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Proposing Adjustments to the Dry Season Inter-Reservoir Operation Rules of the Red River System to Improve Water Use Efficiency of the Reservoirs

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Abstract

The Red-Thai Binh River system is an important water resource to the Northern Delta, serving the development of agriculture, people's livelihood and other economic sectors through its upstream reservoirs and a system of water abstraction works along the rivers. However, due to the impact of climate change and pressure from socio-economic development, the operation of the reservoir system according to Decision No. 740/QD-TTg was issued on June 17, 2019 by the Prime Minister of Government promulgating the Red-Thai Binh River system inter-reservoir operation rules (Operation rules 740) has some shortcomings that need adjustments for higher water use efficiency, meeting downstream water demand and power generation benefits. Through the results of water balance calculation and analysis of economic benefits from water use scenarios, this research proposed adjustment to the inter-reservoir operation during dry season in the Red River system. The result showed that an average water level of 1.0 - 1.7 m should be maintained at Hanoi during the increased release period.

Keywords

Inter-Reservoir Operation Adjustment, Operation Rules, Reservoirs, Red-Thai Binh River Basin

1. Introduction

The Red-Thai Binh River system has a total annual runoff of 135 billion·m^3, accounting for 16% of Vietnam's total water volume (MONRE, 2012; Luu et al., 2010). This is an important water resource of the Northern Delta, which is located in the political, cultural and economic center of the country and the second largest rice bowl of Vietnam (Thien, Phuong, & Huong, 2022). Given such importance, a system of hydraulic works has been built on the Red-Thai Binh River system, with a total number of 11,562 works of all kinds, including 8932 pumping stations, 2070 sluices, 338 reservoirs and 156 weirs (MARD, 2022b). The hydraulic work system proves its efficiency in meeting the water demand for agriculture and people's daily life, in addition to the benefits of electricity generation, flood prevention for downstream, navigation, tourism and other economic sectors (Ha et al., 2023).

Currently, climate change along with extreme weather phenomena, and the strong economic development accompanied by the process of urbanization, have caused the water resources to decline while the water demand has been increasing both in quantity and quality (Ha et al., 2018). Activities of exploiting water and other resources for economic development have also caused fluctuations in the water resources in the river system, from the decreasing flow, lowering water level, and instable riverbed to pollution in irrigation and drainage systems, etc. The water level lowering in downstream reaches is more and more frequent and unceasing (Simons et al., 2016). The energy sector has had to partially reduce its electricity benefits to increase water release from reservoirs at some periods of time, but it is still difficult to abstract water downstream. The water release from the reservoirs is increasing but the downstream water level is even decreasing (Le et al., 2005).

The inter-reservoir system in the Red River Basin consists of seven reservoirs, i.e., Lai Chau, Ban Chat, Huoi Quang, Son La, Hoa Binh, Thac Ba, and Tuyen Quang (Giuliani et al., 2016) with a total active storage capacity of 18.8 billion·m^3, and is operated according to the provisions of the Decision 740/QD-TTg (see **Figure 1** and **Figure 2**).

The Hoa Binh, Thac Ba, Tuyen Quang reservoirs annually supplement with 2 - 3 times of water release in a period of 15 - 18 days, with a total volume of about 3 billion·m^3 (in the years 2009-2012) and about 5 billion·m^3 from 2013 to present, except for some years with higher rainfall (**Figure 3**) to the downstream of the Red-Thai Binh Rivers to serve the rice planting of about 530,000 ha of winter-spring crop (MARD, 2021).

Analysis of surveyed data and the practical operation of the reservoir system in recent years show that the operation of the reservoirs does not meet the requirements of the Operation Rules 740, specifically at the following points:

- During the period of increased release: Although the reservoirs operated all of their turbines with the total discharge of 3600 m^3/s (Hoa Binh with 8 turbines × 300 m^3/s; Thac Ba with 3 turbines × 150 m^3/s, and Tuyen Quang with 3 turbines × 250 m^3/s) but the water level at Hanoi could not be maintained continuously at 2.2 m as required by the operation rules (see **Figure 4**). The water level at Hanoi can only be kept even at an average of over 1.3 m (in 2021) and 1.8 m (in 2020) during the period of increased release.

