance the venting of sediments during floods. The designed sluicing capacity is 1,000 m^3/s. An additional upstream reservoir, Nan-Hau Second (NHS) Reservoir, is currently under planning. It aims to provide more adequate water to enhance hydraulic flushing of the existing NH Reservoir to recover the desilted storage. A submerged dam immediately downstream from the intake of the under-construction sluicing tunnel is also planned to create sufficient backup storage during sediment venting. The submerge dam divides the storage of NH Reservoir into three portions. The zone above the top of submerged dam is termed as the Above Submerged Dam (ASD) portion. The zones below the top of submerged dam include the one that is downstream to the dam of NH Reservoir and the other that is upstream to the dam of the NHS Reservoir. These are termed as the Downstream and Upstream

Submerged Dam portions (DSD and USD) respectively. A gated tunnel is designed in the submerged dam to allow water transmitting from USD to the DSD during regular periods. The gate will be closed when the reservoir initiates hydraulic flushing or sediment venting, during which storage in the DSD backups water supply and the sediments are expected to be vented through the sluicing tunnel and bypass DSD. This paper studies the joint operation strategy of both reservoirs for steady water supply and optimal schedules of empty flushing. Table 1 lists the volume of ASD, USD and DSD corresponding to different height of submerged dam. Figures 1 and 2 show the map and schematic of this joint operation system.

Table 1: The volume of ASD, USD and DSD corresponding to different height of submerged dam

The height of submerged dam (El.m)	The volume of DSD (million m^3)	The volume of USD (million m^3)	The volume of ASD (million m^3)
165	32.00	2.93	61.96
170	43.00	9.08	44.81
175	60.30	12.84	23.80
178	70.00	17.18	9.71

