



Two-Dimensional Hydrodynamic Simulation for Flood Assessment in the Lower Mekong Basin, focusing on the Cambodian Corridor

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Abstract: The Lower Mekong Basin (LMB) hosts a critical transboundary floodplain extending from Prek Kdam and Khsach Kandal in Cambodia to the Vietnamese Mekong Delta. Seasonal inundation in this corridor sustains the region's agricultural productivity and capture fisheries, yet this natural hydrological regime is increasingly challenged by interacting pressures, including upstream hydropower regulation, land use change, and climate variability. These factors intensify flood risks and complicate the governance of shared water resources. To accurately characterize these complex dynamics, this study applies a two-dimensional (2D) hydrodynamic model (HEC-RAS) to simulate the peak flood event of 2022 across the transboundary corridor. The model integrates high-resolution digital terrain data (12m×12m) with observed boundary conditions to capture key hydraulic parameters, including water depth, velocity, and water surface elevation (WSE). Calibration against observed water levels demonstrated strong predictive skill, yielding a Root Mean Square Error (RMSE) of 0.58 m, a Nash–Sutcliffe Efficiency (NSE) of 0.71, and a Percent Bias (PBIAS) of 14.21%. Simulation results highlight pronounced spatial heterogeneity in flood characteristics: deep river channels (5-15 m) exacerbate bank erosion and increase fluvial hazard exposure, while moderate-depth floodplains (1-5 m) support cultivation but are vulnerable to prolonged inundation. Velocity analysis further underscores the dualistic nature of the flood pulse, promoting both beneficial sediment transport and risks of infrastructure damage. The modeling framework developed here provides a robust, high-resolution technical basis for advancing integrated, transboundary water governance, enhancing early warning systems, and informing climate-resilient development strategies across the Lower Mekong Delta.

Index Terms – Two-Dimensional Modeling, HEC-RAS 2D, Transboundary Flood, Hydraulic Modeling, Mekong River

I. INTRODUCTION

Flooding in the Lower Mekong Basin (LMB) is a complex phenomenon driven by the synergy of the Southeast Asian monsoon, the seasonal fluctuations of the Mekong River, and the unique reverse flow of the Tonle Sap Lake [1,2]. Annually, these processes inundate vast floodplains, sustaining one of the world's most productive aquatic and agricultural systems [3]. The transboundary floodplain corridor stretching from Prek Kdam Bridge and Khsach Kandal in Cambodia southward to Châu Đốc and Tân Châu in Vietnam is particularly critical, serving as a hydrological transition zone that delivers essential ecosystem services, though it subjects communities to severe socio-economic impacts from extreme events [5]. However, this vital natural flood regime is increasingly disrupted by multiple, interacting anthropogenic pressures, notably intensive upstream hydropower development and rapid land use transformation. These drivers are altering the flood pulse's characteristics, complicating effective flood risk management [2]. Traditional monitoring methods, such as satellite-based observations from Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat, and the Water Level–Flood Link (WAFL) method, are constrained by low spatial resolution and fail to accurately quantify crucial hydrodynamic parameters like flow velocity and water surface elevation (WSE) across complex floodplains [4, 6]. This deficiency is compounded by the fact that existing research in the LMB tends to focus either regionally on the Tonle Sap system or discretely on the Vietnamese Delta, leading to a critical gap in high-resolution, cross-border hydrodynamic modeling that captures the unified flow dynamics between Cambodia and Vietnam in this shared corridor. This study addresses this gap by developing and applying a two-dimensional (2D) hydrodynamic model using HEC-RAS to investigate the flood dynamics of the transboundary corridor. The primary objectives are:

- To simulate and map the spatial patterns of flood depth, velocity, and water surface elevation (WSE) in the corridor under peak flow conditions.
- To analyze how micro-topography and land use configurations influence flood propagation and inundation extent.
- To provide a robust technical foundation for evidence-based flood risk reduction, transboundary water governance, and climate-resilient development strategies in the Lower Mekong Delta.

