第 48 卷 第 7 期
2021 年 7 月

湖南大学学报（自然科学版）
Journal of Hunan University（Natural Sciences）

Vol. 48. No. 7.
July 2021

Open Access Article

Improvement of Multi-Purpose Reservoirs Operation: A Case Study in Tra Khuc River Basin, Vietnam

Huy Cong Vu, Hung Le, Thuy Nga To*

The University of Danang, University of Science and Technology, Vietnam

Abstract: The Tra Khuc river basin is the largest of basins in Central Vietnam. Every dry season, conflicts among water users often arise. This study aims to contribute to reducing these conflicts by improving the reservoir operation procedure. Currently, these reservoirs are operated according to the guidelines of the inter-reservoir procedures issued by the prime minister. However, because of the complexity of the reservoir system and the arising inadequacies, this procedure must be adapted to address the actual situation. In this study, the flood-limited water level (FLWL) of reservoirs specified in the procedure will be re-evaluated. Simulations of reservoirs operation scenarios were performed to assess the impact of the different FLWL on hydropower generation, water supply, and flood control in this river basin. The results show that the maximum FLWL specified in the procedure should be maintained at 125m instead of 121m for the Nuoc Trong reservoir. In contrast, other reservoirs are recommended to remain unchanged. In this case, the Nuoc Trong reservoir will serve its function of submitting water for the dry season next year well without increasing flood control risk, contributing to more effective management of this region. This result will be the scientific basis to recommend the Prime Minister to adjust the inter-reservoir procedure.

Keywords: reservoir operation, flood control, flood limited water level.

改善多用途水库运营：以越南茶库 河流域为例

摘要：茶库河流域是越南中部最大的流域。每到旱季，用水者之间的冲突就经常发生。本研究旨在通过改进油藏操作程序来减少这些冲突。目前，这些水库是根据总理发布的水库间程序的指导方针运营的。然而，由于储层系统的复杂性和由此产生的不足，该程序必须适应实际情况。在这项研究中，将重新评估程序中指定的水库的洪水限制水位。对水库运行场景进行了模拟，以评估不同限洪水位对该流域的水力发电、供水和防洪的影响。结果表明，程序中指定的最大限洪水位应保持在125仪表，而不是诺创水库的121仪表。相比之下，建议其他水库保持不变。在这种情况下，诺创水库将在不增加防洪风险的情况下很好地发挥明年旱季送水的作用，有助于更有效地管理该地区。这一结果将成为建议总理调整水库间程序的科学依据。

关键词：水库作业, 防洪, 洪水限制水位。

1. Introduction

Vietnam is a country with a dense river system, the economy is mainly based on agriculture, and the electricity output is mainly from hydroelectricity. Consequently, the Vietnamese people have built many reservoirs for power generation, irrigation, and flood control purposes. These reservoir systems have changed the flow and significantly impacted the environment [1], [2], [3], [4], [5], [6], [7], [8], [9]. For having the same benefits as its original goal, an effective operation strategy is essential. The government has issued an inter-reservoir operation procedure for reservoir systems. However, the operation is complex because it is governed by many different water demands, including power generation,

Received: April 19, 2021 / Revised: May 21, 2021 / Accepted: June 17, 2021 / Published: July 31, 2021
About the authors: Huy Cong Vu, Hung Le, Thuy Nga To, The University of Danang, University of Science and Technology, Vietnam
Corresponding Author Thuy Nga To, ttnga@dut.udn.vn

irrigation, downstream residential use, and flood control. The government procedure is in general form, and therefore the actual operation still reveals several limitations. For example, through the simulation and surveying of peoples' experience, Le et al. pointed out that the reservoir operation procedure in Vu Gia -Thu Bon river basin, a large basin in Central Vietnam, is difficult to follow properly [10]. The influence of current operating procedures on saline intrusion has been studied by Vu et al. for the Tra Khuc river basin [7]. The authors proposed to change the time of water discharge to reduce saline intrusion for the dry season. For the flood season, the operation procedure in the Tra Khuc river basin also needs to continue to study and change to suit the actual situation. The purpose of this paper is to re-evaluate the present operation procedure focusing on the flood-limited water levels of the reservoirs system.

The flood-limited water level is the most significant reservoir parameter, and it is specified in the operation procedure. This water level governs the trace-off between flood control activity and other reservoir tasks. During flood season, the water levels in the reservoir are not allowed to exceed the FLWL for flood control. Therefore, this FLWL cannot be kept too high because it will be unsafe in the event of a large flood. On the other hand, this water level cannot be too low because the incoming flow may be too small to refill the reservoir in the dry season, affecting the power generation and other water uses. There have been several studies to improve operational procedures of reservoirs focused on optimizing this water level. Zhang has shown the relationship between FLWL and flow when the parameters of flood peak and total volume change over time [11]. The author pointed out that the value FLWL needs to be re-established to ensure flood safety when the reservoir inflow changes. Liu et al. studied FLWL dynamic control for reservoirs to get the trade-off between power generation and flood control [12]. Most previous studies applied to the single-purpose reservoir and focused on the relationship between FLWL and flood control targets. Few studies on the FLWL of the reservoir in which the influences of other water demand, such as hydropower generation, water shortage, and downstream flood, are considered. In this study, the flood-limited water level specified in the procedure will be re-evaluated for large multi-purpose reservoirs in the Tra Khuc river basin. The study's hypothesis is to find a reasonable FLWL higher than the specified current water level to ensure the water supply without increasing flood control risk. The study will then propose an improvement to the current inter-reservoir operation procedure.

2. Methodology

2.1. Description of Study Area

The Tra Khuc river basin is a major river basin in Central Vietnam. Its two major river systems, including the Tra Khuc and Ve, have a total catchment area of approximately 4500 km^2. The Tra Khuc river originates from the Truong Son mountain range, and the downstream connects to the sea through Dai Co Luy's mouth. With a length of about 135 km, the Tra Khuc river basin has 3240 km^2 [13]. The Ve river is shorter (about 91 km), flows from the southeast to the northeast, and connects to the sea through the Cua Lo estuary. The topography in this region is complex, with the relatively narrow mountainous area at the upstream and the flat coastal zone downstream, of which the high mountains are found in about 2/3 of its length. The study area is shown in Fig. 1.

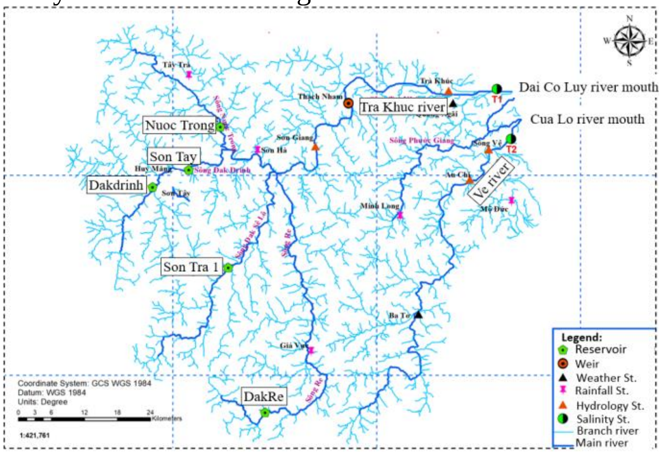

Fig. 1 The study area

The flow in this basin has a marked seasonal variation. The flow in the flood season is large, causing serious flooding, while in the dry season, the flow does not provide enough water for the needs. Therefore, there are five reservoirs constructed in this basin to regulate the flow. However, out of 5 built reservoirs, only two large reservoirs, including Dakdrinh and Nuoc Trong, were assigned additional flood prevention tasks and the tasks of electricity generation and water supply. The remaining reservoirs, including Son Tay, Son Tra 1, and Dak Re, are small. Therefore they are not assigned flood protection tasks. The reservoirs' characteristic parameters are summarized in Table 1.

