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An Efficient Reservoir Operation to Reduce Saltwater Intrusion in the Vu Gia - Thu Bon River Basin

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Abstract: Saltwater intrusion is expected to be more severe in the Vu Gia Thu Bon river basin, the largest river basin in central Vietnam. To the best of our knowledge, there is currently no viable solution for preventing saline intrusion. This study aims to propose an effective operational strategy for existing upstream reservoirs in the Vu Gia – Thu Bon basin to reduce saltwater intrusion. Several scenarios concerning hydropower plants' operating time and flow discharges were analyzed using MIKE NAM, MIKE 11, and HECRESSIM models. The results show that discharge timing significantly impacts salinity prevention in the Vu Gia – Thu Bon basin. The most efficient scenario in lowering salinity is scenario KB2, in which the hydropower plants operate for 6 hours per day. Salinity in scenario KB2 is found to decrease by 3.8‰ to 8‰ compared to other scenarios.

Keywords: saltwater intrusion, reservoir operation, Vu Gia - Thu Bon basin.

有效的水庫操作以減少武嘉 - 秋盆河流域的鹹水入侵

摘要：預計越南中部最大的河流流域武家秋盆河流域的鹹水入侵將更為嚴重。據我們所知，目前還沒有可行的解決方案來防止鹽水入侵。本研究旨在為武嘉-秋盆盆地現有的上游水庫提出一種有效的運營策略，以減少海水入侵。使用麦克风降雨徑流、麦克风 11 和水文工程中心油藏系統模擬模型分析了有關水電站運行時間和流量的幾種情況。結果表明，排放時間顯著影響武嘉-秋盆盆地的鹽度預防。降低鹽度的最有效方案是知识库 2 方案，其中水電站每天運行 6 小時。與其他情景相比，KB2 情景中的鹽度降低了 3.8‰ 至 8‰。

关键词：鹹水入侵，水庫作業，武嘉-秋盆盆地。

1. Introduction

The Vu Gia – Thu Bon river basin has been experiencing the risk of saline intrusion, which has caused severe impacts on irrigation and urban water supply [1, 2]. Furthermore, saltwater intrusion is likely to be more severe, especially during the dry season, when water disputes among diverse stakeholders are widespread. When a natural river flow decreases and reservoir outflow is low during the dry season, seawater intrudes further upstream. This intrusion degrades freshwater quality, posing major challenges for ecosystems and other freshwater users, therefore requiring timely measures to reduce saline intrusion. Managers tried to control saline incursion by implementing structural measures like temporary dams to deflect flows, but these measures were ineffective. In this context, changing the operation of existing upstream reservoirs is considered an alternative solution for increasing discharge and pushing salinity back. In this paper, we propose a numerical model to simulate the operation scenarios of the reservoir systems in the Vu Gia – Thu Bon basin and recommend an effective scenario to reduce saltwater intrusion while still adhering to the Prime Minister's inter-reservoir operation procedure.

In the past, many authors have looked into the relationship between saline intrusion and reservoir operation [3-7]. However, there are still few studies on this topic in the Vu Gia – Thu Bon basin. Hung Le reported the problem of saltwater intrusion in Vu Gia - Thu Bon basin under the influence of climate change and reservoir operation [8]. Only one reservoir, Dakmi 4, was taken into account in his study. Cong recently investigated the operation of the reservoir and saline intrusion in this basin. On the other hand, the author solely looked at the presence and absence of reservoirs,

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ignoring the effects of the operating procedures [1]. Therefore, a comprehensive, systematic approach to saltwater intrusion under the operation of these reservoirs is required. This research will help reservoir operators reduce saltwater intrusion in the Vu Gia – Thu Bon river basin.

2. Study Area

With a catchment area of 10350 km^2, the Vu Gia - Thu Bon river basin is one of the largest in central Vietnam (see Fig. 1). This basin's water resources are widely used for various purposes, including hydropower, irrigation, domestic and industrial water supply. The Quang Hue channel connects the Vu Gia and Thu Bon rivers, distributing water between them, and thus has a significant impact on the downstream flow hydraulic regime. Furthermore, the network of rivers downstream is linked by many small rivers, making salt distribution quite complicated. The coastal area is affected by the tidal regime of the East Sea, which has semi-diurnal characteristics with two peaks and two troughs during a day.