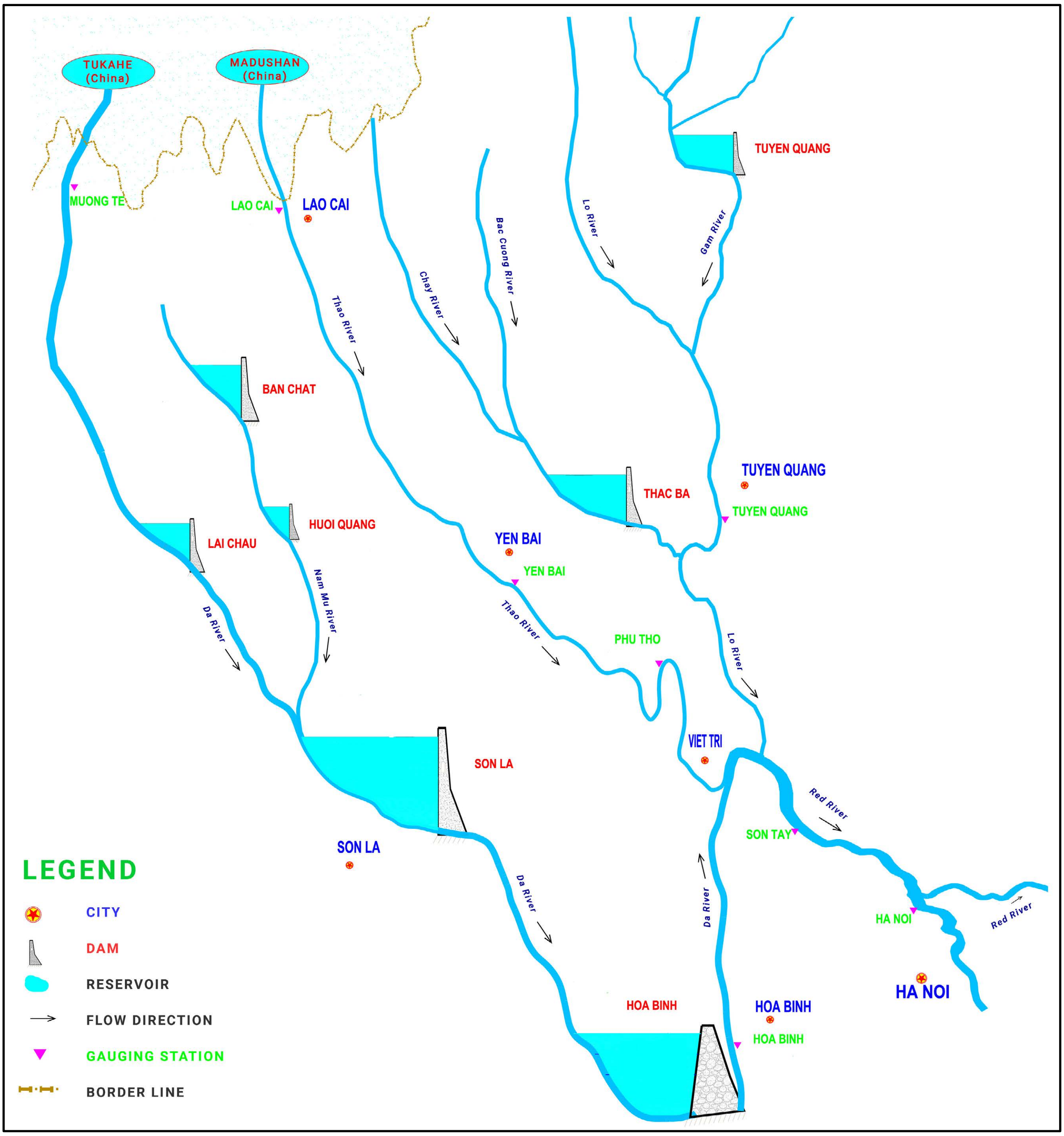


Figure 1. Schematic of the Red-Thai Binh River basin inter-reservoir system.

- During the rest of the dry season, although the reservoirs have been released according to the rules, the water level at Hanoi in most of the months from January to mid-April cannot reach 1.4 m. The low water level is about 0.5 m in the dry season.

As a result, in order to rationally and optimally operate the upstream reservoir system, to ensure the simultaneous service of downstream water demand, to limit conflicts between the agricultural sector and the hydropower industry,

Reservoir	Thac Ba	Tuyen Quang	Hoa Binh (SL, LC, BC, HQ)
Periods of increased water demand			
Common requirement	Number of release periods ≤ 3 - Number of release days ≤ 21 - $H_{HN} \geq 2.2$m		
$Q_{\text{min daily average}}$	280 m^3/s	500 m^3/s	H_{HN}
Periods of normal water demand			
• Duration: 16÷30 Sept and 01÷14 June			
$Q_{\text{min daily average}}$	Proactive operation	Proactive operation	214 m^3/s
• Duration: 01 Oct ÷ 31 May			
$Q_{\text{min daily average}}$	61 m^3/s	• $H_{TQ-1} < 15.85$m release at 94m^3/s • $H_{TQ-1} \geq 15.85$m proactive operation	• $H_{HN-2} < 1.4$m: October: 300 m^3/s November: 600 m^3/s December and January: 700 m^3/s February and April: 800 m^3/s March and May: 600 m^3/s • $H_{HN-2} \geq 1.4$m release at 214 m^3/s

Figure 2. Summary of the dry season inter-reservoir operation rules.

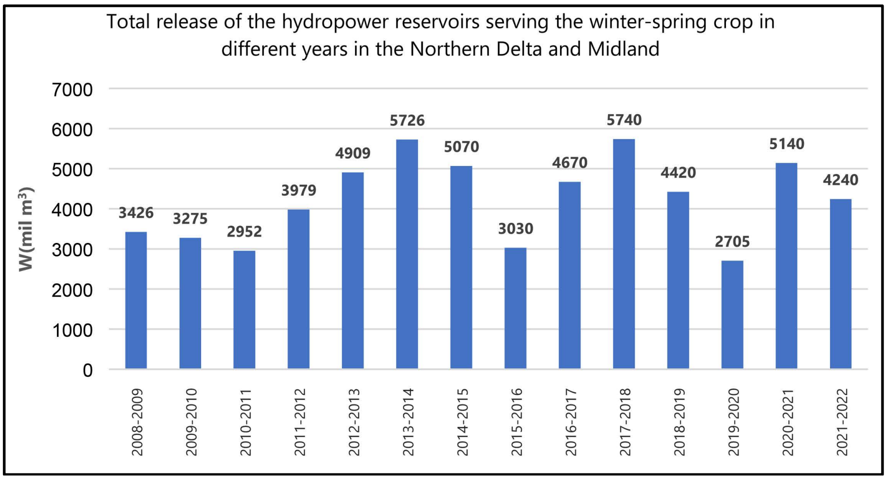


Figure 3. Total release increases from the reservoirs serving the winter-spring cropping season from 2008 to 2022.

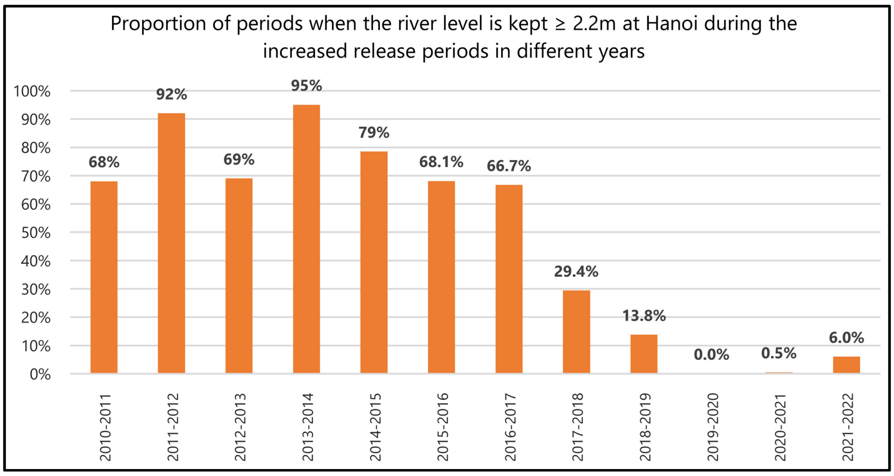


Figure 4. Proportion of periods when the river level is kept above 2.2 m at Hanoi.

Operation rules 740 needs to be adjusted some content towards an integrated approach (wide-basin scope; harmonizing the benefits of all water-using sectors; considering both structural and non-structural solutions; towards the complete remedy of existing problems). In comparison to earlier studies, this approach is thought to be novel.

