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ASSESSING THE IMPACTS OF RESERVOIR OPERATION ON SALTWATER INTRUSION IN TRA KHUC- VE RIVER BASIN

Huy Cong Vu[1], Thuy Nga To[1*], Hung Le[1]

vhcong@dut.udn.vn; ttnga@dut.udn.vn; lehung@dut.udn.vn

[1]The University of Danang, University of Science and Technology, Vietnam

ABSTRACT: The Tra Khuc - Ve is the largest river basin in Quang Ngai province, Vietnam. During dry periods, this estuary often experiences saltwater intrusion, which causes adverse impact on irrigation and urban water supply. Especially, saltwater intrusion is [2]expected to be more severe under the improper operation of the reservoirs upstream. In this study, these variations are investigated using numerical models MIKE 11. A series of scenarios were simulated with different discharge flows from the upstream reservoirs according to the operating procedure issued by the Prime Minister. It has been shown that reducing salinity levels can be achieved by making a reasonable change in operational policy. Among analyzed scenarios, scenario 2B, wherein the hydropower plants are operated at the same time, is the best choice for reservoirs in the Tra Khuc - Ve river basin. Research on saltwater intrusion in Tra Khuc estuary therefore contributes useful findings for the operation of upstream reservoirs to prevent saline intrusion.

KEYWORDS: Saltwater intrusion, Tra Khuc river, operating rule curve, reservoirs

1. INTRODUCTION

Saltwater intrusion is a big challenge in Vietnam's estuaries, and it is getting more attention from many researchers. Besides the causes of climate change and sea level rise, human activities also contribute to exacerbating the problem of saline intrusion. One of the reasons above is due to improper operation of the reservoirs. The reservoir is one of the most important components that make up the water resource system. The main function of the reservoir is to regulate natural flow by storing surplus water in the rainy season and releasing this stored water in the dry season or for specific purposes[1]. The efficient and sustainable use of water resources not only requires careful and accurate design of these reservoirs, but also requires the proper management and operation after construction. Reservoir operation is a very important part of water resource management and exploitation. Once the reservoir is constructed, the instructions need to be issued and the operator will follow it to make appropriate management decisions. However, due to the fluctuating and uncertain amount of incoming water, along with the conflicts among the groups of water users, the actual operation always has problemsand these have been pointed out by a number of researchers (eg.,[2]–[6])

In Vietnam, the massive construction of hydropower reservoirs in the last 10 years and their operation are believed to have had negative impacts on the environment[7]–[13]. In addition, operation is a complex problem because it is influenced by multiple targets such as power generation, flood control, water demand, as well as considerable risks and uncertainties. Most of the reservoirs in Vietnam still operate based on the fix-rule curves. These rules are presented in the form of graphs or tables and guide the discharge according to the reservoir's water level status, hydrological conditions, and the time of year. For large reservoirs, although the government has issued operating procedures to ensure a balance between water demand, the actual operation still has many shortcomings. The degraded rivers combined with altered flow regimes caused by dam operations, in turn, may increase saltwater intrusion in the estuaries[14]. Van Binh also stated that hydropower development is rapid without consideration of downstream water use issues, especially in the Mekong Delta[11]. Le Ngo simulated and compared operating strategies for the Hoa Binh reservoir and offered two alternative operating solutions, confirming that they perform better than the actual operation [2].

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* Corresponding Author: Thuy Nga To (ttnga@dut.udn.vn)

The construction of hydroelectric reservoirs upstream to regulate the flow will have a great impact on the downstream hydrological regime. In fact, owing to the characteristics of the reservoir system and competitive electricity system operation, there have always been shortcomings in the management and operation of the inter-reservoirs in the basins in recent years. For example, due to limited reservoir capacity, most hydroelectric projects prefer to operate during peak hours. The amount of water passing through a hydropower plant increases significantly during the period with high energy demand and greatly decreases during time of lower energy demand. The operation of hydropower plants leading to such flow variation could adversely affect downstream water use [15]. Another negative effect of improper operation of the reservoirs is increasing the risk of saline intrusion.

Tra Khuc - Ve river basin has also been facing these risks. The construction of hydropower plants upstream has changed the downstream hydrological regime and saline intrusion is expected to be more severe. Currently, five hydroelectric stations have been built in the basin. In dry season, there is always a water dispute among different stakeholders. The reservoirs have their own operating procedures and the Government has also issued an inter-reservoir process; however, because of the complexity of the system as well as the arising inadequacies, the operation process always must change to address the actual situation. The existing operating procedures are often based on the electricity generation coordination chart of the independent reservoir, making the water discharge to the downstream intermittent, affecting other water needs. Although there have been several previous studies, the compromise between targets is difficult when there is not an overall coordination and benefit balance across the basin. Due to the inadequate operation of the reservoir upstream, ensuring the water quantity, there is almost always a shortage of water in dry seasons and this is the reason why the process of preventing salinity is not effective.

In Vietnam, research on saline intrusion has been ongoing since the 1960s when people started to conduct salinity monitoring in the two deltas of the Red River and Mekong River. The Mekong Delta - the most important rice bowl in the south of Vietnam due to its topographical characteristics and the decisive impact on agricultural production - the study of saline intrusion here needs more attention, especially after 1976. Mekong River Commission determined the boundary of saline intrusion according to the statistical method in the system canals in the Mekong Delta in 1973. Following that, there have been many studies on saline intrusion in the Mekong Delta such as[16]–[22]. For the large river systems in the north of Vietnam, Nguyen (2017) [23] predicted the saltwater intrusion in the Red Delta region. The salt water intrusion in the Red river was also simulated by [24]. As mentioned above, there are very few studies on saline intrusion in the central rivers of Vietnam, especially under the influence of reservoir operation. To (2003)[25]studied the saline intrusion in the downstream of Vu Gia river – Thu Bon using the VRSAP model. Nguyen (2013) and (Do 2013) predicted salinity intrusion in Vu Gia - Thu Bon river system under the influence of climate change[26], [27]. Trinh (2014) has simulated saline intrusion in the downstream area of Vu Gia - Thu Bon and proposed seven solutions to reduce saline intrusion in downstream areas[28].The above studies have created an initial set of databases for salinity studies for the region. Currently, the Tra Khuc river is facing a saline intrusion problem that adversely affects irrigation and urban water supplies. In recent years, saline intrusion has occurred more frequently and has received considerable attention from local managers. However, there are only a few studies on this problem and most of them have considered the causes of sea level rise and climate change[29]. As such, most of these studies do not take into account the multi-purpose use of reservoirs as well as the interactions among them. There is no specific solution that yields high efficiency in saline prevention. The purpose of this paper is to fill this gap and to predict saltwater intrusion under the impact of upstream reservoirs operations. More specifically, our contribution is to determine whether the current operation of the reservoirs is suitable for the purpose of preventing saline intrusion in the downstream area.