The climate of Vu Gia – Thu Bon basin is characterized by a rainy season from September to December and a prolonged dry season. The dry season starts from January to August and is often accompanied by severe drought. Months from February to April are considered the driest months, accounting for only 3-5% of the total average rainfall resulting in water scarcity and severe saltwater intrusion downstream. Therefore, reservoir operations in this river basin are of particular concern as it is hoped that they can contribute to reducing saline intrusion. Five reservoirs are selected for simulation in this basin, including A Vuong, Song Tranh 2, Song Bung 4, Dakmi 4, and Song Bung 5 reservoirs. Their generating capacities are 210, 162, 156, 141, and 57 megawatts (MW), respectively. The remaining hydropower plants in this basin have a capacity of less than 50 MW. It is worth noting that when the Dakmi 4 power plant operates, water is transferred from the Vu Gia River to the Thu Bon River in order to generate electricity leading to conflicts over water consumption goals and disputes among stakeholders, especially in the dry season.

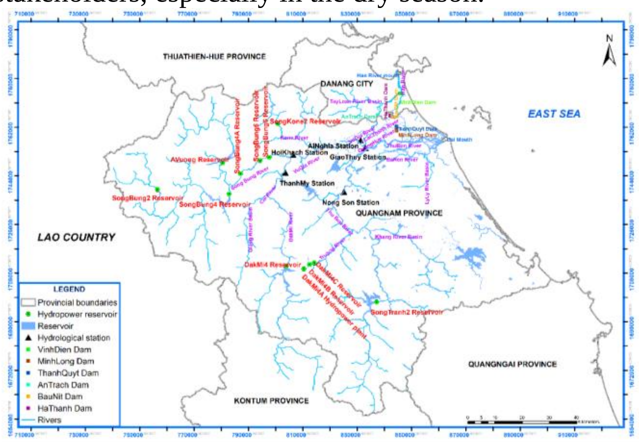


Fig. 1 Vu Gia – Thu Bon river basin

3. Methodology

This research proposes an effective operational solution for existing reservoirs in the Vu Gia – Thu Bon basin to reduce saltwater intrusion. The schematic of the modeling framework is shown in Fig. 2. Accordingly, the flows to the reservoirs and downstream nodes were reconstructed from the precipitation data series using the MIKE NAM model. The MIKE 11 model developed by the Danish Hydraulic Institute (DHI) was selected to simulate hydrodynamics and saline intrusion. In addition, the HECRESSIM model was used to simulate reservoirs operation.

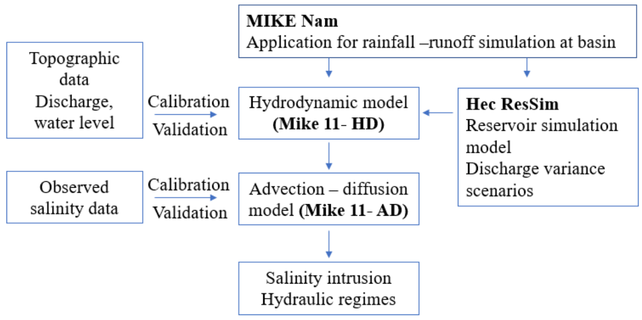


Fig. 2 Schematic of the modeling framework for this study

3.1. MIKE NAM Calibration and Validation

The flow data measured at Nong Son and Thanh My stations are used to calibrate and verify the model. The calibration period is from 1980 to 1995, and the validation period is from 1996 to 2010. Results of calibration and verification are shown in Figs 3 and 4. At Nong Son station, the Nash-Sutcliffe and R coefficients in the calibration and validation periods are 0.87, 0.94, and 0.88, 0.93, respectively. At Thanh My station, these two coefficients in the calibration and validation periods are 0.63, 0.83, and 0.70, 0.83, respectively.