2. Methodologies and Approaches

To determine the scope of adjustment of the rules, the research team made calculations using a hydraulic model and a water balance model with the inflow of 85% probability and the topography of the channels updated to 2021, based on different water release scenarios from the lowest to the highest discharge, including:

- Scenario 1 (KB1): Release at the base flow (no power generation)—selected as base scenario.
- Scenario 2 (KB2): Release at the electricity demand (no incremental release).
- Scenario 3 (KB3): Release at the 2021 practical situation but with a reduced discharge during the period of increased release, ensuring QSon Tay = 2500 m^3/s to prevent salinity intrusion.
- Scenario 4 (KB4): Release at the 2021 practical situation as the most recent year with the full power generation operation and the most accurate topographical data set.
- Scenario 5 (KB5): Release according to the operation rules.
- Scenario 6 (KB6): Release to meet the designed water level of the existing downstream works.

2.1. Description of the Water Use Systems

1) *Reservoirs*

The reservoir storage capacity varies from time to time and depends on inflow, evaporation, and release through the hydropower plants and via bottom outlets and spillways (Sokolov & Chapman, 1974). The reservoirs are described by the following water balance equations:

$$S_{t+1} = S_t + a_{t+1} - r_{t+1} - E_{t+1}$$

$$E_{t+1} = e_{t+1} S_{(St)}$$

$$r_{t+1} = R\left(S_t, u_t, a_{t+1}, e_{t+1}\right)$$

in which:

S_t, S_{t+1} (m^3): the reservoir storage capacity at time t and $t+1$.

a_{t+1} (m^3): the inflow including precipitation on the reservoir surface.

r_{t+1} (m^3): the release from the reservoir to downstream through turbines and spillways or bottom outlets; the release volume depends on storage capacity, inflow, release, evaporation of the reservoirs and the requirements of the operation rules.

E_{t+1} (m^3): the evaporation volume of the reservoirs in the time step t to $t+1$;

e_{t+1}: daily evaporation rate; $S_{(St)}$: the reservoir surface.

2) *Hydropower plants*

The three parameters, i.e., upstream and downstream water heads, discharge via turbines and energy production are related reflecting in the formula:

$$p = \frac{\gamma g \eta H q}{10^6}$$

in which:

p (MW): power generation capacity of the turbines.

H (m): difference of upstream and downstream water heads.

q (m^3/s): discharge via turbines.

γ water weight and g acceleration of gravity.

The turbine performance η can be presented as a function of (q, H) or (p, H); each type of turbines has its own specific routing hydrograph built to reflect the working scope and performance of the turbines.

The water balance model WEAP—a product of the Stockholm Environment Institute (SEI), is applied to depict the water use system at the upstream multi-purpose reservoirs including Son La, Hoa Binh, Thac Ba, and Tuyen Quang (**Figure 5**).

3) *Downstream water uses*

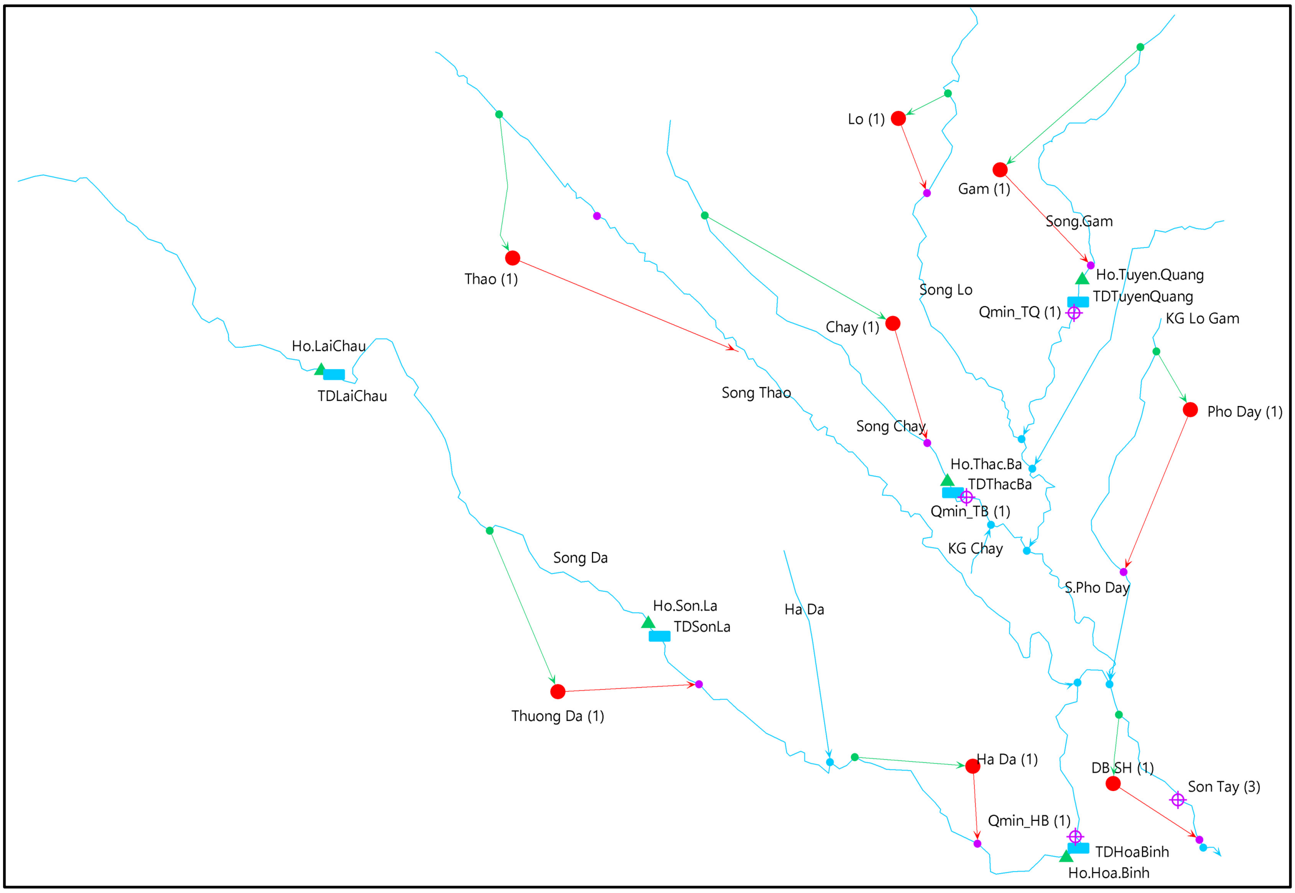


Figure 5. The water balance model of the Red River upstream reservoirs.