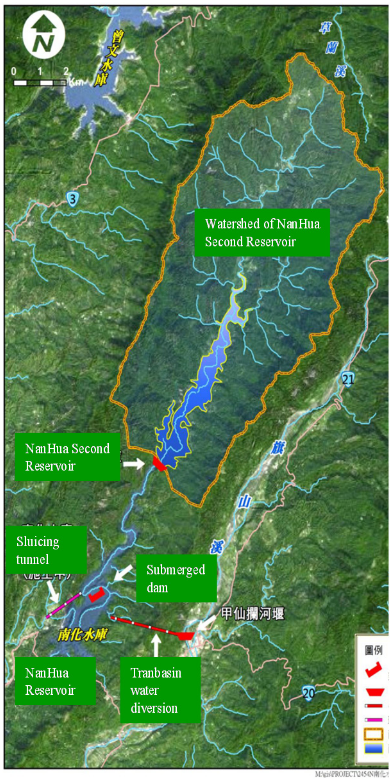

Fig. 1: Map of Nan-Hau and Second Nan-Hau Reservoirs system

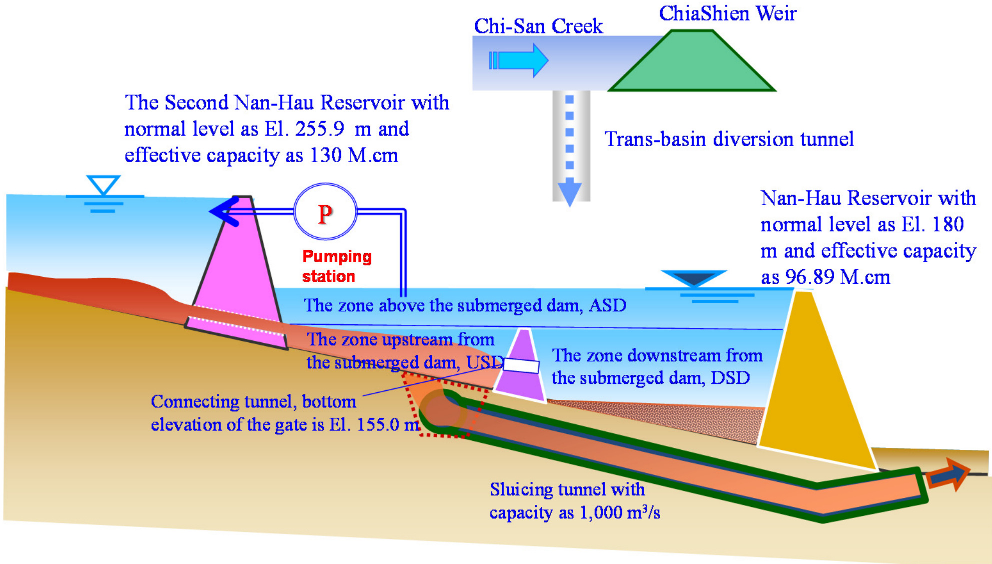

Fig. 2: The schematic of Nan-Hau and Second Nan-Hau Reservoirs system

2 Methodology

2.1 water supply simulation

This study uses GWASIM (Chou and Wu 2010), a generalized water supply allocation model, to simulate daily joint operations of the NH and NHS Reservoirs and the corresponding water resources system. GWASIM, developed based on network flow programming, incorporates required operational characteristics of water resources systems. It is capable of simulating reservoir operating rule curves, peak hydro generation, return flows, environmental instream flow requirement, limited treatment plant capacities imposed by high turbidity of raw water, water transmitting and treatment loss, joint operating rules of a multi-reservoir system, channel routing effect, and conjunctive use of surface water and groundwater. It has already been applied in planning and management analysis for every major water resources system in Taiwan.

The simulation is performed using historical reservoir inflow series according to specific operating rules. The firm yields of water supply (WSY) for different developing or operating scenarios are simulated. WSY represents the water supply capabilities of a water resources system under a specific shortage criterion. The adopted shortage criterion is the shortage index, SI:

$$SI = \frac{100}{NY}\sum_{i=1}^{NY}\left(\frac{DF_i}{DY_i}\right)^2 \quad [1]$$

where, SI = shortage index for the demand of interest, NY = the number of years in the simulation horizon of GWASIM, DY_i = total water demand in the i-th year, DF_i = total water deficits in the i-th year simulated by GWASIM. The WSY of a water resources system is estimated by adjusting the water demand until the simulated SI equals to an acceptable value specified by authorities.

2.2 Scheduling of empty flushing and estimating flushed sediment discharge

In this system, the schedule of empty flushing is designed to be embedded with the joint operating rule curves of NH and NHS reservoirs. The upper limit of the curves specifies the amount of storage is adequate for following water supply, the surplus storage above the upper limit thus can be released to create favorable conditions for empty flushing. During the regular operation of water supply, the storage of ASD will be first consumed for public water supply. If the ASD is empty and the water surface level of NH Reservoir is at the top of the submerged dam, then the storage of NHS Reservoir is released for water supply, thus preserving the storage of NH Reservoir below the top of the submerged dam. Once the total storage of two reservoirs surpasses the upper limit of the joint operating rule curves, the operation is switched to empty flushing. The water-transmitting gate on the submerged dam is first closed and the water supply will be solely provided by the DSD. The gate of the sluiceway of NH Reservoir will then be opened to drawn down and empty the USD. Once the USD is emptied, the NHS Reservoir will then release its storage to flush the emptied thalweg of the USD and the flow is vented downstream through the sluiceway and bypasses the DSD. If the NHS Reservoir is also emptied, empty flushing of NHS and USD is sequentially performed, until the remaining storage in DSD falls below the upper limit of rule curves.

During empty flushing, the empirical formula developed by the International Research and Training Center on Erosion and Sediment (IRTCES) in Tsinghua University, Beijing (IRTCES 1985) is employed for the estimation of releasing sediment discharge from the USD and NHS Reservoir. The formula is based on measurements from 14 reservoirs in China:

$$QC_t = \psi \frac{Q_t^{1.6} S_f^{\ 1.2}}{W^{0.6}} \tag{2}$$

where QC_t and Q_t denote the sediment discharge (T/s) and water discharge (m^3/s) flushed from the primary reservoir during the t-th simulating day, respectively; S_f represents the energy slope associated with the flow in the primary reservoir during empty flushing; W is the width of the flushing channel (m), which can be estimated using the empirical formula $W = 12.8 \cdot Q^{0.5}$ (Atkinson 1996), and ψ is the flushing coefficient, associated with the characteristics of the sediment and topography of the reservoir.

Nonlinear optimization is employed to determine the optimal upper limit, with the objective function as maximizing the desilting volumes from NHS Reservoir and USD. The constraint of optimization is to achieve specific water supply yield.

3 Analysis and discussion

The water supply simulation includes not only the joint operation of NHS and NH Reservoirs, but also the involved adjacent KaoPing River Basin. Figure 3 shows the network schematic of the established water resources system. Six cases with different combinations of facilities, as listed in Table 2, are simulated. The simulated WSYs of these cases are listed in Table 3. It shows that the addition of NHS Reservoir into the joint operating system could elevate the WSY from 0.600 to 0.946 million m^3/day, if the storage of NHS Reservoir is fully preserved for water supply.