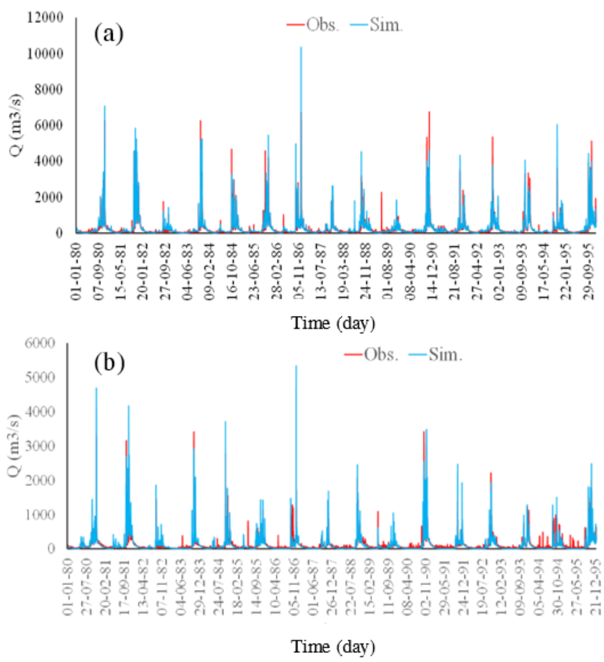


Fig. 3 Calibration of streamflow during 1980-1995: (a) Nong Son station, (b) Thanh My station

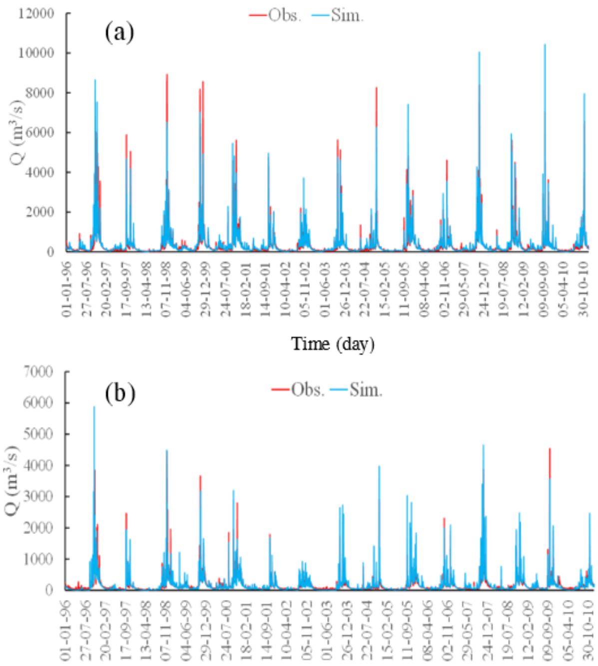
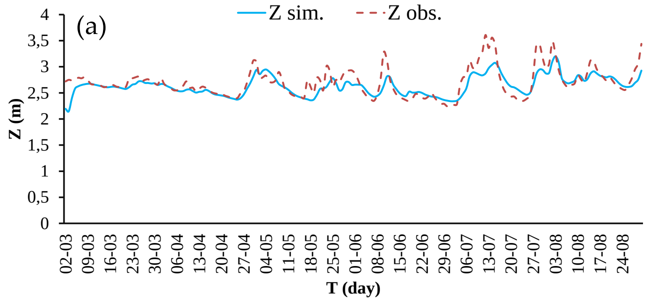


Fig. 4 Validation of streamflow during 1996-2010: (a) Nong Son station, (b) Thanh My station

3.2. MIKE 11 Calibration and Validation

The Mike 11-HD model was calibrated and validated using observed water levels at Ai Nghia, Giao Thuy, and Cam Le stations. The parameters of Mike 11's HD modules were adjusted during this process to improve the model's accuracy. The calibration period was from March to August in 2005, and the validation period was from Jun to July in 2009. Figs 5 and 6 show observed and simulated water levels during the calibration and validation processes, respectively. The rising, falling, and peak of the hydrographs can be seen to be quite accurately predicted. Table 1 shows the statistics for the Nash-Sutcliffe and R coefficients. The comparison between simulated and observed results shows a strong correlation with the R coefficient higher than 0.85. The calibration and validation results at the Cam Le station were better than the other two stations. The agreement between observed and simulated data indicated that the selected parameters of the HD module were reasonable.