2. METHODOLOGY

2.1 Description of study area

The study area is the Tra Khuc – Ve river basin, which is considered to be the largest river basin in Quang Ngai province, Vietnam. The Tra Khuc river originates from the Truong Son mountain range, a famous mountain range in Vietnam, and flows into the sea through Dai Co Luy mouth. The river has the length of 135km and total catchment of approximately 3.240 km^2[30]. The topography is relatively complicated with about one third of the length consisting of mountainous terrain at an elevation of 1000 - 2000m. The Ve river has the length of 91 km of which the high mountains at an elevation of 100 - 1000m are found in about 2/3 of its length. The river has a catchment area of 1.260 km^2 and the network density is 0,79 km/km^2. The study domain is shown in Figure 1.

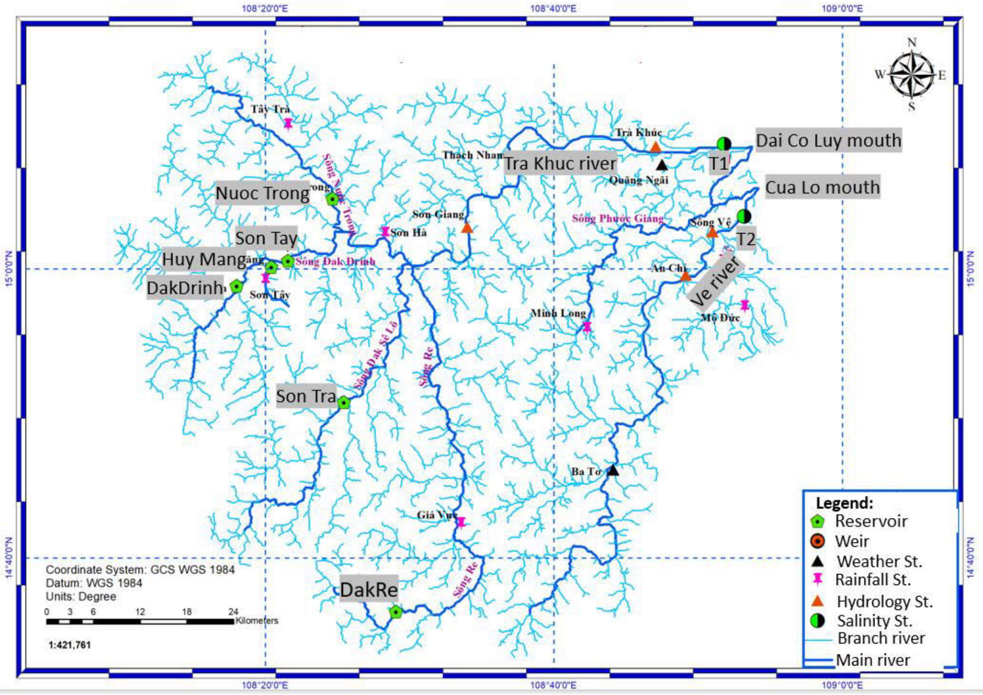

Figure 1: Study area

Currently, along with the socio-economic development, water resources in the lower Tra Khuc river area are seriously degraded. Of particular concern is the impact of the five reservoirs that may alter flow and salinization in the downstream area. The key characteristics of these reservoirs are summarized in table 1. In the Tra Khuc - Ve river basin, there are two large reservoirs including Nuoc Trong and Dak Drinh, the remaining reservoirs are relatively small including Son Tay, Son Tra and Dak Re. These comprise a multi-purpose inter-reservoir system.

In addition to water supply or flood prevention duties, Dak Drinh and Nuoc Trong reservoirs are also responsible for power generation. Dak Drinh plant is the biggest hydro-power plant in Central Vietnam with a capacity of 125MW and the main duty of this reservoir is electricity generation. According to the inter-reservoir operation process, this reservoir must meet the limits of reservoir water levels when operating in the flood and dry seasons, as well as the minimum amount of water that needs to be discharged downstream. For the Nuoc Trong reservoir, the main duty is to supply irrigation water for the Thach Nham area downstream, and this amount of water is mainly through electricity generation. This water supply target is prioritized during the dry season according to the single-reservoir operation process and the inter-reservoir operation process. Nuoc Trong has the installation capacity of 16,5 MW, the annual power output of 10 million kWh. The imbalance between exploitation and use and protection of water resources has been increasing the level of saline intrusion into the Tra Khuc river. One of the major problems affecting the decline of water resources in the lower Tra Khuc river is the increase of water use for agriculture and industry of the Thach Nham irrigation system.

Although there is a reservoir operation procedure in Tra Khuc- Ve river basin including Dak Drinh, Nuoc Trong, Son Tay, Son Tra and Dak Re reservoirs, this inter-reservoir operation is still requires additional support tools to meet the actual operating requirements. One of the shortcomings in reservoir operation during the dry season is downstream flow varies and affects the water consumption. The generation of electricity in peak hours (a few hours a day for the not-regulating or day-regulating reservoirs; and about 8-10 hours per day for the annual regulated reservoir) leads to intermittent downstream flow. For Nuoc Trong reservoir, there is a big difference between the downstream discharge requirements of the single reservoir process and the inter-reservoir process (911 / QD-TTg) to meet irrigation demand. The improper operation has led to the risk of saline intrusion downstream. In March 2015, salinity penetrated deeply into Hoa Ha area, Dung Dinh - Vo Hoi field in Nghia Hoa commune, Tu Nghia district, Quang Ngai province, damaging rice and other crops of local farmers.

Table 1: Information of hydropower plants in the Tra Khuc- Ve river basin.

Reservoirs	Installed capacity (MW)	Reservoir volume ($m^3 \times 10^6$)	Maximum discharge through turbine (m^3/s)
Dak Drinh	125,00	249,3	55
Nuoc Trong	16,5	289,5	42
Son Tay	18,0	0,535	22
Son Tra	4,4	6,83	82
Dak Re	60,0	10,34	10,69

Previous research has indicated that the saltwater intrusion is strongly dependent on the amount of freshwater discharge from the river, the estuary shape and tidal behavior. The study area is located in western East Sea and has irregular diurnal and semi-diurnal tidal regime. The tidal range of estuaries in the dry season averages at 1,2 – 1,3m, the maximum does not exceed 1,5m; The Tra Khuc and Ve rivers interacts with the sea directly through the Dai Co Luy and Cua Lo mouths, respectively. During the flood season, the upstream flow is quite large so saline intrusion is greatly limited. In the dry season, the small flow creates conditions for seawater to penetrate deeply into the river, greatly affecting production and living.