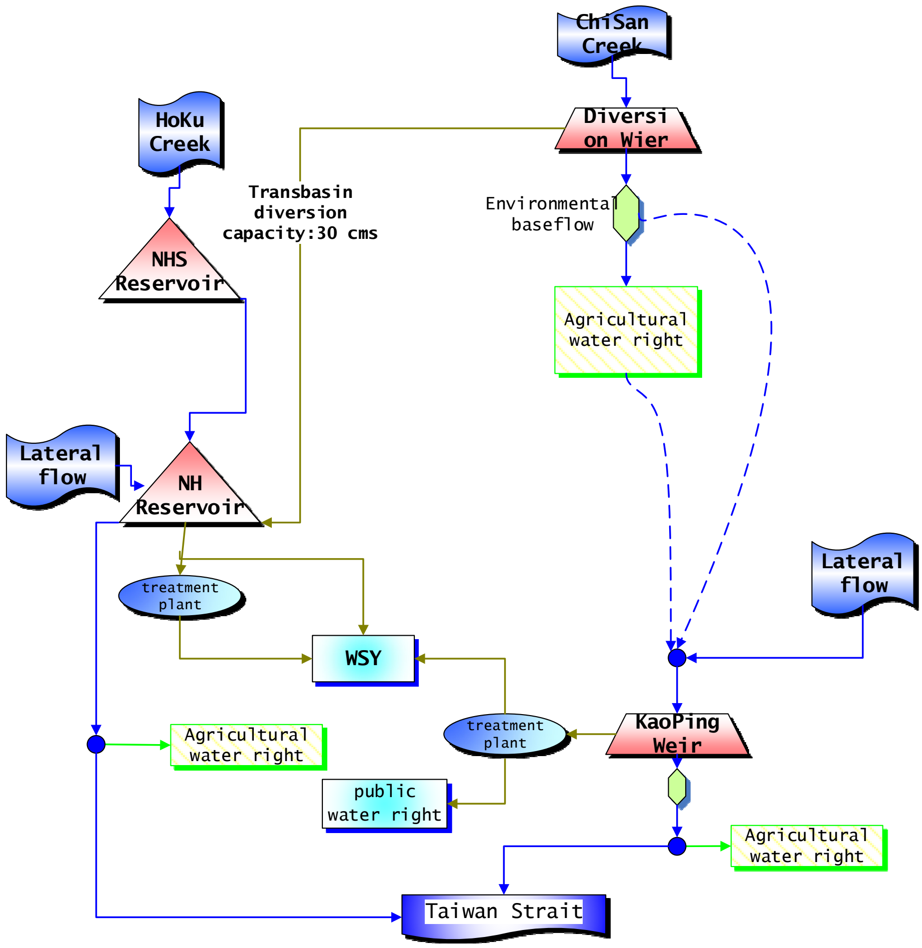

Fig. 3: The schematic of Nan-Hau and Second Nan-Hau Reservoirs system

Table 2: Simulated cases

cases	Involving facilities
1	Nan-Hau Reservoir
2	Nan-Hau Reservoir and trans-basin diversion from Chi-San Creek
3	Nan-Hau Reservoir, trans-basin diversion from Chi-San Creek and surplus re-allocation from KaoPing Weir
4	Case 1+ Nan-Hau Second Reservoir
5	Case 2+ Nan-Hau Second Reservoir
6	Case 3 + Nan-Hau Second Reservoir

Table 3: Simulated WSYs of different cases without empty flushing

Case number	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Simulated water supply yield (million m^3/day)	0.334	0.526	0.600	0.469	0.830	0.946

Table 3 shows the water yield of the joint operating system, without consideration of desilting operations. The implemented desilting operations of this system include sediment venting during floods and empty flushing, while this study focuses on the latter of which. Since emptying the storage of reservoir essentially conflicts with the water conservation purpose, an optimal strategy for empty flushing should maximize the desilting volume while maintaining the water supply yield at an acceptable standard. Six different water supply yields (0.6, 0.7, 0.75, 0.8, 0.85, 0.9 million m^3/day) and four different possible heights of the submerged dam (165, 170, 175, 178 El.m) are analyzed to generate 24 combinations, each of which corresponds to a specific set of optimal upper limit, desilting volumes and schedules for empty flushing. The optimized results are tabulated in Table 4. Figure 4 depicts the optimized upper limit and the simulated storage trajectories of simulated years for the scenario of WSY as 0.8 million m^3/day, height of submerged dam as 175 El.m.

4 Conclusions

This study aims to optimize the performance of empty flushing in a multi-reservoir system. Prior to empty flushing, the total available storage in a system is allocated to create favorable initial conditions and prepare backup water to be supplied during empty flushing. The activation and termination conditions of an empty flushing operation are determined according to whether backup storage satisfies applicable rule curve or not. Optimization analysis calibrates these rule curves to maximize the desilting volume without inducing intolerable water shortage.