II. RESEARCH METHODOLOGY

The methodology for this study follows a rigorous, sequential workflow involving five primary stages: data acquisition and processing, model setup, simulation execution, calibration and validation, and results analysis. First, the high-resolution Digital Elevation Model (DEM) and hydrological time-series data (discharge and stage hydrographs) are collected and processed for the study domain. Second, the HEC-RAS 2D model is configured within RAS-Mapper, involving the delineation of the 2D flow area, generation of a variable computational mesh, and assignment of hydraulic parameters, such as Manning's roughness coefficients. Third, the unsteady flow simulation is executed using the defined boundary conditions over the entire 2022 flood season to dynamically replicate flood behavior. Fourth, the model's predictive skill is rigorously assessed through calibration and validation against observed water levels using statistical metrics (RMSE, NSE, PBIAS). Finally, the validated model outputs (flood depth, velocity, and WSE) are extracted and analyzed to characterize spatial flood patterns and inform flood risk assessment for the transboundary corridor.

2.1 Study Area

The study focuses on the transboundary region connecting the Cambodian floodplains near Prek Kdam and Khsach Kandal with the Vietnamese border stations of Châu Đốc and Tân Châu. This low-lying area is heavily influenced by the seasonal fluctuations of the Mekong and Bassac Rivers and is critical for both countries' agricultural and hydrological connectivity. The recurring social and economic impacts of flooding here underscore the urgent need for high-resolution modeling to support sustainable management. The geographical extent of the study domain is illustrated in **Figure 1**.

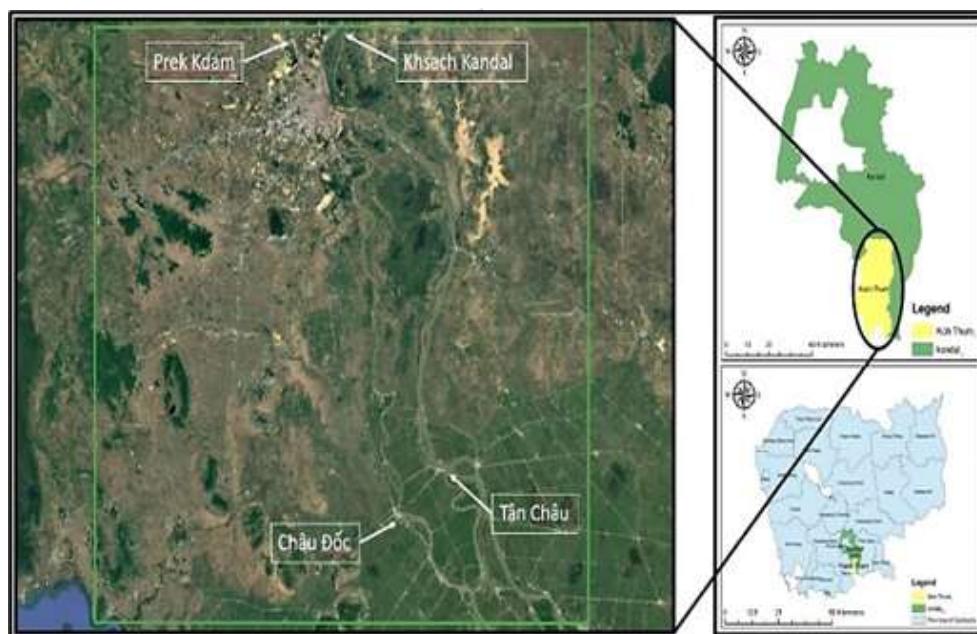


Figure 1. Map of the Tonle Sap, Mekong, Bassac River system showing the sixteen sampling sites

2.2 Data Acquisition and Processing

The hydraulic model relies on both high-resolution topographic data and comprehensive hydrological time-series inputs, summarized in **Table 1**.

Table 1. Root Mean Square Error (RMSE) and Model Performance Classification RMSE

RMSE (m)	Model Performance
< 0.30	Very Good
0.30 – 0.60	Good
0.60 – 1.00	Fair
> 1.00	Poor

2.2.1 Digital Elevation Model (DEM)

A high-resolution Digital Elevation Model (DEM) with a spatial resolution of 12m×12m was imported into HEC-RAS to generate the terrain layer. The DEM was provided as a Georeferenced Tagged Image File Format (GeoTIFF) and projected to EPSG:32648 (WGS84/UTM Zone 48N), referencing the Ha Tien height datum. This fine resolution is essential for accurately capturing intricate features such as river channels, levees, and the complex canal network of the Koh Thum District (Figure 3).