2.2 Model set-up

This paper focuses on analysis of salinity distribution along the Tra Khuc river under the impact of upstream reservoirs operation. The MIKE 11 model from the Danish Hydraulic Institute was used to predict the change of water intrusion in this paper. The MIKE 11 is a suitable model for simulating the flow and water level, water quality, as well as sediment transport in rivers, flood plains, reservoirs, and other inland bodies of water. It is a very effective tool for complex river systems and in limited data conditions. This software includes two main modules of hydrodynamic (HD) and advection–dispersion (AD). The main governing equations are known as Saint-Venant equations [31] as below:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (1)$$

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

where Q is discharge. *A* is cross-sectional area, *q* is lateral flow, *h* is depth, *C* is chezy resistance coefficient, *R* is hydraulic radius and $\alpha$is momentum distribution coefficient. Equation (3) present the advection- dispersion equation in MIKE11.

$$\frac{\partial AC}{\partial t}+\frac{\partial QC}{\partial x}+\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right)=-AKC+C_2q \qquad (3)$$

where C is the concentration, D is the dispersion coefficient, K is the linear decay coefficient, C_2 is the source concentration, and t is the time coordinate [31].

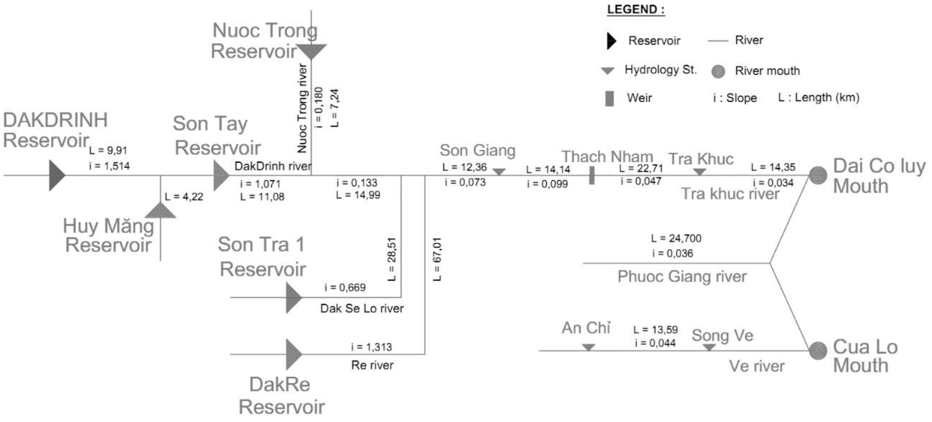

Figure 2: River network in the Tra Khuc – Ve river basin, including the reservoirs system.

In this study, the 1-D model was used to simulate and this 1-D model has also been successfully applied in many studies on saline intrusion, such as[9], [20], [32], [33].The hydraulic and hydrological regime as well as saline intrusion in the Tra Khuc river basin depends mainly on factors including upstream discharge, rainfall and the tidal regime of the East Sea. In HD module, the flow boundaries were defined at Son Giang station (Tra Khuc river) and An Chi station (Ve river). The downstream boundaries are forced with water levels that were collected from the national hydro-meteorological stations. Water level data setting for two downstream boundaries are located at Cua Lo and Dai Co Luy. The salinity at the upstream boundary is zero, where no salt water intrudes. At downstream boundaries, the salinity is estimated at $25^0/_{00}$.

2.3 Calibration and validation

The calibration and validation processes were conducted based on the observed water level and salinity at two positions T1 and T2, as shown in Figure 2. The correlation coefficient, Nash-Sutcliffe coefficient are used as model efficiency criteria, as shown in equations 4, 5 respectively.

$$R=\frac{\sum_{\mathrm{i}=1}^{n}\left(X_{\mathrm{obs,i}}-\bar{X}_{\mathrm{obs}}\right).\left(X_{\mathrm{model,i}}-\bar{X}_{\mathrm{model}}\right)}{\sqrt{\sum_{\mathrm{i}=1}^{n}\left(X_{\mathrm{obs,i}}-\bar{X}_{\mathrm{obs}}\right)^{2}.\sum_{\mathrm{i}=1}^{n}\left(X_{\mathrm{model,i}}-\bar{X}_{\mathrm{model}}\right)^{2}}} \qquad (4)$$

$$E=1-\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(\mathrm{X}_{\mathrm{obs,i}}-\mathrm{X}_{\mathrm{model,i}}\right)^{2}}{\sum_{\mathrm{i}=1}^{n}\left(X_{\mathrm{obs,i}}-\bar{X}_{\mathrm{obs}}\right)^{2}} \qquad (5)$$

where the X_{obs} is observed value and X_{model} is modelled value at time/ place *i*.

The results of water level for the calibration and validation performance are presented in Figure 3 and 4. It can be seen that the model predicted the water level are in good agreement with observed data. The results of calculated and measured water level data with Nash-Sutcliffe ranges from 0.810-0.933 and 0.789 - 0.916, respectively, see table 2. This demonstrates that the water level data boundary in the model is reliable.

Table 2: Statistical performance of calibration and validation of water level

Stations	Calibration		Validation	
	Nash (E)	R	Nash (E)	R
T1	0,810	0,975	0,789	0,972
T2	0,933	0,97	0,961	0,982

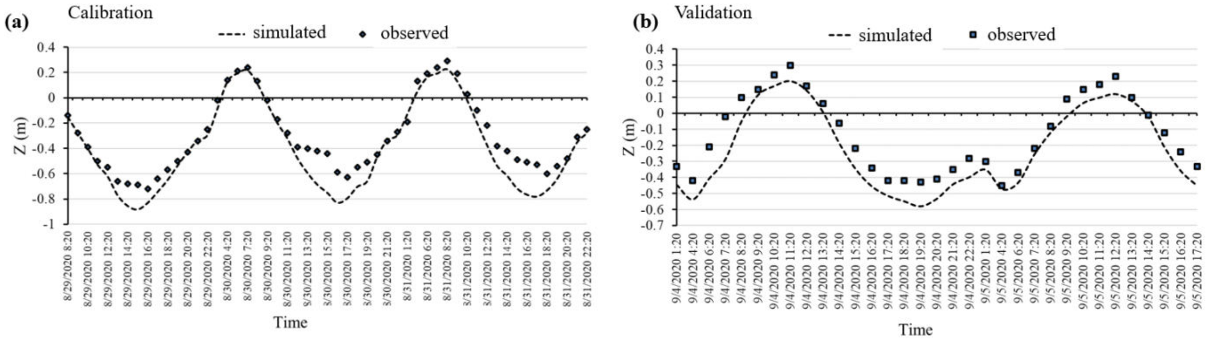

Figure 3. Calibration and validation of water level at T1 station.

