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[FEATURES]

SCIENCE AND TECHNOLOGY

- T2** Orientation for development and modernization of Vietnam's water resources monitoring, data management and mining based on south Korea's experiences
Hoang Thi Hanh, Pham Huy Thong, Pham Thi Thu, Than Van Don, Nguyen Tuan Linh, Nguyen Tiep Tan, Ngo Le Long
- T12** Flood assessment in the downstream area of Gia Ui reservoir under climate change and the Dau Giay - Phan Thiet expressway
Phan Thi Ha Tuyen, Truong Thi Nhan, Do Hoai Nam
- T22** Numerical modelling waves from field measurement over wooden fences
Ngo Thi Thuy Anh, Nguyen Trong Tu, Mai Van Cong, Dao Hoang Tung, Mai Cao Tri
- T31** Research on drip irrigation regimes for durian trees in the Central Highlands region of Vietnam, consideration of drought conditions
Nguyen Gia Vuong, Tran Hung, Nguyen Thi Lan Anh, Pham Duc Trung, Nguyen Thi Lan Anh
- T42** Saline intrusion in farming communities: Identify driving forces and nature-based measures as sustainable development solutions
Hung Tan Nguyen, Kiet Anh Ly Ngo, Van Hiep Huynh
- T54** Analysis, assessment, and forecasting of domestic water supply demand for the Phu Thai, Hai Phong
Nguyen The Anh, Tran Tuan Thach
- T62** Safety analysis of retaining walls according to reliability theory - application of safety assessment for retention walls on road number 7, section 2 in Ong Tuong hill area, Hoa Binh city
Nguyen Lan Huong
- T70** Techno-economic comparison of conventional turbines and pumps as turbines (PATs) in small and micro hydropower systems
Nguyen Thi Nho
- T79** Application of hydraulic models to assess the flow regime and saltwater intrusion in the Huong river downstream under the impact of the operation of the Thao Long Dam and the reservoir system
Nguyen Van Tuan, Pham The Vinh
- T89** Application of mathematical models for forecasting flow and channel morphology evolution at the intake location - Song Da water plant
Vu Thu Hien, Tran Vu Long, Dao Duc Bang, Duong Thi Thanh Thuy
- T97** Calibration and assessment of landslide-generated impulse waves in reservoirs using Flow-3D
Tran Duc Thanh, Nguyen Phuong Dung
- T104** Applying structural equation modeling (SEM) to study BIM adoption in construction project management: An international review and implications for Vietnam
Thai Ngoc Thang, Le Van Chinh, Bui Ngoc Toan
- T113** The impact of changes in water level and quality on pumps during groundwater extraction process
Nguyen Manh Truong, Ngo Van Dat, Dinh Anh Tuan, Hoang Thi Phuong Thuy, Pham Song Hung, Tran Bang Giang, Dang Sy Lan

APPLICATION OF MATHEMATICAL MODELS FOR FORECASTING FLOW AND CHANNEL MORPHOLOGY EVOLUTION AT THE INTAKE LOCATION - SONG DA WATER PLANT

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Abstract: This paper presents the application of MIKE11 and MIKE21 hydrodynamic models to forecast the flow dynamics and morphological evolution of the riverbed in the intake area of the Song Da Water Plant. Based on hydrological, topographical, geological, and sediment data, the models were developed to simulate hydraulic conditions and sedimentation–erosion trends under the influence of the Hoa Binh reservoir operation regime. Model calibration and validation yielded high correlation coefficients (Nash = 0.89 - 0.97) and small water level errors ($< \pm 0.1$ m), indicating good model performance. The study identified the minimum water level ($H_{min} = 7.2 - 8.8$ m) and maximum water level ($H_{max} = 21.0 - 22.4$ m) corresponding to different reservoir operation scenarios. Results indicate a slight but stable erosional trend of the riverbed in the intake area over the next decade. The modeling outcomes provide a scientific basis for the design, operation, and safety management of the water intake structure.