The Red-Thai Binh River Delta are one of the complex water transport and use systems. The system includes rivers, intake structures and canals in the hydraulic work systems.

- River flows:

The river water transport can be simulated by describing the system of Saint Vernant equations:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\alpha\frac{Q^2}{A}\right)}{\partial x}+gA\frac{\partial h}{\partial x}+\frac{gQ|Q|}{C^2AR}=0$$

in which:

Q: discharge;

A: areas where flows happen;

c: Chezy resistance coefficient;

R: hydrodynamic radius or drag;

Q: momentum distribution coefficient.

MIKE, the mathematical model developed by the Danish Hydraulic Institute (DHI) is used to simulate river flows. The dry season hydraulic model of the Red and Thai Binh river systems is simulated with 34 rivers and cross-sections updated to 2021; 13 upstream boundaries and 37 lateral-flows as flows from upstream and along the rivers; 9 downstream boundaries as the water level at the estuaries. Among the above 13 upstream boundaries are the releases from the 3 large-scale reservoirs including Hoa Binh, Thac Ba and Tuyen Quang (see **Figure 6**). The most important problem of the Red-Thai Binh River downstream is the fact that the river section is increasingly being incised, causing disequilibrium to the system and lowering the water level in most rivers.

- Water supply schemes:

There are 349 water intake structures that are simulated in the model, including sluices and pumping stations for 28 irrigation districts. The pumping stations are usually located behind the sluices under the dykes except for some submersible pumping stations that intake water directly from the rivers. The water intake flows of the structures depend on the dimension of the structures and the river water level, which is described as follows:

If $Z_s > Z_d$ then $Q = f(Z_s, Z_d, Q_{tk})$

On contrary $Q = 0$

In which:

Q (m^3/s): water abstraction discharge of the structure;

Z_s (m): Water level upstream of the structure (river water level);

Z_d (m): Water level downstream of the structure (on-farm water level);

Q_{tk} (m^3/s): Designed discharge of the structure corresponding to $Z_s = Z_{tk}$;

Z_{tk} (m): Designed water level of the structure;

Function f of each structure is built and described corresponding the to correlation $Q = f(Z_s)$ and incorporated into the model.

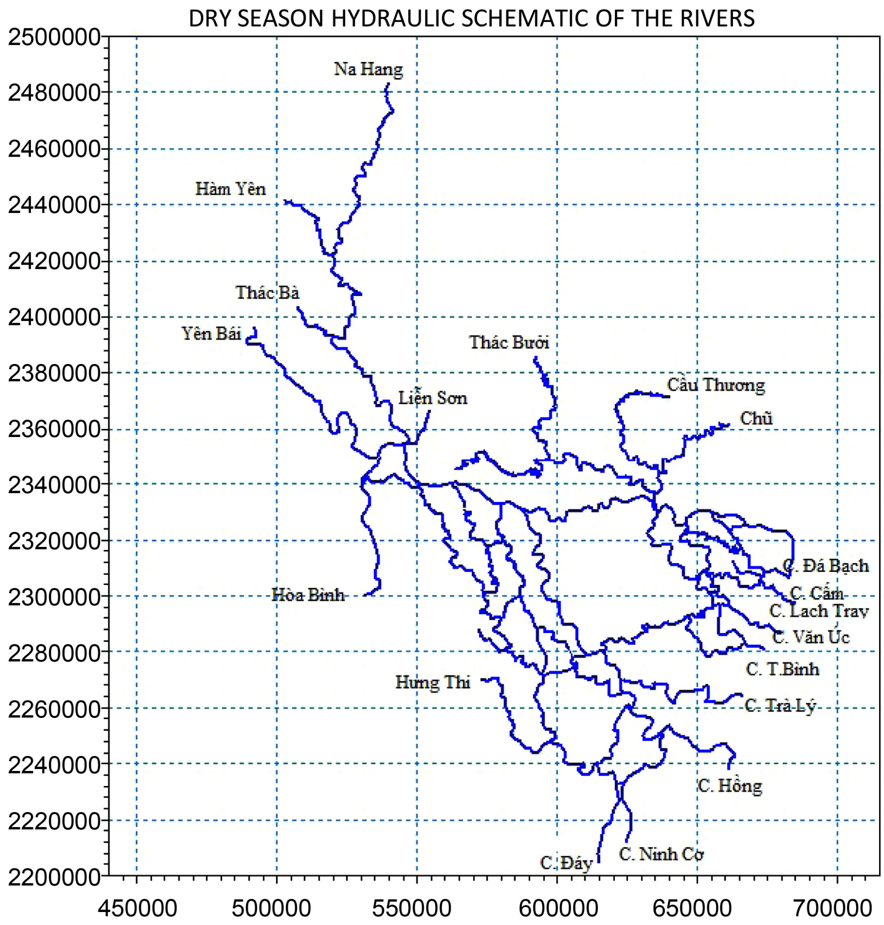


Figure 6. The river network in the hydraulic model of the lower Red-Thai Binh Rivers.

2.2. Setting Objective Functions for Inter-Reservoir Operation

1) *Hydropower*

Electricity of Vietnam (EVN) sets the goal of the industry as to operate and provide safe, stable and reliable electricity to the national power system, in not only ensuring energy security but also minimizing production costs.

Regarding the Red-Thai Binh River system, all relevant studies as well as practice prove that EVN's goal is to reduce the output of hydropower plants in the first months of the dry season to save water for the end of the dry season. The reason lies in the fact that although the water head is high at the beginning of the dry season, the electricity demand is not as high as at the end of the season. It is proved that at the end of the dry season most of the energy in the national power system is supplied by the thermal power plants, while the cost of hydropower generation is lower according to the data analysis from the electricity production plan of the year 2021 (MIT, 2020).

EVN's goal is to increase the economic efficiency of not only one power plant but the entire power system. To be able to analyze the economic efficiency, it is necessary to estimate the economic price of hydroelectricity over time of the year. The value of each KWh of electricity in each month varies due to the different supply-demand relationship of the months. The share of value per KWh generated by hydropower plants can be calculated based on the share of electricity produced each month of the year by all thermal power plants based on alternative cost method (**Figure 7**).

The economic price of hydroelectricity is calculated as follows:

$$c_i = \theta_i \cdot C$$

in which:

c_i: converted price of electricity of month i^{th}.