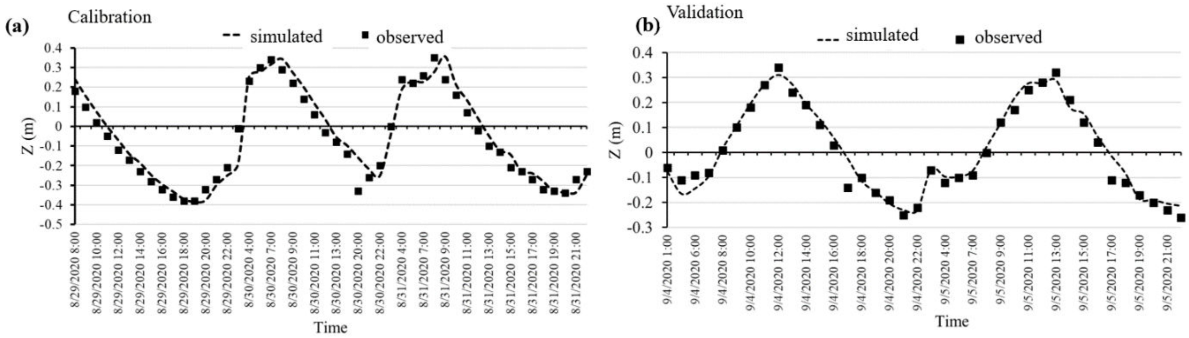

Figure 4. Calibration and validation of water level at T2 station

The calibration and validation process for simulated and observed salinity are shown in Figure 5, 6 and table 3. In the calibration and validation, the salinity between calculated and observed ranges are in line with the phase and amplitude, of Nash-Sutcliffe ranges from 0.722-0.774 for T1 position and 0.692-0.65 for T2 position. Comparing the measured and simulated values shows that the model has a relatively accurate prediction of the salinity value.

Table 3: Statistical performance of calibration and validation of salinity

Stations	Calibration		Validation	
	Nash	R	Nash	R
T1	0.722	0.89	0.774	0.91
T2	0.692	0.84	0.65	0.812

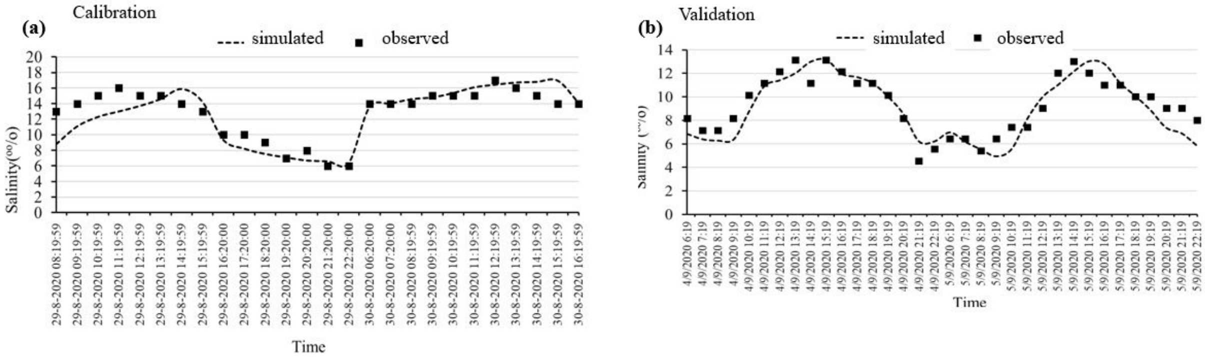

Figure 5: Calibration and validation of salinity at T1 station

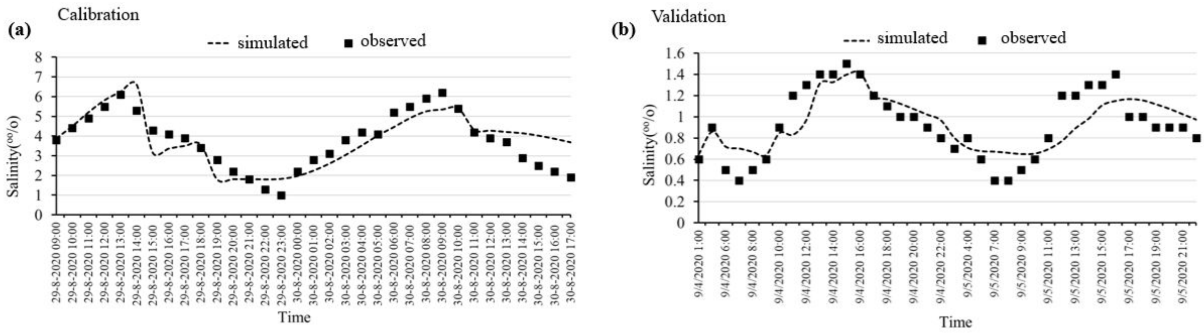

Figure 6: Calibration and validation of salinity at T2 station

Taken overall, the calibration and validation results show that this model is suitable for further research scenarios..

2.4 Reservoir operation

In the original design, each of the reservoirs uses its own operating rule curves to guide reservoir releases. For example, the individual operating rule curves of Nuoc Trong and Darking reservoirs are shown in Figure 7 and 8, respectively. According to the operating rule curves, the entire storage space is divided into three operational zones: (i) when the reservoir water level lies in zone 1, the power plants are operated at maximum capacity; (ii) if the water level falls into zone 3, the power plants are operated with the discharge through turbines that meet minimum downstream water demand; (iii) when the reservoir water level is in zone 2, the power plant's discharge varies between the minimum and maximum capacity with respect to the water level.