Keywords: Hydrodynamic modeling, forecasting, channel evolution, river flow.

1. INTRODUCTION

The Song Da Water Plant, located in Hop Thanh commune, Ky Son district (currently within Hoa Binh City), abstracts water from the right bank of the Da River through a system of conveyance channels and pumping stations. The intake structure is situated approximately 20 km downstream of the Hoa Binh hydropower dam, where the flow regime is strongly affected by reservoir releases for power generation and flood discharge.

The Da River basin plays a particularly important role, contributing about 31% of the total water volume of the Red River system. However, the development of large-scale hydropower projects (Lai Chau, Son La, Hoa Binh) has profoundly altered the river's hydrological and sediment regimes. Statistics show that the sediment load has decreased by up to 97% compared with pre-dam conditions, leading to sediment imbalance and extended

downstream erosion. In this context, the application of advanced mathematical models to predict riverbed and water level variations in the intake zone is essential to ensure the safety and stability of the water supply system.

This study focuses on evaluating the variation of river water levels in the study area and forecasting morphological changes of the riverbed at the intake location for future operation years. The analysis is based on historical flow series and simulated scenarios to determine the trend of riverbed degradation and flow pattern evolution along the section crossing the intake structure.

2. SCIENTIFIC BASIS AND METHODOLOGICAL APPROACH

Assessing river and channel morphological evolution is inherently complex, requiring extensive hydrological, topographical, and sediment data, as well as simulation tools capable of accurately reproducing natural flow dynamics. For detailed studies, physical or mathematical models are often employed to reproduce hydraulic and sediment transport

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processes at reduced scales or through computational simulations.

In this research, the authors applied a numerical modeling approach using the MIKE software suite developed by DHI Water & Environment. This package is designed to simulate river discharge, water quality, and sediment transport processes in rivers, estuaries, irrigation channels, and other water bodies.

Among the various modules available, the following were used:

- MIKE11/MIKE11 ST: One-dimensional hydrodynamic and sediment transport model, applied to simulate the flow regime of the entire Da-Red River system.
- MIKE21FM/MIKE21ST: Two-dimensional model used for detailed simulation of the intake zone and evaluation of local sedimentation and erosion processes.

The use of MIKE21ST enables the simulation of morphological changes in both longitudinal and transverse directions, reflecting the spatio-temporal evolution of the riverbed topography.

3. MODEL SETUP FOR HYDRODYNAMIC AND MORPHOLOGICAL SIMULATION

3.1. Study Area and Computational Domain

The study area for channel evolution analysis is located approximately 12.45 km downstream of the Hoa Binh hydrological station. However, to accurately define boundary conditions and assess their influence on water levels, discharge, and morphological dynamics, the entire Da River reach from Hoa Binh hydropower dam to the Red River confluence was included in the simulation. The computational domain was further extended to the downstream tributaries within the Red-Thai Binh river system.

The modeled river network includes:

- Da River: From downstream of Hoa Binh dam to the Red River confluence (57.3 km, 34 cross-sections);

- Tributaries: Thao River (Yen Bai - Trung Ha), Lo River (Vu Quang - Viet Tri), and Red River (Trung Ha - Son Tay).

A detailed 2D model domain of approximately 6 km was developed, covering 3 km upstream and 3 km downstream of the water intake site to capture local hydraulic and morphological variations.



Figure 1: Simulation domain of the MIKE21 hydrodynamic model

3.2. Input Data

The datasets used for model construction and calibration include the following:

- Topography and geology: A total of 103 surveyed cross-sections and a detailed topographic map at a 1:1,000 scale were used. Eight boreholes were drilled to determine sediment characteristics, with median grain size (D_{50}) ranging from 0.01-30 mm and particle specific gravity between 2.65- 2.72 g/cm³.
- Hydrology: Water level and discharge data were collected from the Hoa Binh, Trung Ha, Yen Bai, Viet Tri, and Son Tay hydrological stations to define boundary and calibration conditions.
- + Sediment: Suspended sediment samples were obtained from five locations surrounding the intake area, with concentrations varying between 14 - 21 g/m³.
- + Hydraulic structures: Major structures influencing the hydraulic regime include the Hoa Binh Dam, Hoa Binh Bridge, Dong

Quang Bridge, Trung Ha Bridge, as well as the intake channel and riverbank protection works.