θ_i: the share of electricity generated in each month of all thermal power plants of month i^{th}.

C: the annual average price of electricity.

Given such approach, the converted monthly price of electricity varies from the lowest of about VND 1000 in February and September to the highest of about VND 1400 in May (**Figure 8**).

The hydroelectricity index applied in the study is the economic loss of energy produced in the year of 4 reservoirs: (Hoa Binh, Son La, Thac Ba, and Tuyen

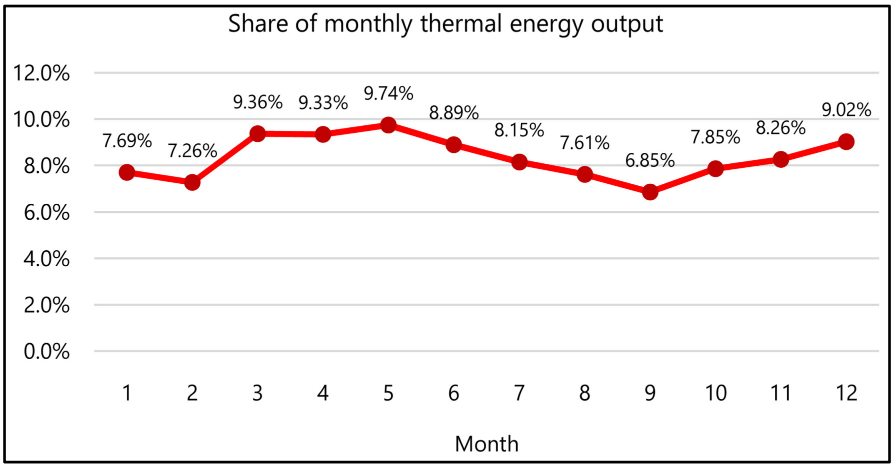


Figure 7. Share of monthly thermal energy output.

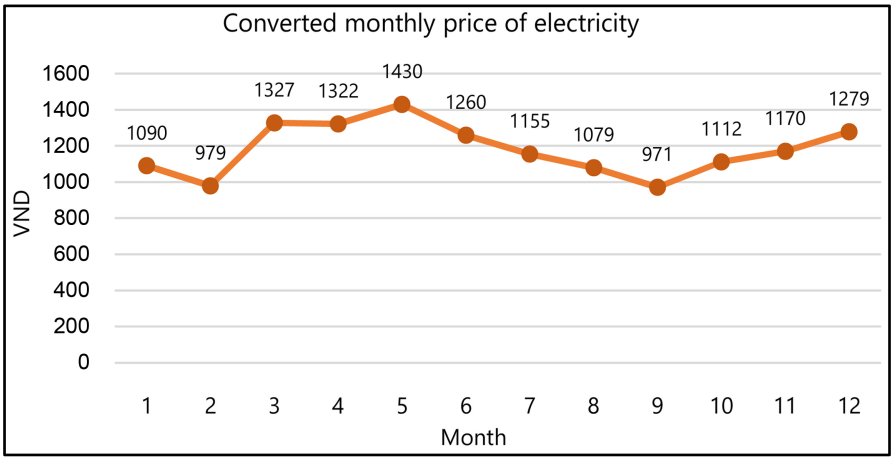


Figure 8. Economic value of electricity.

Quang), calculated as follows:

$$T_p = \sum_{i=1}^{12} c_i \cdot (D_i - E_i)$$

In which:

T_p: economic loss of electricity of the system in the year.

c_i: price of electricity at month i^{th}.

D_i: total electricity demand of the inter-reservoir system at month i^{th}.

E_i: total electricity output of the inter-reservoir system at month i^{th}.

2) *Water supply for agriculture*

Water supply for the winter-spring crop is the most stressful period due to the seasonal lack of rain, especially in January and February when most provinces simultaneously prepare land, and sow and plant rice. Although many structural measures such as rehabilitation of pumping stations and non-structural measures such as the development of an increased annual water release plan have been used, water shortages still occur frequently in recent years and tend to increase.

According to the design of the water abstraction system and the state of the river bed in the past (from 2004 backward), the water level of 2.5 m at Hanoi can ensure normal operation of the entire downstream water supply structures. However, in recent years, with the riverbed topography continuously changed and according to calculations from the hydraulic model, the water level at Hanoi must be 3.5 m to ensure water abstraction for the upstream of Hanoi.

The goal set by the Ministry of Agriculture and Rural Development is to provide irrigation water for the entire cultivated land, which not only ensures food security but also minimizes losses due to reduced agricultural output and irrigation costs. The irrigation industry index applied in the study is the economic loss of agricultural production:

$$T_a = \sum_{i=1}^{25} f(F_i, R_i, D_i)$$

In which:

T_a: losses to agricultural production due to irrigation water shortage downstream.

F_i: Agricultural land affected by water shortage.

R_i: Irrigation requirement of the irrigation district i^{th}.

D_i: Water volume supplied to the irrigation district i^{th}.

f: the function of productivity loss of each irrigation district depends on the water deficit in each development stages of crop. The function of productivity loss that simulated the linear relation of productivity, maximum crop yield coefficient and evapotranspiration, specifically as follows (Hanks & Hill, 1980):

$$1 - \frac{Y_a}{Y_m} = K_y \cdot \left(1 - \frac{Et_a}{Et_m}\right)$$

in which:

Y_a: actual crop yield.

Y_m: maximum crop yield.

K_y: crop yield coefficient during the growing stages.

Et_a: actual evapotranspiration.

Et_m: potential evapotranspiration.

3) *Domestic water supply*

Domestic water supply structures are designed at the probability of 95% (MARD, 2022a) that is higher than that of agricultural water supply structures (85%). The domestic water supply works have not been significantly affected when the river water level is low. However, since 2021, the water intake structures feeding for the Da River clean water plant (the water plant that supplies 700,000 m³/day for the western parts of Hanoi capital) has faced with difficulty intaking water. At the beginning of the dry season in 2022, the plant could not get water and had to build 2 temporary pumping stations to pump water from the deeper water in the middle of the river to the shore and then from the shore to the storage.

The water supply industry's objective is to ensure a stable water supply for people's daily life and especially in the Hanoi capital area, minimize damage caused by lowered river water level. The water supply sector index applied in the study is the economic loss of drinking water supply:

$$T_w = \sum_{i=1}^{n} d \cdot \left(D_i - W_i\right)$$

In which:

T_w: loss due to water shortage to the water plant.

n: number of water plants.