Table 1 Summary of the characteristics and parameters of reservoir system in the Tra Khuc river basin

Items	Unit	Reservoir				
		Dak drinh	Nuoc Trong	Son Tay	Son Tra 1	Dak Re
Catchment area	km^2	420	460	186	378	73.8
Mean annual precipitation	mm	3380	3200	3410	2840	
Mean annual flow	m^3/s	31.9	34.4	13.7	24.4	4.59
Retention water level	m	410	129.5	192.5	192.5	936
Dead water level	m	375	96	183	183	918
Total storage	10^{6}m^3	249.3	289.5	0.53	6.83	10.3
Active storage	10^{6}m^3	205.2	258.7	0.39	4.07	9.22
Inactive storage	10^{6}m^3	43.3	30.8	0.14	2.76	1.12
Minimum	m^3/s	18.25	10	5.55		1.43

discharge through a turbine						
Maximum discharge through a turbine	m^3/s	55.00	42	22.2	82.2	10.7
Installed capacity	MW	125	16.5	18	4.4	60

These reservoirs are operating under the inter-reservoir procedure issued by the prime minister. Even so, this procedure still needs to be continually evaluated and improved to address the actual situation. The efficient operation of these reservoirs is expected to mitigate drought, flooding, and saline intrusion, which have been occurring more frequently.

2.2. Model Setup and Data Collection

The reservoir operational efficiency was assessed through numerical simulation using the MIKE NAM, HEC-ResSim, and MIKE Flood models. Schematic diagrams of simulation models and their applications are shown in Fig. 2. First, due to the limited data of this area, the MIKE NAM model is used to reconstruct the flow to the reservoir and downstream nodes. The output data from the MIKE NAM model were fed to the HEC-ResSim model to simulate reservoir operations under different scenarios of water levels. In addition, the MIKE Flood model is also used to evaluate the flood levels occurring downstream, thereby demonstrating the effectiveness of the reservoir operating scenarios.

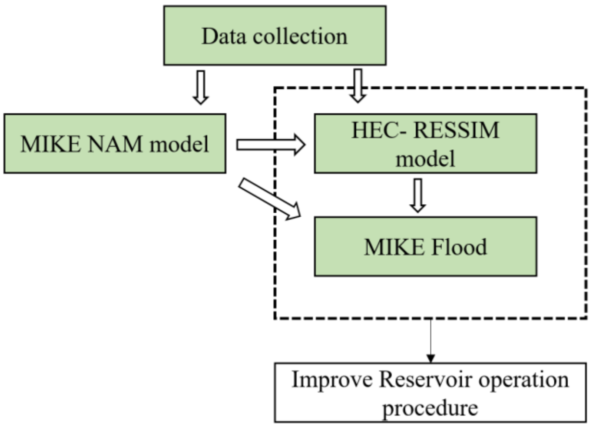

Fig. 2 Schematic of the modeling framework

In this study, five reservoirs, namely Dakdrinh and Nuoc Trong, Son Tay, Son Tra 1, and DakRe, are considered. However, only two large reservoirs, including Dakdrinh and Nuoc Trong, were assigned flood control tasks, so scenarios of FLWL were developed for only these two reservoirs. The schematic diagram of reservoirs is shown in Fig. 3. The characteristics of reservoirs (dam height, width, power plant discharge, installed capacity, water use, etc.) and their operations were obtained from the reservoir management agencies. These parameters are shown in Table 1. The relationship between surface area, storage capacity, and water level for each reservoir was also obtained.

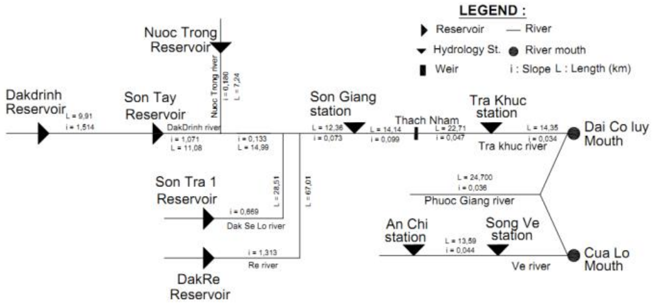

Fig. 3 The schematic diagram of reservoirs in the Tra Khuc river basin

The Tra Khuc river basin has 4 main hydrological stations, including Son Giang and An Chi are for the discharge, water level, and rainfall measurement, and Tra Khuc and Song Ve are only for water level and rainfall measurement. The relative positions of these measuring stations are shown in Fig. 3. In addition, there are 8 minor hydrological stations in this river basin, which are mainly to measure rainfall. The rainfall data at all these stations are available from 1981 onwards.

Reservoirs constructed upstream since 2012 have changed the laws of the natural flow. For reconstructing the natural flow without the impact of the reservoirs, measurement data from 1981-2012 were selected. This data was used to calibrate and verify the hydrological model to reconstruct the annual flow. To reconstruct the flood flows, we used the data of major floods in 2007, 2009, and 2013 to calibrate and verify the hydrological and hydraulic models. The topographic map of the Tra Khuc river basin downstream with the scale of 1:10000 was collected to simulate floodplains and inundation areas using MIKE Flood.

2.3. Model Calibration and Validation

In this study, calibration and verification were performed for both the annual and flood flows. This process was carried out at Son Giang station. The correlation coefficient (R), Nash-Sutcliffe coefficient (NSE) are used as model efficiency criteria in calibration and validation processes (see equations 1, 2, respectively).

$$R=\frac{\sum_{i=1}^{n}\left(Q_{obs,i}-\bar{Q}_{obs}\right).\left(Q_{sim,i}-\bar{Q}_{sim}\right)}{\sqrt{\sum_{i=1}^{n}\left(Q_{obs,i}-\bar{Q}_{obs}\right)^{2}.\sum_{i=1}^{n}\left(Q_{sim,i}-\bar{Q}_{sim}\right)^{2}}} \quad (1)$$

$$NSE=1-\frac{\sum_{i=1}^{n}\left(Q_{obs,i}-Q_{sim,i}\right)^{2}}{\sum_{i=1}^{n}\left(Q_{obs,i}-\bar{Q}_{obs}\right)^{2}} \quad (2)$$

where the Q_{obs} is observed discharge and Q_{sim} is modeled discharge at time *i*.

2.3.1. MIKE NAM Model

The MIKE NAM model was calibrated and validated at the Son Giang station for 1981-1996 and

1997 to 2012, respectively. The simulated and observed flows are presented in Fig. 4. The result shows that the model predicted flows are in good agreement with observed data. The NSE and R coefficients in the calibration and validation at Son Giang are 0.746, 0.904, and 0.821, 0.91, respectively.