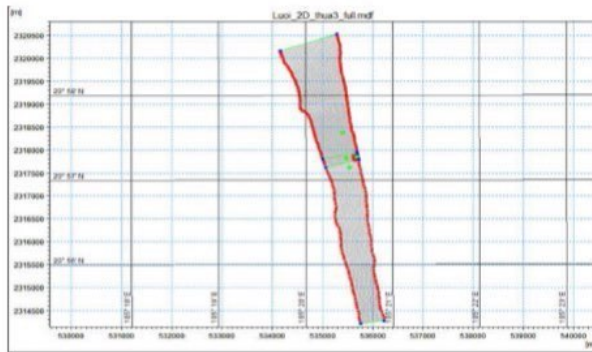


Figure 2: Computational mesh of the study area in the MIKE21 model

4. MODEL CALIBRATION AND VALIDATION

Two main stages of model validation were conducted to ensure the reliability and accuracy of the simulation results:

1. Hydrodynamic calibration (MIKE11)

- The calibration was performed using observed data from May 18- 31, 2019, and the 2017 flood event.

- The simulated water levels at key hydrological stations showed an error margin of less than ± 0.1 m.

- The Nash–Sutcliffe efficiency coefficient (Nash = 0.89 - 0.97) indicates excellent agreement between simulated and observed hydraulic processes.

2. Sediment transport and riverbed morphology calibration (MIKE11ST, MIKE21ST)

- The simulated bed-level variations were compared with measured topographic changes from 2016 - 2017, showing consistent erosion–deposition patterns across representative cross-sections.

- The downstream reach of the Hoa Binh Dam exhibited stable morphology, while the lower section of the Da River showed significant local fluctuations due to intensive sand mining activities.

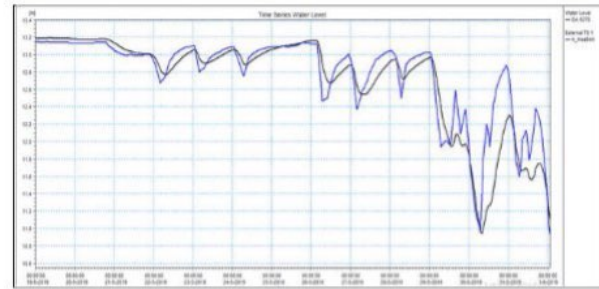


Figure 3: Calibration results – comparison between simulated and observed water level hydrographs at Hoa Binh Hydrological Station during the period May 18 – June 31, 2019

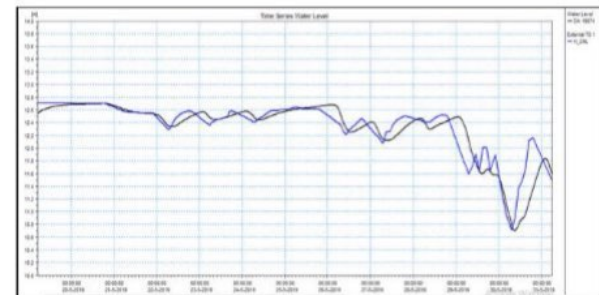


Figure 4: Calibration results – comparison between simulated and observed water level hydrographs at the intake area during the period May 18 – June 31, 2019

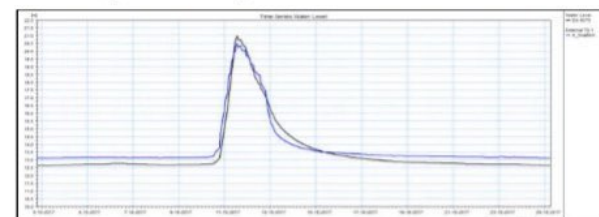


Figure 5: Comparison between simulated and observed water level hydrographs at Hoa Binh Hydrological Station during the 2017 flood event