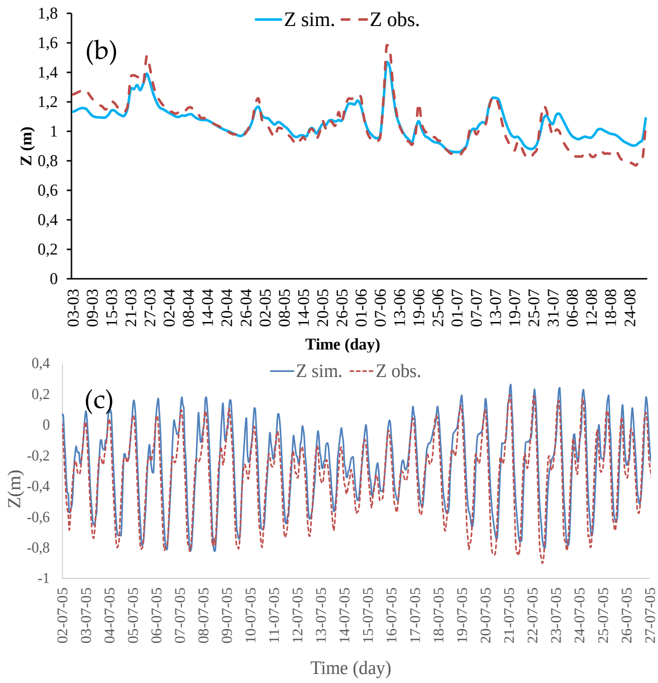
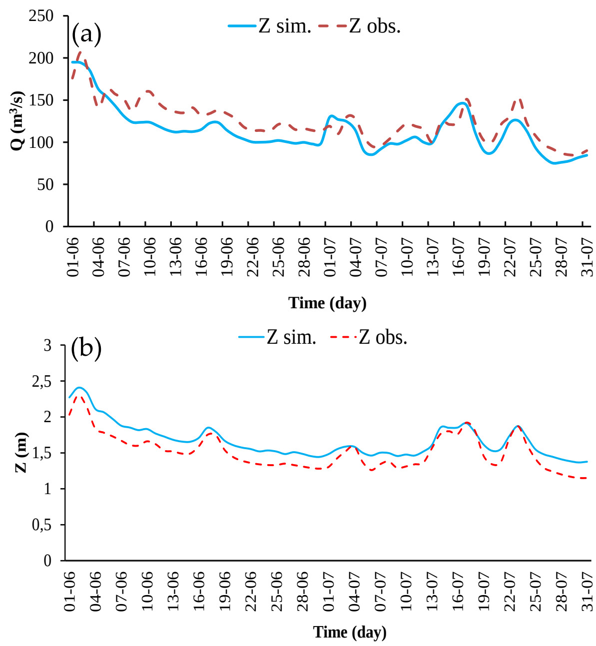


Fig. 5 Calibration of water level at (a) Ai Nghia, (b) Giao Thuy, and (c) Cam Le stations

Table 1 Statistical performance of calibration and validation of water levels

Station	Calibration (3-8/2005)		Validation (6-7/2005)	
	Nash	R	Nash	R
Ai Nghia	0,66	0,86	0,51	0,84
Giao Thuy	0,81	0,92	0,543	0,98
Cam le	0,71	0,93	0,894	0,95



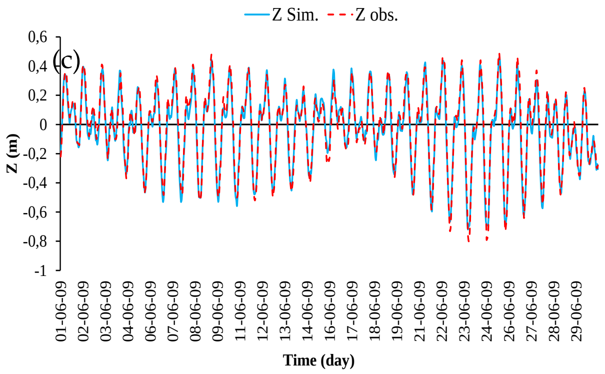


Fig. 6 Validation of water level at (a) Ai Nghia, (b) Giao Thuy, and (c) Cam Le stations