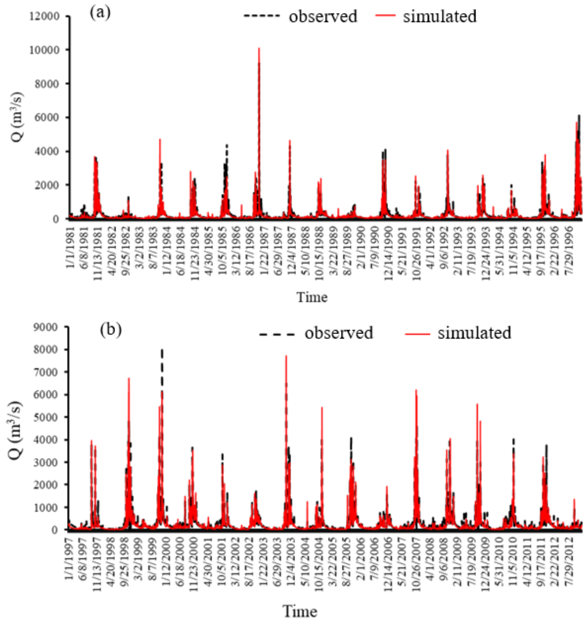

Fig. 4 Simulated and observed flows at Son Giang station: (a) calibration, (b) validation

For flood flows, the model is calibrated and validated with past floods. The flood event recorded in 2013 was used for the calibration, whereas the flood event recorded in 2009 was used for validation. The calibration and validation results for the floods are shown in Fig. 5. The results show an agreement about the phase and vibration amplitude in both floods. The simulated and observed flood peaks are also quite close in both time and value. The NSE and R coefficients in the calibration (2013) and validation periods (2009) at Son Giang are 0.921, 0.981, and 0.940, 0.983, respectively.

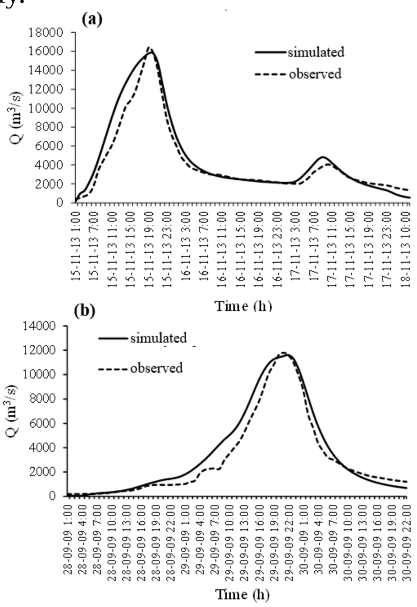

Fig. 5 Simulated and observed flood flow at Son Giang station: (a) calibration, (b) validation

2.3.2. HEC-RESSIM Model

The HEC-ResSim model was calibrated and validated at the Son Giang station for the floods recorded in 2013 and 2009. The results are presented in Fig. 6. It can be seen that the HEC-ResSim model predicted flows are in good agreement with observed data. The NSE and R coefficients in the calibration and validation periods are 0.921, 0.992 and 0.965, 0.988, respectively (Table 2). In details, the simulated and observed peak flow values in 2013 are 16484 m^3/s and 16400 m^3/s, respectively. The error of peak flow is 0.5%. In 2009, these values were 11540 m^3/s and 11800 m^3/s, respectively. The error of peak flow is 2.2%. It can be seen that in both calibration and validation, the calculated and observed peak flow error is smaller than 2.5%. It proves that the established HEC-RESSIM model guarantees the reliability to simulate flood regulation according to the scenarios.

Table 2 Statistical performance of calibration and validation of water flows

Station	Calibration (2013)			Validation (2009)		
	NSE	R	Peak flow error	NSE	R	Peak flow error
Son Giang	0.921	0.992	0.5%	0.965	0.988	2.2%

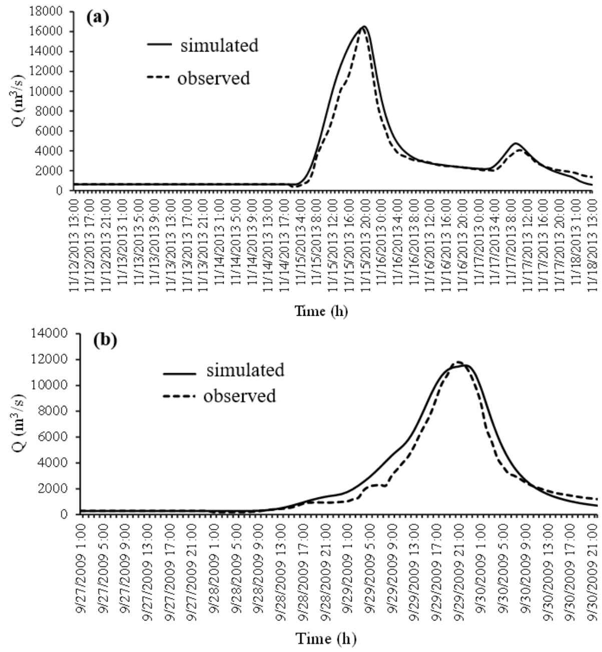

Fig. 6 Simulated and observed flow at Son Giang station: (a) calibration, (b) validation

2.3.3. MIKE Flood Model

The calibration and validation of the MIKE Flood model were performed based on the investigation flood traces obtained during the flood in 2013 (21 values) and 2009 (13 values), respectively. In addition, the flood depth time series at Tra Khuc is also used for calibration and validation models.

For the calibration, simulated and observed flood traces are shown in Fig. 7. The results showed that the

Mike Flood model works relatively well to simulate the flood. Most of the flood traces closely followed the simulation results. However, there are a few locations with relatively large differences compare to the simulation results. The calibration of the model was also performed by comparing water levels at Tra Khuc station during the 2013 flood (Fig. 8). The simulation results are in good agreement with the observed results. The NSE and R values for calibration of water level at Tra Khuc station are 0.94 and 0.98.

The validation model was based on investigating flood traces collected during the flood in 2009 (Fig. 9). Although there are a few locations with relatively large differences, the model is generally still responsive in flood simulation. The time series simulated water level results at Tra Khuc station are in good agreement with observed results (Fig. 10). The NSE and R values for validation of water level are 0.97 and 0.99, respectively. In conclusion, the simulation results were close to the actual measured data for both processes and the values. The MIKE Flood model is reliable enough to simulate the inundation area.