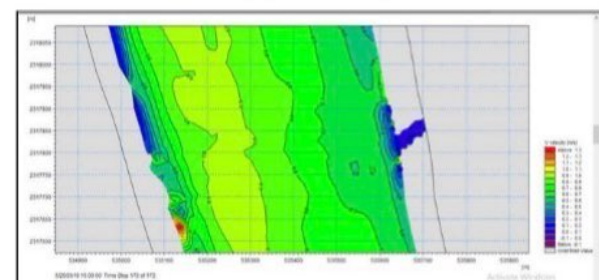


Figure 6: Two-dimensional model simulation results based on observed data series at the intake area - Flow velocity distribution around the water intake

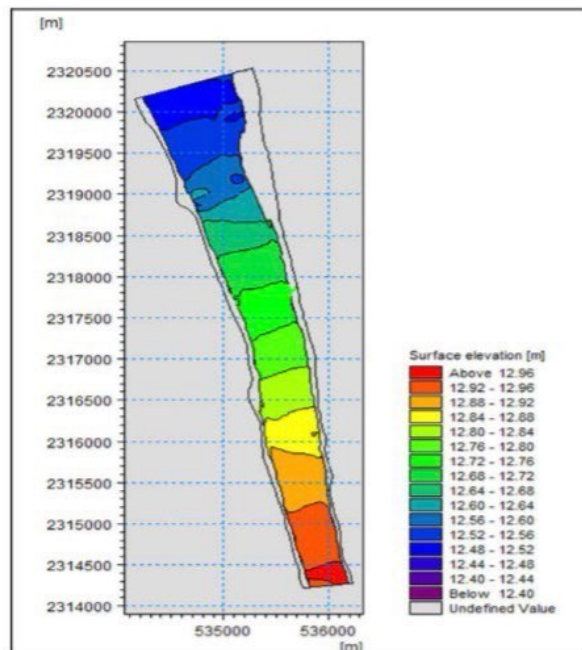


Figure 7: Two-dimensional model simulation results based on observed data series at the intake area - Simulated water surface levels.

The calibration and validation results demonstrate a high level of agreement between simulated and observed data, confirming the reliability of the model. Therefore, the model can be confidently applied to forecast riverbed evolution in the intake channel area and adjacent zones.

5. MODELING RESULTS AND FORECASTS

5.1. Design Water Levels

The minimum water level (H_{min}) corresponding to a 95% probability of exceedance ranges from 7.2 to 8.8 m, depending on the flow combinations of the downstream tributaries. The computations were performed under the following scenarios: 1: Calculate the minimum water level (H_{min}) at the intake corresponding to the instantaneous minimum discharge (95% exceedance) at the intake area, while other boundaries and intermediate inflows were computed using corresponding discharge values. 2: Calculate H_{min} at the intake corresponding to the instantaneous minimum

discharge (95% exceedance), while the other boundaries and intermediate inflows were set according to the 95% daily minimum discharge. 3: Calculate H_{min} at the intake corresponding to the instantaneous minimum discharge (95% exceedance), while other boundaries and intermediate inflows were computed using the average low-flow discharge (95% exceedance). 4: Calculate H_{min} at the intake corresponding to the instantaneous minimum discharge (95% exceedance), while other boundaries and intermediate inflows were defined by the mean annual discharge. Additional scenarios were developed to assess the influence of the Hoa Binh reservoir operation on downstream water levels: 5: Calculate with the minimum recorded discharge since the operation of Hoa Binh Hydropower Plant ($Q_{min} = 14.6 \text{ m}^3/\text{s}$). Other boundaries and intermediate inflows were set to the average low-flow discharge (95% exceedance). 6: Calculate according to the minimum downstream flow requirement specified in the Inter-Reservoir Operation Procedure for the Red River Basin (Decision No. 1622/QĐ-TTg, dated September 17, 2015, by the Prime Minister). According to Article 17, during the normal storage period in the dry season, the minimum continuous release from Hoa Binh Reservoir shall not be less than $214 \text{ m}^3/\text{s}$. Other boundaries and intermediate inflows were computed using the 95% low-flow daily discharge. 7: Calculate with the minimum turbine discharge for one generator unit, corresponding to the smallest operational flow rate of the hydropower plant (Q_{min} , one unit = $260 \text{ m}^3/\text{s}$). Other boundaries and intermediate inflows were computed using the 95% low-flow daily discharge. 8: Calculate with the design turbine discharge for one generator unit, representing the regular maximum discharge during normal operation (Q_{design} , one unit = $300 \text{ m}^3/\text{s}$). Other boundaries and intermediate inflows were also computed using the 95% low-flow daily discharge.