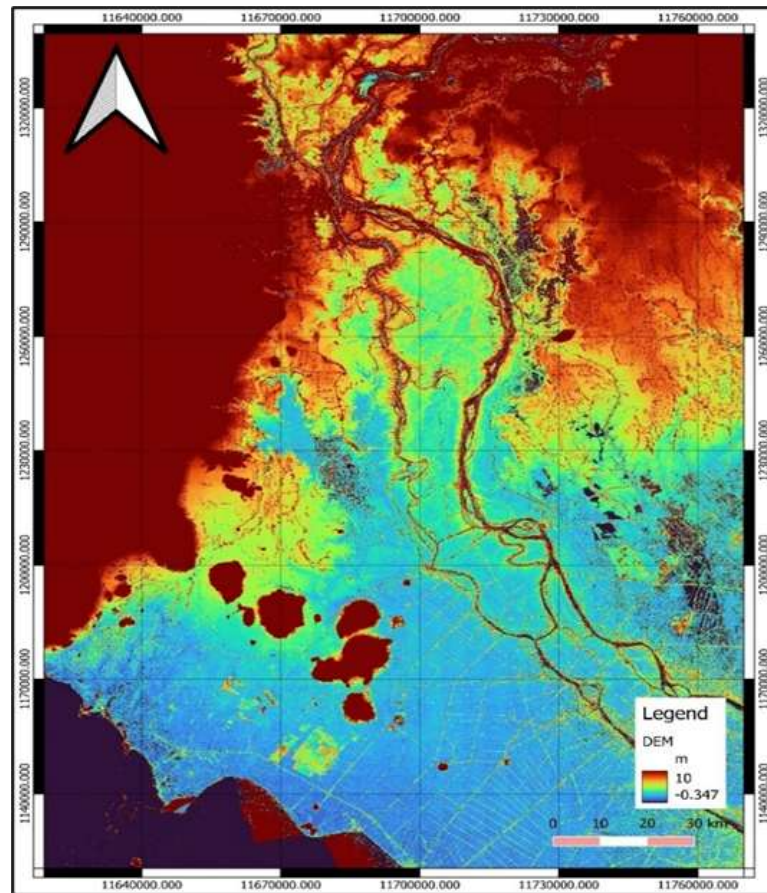


Figure 2. Digital Elevation Model map.

2.2.2 Hydrological Boundary Conditions

The simulation period was set from January 1 to December 30, 2022, capturing the full hydrological variability, including the extreme peak flood event observed on October 2, 2022. Unsteady, time-varying inputs were specified for the model boundaries:

- Upstream Inflow: Daily discharge hydrographs from the Mekong River at the Kampong Cham station (Figure 3).
- Downstream Boundaries (Stage): Daily water level hydrographs from the Bassac River at Chau Doc and the Mekong River at Tan Chau (Figure 4, Figure 5).
- Lateral Influence: Daily water level data from the Tonle Sap River at Prek Kdam station (Figure 6) were incorporated to account for the influence of the seasonal reverse flow on floodplain hydrodynamics.