Table 4: The performances of optimal upper limits corresponding to different heights of submerged dam

The height of submerged dam (El.m)	Water supply yield (million m^3/day)	Annual desilting volume of Nan-Hau Second Reservoir by empty flushing (million ton/year)	Annual desilting volume of DSD Reservoir by empty flushing (million ton/year)	Optimized schedules for empty flushing (ten-day)
165	0.60	2.65	4.73	15th ~23 th
165	0.70	1.77	3.54	15 th ~20 th
165	0.75	1.64	3.01	15 th ~19 th
165	0.80	1.29	2.56	15 th ~18 th
165	0.85	1.06	2.08	15 th ~17 th
165	0.90	0.85	0.47	15 th ~16 th
170	0.60	2.93	5.00	15 th ~23 th
170	0.70	2.35	4.30	15 th ~21 th
170	0.75	1.78	3.71	15 th ~19 th
170	0.80	1.57	3.02	15 th ~18 th
170	0.85	1.38	2.46	15 th ~17 th
170	0.90	1.08	1.73	15 th ~16 th
175	0.60	3.22	5.30	15 th ~23 th
175	0.70	2.82	4.32	15 th ~22 th
175	0.75	2.55	3.45	15 th ~21 th
175	0.80	1.90	2.66	15 th ~19 th
175	0.85	1.68	2.50	15 th ~18 th
175	0.90	1.32	1.43	15 th ~16 th
178	0.60	3.25	6.06	15 th ~23 th
178	0.70	2.99	4.15	15 th ~22 th
178	0.75	2.55	3.45	15 th ~21 th
178	0.80	2.24	2.72	15 th ~20 th
178	0.85	1.89	2.18	15 th ~18 th

The operators of major reservoirs in Taiwan are currently very conservative regarding empty flushing, probably due to the high pressure of water shortage, even though reservoir sedimentation imposes a more severe threat in the long term. Nonetheless, this perspective might change while the need of desilting becomes more urgent in the future. This urgent need also endows a new role to the conventional projects of water resources development. In addition to elevating the yield of water supply, it also provides more adequate water to allow recovery and enhanced desilting of existing reservoirs, thus allowing the entire system to advance toward the goal of sustainability.

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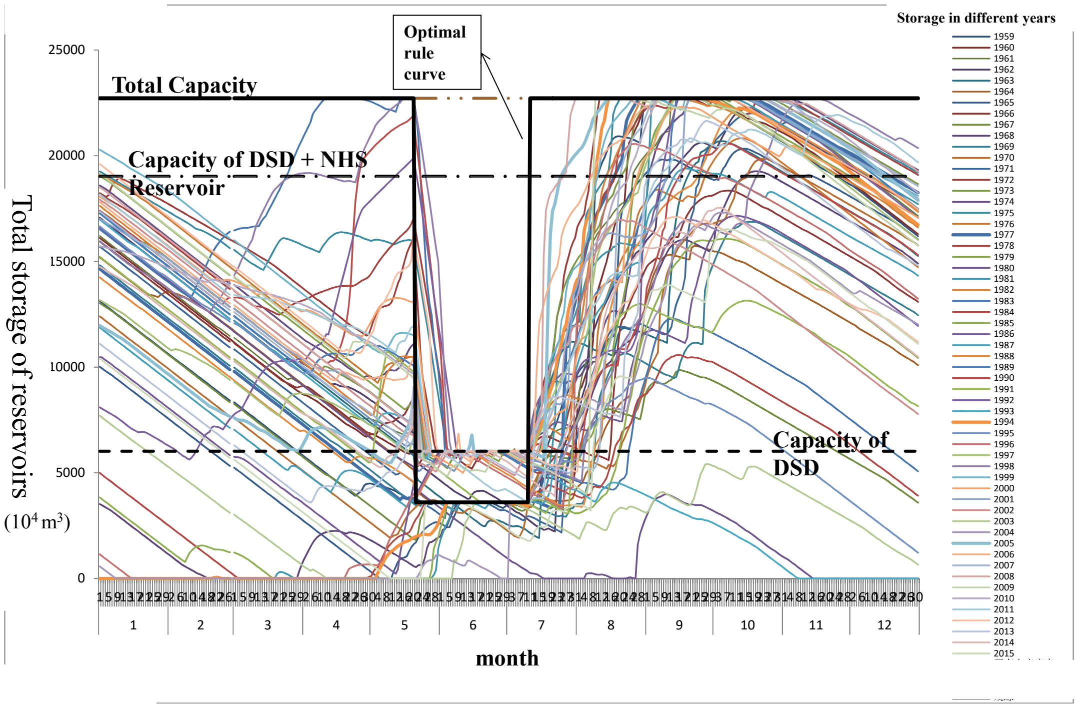

Fig. 4: The optimal rule curve for the scenario of WSY as 0.8 million m^3/day and height of submerged dam as 175 El.m

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