The salinity calibration and validation were performed at three measuring locations, including Nguyen Van Troi, Cam Le, Tu Cau. The calibration and validation periods were in 2005 and 2009, respectively. Figs 7 and 8 show the results of salinity calibration and validation, respectively. The simulated salinity values are presented and compared to the discrete observed salinity values at the three mentioned locations. For the current analyses, at Cam Le station, only a few observed salinity data are available. Results showed that the simulated salinity is in relatively good agreement with observed values except for a couple of outliers. Overall, the results demonstrate that the model is reliable for investigating saltwater intrusion.

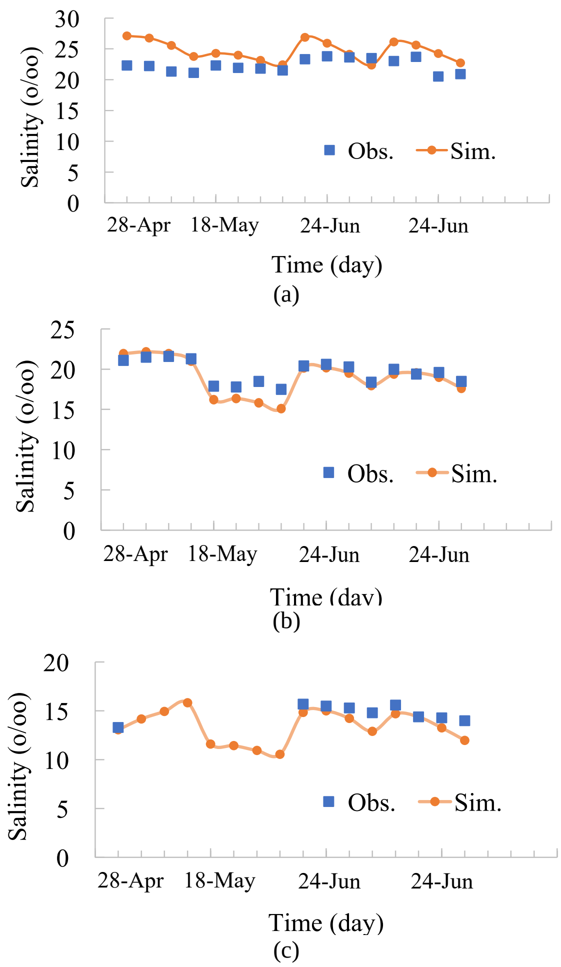


Fig. 7 Calibration of salinity at (a) Nguyen Van Troi, (b) Cam Le, and (c) Tu Cau locations