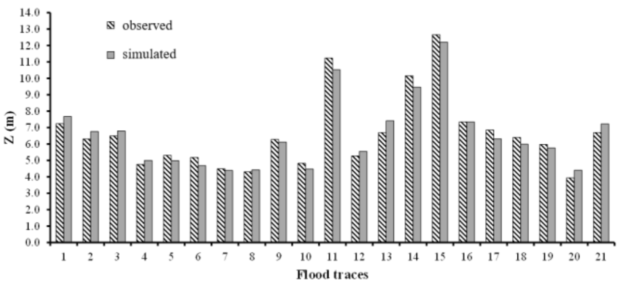

Fig. 7 Simulated and observed flood depth for the flood in 2013

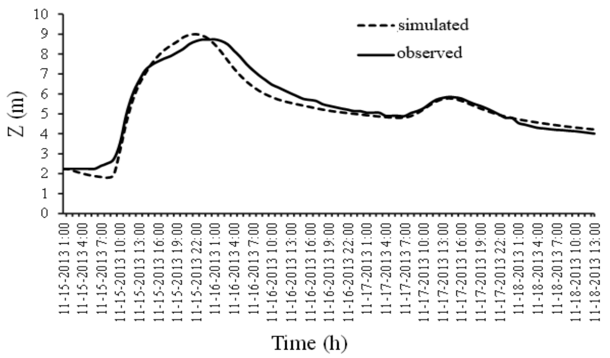

Fig. 8 Flood depth time series at Tra Khuc station for the flood in 2013

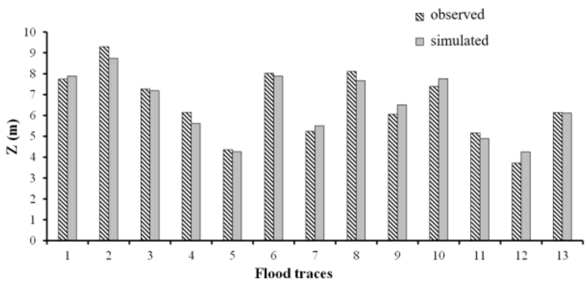

Fig. 9 Simulated and observed flood depth for the flood in 2009

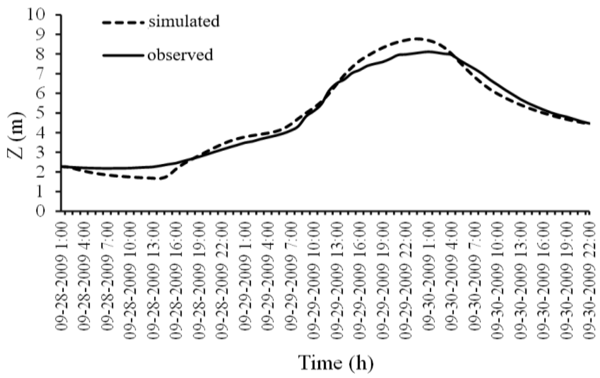

Fig. 10 Flood depth time series at Tra Khuc station for the flood in 2009

2.4. Reservoir Operation Procedure

The reservoirs system in the Tra Khuc river basin, including Dakdrinh, Nuoc Trong, Son Tra 1, Dak Re, and Son Tay, is currently operating according to government procedures [14]. Within one year of operation, the operation pattern is executed according to two main seasons: flood season (from September 1 to December 15) and dry season (from December 16 to August 31). During the flood season, the rule specified in the procedure prioritizes reducing floods for downstream areas and ensuring efficient water supply and electricity generation. However, only two large reservoirs, including Dakdrinh and Nuoc Trong, were assigned flood control tasks, so scenarios of FLWL were developed for only these two reservoirs. The maximum and minimum flood limited water levels (FLWLmax, FLWLmin, see Fig. 11) of the two largest reservoirs during flood season are specified in Tables 3, 4. During the dry season, the rules prioritize the task of minimum flow for drinking water, irrigation, industrial needs, ecosystems and ensure efficiency in electricity generation.

Table 3 The maximum flood limited water level

Reservoir	**The maximum flood limited water level (FLWLmax)**		
	1/9 - 20/9	21/9 – 14/11	15/11 – 15/12
Nuoc Trong	116	120	121
Dakdrinh	405	405	405

Table 4 The minimum flood limited water level

Reservoirs	**The minimum flood limited water level (FLWLmin)**		
	1/9 - 20/9	21/9 – 14/11	15/11 – 15/12
Nuoc Trong	115.5	118.5	119.5
Dakdrinh	400	400	400

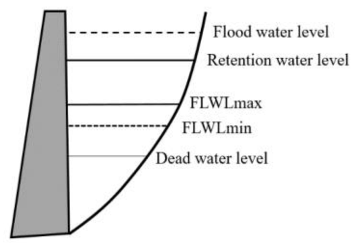

Fig. 11 Sketch of index levels of Nuoc Trong and Dakdrinh reservoirs in Tra Khuc river basin

2.5. Application Scenarios

The FLWL needs to be maintained at a reasonable level to create enough free capacity to prevent floods, but if there is no flood, the reservoir still ensures water supply. In addition, at the end of the flood season, the reservoir must be fully stored to serve the needs in the next dry season. In other words, the specified FLWLs during operation in the procedure must be reasonable to ensure flood prevention and minimize the degree of water shortage in the dry season.

In order to determine the appropriate FLWL during the flood season, scenarios will be established in which the FLWL is assumed to change from dead water level to retention water level. Four scenarios of different FLWLmax and FLWLmin values are shown in Table 5. The flood in 2013 was selected as an example for analysis. In addition, to assess the impact of the operation on power generation and water shortage, the model needs to be simulated over a long time with the annual flow, so a simulation period of 32 years (from 1981 to 2012) was chosen.

Table 5 Simulated scenarios

Scenario	S1	S2	S3	S4
FLWLmax (m)				
Nuoc Trong reservoir	116	120	125	129.5
Dakdrinh reservoir	395	400	405	410
FLWLmin (m)				
Nuoc Trong reservoir	116	120	120	120
Dakdrinh reservoir	395	400	400	400

3. Results and Discussion

3.1. The Flood Regulation Schemes for Each Scenario

The flood regulation schemes for different scenarios concerning the FLWLmax are shown in Fig. 12 - 15. Fig. 12 shows the regulation in case the FLWLmax is kept constant until the flood arrives. In the early stage of the flood, the discharge rate equals the inflow rate for both reservoirs. In the 12 hours before the flood peaks occur (assuming that the inflows are forecasted 12 hours in advance), the discharge rate starts to increase to prevent a flood. In this case, the effectiveness of flood control for downstream is at the highest, with discharge rates of about 365 m^3/s and 371.65 m^3/s for the Darkdrinh and Nuoc Trong reservoirs, respectively. In this case, the flow rate at Son Giang station is the smallest and equals 11818 m^3/s.

Fig. 13, 14, 15 show the flood control regulation for scenarios S2, S3, and S4. Depending on the FLWLmax, there are different water release options. In Fig. 13a, when the FLWLmax of DaKdrinh is 400m, the discharge rate is maintained constant until the flood arrives (scenario S2). This regulation is similar to the case described in scenario S1. For other cases, the reservoirs must release earlier to reduce the water level and create empty capacity to catch flood. Depending on the FLWLmax, the time required to release water in advance is different. In scenario S3 (see Fig. 14a), when the FLWLmax of Dakdrinh reservoir is 405m, the reservoir is required to increase the discharge rate in the 24 hours before the flood peak occurs. The water level gradually decreases to FLWLmin (400m) to create flood prevention capacity. For scenario S4 (see Fig. 15), the Dakdrink and Nuoc Trong reservoirs increase the discharge rates 48 hours before the flood peaks occur. In this scenario, although FLWLmax can be regulated to prevent the flood, the discharge rates are still the largest, reaching 810 and 850 m^3/s for the Nuoc Trong and Darkdrinh reservoirs, respectively. The maximum values of the inflow rate and the discharge rate are listed in Table 6.