- $Q_{min} = 14.6 \text{ m}^3/\text{s} \rightarrow H = 8.0 \text{ m}$

- Inter-reservoir operation ($Q \geq 214 \text{ m}^3/\text{s}$) $\rightarrow$ $H = 9.3 - 9.8 \text{ m}$
- Single-unit operation ($Q = 300 \text{ m}^3/\text{s}$) $\rightarrow$ $H \approx 9.8 \text{ m}$

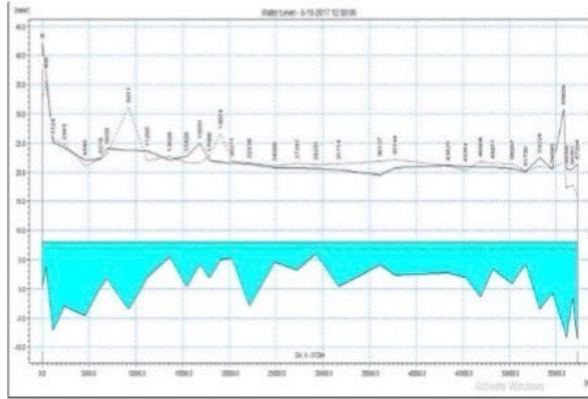


Figure 8: Longitudinal water level profile along the Đà River corresponding to the low-flow scenario with a 95% probability of occurrence (Scenario 5)

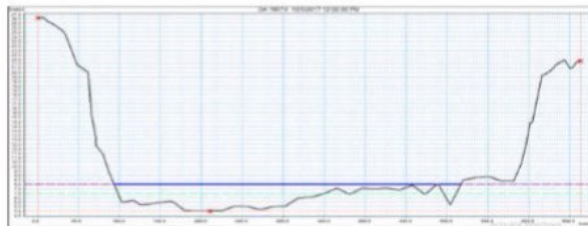


Figure 9: Water level at cross-section MC07, located upstream of the intake channel, corresponding to the low-flow scenario with a 95% probability of occurrence (Scenario 5)

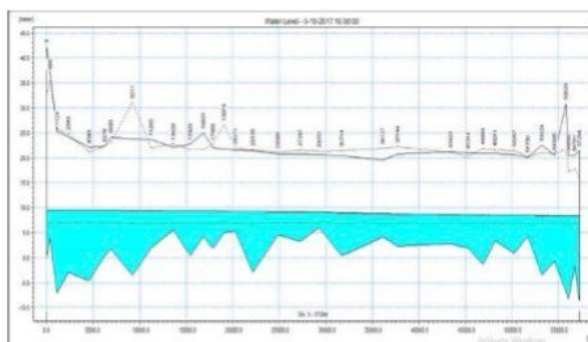


Figure 10: Longitudinal water level profile along the Da River under the minimum regulated discharge scenario according to the Inter-reservoir Operation Procedure No. 1622/QĐ-TTg - Scenario 6