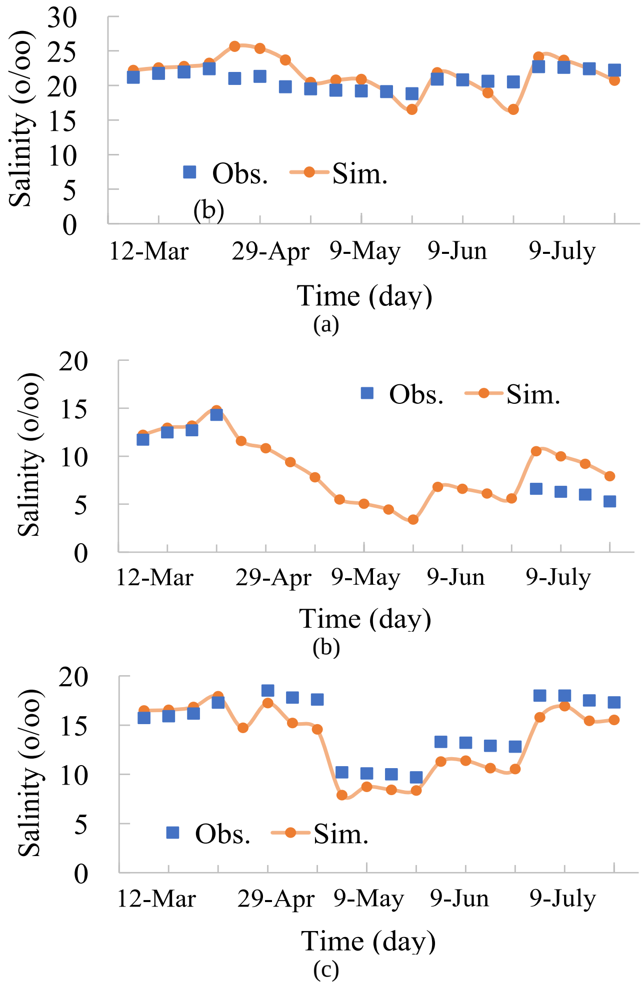


Fig. 8 Validation of salinity at (a) Nguyen Van Troi, (b) Cam Le, and (c) Tu Cau locations

4. Simulated Scenarios

All reservoirs in the Vu Gia – Thu Bon river basin must operate under the Prime Minister-approved inter-reservoirs procedure. This procedure specifies the minimum amount of water that reservoirs must release downstream (via the turbine or spillway) during each dry season to ensure water supply. This procedure specifies the start time of the release but not the end time. The question is how the discharge time affects saline intrusion. In order to answer this question, we propose three scenarios of discharge times of 6, 12, and 24 hours, respectively. In addition to discharge time, this study considers cases where the reservoir water level is below or above the limited supply water curve.

According to the above-proposed discharge time and the total amount of water, the corresponding flow rates are calculated and presented in Table 2. The scenarios are based on the Prime Minister's inter-reservoir procedure; thus, other water usage targets are still met.

Table 2 Five scenarios of changing of operation time and releases from reservoirs

Scenario	Description

KB1	The water level is below the limited supply water curve; Reservoirs release water to generate electricity for 6 hours per day; Total water release volume: 19.87 $\times 10^6$ m^3 A Vuong: Q = 110m^3/s, T = 9h00 : 14h00 DakMi 4: Q = 100m^3/s, T = 21h00 : 2h00 the following day Song Tranh 2: Q = 300 m^3/s, T= 9h00 : 14h00 Song Bung 4: Q =150 m^3/s, T= 9h00 : 14h00 Song Bung 5: Q = 260 m^3/s, T= 9h00 : 14h00
KB2	The water level is between the limited and upper supply water curves; Reservoirs release water to generate electricity for 6 hours per day; Total water release volume: 22.46 $\times 10^6$ m^3 A Vuong: Q = 130m^3/s, T = 9h00 : 14h00 DakMi 4: Q = 100m^3/s, T = 21h00 : 2h00 the following day Song Tranh 2: Q = 340 m^3/s, T = 9h00 : 14h00 Song Bung 4: Q =170 m^3/s, T = 9h00 : 14h00 Song Bung 5: Q = 300 m^3/s, T = 9h00 : 14h00
KB3	The water level is between the limited and upper supply water curves; Reservoirs release water to generate electricity for 12 hours per day. Total water release volume: 22.46 $\times 10^6$ m^3 A Vuong: Q = 65 m^3/s, T = 9h00 : 20h00 DakMi 4: Q = 50 m^3/s, T = 21h00 : 8h00 the following day Song Tranh 2: Q = 170 m^3/s, T = 9h00 : 20h00 Song Bung 4: Q = 85 m^3/s, T = 9h00 : 20h00 Song Bung 5: Q = 150 m^3/s, T = 9h00 : 20h00
KB4	The water level is between the limited and upper supply water curves; Reservoirs release water to generate electricity for 24 hours per day; Total water release volume: 22.46 $\times 10^6$ m^3 A Vuong: Q = 32.5 m^3/s, T = 9h00 : 20h00 DakMi 4: Q = 25 m^3/s, T = 21h00 : 8h00 the following day Song Tranh 2: Q = 85 m^3/s, T = 9h00 : 20h00 Song Bung 4: Q =42.5 m^3/s, T = 9h00 : 20h00 Song Bung 5: Q = 75 m^3/s, T = 9h00 : 20h00
KB5	In the absence of reservoirs (the outflow is equal to the inflow)