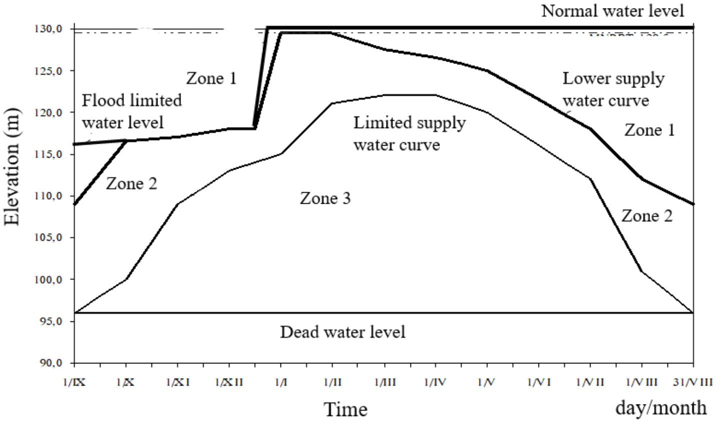

Figure 7: Designed operation rule curve of Nuoc Trong reservoir

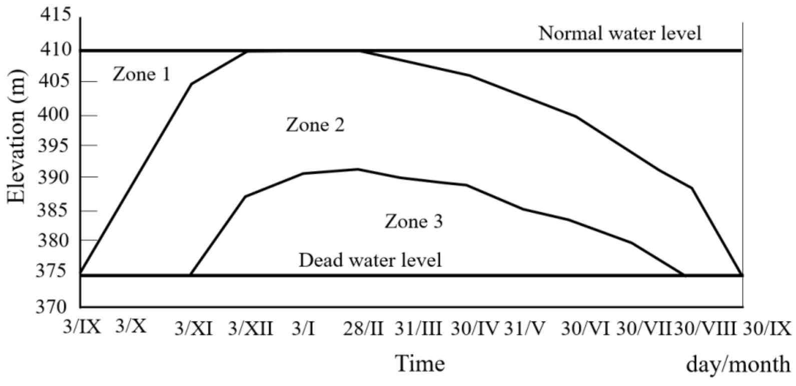

Figure 8: Designed operation rule curve of Dak Drinh reservoir

In addition, on July 25th, 2018, the Prime Minister signed decision No. 911/QD-TTg (hereinafter referred to as Rule 911) for operating inter-reservoirs in Tra Khuc – Ve river basin, including Dak Drinh, Nuoc Trong, Son Tra, Dak Re and Son Tay reservoirs. Within one year of operation, the pattern of operation is executed according to two models: flood season (from September 1 to December 15) and dry season (from December 16 to August 31). During flood season, this rule: *(1)* ensures absolute safety of Dak Drinh hydropower plants, prevents reservoir's water level from exceeding the maximum water level for all floods with a repeated cycle of less than or equal to 5,000 years; (2) ensures absolute safety of Nuoc Trong reservoir, prevents reservoir's water level from exceeding the maximum water level for all floods with a repeated cycle of less than or equal to 1,000 years; (3) ensures absolute safety of Son Tra, Dak Re and Son Tay, prevents reservoir's water level from exceeding the maximum water level for all floods with a repeated cycle of less than or equal to 500 years. In addition, during the flood season, this rule also specifies the task of reducing floods for downstream areas and ensuring efficient water supply and electricity generation. During dry season, this rule specifies the task of ensuring safety of hydropower plants; minimum river runoff and lowlands' water demand and ensuring efficiency in electricity generation. The minimum reservoir water level in various periods is enclosed with Rule 911 as shown in table 4. The water demand of the reservoirs differ from time to time of the year. The rule 911 also states that the period of supplementary water use is from May 5 to June 10 and from July 1 to August 20 each year. The rest of the year is considered normal water use.

Table 4. The reservoir water level in various periods (Enclosed with the Rule 911)

No.	**Date**		**Reservoir water level (m)**			
			Dak Drinh		**Nuoc Trong**	
	From	**to**	**from**	**to**	**from**	**to**
1	16/12	20/12	407,4	409,0	123,0	126,0
2	21/12	31/12	407,4	409,0	123,0	126,0
3	1/1	10/01	407,3	408,9	123,0	126,0
4	11/1	20/01	407,3	408,9	123,0	126,0
5	21/1	31/01	407,2	408,8	123,0	126,0
6	1/2	10/02	407,2	408,8	122,9	125,9
7	11/2	20/02	407,1	408,7	122,7	125,7
8	21/2	28/02 (29/02)	407,0	408,6	122,5	125,5
9	1/3	10/3	406,6	408,2	121,9	124,9
10	11/3	20/3	405,9	407,5	121,2	124,2
11	21/3	31/3	405,1	406,7	120,2	123,2
12	1/4	10/4	404,1	405,7	118,9	121,9
13	11/4	20/4	403,5	405,1	118,0	121,0
14	21/4	30/4	402,7	404,3	117,1	120,1
15	1/5	10/5	401,8	403,4	116,5	119,5
16	11/5	20/5	400,1	401,7	115,5	118,5
17	21/5	31/5	398,2	399,8	113,8	116,8
18	1/6	10/6	396,4	398,0	111,9	114,9
19	11/6	20/6	395,1	396,7	110,4	113,4
20	21/6	30/6	393,5	395,1	109,2	112,2
21	1/7	10/7	391,9	393,5	108,3	111,3
22	11/7	20/7	389,8	391,4	106,5	109,5
23	21/7	31/7	387,3	388,9	104,2	107,2
24	1/8	10/8	384,7	386,3	101,6	104,6
25	11/8	20/8	381,8	383,4	100,0	103,0
26	21/8	31/8	380,0	381,6	97,7	100,7

2.5 Application Scenarios

The salinity in Tra Khuc river was investigated with different scenarios of reservoirs operation. The baseline scenarios, operating according to the inter-reservoir process (Rule 911) and original design rule curves, are simulated to assess the degree of changes in saline intrusion along the river. It should be noted that the salinity intrusion is simulated ina year of low flow (with frequency of 85%) corresponding to the flow in 1997. This frequency is also consistent with the previous study[9][34]. The selection of this hydrological year is based on the hydrological data at the Son Giang and An Chi stations. The study on operation of reservoirs system includes 5 scenarios, divided into 2 groups as follows:

1. Baseline scenario 1A: The flow in the river is considered the same as the natural condition. No reservoirs are included in this scenario.
2. Scenario 1B: The reservoirs are operated according to the original design rule curve of each reservoir.
3. Scenario 1C: The reservoirs are operated according to the inter-reservoir's operation rules (Rule 911).

It is noted that all three above scenarios are simulated with two periods: a period of normal water use and a period of increasing water use. The power generation strategies determine the amount of water flowing downstream, thus greatly affecting saline intrusion. Generating continuously or alternately will have different effects on saline intrusion downstream. To assess the impact of these operations, several scenarios are given as follows (group 2):

4. Scenario 2A: Dak Drinh and Nuoc Trong hydropower reservoirs generate electricity alternately (Dak Drinh reservoir operates from 9:00 to 21:00 and Nuoc Trong reservoir operates from 21:00 to 9:00 the next morning), other reservoirs such as Dak Re, Son Tay and Son Tra reservoirs generate electricity at peak hours with 5 hours a day (i.e., from 9:30 to 11:30 and from 17:00 to 20:00).
5. Scenario 2B: Dak Drinh and Nuoc Trong hydropower reservoirs generate electricity for 12 hours (from 9:00 to 21: 00), other reservoirs such as Dak Re, Son Tay and Son Tra generate electricity at peak hours with 5 hours a day (i.e., 9:30 to 11:30 and 17:00 to 20:00).