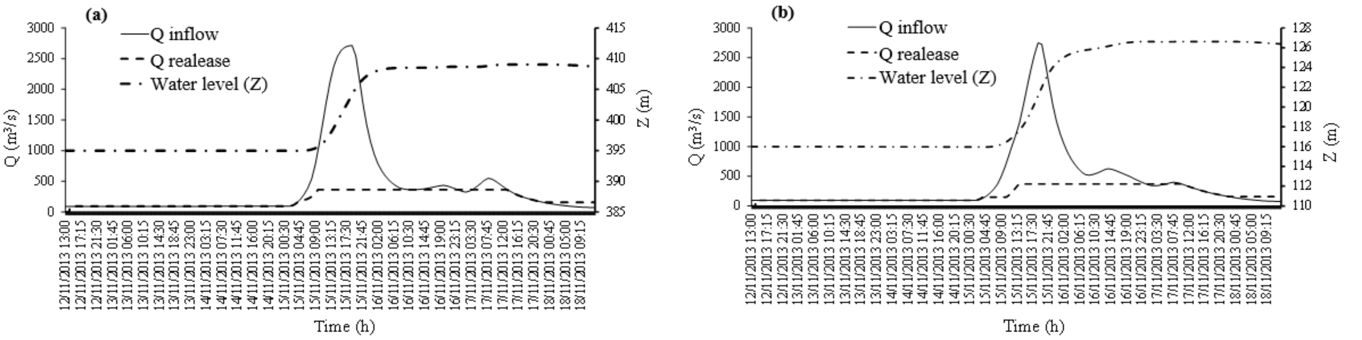

Fig. 12 Time series inflow rate and discharge rate of (a) Dakdrinh and (b) Nuoc Trong reservoirs (flood in 2013 – scenario S1)

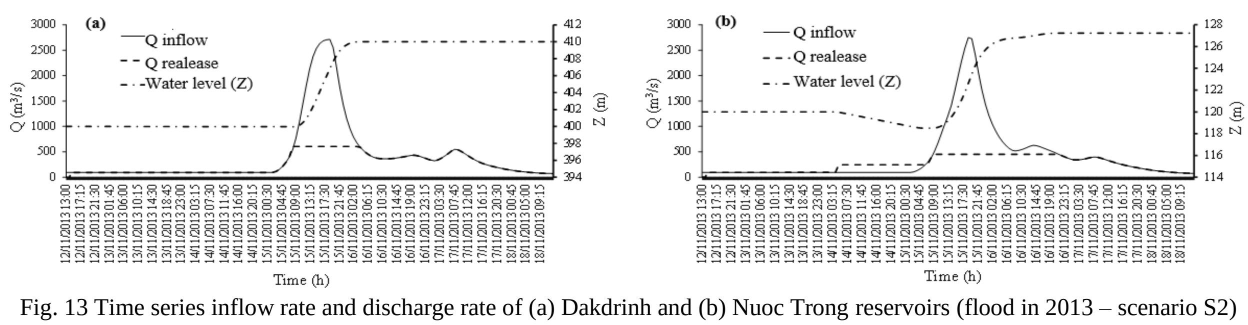

Fig. 13 Time series inflow rate and discharge rate of (a) Dakdrinh and (b) Nuoc Trong reservoirs (flood in 2013 – scenario S2)

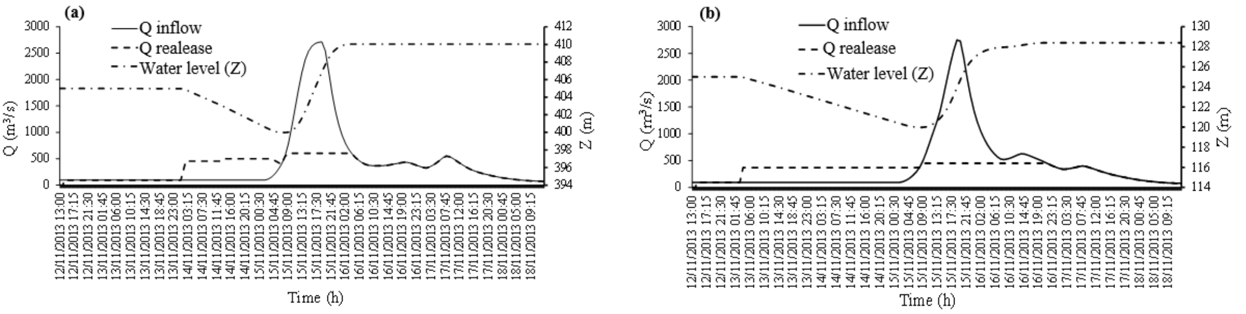

Fig. 14 Time series inflow rate and discharge rate of (a) Dakdrinh and (b) Nuoc Trong reservoirs (flood in 2013 – scenario S3)

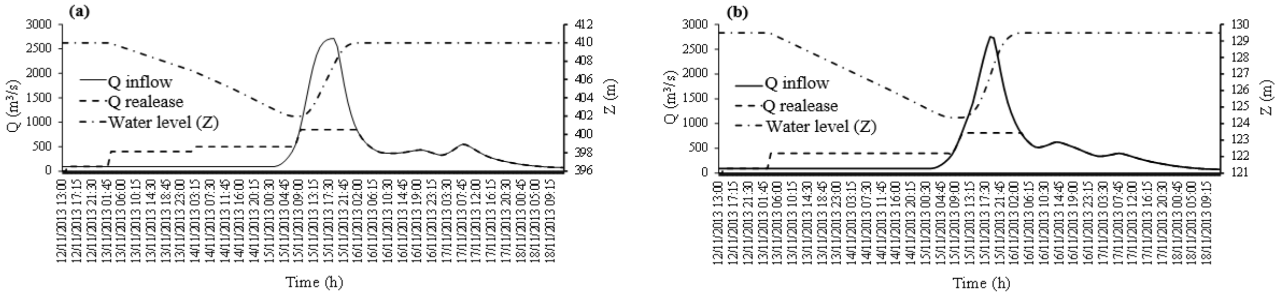

Fig. 15 Time series inflow rate and discharge rate of (a) Dakdrinh and (b) Nuoc Trong reservoirs (flood in 2013 – scenario S4)

Table 6 Statistics of the maximum flow rate at reservoirs scenario

Scenario	**Flow (m^3/s)**	**Nuoc Trong reservoir**	**Dakdrinh reservoir**
S1	Q inflow_max	2750.2	2714.2
	Q release_max	371.65	365
S2	Q inflow_max	2750.2	2714.2
	Q release_max	450	605
S3	Q inflow_max	2750.2	2714.2
	Q release_max	450	605
S4	Q inflow_max	2750.2	2714.2
	Q release_max	810	850

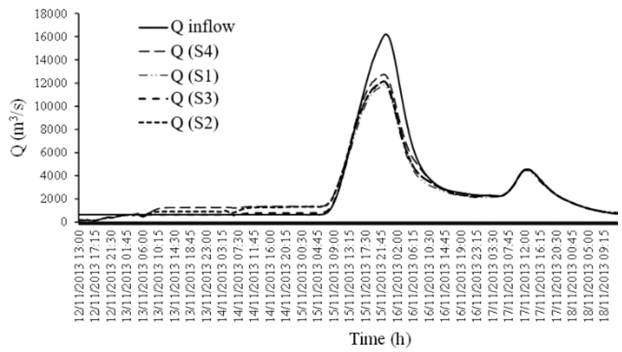

Fig. 16 Flow discharge time series at Son Giang station (flood in 2013)

In summary, Fig. 16 presents a comparison of the discharge rate of the four different scenarios with the observed inflow at Son Giang station. It can be concluded that the Nuoc Trong and Dakdrinh reservoirs play a major role in flood control. The flood peak discharge at Son Giang station decreases from 16211 m^3/s to around 12000 m^3/s, decreasing approximately 25%. The results also show that when the FLWLmax varies between 395m - 410m for Dakdrinh reservoir and 116m – 129.5m for Nuoc Trong reservoir, downstream Son Giang flows downstream station does not change much. The lower the FLWLmax is, the higher the risk of filling the reservoir after the flood, leading to a lack of water for the next year's dry season. Therefore, with the goal of safety for downstream water supply during the dry season, the FLWLmax should be maintained as high as possible.