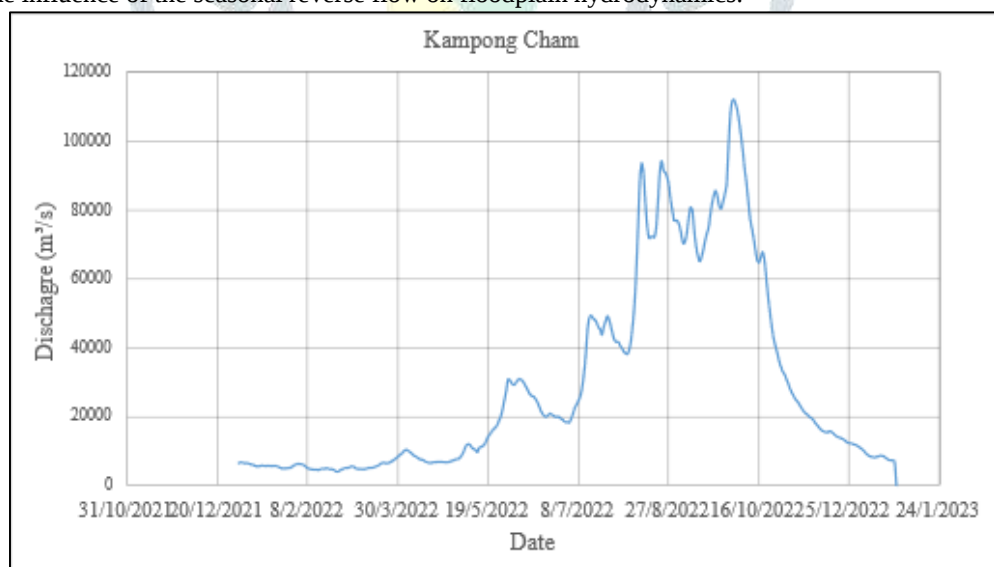


Figure 3. Daily Discharge of Mekong River at Kampong Cham Station (01 Jan to 31 Dec 2022)