5. Results

5.1. Changes in Saline Concentration along the Vu Gia River

The effects of hydropower plant operating regimes on saline intrusion are shown in Figs 9-11. Fig. 9 shows the salinity distribution along the Vu Gia River from its mouth. The salinity concentration along the river is lowest in scenario KB2, with a discharge time of 6 hours per day. For the same total amount of water discharged downstream, scenario KB2 has a lower salinity than scenarios KB3 and KB4. It is also worth noting that although the total discharge volume in scenario KB1 is smaller than in scenarios KB3 and KB4, the salinity remains lower, demonstrating that the discharge time has a significant impact on salinity reduction. In other words, with the characteristics of this basin's reservoir distribution and river network as described above, the time of reservoir discharge plays a critical role in salt suppression. This statement is also consistent with previous research findings, which indicated that concentrating the flow on a shorter period can help reduce salinity [7].

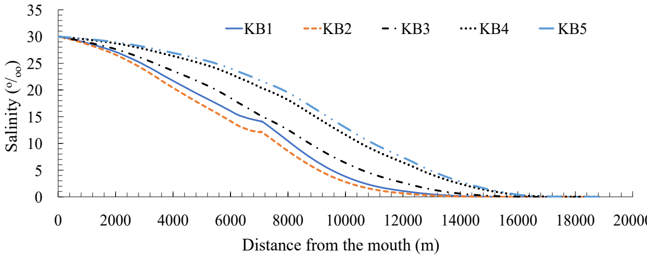


Fig. 9 Salinity distribution along the Vu Gia river under different scenarios

Fig. 10 shows the salinity boundaries of 1‰ and 4‰ in the Vu Gia River. In scenario KB2, the salinity boundary of 1‰ is located approximately 11.4 km from the river mouth. For scenarios KB1, KB3, and KB5, these values are 12.2 km, 13.3 km, and 15.6 km from the river mouth. In other words, the salinity boundary of 1‰ in scenarios KB1, KB3, KB4 moves further upstream by 0.7 km, 1.7 km, and 3.7 km, respectively, compared to scenario KB2. The salinity boundary of 4‰ is also pushed upstream by roughly the same amount.

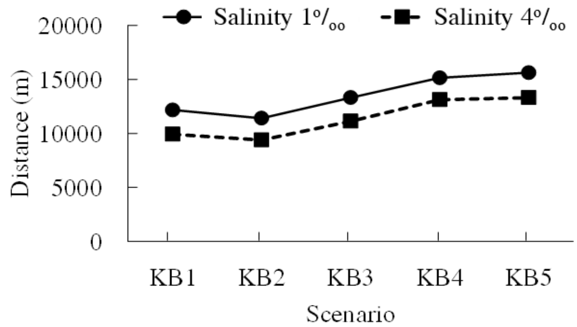


Fig. 10 Salinity intrusion length for thresholds of 1‰ and 4‰ in the Vu Gia river for five scenarios

Fig. 11 depicts the change in salinity at Tuyen Son Bridge, which is approximately 6.7 km from the estuary. Again, the salinity value demonstrates the significant impact of the plants' operating time (discharge rate) on the change in salinity concentration downstream. Accordingly, the salinity values of scenarios KB1, KB2, KB3, and KB4 are 14.5‰, 12.4‰, 16.3‰, and 21.3‰, respectively. In other words, the salinity level in scenario KB2 is reduced by 3.8‰ and 8‰, compared to scenarios KB3 and KB4. This study also demonstrated the role of reservoir regulation in reducing saline intrusion compared to the case without reservoirs. The highest salinity, 22.5‰, is obtained in this scenario at Tuyen Son Bridge. Salinity in scenario KB2 has decreased by 10.1‰ when compared to scenario KB5.