3.2. Impact Assessment of Reservoir Operation

Reservoir operations under different FLWL will impact power output, downstream flood area, and water supply capacity. These results are analyzed and discussed for each pair of subjects and are presented in the following sections:

3.2.1. Compromise between Power Generation Targets and FLWLmax

The relationship between the FLWLmax and hydropower generation is plotted in Fig. 17. For the Dakdrinh reservoir, power production gradually increases when FLWLmax decreases. It can be explained by when the FLWLmax is maintained at a low level; the larger the incoming flow, the more electricity is produced. Similarly, for the Nuoc Trong reservoir, hydropower generation tends to increase as the FLWLmax decreases.

Fig. 18 shows the relationship between the maximum discharge and the FLWLmax. When the FLWLmax is maintained at a high level, the maximum discharge is also higher. Interestingly, the FLWLmax is

400 or 405m; the maximum discharge would still be 605 m^3/s for the Dakdrinh reservoir. The vertical segment in Fig. 18a shows this. Similarly, for the Nuoc Trong reservoir, the FLWLmax of 120 or 125 m does not change the value of the maximum discharge (approximately 450 m^3/s). From this important finding, it is possible to propose recommendations for changes in the FLWLmax specified in the inter-reservoir procedure. That will be discussed in the recommendations part.

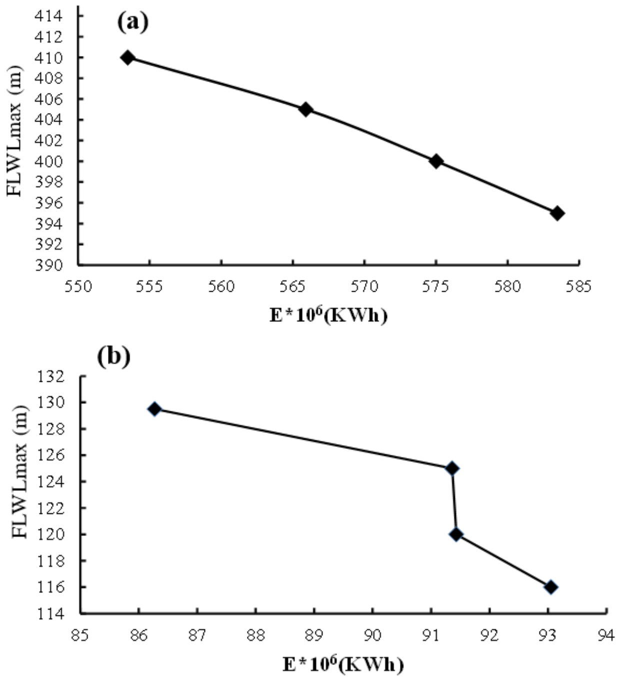

Fig. 17 The relationship between the FLWLmax and hydropower generation: (a) Dakdrinh reservoir, (b) Nuoc Trong reservoir

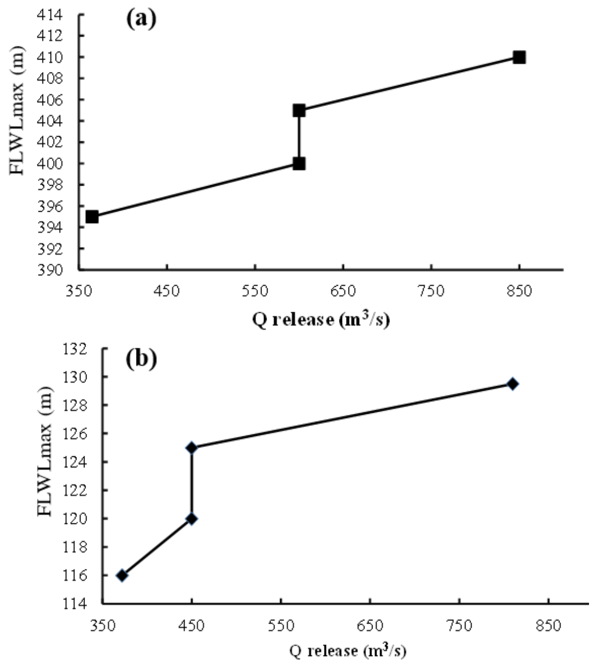

Fig. 18 The relationship between the FLWLmax and the maximum discharge: (a) Dakdrinh reservoir, (b) Nuoc Trong reservoir

3.2.2. Compromise between Flood Area Downstream and the FLWLmax

The relationship between the downstream inundation area and the FLWLmax of Dakdrinh and Nuoc Trong reservoirs is shown in Fig. 19.

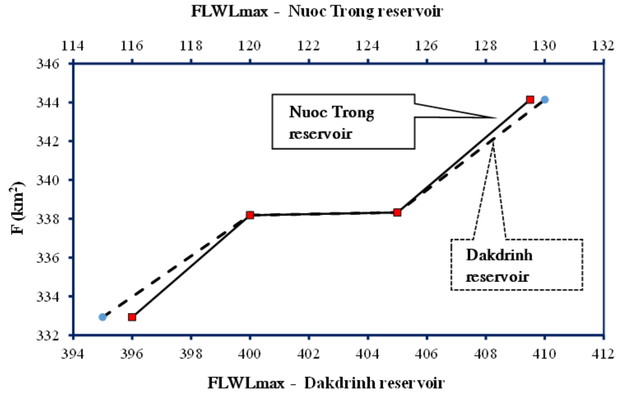

Fig. 19 Downstream inundation area and the FLWLmax of Dakdrinh and Nuoc Trong reservoirs

It can be seen that when the FLWLmax is higher, the flood storage of the reservoir will be smaller. The flow downstream will increase and therefore increase the flood area and depth. For the Nuoc Trong reservoir, when the FLWLmax is 129.5 m, the flood area downstream is the largest, about 256 km^2. Otherwise, when the FLWLmax is 116m, the flooded area is the smallest, 248 km^2. Similarly, for the Dakdrinh reservoir, the flooded area is at its maximum when the FLWLmax is 410 m and at its minimum when the FLWLmax is 395 m. Interestingly, when the FLWLmax varies between 400 – 405 m for the Dakdrinh or 120 – 125m for the Nuoc Trong reservoir, the downstream discharges are similar. Therefore, the flood areas are almost constant, as shown by the horizontal section in Fig. 19.

3.2.3. Compromise between Power Generation Targets and Water Shortages

The water shortage of the reservoir is indicated and measured by the number of years in which the reservoir is not full. In the inter-reservoir procedure, the full water levels are 408 m for the Dakdrinh reservoir and 124.5m for the Nuoc Trong reservoir. The time to determine whether the reservoir is full or not in a year is from December 16 to December 31. Fig. 20 shows the number of years of water shortage for Dakdrinh and Nuoc Trong reservoirs.

For the Dakdrinh reservoir, when the hydroelectric plant generates a maximum capacity of 583.493×10^6 KWh and the FLWLmax is 395 m (scenario S1), the time of water shortage is 7 years out of 32 years of operation, accounting for 21.8%. The water shortage is the shortest, 1 year if the power plant generates $553{,}472\times10^6$ Kwh and the FLWLmax is maintained at 410 m (scenario S4) during the flood season.