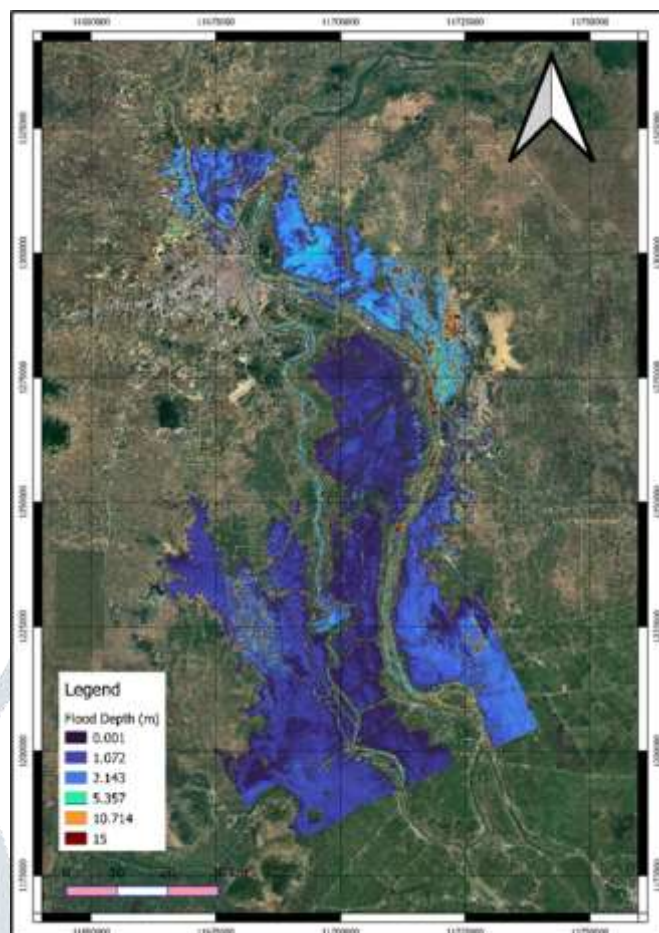


Figure 4. Simulated flood depth map flood date on 02 October 2022

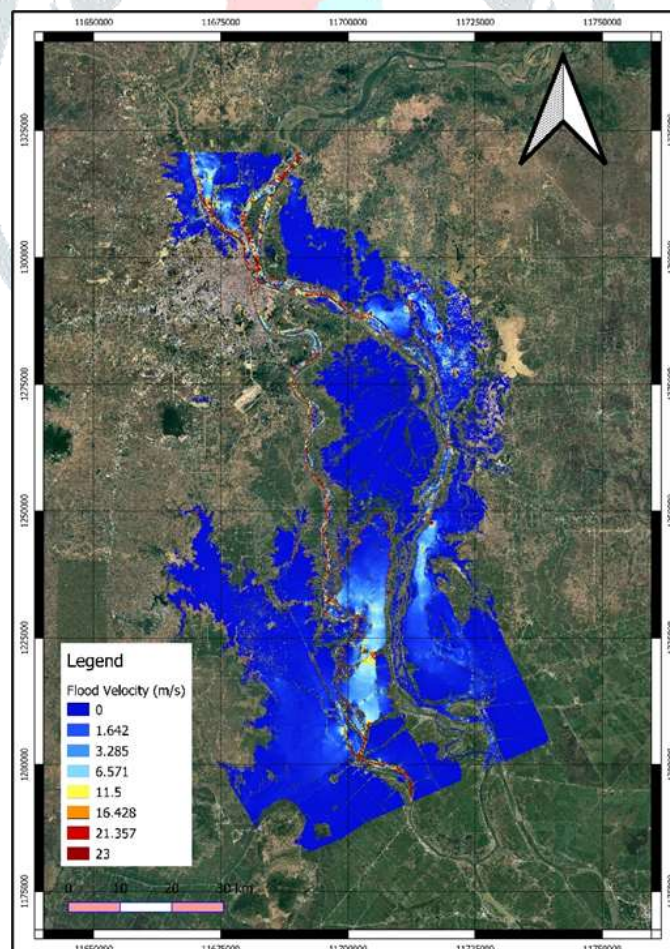


Figure 5. Simulated flow velocity map on 02 October 2022

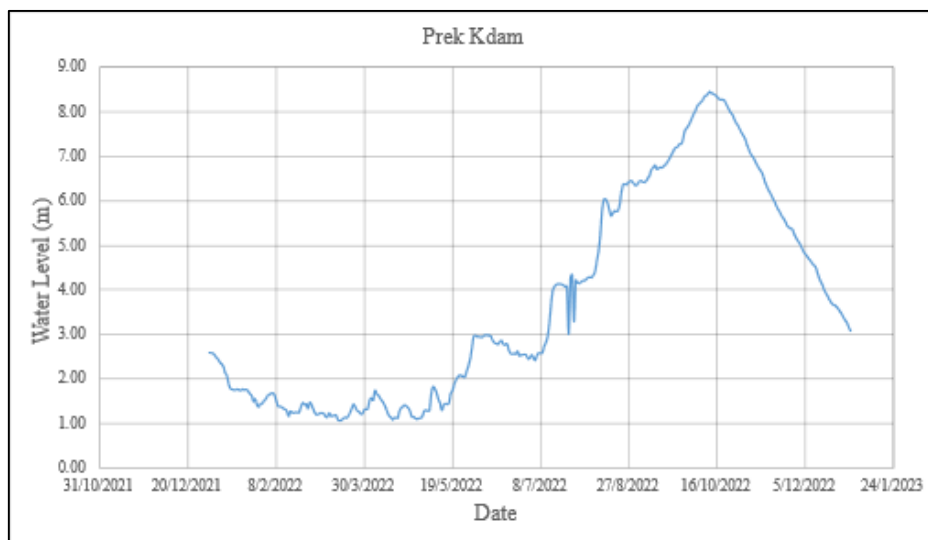


Figure 6. Daily of Water Level of Tole Sap River at Prek Kdam Station (01 Jan to 31 Dec 2022)

Table 1 is essential as it summarizes the four fundamental categories of data required to build and run the two-dimensional (2D) HEC-RAS hydrodynamic model. The table ensures transparency and reproducibility by clearly detailing the source, resolution, temporal coverage, and specific role of each input dataset.

Table 2. Summary of Data Input for the HEC-RAS 2D Model

Parameter	Data source/Types	Spatial Resolution/Period	Role in Model
Terrain Data (DEM)	Coastal and Wetland Environmental Research Laboratory	12m x 12m	Foundation for 2D flow area and mesh generation.
Upstream in flow	Daily Discharge Hydrograph (Kampong Cham)	Jan 1 – Dec 30, 2022	Controls flow volume and wave propagation.
Downstream Stage	Daily Water Level Hydrographs (Tan Chau, Chau Doc)	Jan 1 – Dec 30, 2022	Defines boundary conditions and backwater effects.
Lateral Stage	Daily Water Level Hydrograph (Prek Kdam)	Jan 1 – Dec 30, 2022	Accounts for Tonle Sap influence.

2.3 HEC-RAS 2D Model Setup

The 2D hydraulic modeling followed a structured workflow (Figure 7). A 2D flow area encompassing the Bassac River and its adjacent floodplain was delineated within RAS-Mapper. To balance computational accuracy and efficiency, a computational mesh was developed using a variable resolution strategy [8]. Finer mesh cells were applied in regions with complex flow patterns, such as the main river channels, steep riverbanks, and areas around hydraulic structures, to enhance spatial detail, while coarser cells were used in the broader, more uniform areas of the floodplain. Model parameters, primarily Manning's roughness coefficients (n), were defined based on land use and calibrated against observed data. The entire setup was used to execute an unsteady flow simulation over the defined period (2022) using the HEC-RAS 2D solver. Short computational time steps were applied internally to ensure numerical stability, and outputs were aggregated to a daily time step to dynamically calculate water levels, flow velocities, and discharge distributions over time.