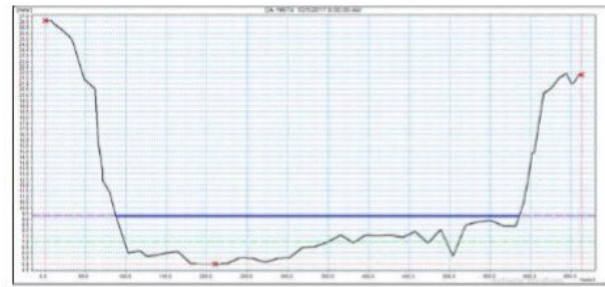


Figure 11: Water level at cross-section MC07, upstream of the intake canal, under the minimum regulated discharge scenario according to the Inter-reservoir Operation Procedure No. 1622/QĐ-TTg - Scenario 6

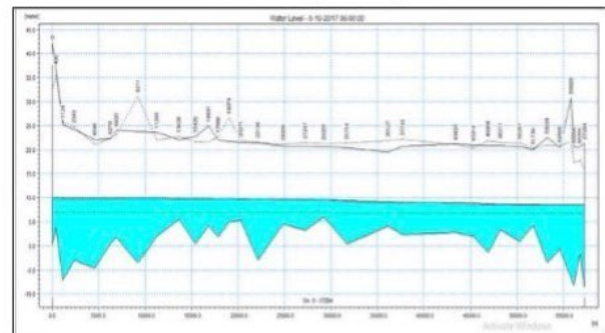


Figure 12: Longitudinal water levels along the Da River under the scenario of Hoa Binh Hydropower Plant operating with one generating unit - Scenario 8

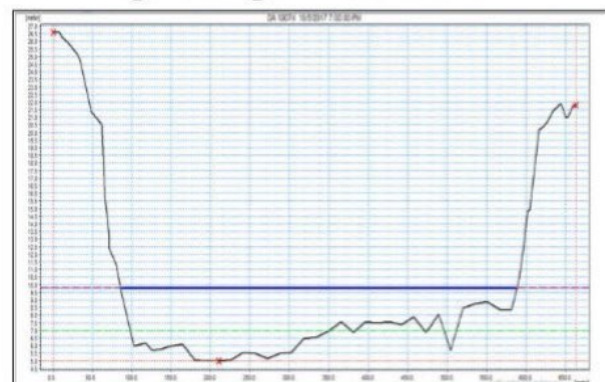


Figure 13: Water level at cross-section MC07, upstream of the intake canal, under the scenario of Hoa Binh Hydropower Plant operating with one generating unit - Scenario 8

5.2. Maximum Water Level (Hmax)

According to the design standards for flood control, the design and verification floods correspond to return periods of 2% and 1%, respectively. Therefore, model simulations for

design calculations were carried out using boundary conditions representative of these 1% and 2% flood frequencies.

For floods with a frequency of 1- 2%, several operational scenarios of the Hoa Binh Reservoir were simulated, including opening 6 to 8 bottom sluice gates in combination with power generation:

- When six bottom gates are opened, the water level at the intake ranges from approximately 21.0 to 21.5 meters.
- When eight bottom gates are opened, the water level can reach approximately 22.0 to 22.4 meters, which remains within the safe design limits of the intake structure.

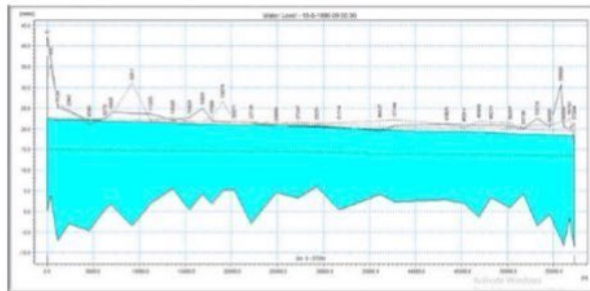


Figure 14: Longitudinal water levels along the Da River under the scenario of Hoa Binh Reservoir discharging through six bottom sluice gates, with boundary conditions corresponding to the 1% flood frequency