For the Nuoc Trong reservoir, when the power plant generates 93.048×10^6 Kwh and the FLWLmax is 116m (scenario S1), the reservoir has 3 years of water shortage, accounting for 9.4%. Especially if the reservoir generates electricity with a slightly lower output, 86.272×10[6] Kwh, and FLWLmax is 129.5 m (scenario S4), there is no year of water shortage. In addition, the FLWLmax are kept either at 120m or 125m (scenarios S2, S3), the electricity outputs are similar, and the time of water shortage is 2 years (accounting for 6.3%).

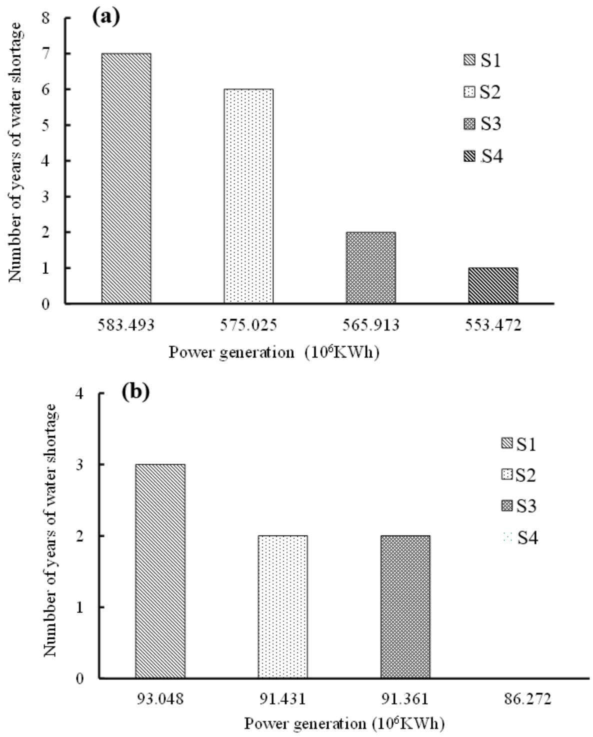

Fig. 20 Hydropower generation and the number of years of water shortage: (a) Dakdrinh reservoir, (b) Nuoc Trong reservoir

Fig. 21, 22 show the average annual electricity output of each scenario. It is easy to see that the hydropower generation in scenario S1 is the largest among the scenarios. When the required FLWLmax is small, the more water the reservoir releases for power generation, the more electricity it produces. As mentioned above, when this water level increases (from scenario S1 to scenario S4), the amount of water for power generation is reduced, leading to a decrease in power output, as seen in most years. However, in some years (e.g., 1983, 1990), the trend is the opposite. It can be explained by the fact that there were no floods during these years, and the water head remained low according to the measured data. The water head is maintained at a low level, and the reservoir has water shortage also results in small output power.

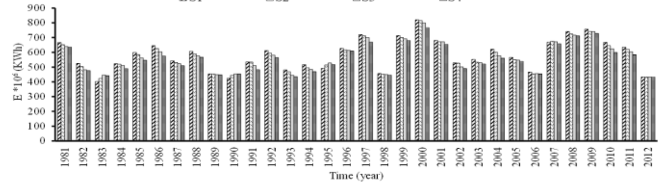

Fig. 21 Average annual power of Dakdrinh reservoir under different scenarios

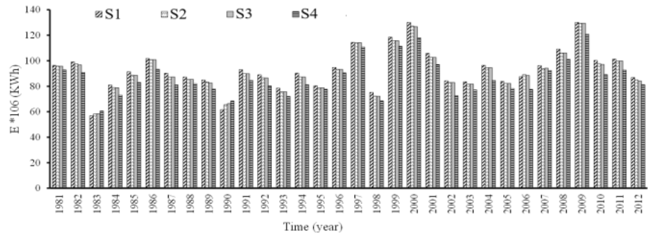

Fig. 22 Average annual power of Nuoc Trong reservoir under different scenarios

4. Recommendations

For the Nuoc Trong reservoir, the simulation results showed that when the FLWLmax is kept at 120m or 125m, the reservoir can still prevent floods. There are no significant changes in the flooded area downstream, the electricity generation output, and the time of water shortage. It is worth mentioning that if FLWLmax is low, it is more difficult for the reservoir to store enough water at the end of the flood season. In this case, maintaining a higher FLWLmax will increase the reservoir's operating capacity and ensure water demand. In other words, the reservoir will serve its function of supplying water for the dry season next year well without increasing flood control risk. Thus, it is suggested that the FLWLmax of Nuoc Trong reservoirs should be increased by 5m. It means that the FLWLmax should increase to 125m instead of its current level at 121m (see Table 7). In recent years, the water shortage has occurred more frequently, having a great impact on the water consumption goals of the reservoirs, leading to more severe conflicts. Raising FLWLmax can contribute to reducing conflicts between water consumption goals of Nuoc Trong reservoir. However, the limitation of this change is that the incoming flow needs to be well forecasted, and the reservoir operation team must have experience and expertise.

Table 7 Recommendation to government procedure

Reservoir	FLWLmax	
	Government procedure	**Recommend**
Nuoc Trong	121	125
Dakdrinh	405	No change

5. Conclusion

The study has implemented operation simulations for reservoirs in the Tra Khuc river basin. The compromises among the groups of 3 main water demands: flood control, water supply (water shortage), and power generation have been considered. When the FLWLmax ranges in 400 – 405 m for the Dakdrinh reservoir or 120 – 125 m for the Nuoc Trong reservoir, the downstream discharges are similar, and therefore, the flooding areas are almost constant. The water shortage is the smallest, 1 year if the FLWLmax of Dadrkinh is maintained at 410 m during the flood season. There is no year of water shortage when the FLWLmax of the Nuoc Trong is 129.5 m.

The study also demonstrated a scientific basis for improving the inter-reservoirs operation procedure. Accordingly, when the FLWLmax of the Nuoc Trong ranges in 120-125 m, the water level downstream and flooded area are almost unchanged. In other words, when increasing the FLWLmax, the flood prevention goal is still guaranteed and increases the effectiveness of the water supply targets. The FLWLmax in the reservoir should be maintained at 125 m instead of 121m specified in the government operation procedure. The Nuoc Trong reservoir has the main task of water supply. Therefore this change has an important role in increasing the water supply capacity of the reservoir.

Acknowledgments

This work was supported by The University of Danang, University of Science and Technology, code number of Project: T2020-02-40.