More information about these scenarios is presented in the table:

Table 4: Simulated scenarios

Scenario	Nuoc Trong	Dak Drinh	Son Tra	Dak Re	Son Tay
1A	-	-	-	-	-
1B	original design rule curve	original design rule curve	original design rule curves	original design rule curve	original design rule curve
1C	Rule 911	Rule 911	Rule 911	Rule 911	Rule 911
2A	generate electricity from 21:00 to 9:00 next morning	generate electricity from 9:00 to 21:00	generate electricity from 9:30 to 11:30 and from 17:00 to 20:00	generate electricity from 9:30 to 11:30 and from 17:00 to 20:00	
2B	generate electricity from 9:00 to 21:00	generate electricity from 9:00 to 21:00	generate electricity from 9:30 to 11:30 and from 17:00 to 20:00	generate electricity from 9:30 to 11:30 and from 17:00 to 20:00	

3. RESULTS AND DISCUSSIONS

3.1 Change in salinity intrusion under the group 1 scenarios

Salinity simulation results corresponding to scenarios from 1A to 1C are shown in Figures 9 - 12. It should be noted that the maximum concentration was calculated and is presented in the figures.

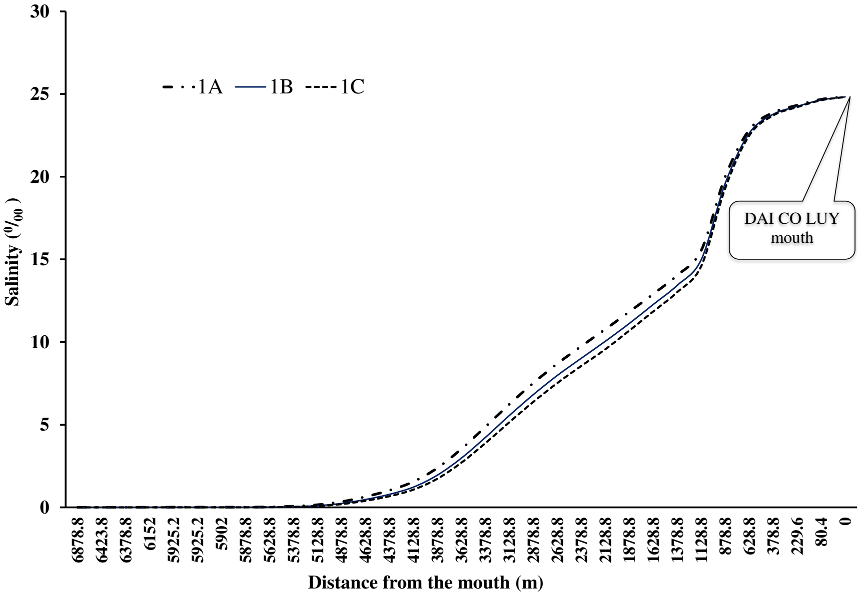

Figure 9: Salinity distribution along the Tra Khuc river during the period of normal water use (the group 1 scenarios)

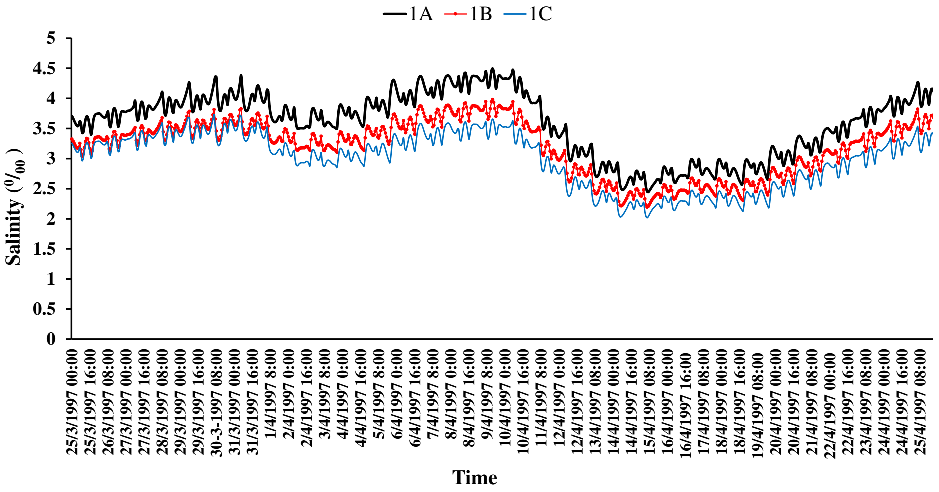

Figure 10: Salinity concentration in Tra Khuc river at location of 3.5km from the mouth during the period of normal water use (the group 1 scenarios)

In figure 9, salinity is found to be similar for all scenarios in the range from the mouth (Dai Co Luy) to location of 878m and from location of 5100m to the upstream of river. In these locations, the change of water use and reservoir operation have no impact on saline intrusion levels. In contrast, the salinity in the river varies markedly between locations of 878m and about 5100m from the mouth. For scenario 1A, during normal water use period (see Figures 9 and 10), when the effect of reservoirs water is not present, the salinity is the highest. This also shows the role of reservoirs in reducing saline intrusion into the river. This result disagrees with several previously studies [35]which found that the reservoirs sometime increase saline intrusion. This suggests that the operation of the reservoirs could either increase or decrease it. In this case, salinity is reduced by more than 1 $^0/_{00}$ compared to the scenarios of without reservoir. In addition, the study also shows that the operation with rule 911 (scenario 1C) or original design rule curve (1B) does not significantly affect the salinity intrusion level. Compared to other scenarios, the operation according to rule 911 or original design rule curve gives the lowest results of saline intrusion. The results showed that the salinity boundary of 1‰ can penetrate to 4378m, 4253m, 4200m from the mouth for scenarios of 1A, 1B, 1C, respectively.