D_i: water demand of the water plant i^{th}, depending on the river water level.

W_i: Water volume that can be supplied to the water plant i^{th}.

d: unit price of bulk water.

4) *Navigation*

For navigation, the minimum water level required at Long Bien station is 1.1 m (MoT, 2009). The goal of the navigation industry is to ensure safety and limit disruption to navigation.

When the water level at Hanoi falls below the navigable threshold, the Ministry of Communication and Transport conducts dredging of the river bed in the most critical sections. The cost of this type of intervention depends on the water level in the river, so it should be considered, as an indicator:

- Cost of dredging:

$$T_t = \sum_{i=1}^{34} d \cdot V_i$$

In which:

T_t: Dredging cost (VND billion) of the 34 downstream navigation routes to ensure accessibility.

i: navigation route i^{th}.

d: unit cost of dredging (VND billion/m³).

V_i: Volume to be dredged (m³).

In addition to the incurred dredging costs, the number of days when the water level is low also causes difficulties for the operation of water transport means:

- $X_{t1.1}$: Number of days in the year when the water level at Long Bien, Hanoi station is lower than the navigable threshold [day]

$$X_{t1.1} = \begin{cases} 1 & htHN < 1.1\,\text{m} \\ 0 & \text{otherwise} \end{cases}$$

When the water level at Hanoi falls below the discontinuity threshold of 0.4 m, transport on the Red River becomes complete standstill, so the following sub-indices should also be considered when analyzing the scenarios:

- $X_{t0.4}$ Number of days in the year when the water level at Long Bien, Hanoi station is lower than the discontinuity threshold [day]

$$X_{t0.4} = \begin{cases} 1 & htHN < 0.4\,\text{m} \\ 0 & \text{otherwise} \end{cases}$$

5) *Environment*

In order to protect the ecological environment of rivers and wetlands, all hydraulic works must release, or discharge downstream a minimum volume of water corresponding to a probability of 90% ($Q_{90\%}$) in dry season (MARD, 2022a).

Calculated results of salinity concentration at the estuaries according to different discharge levels from the reservoir and the water level at Hanoi (Nguyen et al., 2021) show that it is necessary to maintain a flow at Son Tay of 2500 m^3/s in order to ensure salinity repulsion for intaking water during land preparation period.

During the rest of the dry season, only 1100 m^3/s is enough to push saline water for water intaking, so the prevention thresholds are set at 2500 m^3/s and 1100 m^3/s and the following indices are determined to monitor compliance with these thresholds (IWRP, 2012):

- Index of environmental requirement during the increased water release period: number of days when inflows to Son Tay is below 2500 m^3/s

$$X_{e2500} = \begin{cases} 1 & QtST < 2500 \\ 0 & \text{otherwise} \end{cases}$$

- Index of environmental requirement during the normal period:

$$X_{e1000} = \begin{cases} 1 & QtST < 1100 \\ 0 & \text{otherwise} \end{cases}$$

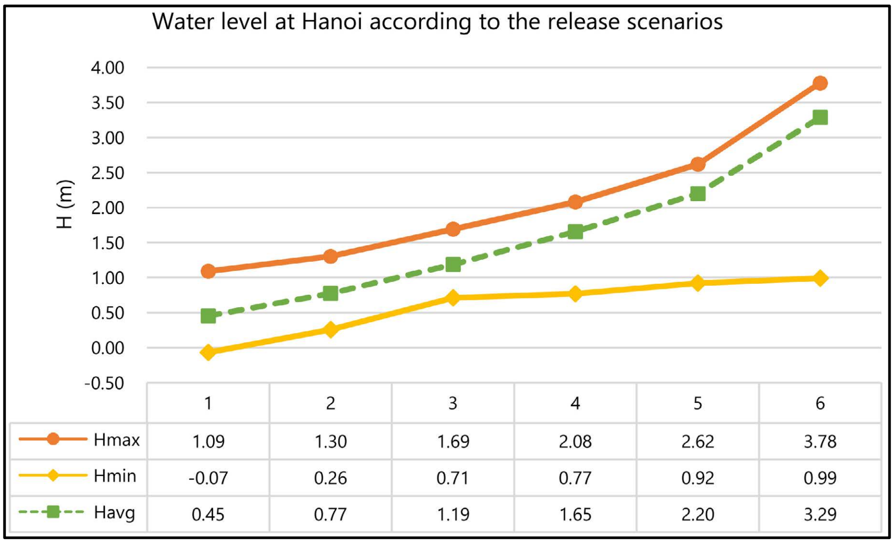
3. Results and Discussions

3.1. Analysis of Operation Indices in Dry Season

Given the status quo of deeply incised riverbed, the water level at Hanoi maintained during the release periods cannot be met as required by the Operation Rules 740 (see **Table 1** and **Figure 9**). Although the required release volume increases according to the scenarios but the release duration is limited in just 3 times, the total amount of water intaken into the systems is still of 17% deficit

Table 1. Summary of calculated results for the different scenarios of increased release periods.

No	Item	KB 1	KB 2	KB 3	KB 4	KB 5	KB 6	Requirement
1	**Water level at Hanoi (m)**							
	Hmax of the release period	1.09	1.30	1.69	2.08	2.62	3.78	1.09
	Hmin of the release period	−0.07	0.26	0.71	0.77	0.92	0.99	−0.07
	Havr of the release period	0.45	0.77	1.19	1.65	2.20	3.29	0.45
2	**Average release discharge of the reservoirs (m^3/s)**							
	Qrelease Hoa Binh	343	885	1091	2025	2946	4893	343
	Qrelease Thac Ba	52	173	434	434	450	450	52
	Qrelease Tuyen Quang	79	190	634	634	684	684	79
	Total release volume (10^9 m^3)	0.70	1.83	3.18	4.56	6.13	9.09	0.70
3	**Discharge at Son Tay (m^3/s)**							
	Q max (m^3/s)	1091	2379	2761	3796	5200	7603	1091
	Q avg (m^3/s)	864	1598	2492	3358	4271	6069	864



	1	2	3	4	5	6
Hmax	1.09	1.30	1.69	2.08	2.62	3.78
Hmin	-0.07	0.26	0.71	0.77	0.92	0.99
Havg	0.45	0.77	1.19	1.65	2.20	3.29

Figure 9. Water level at Hanoi according to the release scenarios.