References

[1] MAI N. P., KANTOUSH S., SUMI T., THANG T. D., TRUNG L. V., and BINH D. V. Assessing and adapting the impacts of dams operation and sea level rising on saltwater intrusions into the Vietnamese Mekong Delta. *Journal of Japan Society of Civil Engineers, Series B1 (Hydraulic Engineering)*, 2018, 74(5): 373-378. https://doi.org/10.2208/jscejhe.74.5_I_373

[2] FIROZ A. B. M., NAUDITT A., FINK M., and RIBBE L. Quantifying human impacts on hydrological drought using a combined modelling approach in a tropical river basin in central Vietnam. *Hydrology and Earth System Sciences*, 2018, 22(1): 547-565. https://doi.org/10.5194/hess-22-547-2018

[3] NGO L. A., MASIH I., JIANG Y., and DOUVEN W. Impact of reservoir operation and climate change on the hydrological regime of the Sesan and Srepok Rivers in the Lower Mekong Basin, *Climatic Change*, 2018, 149(1): 107–119. https://doi.org/10.1007/s10584-016-1875-y

[4] NGA T. T., CONG V. H., and HUNG L. Assessing the Impacts of Climate Change and Reservoir Operation on Saltwater Intrusion in the Vu Gia-Thu Bon River Basin. In *International Conference on Asian and Pacific Coasts*, 2019: 1207–1212. https://doi.org/10.1007/978-981-15-0291-0_165

[5] BINH D. V., KANTOUSH S., SUMI T., and MAI N. P. Impact of Lancang cascade dams on flow regimes of Vietnamese Mekong Delta. *Journal of Japan Society of Civil Engineers B1*, 2018, 74(4): 487-492. http://dx.doi.org/10.2208/jscejhe.74.I_487

[6] LE N. D., LE T. P. Q., PHUNG T. X. B., DUONG T. T., and DIDIER O. Impact of hydropower dam on total suspended sediment and total organic nitrogen fluxes of the Red River (Vietnam). *Proceedings of the International Association of Hydrological Sciences*, 2020, 383: 367–374. https://doi.org/10.5194/piahs-383-367-2020

[7] VU H. C., TO T. N., and LE H. Assessing the impacts of reservoir operation on saltwater intrusion in Tra Khuc-Ve river basin. *Journal of Critical Reviews*, 2021, 8(2): 536–549. http://dx.doi.org/10.31838/jcr.08.02.57

[8] VU T. T., & NGUYEN T. H. An Assessment the Role of Reservoirs on Salinity Intrusion in the Ma River Basin. In *International Conference on Asian and Pacific Coasts*, 2019: 751–758. https://doi.org/10.1007/978-981-15-0291-0_103

[9] DANG N. M., TUNG N. B., DUONG T. A., and DANG T. D. Assessments of Climate Change and Sea Level Rise Impacts on Flows and Saltwater Intrusion in the Vu Gia-Thu Bon River Basin, Vietnam. In *International Conference on Asian and Pacific Coasts*, 2019: 1367–1374. https://doi.org/10.1007/978-981-15-0291-0_185

[10] LE A. T., NGUYEN T. T., DANG N. V., PHAM T. D. M., and LAM T. T. S. Impact of operation of hydropower reservoirs on Vu Gia-Thu Bon river basin downstream Vu Gia-Thu Bon: from simulation data to the reality of residents' reflection. *Vietnam River Networks*, 2014.

[11] ZHANG X., LIU P., WANG H., LEI X., and YIN J. Adaptive reservoir flood limited water level for a changing environment. *Environmental Earth Science*, 2017, 76(21): 1–14. https://doi.org/10.1007/s12665-017-7086-7

[12] LIU G., QIN H., SHEN Q., TIAN R., and LIU Y. Multi-objective optimal scheduling model of dynamic control of flood limit water level for cascade reservoirs. *Water*, 2019, 11(9): 1-18. https://doi.org/10.3390/w11091836

[13] LINH N. T. M., TRI D. Q., THAI T. H., and DON N. C. Application of a two-dimensional model for flooding and floodplain simulation: Case study in Tra Khuc-Song Ve river in Viet Nam. *Lowland Technology International Journal*, 2018, 20(3): 367–378. https://cot.unhas.ac.id/journals/index.php/ialt_lti/article/view/548/434

[14] GOVERNMENT OF VIETNAM. *Decision No. 911/QD-TTg: The inter-reservoirs operation procedure for Tra Khuc river basin*. 2018.

参考文:

[1] MAI N. P., KANTOUSH S., SUMI T., THANG T. D., TRUNG L. V., 和 BINH D. V. 评估和调整大坝运行和海平面上升对越南湄公河三角洲海水入侵的影响。日本土木学会会刊乙1系列（水力工程）, 2018, 74(5): 373-378. https://doi.org/10.2208/jscejhe.74.5_I_373

[2] FIROZ A. B. M., NAUDITT A., FINK M., 和 RIBBE L. 使用组合建模方法在越南中部热带河流域量化人类对水文干旱的影响。水文与地球系统科学, 2018, 22(1): 547-565. https://doi.org/10.5194/hess-22-547-2018

[3] NGO L. A., MASIH I., JIANG Y., 和 DOUVEN W. 水库运行和气候变化对湄公河流域下游瑟桑河和斯雷波克河水文状况的影响, 气候变化, 2018, 149(1): 107–119. https://doi.org/10.1007/s10584-016-1875-y

[4] NGA T. T., CONG V. H., 和 HUNG L. 评估气候变化和水库运行对武嘉-秋盆河流域咸水入侵的影响。亚洲及太平洋沿岸国际会议, 2019: 1207–1212. https://doi.org/10.1007/978-981-15-0291-0_165

[5] BINH D. V., KANTOUSH S., SUMI T., 和 MAI N. P. 澜沧江大坝对越南湄公河三角洲流态的影响。日本土木学会会刊乙1, 2018, 74(4): 487-492. http://dx.doi.org/10.2208/jscejhe.74.I_487

[6] LE N. D., LE T. P. Q., PHUNG T. X. B., DUONG T. T., 和 DIDIER O. 水电站大坝对红河（越南）总悬浮泥沙和总有机氮通量

的影响。国际水文科学协会会刊, 2020, 383: 367–374. https://doi.org/10.5194/piahs-383-367-2020
[7] VU H. C., TO T. N., 和 LE H. 评估水库运行对茶库画河流域咸水入侵的影响。批判性评论杂志, 2021, 8(2): 536–549. http://dx.doi.org/10.31838/jcr.08.02.57
[8] VU T. T., 和 NGUYEN T. H. 马河流域水库对盐渍化作用的评价。亚洲及太平洋沿岸国际会议, 2019: 751–758. https://doi.org/10.1007/978-981-15-0291-0_103
[9] DANG N. M., TUNG N. B., DUONG T. A., 和 DANG T. D. 评估气候变化和海平面上升对越南武嘉-秋盆河流域水流和咸水入侵的影响。亚洲及太平洋沿岸国际会议, 2019: 1367–1374. https://doi.org/10.1007/978-981-15-0291-0_185
[10] LE A. T., NGUYEN T. T., DANG N. V., PHAM T. D. M., 和 LAM T. T. S. 水电站运行对武嘉-秋盆下游武嘉-秋盆河流域的影响：从模拟数据到居民反映的现实。越南河网, 2014.
[11] ZHANG X., LIU P., WANG H., LEI X., 和 YIN J. 适应性水库洪水限制水位以适应不断变化的环境。环境地球科学, 2017, 76(21): 1–14. https://doi.org/10.1007/s12665-017-7086-7
[12] LIU G., QIN H., SHEN Q., TIAN R., 和 LIU Y. 梯级水库洪水极限水位动态控制多目标优化调度模型.水, 2019, 11(9): 1-18. https://doi.org/10.3390/w11091836
[13] LINH N. T. M., TRI D. Q., THAI T. H., 和 DON N. C. 二维模型在洪水和洪泛区模拟中的应用：以越南茶库-宋威河为例。低地技术国际期刊, 2018, 20(3): 367–378. https://cot.unhas.ac.id/journals/index.php/ialt_lti/article/view/548/434
[14] 越南政府. 第 911/量子点-TTg 号决定：茶库河流域的水库间操作程序. 2018.