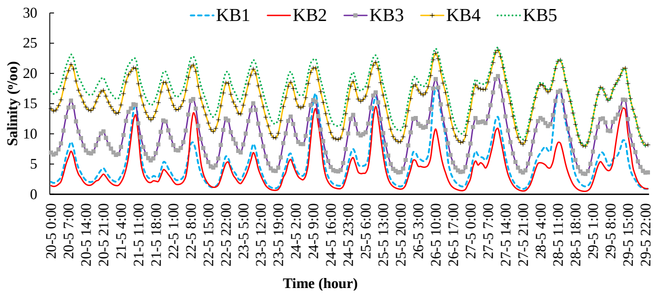


Fig. 11 Time series of simulated salinity at Tuyen Son bridge under different scenarios

5.2. Changes in Saline Concentration along the Thu Bon River

Fig. 12 shows the salinity distribution along the Thu Bon River for various operating scenarios. Unlike the Vu Gia River, where salinity decreases gradually along the river, the salinity in the Thu Bon River decreases dramatically in a 4 km stretch from the river's mouth that could be attributed to the impact of two estuaries, Cua Dai and Cua Lo, which resulted in high salinity in this area.

The operating time effect on salinity distribution in the Thu Bon River is similar to that in the Vu Gia River. The greatest decrease in salinity is seen in scenario KB2. Salinity was found to gradually increase in scenarios KB1, KB3, KB4, and KB5. Scenario KB5 has the highest salinity. As a result, the discharge of upstream hydroelectricity reservoirs in a short period has a better effect on reducing salinity.

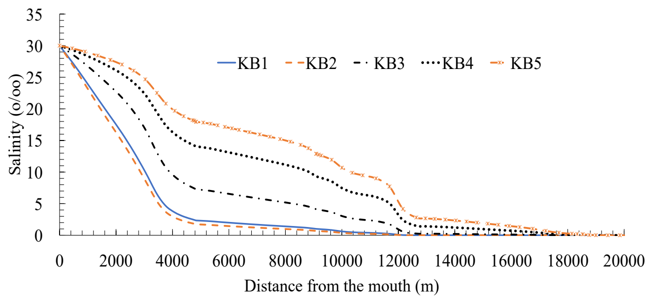


Fig. 12 Salinity distribution along the Thu Bon river under different scenarios

Fig. 13 depicts the salinity boundaries of 1‰ and 4‰ corresponding to different scenarios. For scenario KB2, salinity boundaries of 1‰ and 4‰ were found at 7.8 km and 3.6 km from the river mouth, respectively. The saline boundary of 1‰ in scenario KB1 was pushed far upstream by 1.2 km compared to scenario KB2. Similarly, in scenarios KB3 and KB4, the 1‰ saline boundary was further upstream by 4.1 km and 7 km, respectively.

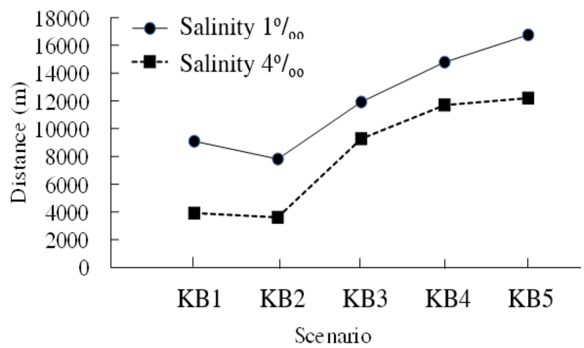


Fig. 13 Salinity intrusion length for thresholds of 1‰ and 4‰ for five scenarios in Thu Bon river

6. Conclusion

In this study, the impacts of the operation of the reservoirs on saline intrusion were investigated using numerical simulation. In a basin with several reservoirs and complex river systems, such as the Vu Gia – Thu Bon basin, the results showed that discharge timing has a substantial impact on salinity prevention. Among the scenarios with the same discharge amount, scenario KB2, in which hydropower reservoirs are operated for 6 hours per day, is the most effective in reducing salinity. At 6.7 kilometers from the river's mouth, the salinity level in the KB2 scenario decreases by 3.8‰ and 8‰, respectively, compared to the KB3 and KB4 scenarios. To the best of the author's knowledge, there is currently no effective solution to reduce salinity in the Vu Gia – Thu Bon basin; therefore, this operating scenario can be considered a good option to reduce salinity intrusion. However, because these reservoirs serve multiple purposes, further studies are needed to assess the effect of operating time on other water uses.

Acknowledgments

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