(KB6). This is because the stressful period of water use lasts from January to March, but the increased reservoirs release only happens in 15 - 20 days and the capacity of hydraulic works cannot intake enough water in such a short duration to feed for the remaining 2 months. Thus, it is necessary to increase the release duration as well in order to reduce the amount of water shortage downstream.

3.2. Analysis of Economic Effectiveness of the Release Scenarios

1) *Hydropower*

Power output is the lowest at 30.97 million MWh in KB1—base flow release and the highest at 32.99 million MWh in KB4—actual release in 2021. However, in terms of economics with electricity prices varying by month, the power output in KB2—release according to electricity demand—is the highest and higher than that of KB1 and KB6 about VND 2600 billion/year and VND 1600 billion/year, respectively.

2) *Water supply for the downstream*

In terms of water supply for agriculture, the proportion of downstream cultivated areas affected by water shortage gradually decrease from 28% in KB1 to 17% in KB6. Productivity loss due to water shortage is estimated at about VND 5.6 to 9.4 trillion and the difference of agricultural loss between KB2 and KB6 is about VND 3750 billion (see **Figure 10**).

For navigation, the volume to be dredged increases from 160,000 m^3 in KB6 to 256,000 m^3 in KB1. Damage caused by lowered water level that leads to compulsory dredging is about VND 38 to 61 billion depending on the scenarios. The dredging volume is the smallest in KB4 with release according to reality in 2021, and bigger in KB5 and KB6 because the release in KB5 and KB6 is concentrated in the increased release period and is less than that in KB2 and KB4 in normal release period.

3) *Economic analysis*

Calculations of benefits and losses of the relevant sectors shows that there is an imbalance between the benefits of electricity generation and the reduction of

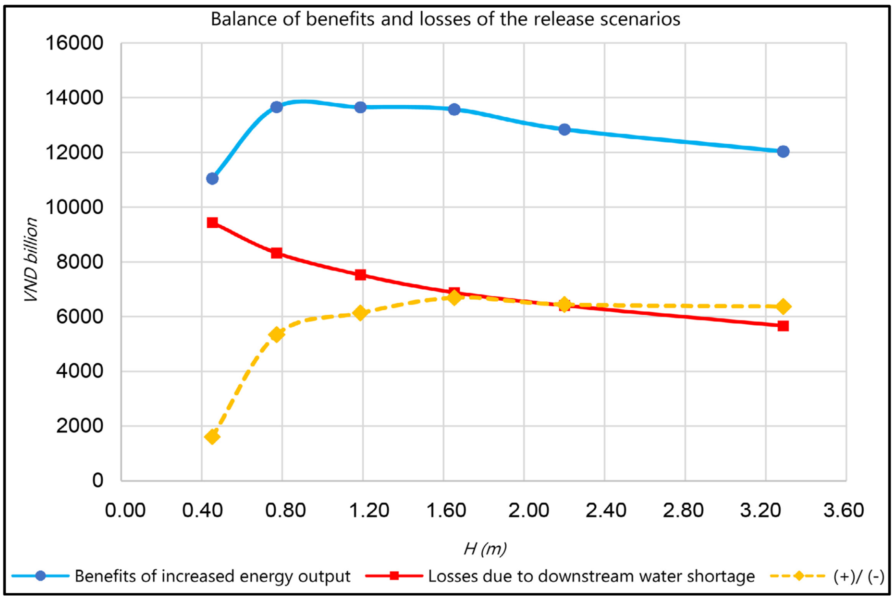


Figure 10. Balance of benefits and losses according to the release scenarios.

downstream water supply losses. Economic benefits from electricity generation is much larger than those of downstream agricultural production. This is why the economic optimization method should not be used to analyze and select the operation rules. Thereby, the study applied the scenario analysis method to choose reasonable release alternatives.

In the scenarios, the mean water level at Hanoi varies in the range of 0.45 to 3.29 m during the increased release periods. Economic analysis reveals that although KB2 gives the best energy economic efficiency, the overall economic efficiency of all downstream industries increases gradually from KB2 to KB6 though the increase is not much. Considering the efficiency of power generation along with the goal of ensuring energy security (saving water for the end of the dry season, beginning of the flood season), KB2 is selected. However, for downstream economic sectors, especially agricultural production, KB6 should be chosen to ensure water supply during the increased release period.

The use of a large amount of water in January and February (as in KB5 and KB6) will affect water security for the rest of the dry season as well as energy security in the hot weather at the beginning of the rainy season as besides the release through maximum power generation in those scenarios, bottom outlet release is sometime required that should rarely happen. The scenario that could harmonize the stakeholders' benefits would range from KB2 (no increased release) to KB4 (release via maximum power generation).

Given the present channel incision, the irrigation industry cannot afford to invest in rehabilitating and upgrading hydraulic works to meet the new conditions, then the KB4 is said to be the scenario that brings benefits harmony among the sectors. KB4 is the actual operation scenario in 2021 that has been agreed between representatives of the two largest water users, the Ministry of Industry and Trade (EVN) and the Ministry of Agriculture and Rural Development (Directorate of Water Resources).

3.3. Proposal of Adjustments to the Dry Season Operation Rules

3.3.1. During the Increased Release Period

The water level at Hanoi and Son Tay is rather clearly influenced by tide reflected through the fact that the water level is unstable and rising and falling according to the tide. It is, therefore, difficult to enforce the regulation of continuously maintaining the water level to a certain level, so instead of the regulation to maintain the water level (minimum water level), an average water level should be provided for during the release periods.

- Given the river water level fluctuates strongly, it will be difficult to implement Operation Rules 740, which regulates the fixed control of a downstream water level (2.2 m at Hanoi). Meanwhile, the reservoir system is operated every year to release depending on the requirements of the 3 different release periods and actual rainfall. According to the hydraulic calculations, the economic analysis and the above operation indicators, the water level in Hanoi can presently only be ensured at the minimum level of 0.8 m on average (without increased release as in KB2) and the maximum of 1.7 m (with maximum release from the hydropower plants as in KB4). Therefore, **an average water level at Hanoi in the range of 1.0 m - 1.7 m** should be considered to maintain during the increased release. This proposal is consistent with the assessment of the General Department of Water Resources (Ministry of Agriculture and Rural Development) in the summary reports on water collection for winter-spring rice cultivation in the Midlands and Northern Delta continuously in the years 2020, 2021, 2022 (MARD, 2020-2022).