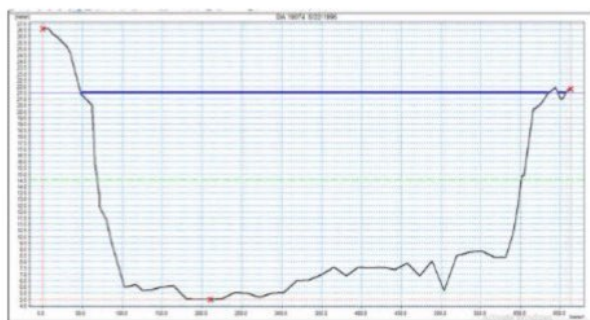


Figure 15: Longitudinal water levels along the Da River under the scenario of Hoa Binh Reservoir discharging through eight bottom sluice gates, with boundary conditions corresponding to the 1% flood frequency

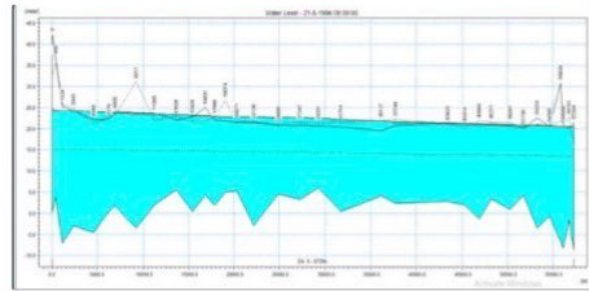


Figure 16: Longitudinal water levels along the Da River under the scenario of Hoa Binh Reservoir discharging through eight bottom sluice gates, with boundary conditions corresponding to the 1% flood frequency

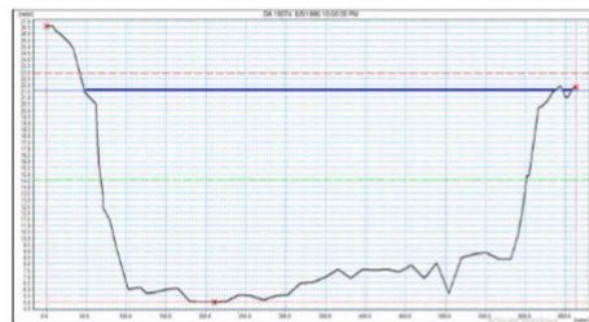


Figure 17: Longitudinal water levels along the Da River under the scenario of Hoa Binh Reservoir releasing flow through eight bottom sluice gates, with upstream and downstream boundary conditions corresponding to the 1% flood frequency

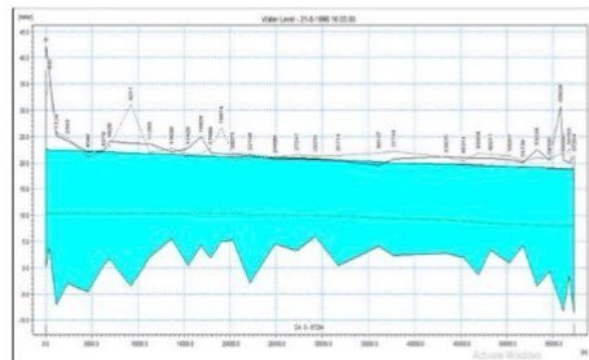


Figure 18: Longitudinal water levels along the Da River under the scenario of Hoa Binh Reservoir discharging through six bottom sluice gates, with boundary conditions corresponding to the 2% flood frequency



Figure 19: Longitudinal water levels along the Da River under the scenario of Hoa Binh Reservoir releasing flow through eight bottom sluice gates, with boundary conditions corresponding to the 2% flood frequency

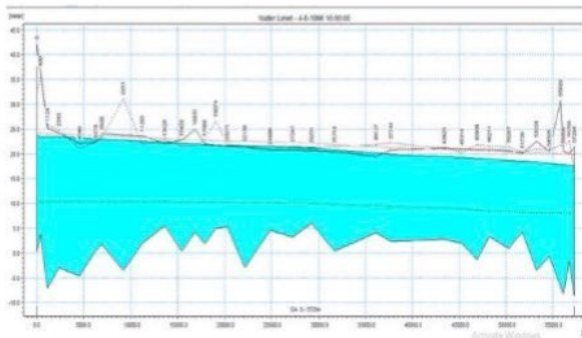


Figure 20: Longitudinal water levels along the Da River under the scenario of Hoa Binh Reservoir discharging through eight bottom sluice gates, with boundary conditions corresponding to the 2% flood frequency