For the normal water use period, the difference in salinity along the river corresponding to the scenarios is relatively small compared to the period of supplementary water use, when the demand for irrigation water is higher (see figures 11 and 12). For the period of increased water use, the difference in salinity in the scenarios with and without reservoir is significant. During this period, the operation of reservoirs plays a more important role in reducing salinity. Salinity decreased by about 2-3 $^{0}/_{00}$ compared to other scenarios. At the location of 3.5km from the mouth, the salinity values in scenarios 1C and 1B are about 3.5 $^{0}/_{00}$ while for scenario 1A it is at 5.5 $^{0}/_{00}$ (see figure 12). In addition, the operation following private rule curve (scenario 1B) compared with the operation based on rule 911 (scenario 1C) showed small difference in salinity level.

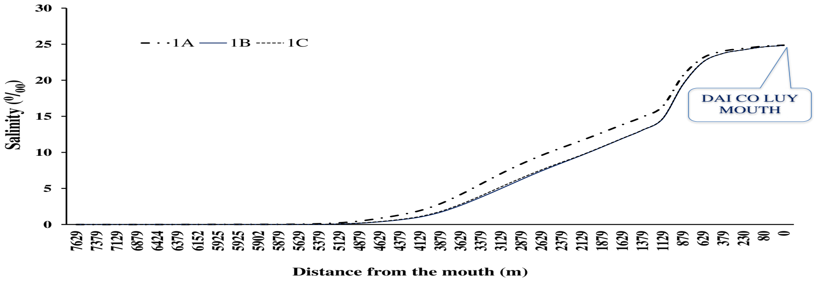

Figure 11:Salinity distribution along the Tra Khuc river during the period of supplementary water use (the group 1 scenarios)

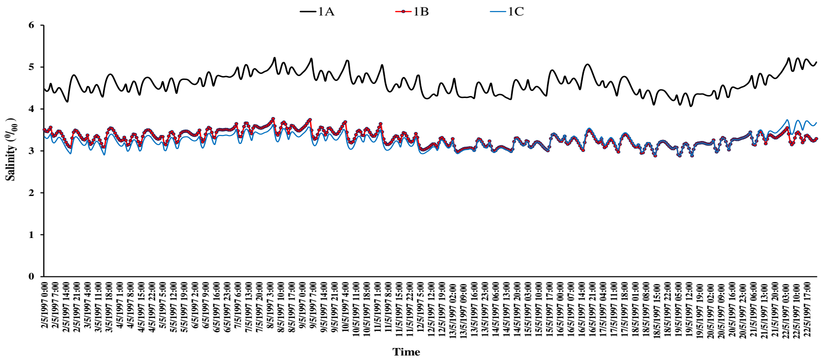

Figure 12: Salinity concentration in Tra Khuc river at location of 3.5km from the mouth during the period of supplementary water use (the group 1 scenarios)

3.2 Change in salinity intrusion under the group 2 scenarios

The continuous or alternating operation of hydropower stations also greatly affects the level of saline intrusion. Figure 13 present the distributions of maximum salinity levels along the Tra Khuc rivers under the scenarios of 2A, 2B.

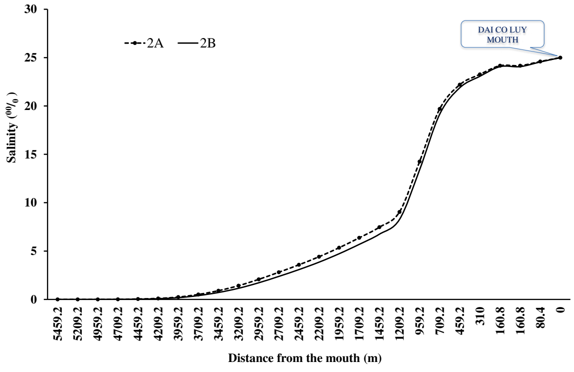

Figure 13: Salinity distribution along the Tra Khuc river (the group 2 scenarios)

Figure 13 shows that the salinity concentration in scenario 2B is smaller than that in scenario 2A. For example, the salinity decreases by 9% compared to that of scenario 2A at location of 1km from the mouth. In other words, the alternating water discharge through the power generation of Dak Drinh and Nuoc Trong reservoirs (scenario 2A) does not reduce salinity compared to the case in which these two plants generate electric at the same time from 9:00 to 21:00. Large flow occurring over a period of time generally have a greater salinity reduction effect than evenly distributing the flow, but the discontinuous flow distribution may also affect downstream water availability. This statement is consistent with the conclusion in research on salinity on the Vu Gia - Thu Bon rivers of author Le Hung [36].

4. CONCLUSION

The present study simulated the saltwater intrusion in Tra Khuc- Ve river basin under the effect of upstream reservoirs operation. The model was calibrated and verified using observation water level, salinity data in 2020 and showed a good agreement. The result of the study indicates that in the presence of reservoirs, the salinity is reduced. The present operating policy of these reservoirs can cause varying degrees of salinity. It has been shown that reducing salinity levels can be achieved by making a reasonable change in operational policy. Among analyzed scenarios, scenario 2B, wherein the hydropower system is operated at the same time, is the best choice for reservoirs in the Tra Khuc- Ve river basin. This operation should be recommended for the managers to reduce saline intrusion at the same time to ensure the power output.

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REFERENCES

[1] S. K. Jain and R. NIH, “Introduction to Reservoir Operation,” Technical Report, 2019.

[2] N. L. Le, H. Madsen, D. Rosbjerg, and C. B. Pedersen, “Implementation and comparison of reservoir operation strategies for the Hoa Binh reservoir, Vietnam using the MIKE 11 model,” *Water Resour. Manag.*, vol. 22, no. 4, pp. 457–472, 2008.

[3] J. W. Labadie, “Optimal operation of multireservoir systems: State-of-the-art review,” *J. water Resour. Plan. Manag.*, vol. 130, no. 2, pp. 93–111, 2004.

[4] L. Chen, “Real coded genetic algorithm optimization of long term reservoir operation 1,” *JAWRA J. Am. Water Resour. Assoc.*, vol. 39, no. 5, pp. 1157–1165, 2003.

[5] R. Oliveira and D. P. Loucks, “Operating rules for multireservoir systems,” *Water Resour. Res.*, vol. 33, no. 4, pp. 839–852, 1997.

[6] G. Guariso, S. Rinaldi, and R. Soncini-Sessa, “The management of Lake Como: A multiobjective analysis,” *Water Resour. Res.*, vol. 22, no. 2, pp. 109–120, 1986.

[7] T. D. LUU and J. Von Meding, “Hydropower development and environmental impact assessments in Vietnam: current practice and short-comings,” in *Sustainable water and sanitation services for all in a fast changing world: Proceedings of the 37th WEDC International Conference, Hanoi, Vietnam*, 2014, pp. 15–19.

[8] A. T. Le, T. T. Nguyen, N. V Dang, T. D. M. Pham, and T. T. S. Lam, “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.