- Currently, when the irrigation works in the Red River Delta have not been rehabilitated to suit the situation of lowering water level, there should be, **among the release periods, at least one release period at the maximum installed capacity of the Hoa Binh, Thac Ba and Tuyen Quang hydropower plants.**

3.3.2. During the Normal Dry Season Water Use

The water level in the downstream during the normal dry season water use is also lowered, causing many difficulties for water abstraction, navigation, and saline repulsion. The provisions of the operation rules are mainly based on the monthly discharge which does not affect the lowering of downstream water level. However, with such discharge, the water level at Hanoi usually does not reach 1.4 m. The number of hours when the water level reaches 1.1 m only accounts for 70% of the dry season (see Figure 11). **Therefore, it is proposed to adjust the provision on Hanoi water level used to control the discharge released from Hoa Binh from 1.4 m to 1.1 m.** This discharge is also in accordance with the calculations required for navigation of 1.1 m as well as a discharge of 1100 m^3/s which can push saline water in normal period.

4. Conclusion and Recommendations

Based on the economic analysis, the level of satisfaction of the stakeholders and the impact of the existing channel lowering, it is proposed to adjust some contents

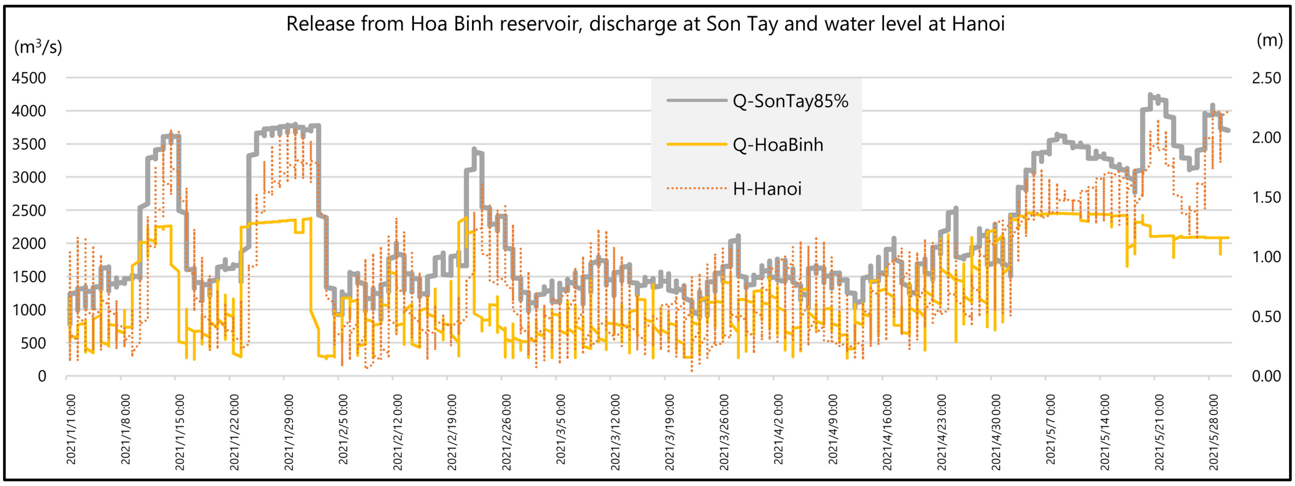


Figure 11. Release from Hoa Binh reservoir, discharge at Son Tay and water level at Hanoi according to the 2021 release model.

of Operation Rules 740, specifically in Table 2.

Given the situation of the riverbed getting lower and lower, the operation of the inter-reservoir system of the Red-Thai Binh River cannot exactly meet the requirements of the Operation Rules. During the increased release periods,

Table 2. Suggestion to adjust some contents of the Operation Rules 740.

Provisions of the Operation Rules 740	Suggested adjustments
Article 13. Dry season operation principles: section 3	
Hoa Binh, Thac Ba and Tuyen Quang reservoirs jointly operate to ensure the water level of **not below 2.2 m** at the Hanoi Hydrological Station during the increased release period.	Hoa Binh, Thac Ba and Tuyen Quang reservoirs jointly operate to maintain the **average** water level at the Hanoi Hydrological Station **from 1.0 m - 1.7 m depending on each release period** of the increased release periods.
Article 15. Operation of Hoa Binh, Thac Ba and Tuyen Quang reservoirs in the increased water use period: section 2	
Hoa Binh reservoir: based on the water level at the Hanoi Hydrological Station, to operate the reservoir to maintain **continuously** the water level of **not below 2.2 m** at the Hanoi Hydrological Station, except for the first day of each release period.	Hoa Binh reservoir: based on the water level at the Hanoi based on the water level at the Hanoi Hydrological Station, to operate the reservoir to maintain the **average** water level **from 1.0 m - 1.7 m** at the Hanoi Hydrological Station, except for the first day of each release period.
	Supplement to Section 3. **During the release serving the period of increased water use, there should be at least one period of release at maximum capacity of the Hoa Binh, Thac Ba and Tuyen Quang hydropower plants.**
Article 16. Operation of Hoa Binh, Thac Ba and Tuyen Quang reservoirs during normal water use period: section 3c	
During the operation pursuant to the provisions of Point b of this Article, if the average water level of "the day before yesterday" at the Hanoi Hydrological Station **exceeds 1.4 m**, the reservoir is allowed to proactively reduce the release discharge but must ensure continuous release with a flow rate of not less than 214 m^3/s. In case the average water level of "the day before yesterday" at the Hanoi Hydrological Station **falls below 1.4 m**, the reservoir must operate to release at the discharge specified at Point b of this Article.	During the operation pursuant to the provisions of Point b of this Article, if the average water level "the day before yesterday" at the Hanoi Hydrological Station **exceeds 1.1 m**, the reservoir is allowed to proactively reduce the release discharge but must ensure continuous release with a flow rate of not less than 214 m^3/s. In case the average water level of "the day before yesterday" at the Hanoi Hydrological Station **falls below 1.1 m**, the reservoir must operate to release at the discharge specified at Point b of this Article.

although the reservoirs have been operated at their maximum power generation capacity, the water level at Hanoi still cannot reach 2.2 m as required by the Operation Rules. The use of large amounts of water in January and February will affect water security for the rest of the dry season as well as energy security for the hot period of the beginning of the rainy season. The Government and the Ministry of Natural Resources and Environment should consider adjusting the Operation Rules of the Red River inter-reservoir system in the direction of providing framework regulations so that the Ministry of Agriculture and Rural Development and the Ministry of Industry and Trade can decide flexibly on release time and controlled water level at Hanoi that is suitable to the practical situation of each release period in each specific year.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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