5.3. Riverbed Evolution

The simulated results indicate distinct morphological changes in the riverbed under different flow scenarios. The main thalweg section of the river shows a tendency toward bed scouring, particularly in the deeper channels. In contrast, the area near the intake structure, located on the right bank, exhibits continuous sediment deposition, forming and expanding a sandbar over time.

The primary cause of this pattern is the morphological shift occurring approximately 2 km upstream of the intake, where erosion at the head of the sandbar leads to downstream sediment transport and accumulation near the intake zone.

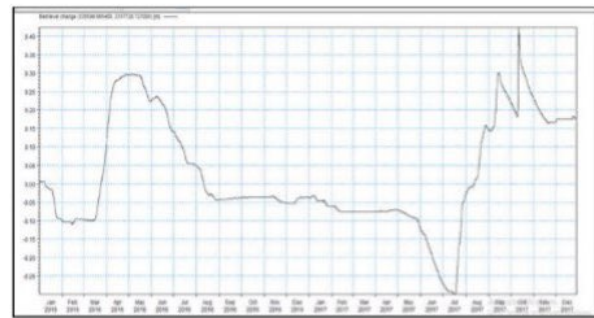


Figure 21: Simulated patterns of sediment deposition and erosion at the main channel near the intake location under the two-year forecast scenario (based on annual flow conditions for 2016 - 2017)

6. DISCUSSION

The hydraulic and morphological simulations for the downstream section of the Da River and the intake area, performed using the MIKE11ST and MIKE21ST models, provide a comprehensive understanding of channel evolution and sediment transport processes in the intake region during operation.

Model results indicate that the riverbed at the intake site tends to experience mild local scouring, with an average erosion depth of approximately 7 - 18 cm/year. Significant scouring mainly occurs during major historical floods, while under average or low-flow conditions, the riverbed remains relatively stable. Sediment deposition and erosion patterns vary across the cross-sections - the intake area is prone to localized sedimentation due to the influence of flow dynamics and the large sandbar adjacent to the right bank. Annual sediment accumulation rates are small; however, water withdrawal operations can induce sediment deposition at the intake mouth and partially within the channel.

The intake is located adjacent to a major sandbar that extends roughly 2.0 km downstream. The sandbar tends to grow gradually toward the intake area and migrate downstream as the main flow channel shifts closer to the right bank. The average annual sedimentation rate is less than 0.2 m. Deposition mainly occurs during the flood

season, whereas slight scouring is observed during the dry season, resulting in an overall balanced sediment regime in years with normal or low flows. In years with large floods, deposition dominates; however, scouring during subsequent years without floods gradually restores balance. Therefore, over a multi-year period, the topography of the intake zone remains relatively stable compared with morphological changes in the broader river reach.

7. CONCLUSION

The morphological evolution of the study area is governed not only by natural hydrodynamic and geological factors but also significantly influenced by sand mining activities along the Da River. These operations alter the local riverbed topography, affecting simulation accuracy and making it difficult to predict morphological trends solely due to hydraulic processes.

Given the observed decline in water levels near the intake in recent years - influenced by both reservoir operation and downstream

water levels - the design water level corresponding to the 95% low-flow condition ($H_{min95\%}$) is recommended to be 7.21 m. This represents the most critical scenario, where all model boundaries correspond to the 95% instantaneous low-flow condition.

As the intake area continues to accumulate sediment annually, it is recommended that the project owner implement long-term structural measures and perform regular dredging to maintain the intake's designed operational capacity.

The results of this study provide a scientific basis for the design, operation, and sustainable management of the Da River downstream intake works and associated water resources.

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