[9] T. T. Nga, V. H. Cong, and L. Hung, “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, pp. 1207–1212.

[10] T. Piman, T. A. Cochrane, M. E. Arias, A. Green, and N. D. Dat, “Assessment of flow changes from hydropower development and operations in Sekong, Sesan, and Srepok rivers of the Mekong basin,” *J. Water Resour. Plan. Manag.*, vol. 139, no. 6, pp. 723–732, 2012.

[11] D. Van BINH, S. Kantoush, T. Sumi, and N. P. Mai, “Impact of Lancang cascade dams on flow regimes of Vietnamese Mekong Delta,” *土木学会論文集 B1*, vol. 74, no. 4, p. I_487-I_492, 2018.

[12] N. P. Mai, S. Kantoush, T. Sumi, T. D. Thang, L. V. Trung, and D. Van BINH, “Assessing and adapting the impacts of dams operation and sea level rising on saltwater intrusions into the Vietnamese Mekong Delta,” *J. Japan Soc. Civ. Eng. Ser. B1 (Hydraulic Eng.*, vol. 74, no. 5, p. I_373-I_378, 2018.

[13] N. Van Manh, N. V. Dung, N. N. Hung, M. Kummu, B. Merz, and H. Apel, “Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise,” *Glob. Planet. Change*, vol. 127, pp. 22–33, 2015.

[14] D. Van Binh, S. Kantoush, and T. Sumi, “Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams,” *Geomorphology*, vol. 353, p. 107011, 2020.

[15] T. Q. Viet, “Estimating the Impact of Climate Change Induced Saltwater Intrusion on Agriculture in Estuaries: The Case of Vu Gia Thu Bon, Vietnam.” Universität Bochum, 2014.

[16] N. Huu-Thoi and A. Das Gupta, “Assessment of water resources and salinity intrusion in the Mekong Delta,” *Water Int.*, vol. 26, no. 1, pp. 86–95, 2001.

[17] A. D. Nguyen and H. H. G. Savenije, “Salt intrusion in multi-channel estuaries: a case study in the Mekong Delta, Vietnam,” *Hydrol. Earth Syst. Sci. Discuss.*, vol. 3, no. 2, pp. 499–527, 2006.

[18] S. Le, “Salinity intrusion in the Mekong Delta,” 2006.

[19] L. A. Tuan, C. T. Hoanh, F. Miller, and B. T. Sinh, “Flood and salinity management in the Mekong Delta, Vietnam,” 2007.

[20] N. D. Khang, “Sensitivity of salinity intrusion to sea level rise and river flow change in Vietnamese Mekong Delta-impacts on availability of irrigation water for rice cropping,” 農業気象, vol. 64, no. 3, pp. 167–176, 2008.

[21] Q. T. Doan, C. D. Nguyen, Y. C. Chen, and K. M. Pawan, “Modeling the influence of river flow and salinity intrusion in the Mekong river estuary, Vietnam,” *Lowl. Technol. Int.*, vol. 16, no. 1, pp. 14–25, 2014.

[22] D. Tran Anh, L. P. Hoang, M. D. Bui, and P. Rutschmann, “Simulating future flows and salinity intrusion using combined one-and two-dimensional hydrodynamic modelling—the case of Hau River, Vietnamese Mekong delta,” *Water*, vol. 10, no. 7, p. 897, 2018.

[23] Y. T. B. Nguyen, A. Kamoshita, H. Matsuda, and H. Kurokura, “Salinity intrusion and rice production in Red River Delta under changing climate conditions,” *Paddy Water Environ.*, vol. 15, no. 1, pp. 37–48, 2017.

[24] N. T. Hiền, R. Ranzi, and V. M. Cát, “Potential use of reservoirs for mitigating saline intrusion in the coastal areas of Red river delta,” in *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, 2018, pp. 1–6.

[25] T. N. To, “Research on saline intrusion on the downstream of Vu Gia Thu Bon river,” *Rep. Proj. Danang Univ. Da Nang*, 2003.

[26] T. P. Nguyen, V. T. To, and N. V. D, “Research on calculation of saline intrusion on Vu Gia Thu Bon river system considering the impact of climate change,” *Tap chi khoa hoc cong nghe thuy loi (iin Vietnamese)*, vol. 8, 2013.

[27] H. N. Do, Q. D. Nguyen, U. Keiko, and M. Akira, “Future Salinity Intrusion in Central Vietnam Assessed Using Super-High Resolution Climate Model Output and Sea Level Rise Scenarios,” *J. water Resour. Hydraul. Eng.*, vol. 2, no. 4, pp. 116–124, 2013.

[28] T. Q. Viet, “Estimating the impact of climate change induced saltwater intrusion on agriculture in estuaries,” 2015.

[29] T. K. . Dang, V. N. Dang, and D. H. Nguyen, “Evaluating and forecasting the form of saline intrusion in the downstream area of Tra Khuc-Song Ve river,” *Tap chi khoa hoc ky thuat thuy loi va moi truong*, vol. 50, 2015.

[30] N. T. M. Linh, D. Q. Tri, T. H. Thai, and N. C. Don, “Application of a two-dimensional model for flooding and floodplain simulation: Case study in Tra Khuc-Song Ve river in Viet Nam,” *Lowl. Technol. Int.*, vol. 20, no. 3, Dec, pp. 367–378, 2018.

[31] DHI, *Mike 11 User Manual*. 2017.

[32] J. I. A. Gisen, H. H. G. Savenije, R. C. Nijzink, and A. K. Abd. Wahab, “Testing a 1-D analytical salt intrusion model and its predictive equations in Malaysian estuaries,” *Hydrol. Sci. J.*, vol. 60, no. 1, pp. 156–172, 2015.

[33] D. H. Nguyen, M. Umeyama, and T. Shintani, “Importance of geometric characteristics for salinity distribution in convergent estuaries,” *J. Hydrol.*, vol. 448, pp. 1–13, 2012.

[34] X. L. Nguyễn and Q. A. Nguyễn, “Đánh giá tác động điều tiết hồ chứa đến xâm nhập mặn hạ du lưu vực sông Mã,” *Tạp chí KH&CN Thủy lợi Viện KHTLVN*, pp. 1–12.

[35] Q. An, Y. Wu, S. Taylor, and B. Zhao, “Influence of the Three Gorges Project on saltwater intrusion in the Yangtze River Estuary,” *Environ. Geol.*, vol. 56, no. 8, pp. 1679–1686, 2009.

[36] H. Le, “Evaluate the impact of the regulation of water flow from hydropower reservoirs in the Vu Gia Thu basin on saline intrusion in the downstream area,” 2020.