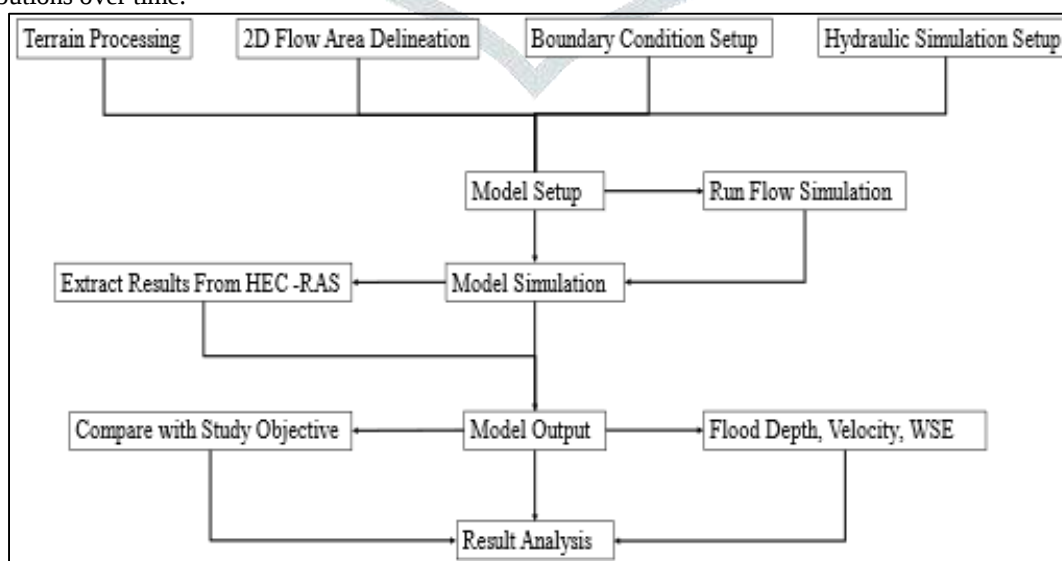


Figure 7. Daily of Water Level of Tole Sap River at Prek Kdam Station (01 Jan to 31 Dec 2022)

2.4 Model Calibration and Validation

Calibration is a critical step in hydraulic modeling using HEC-RAS, aimed at aligning simulated results with observed data to enhance model accuracy. One key statistical metric used in this process is the Root Mean Square Error (RMSE), which quantifies the average difference between simulated and observed values. The calibration process begins by running an initial unsteady or steady flow simulation using estimated input parameters like Manning's roughness, boundary conditions, and flow data. Next, observed data typically water levels from gauging stations are collected and prepared to match the model's temporal and spatial resolution. Then, simulated results are extracted from HEC-RAS using output tools such as time series plots or tables, ensuring they correspond to the same time and location as the observed data [10].

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (W_{Ob} - W_{Sim})^2} \quad (\text{Eq. 2.2})$$

There is no strict universal threshold for a "good" RMSE, as acceptable values depend on model scale, data accuracy, and project objectives. However, the following general guidelines can be helpful for evaluating RMSE in water surface elevation (in meters):

Table 3. Root Mean Square Error (RMSE) and Model Performance Classification RMSE

RMSE (m)	Model Performance
< 0.30	Very Good
0.30 – 0.60	Good
0.60 – 1.00	Fair
> 1.00	Poor

Model calibration was performed to adjust key parameters so that the simulated outputs (e.g., discharge, water level) closely matched observed data. The performance of the model was quantitatively evaluated using the Nash–Sutcliffe Efficiency (NSE), which is widely applied in hydrological modeling to assess predictive accuracy.

$$NSE = 1 - \frac{\sum_{t=1}^n (w_{Ob,t} - w_{Sim,t})^2}{\sum_{t=1}^n (w_{Ob,t} - \bar{w}_{Ob})^2} \quad (\text{Eq. 2.1})$$

Table 4. Following commonly used thresholds [11] :

NSE (m)	Model Performance
≥ 0.75	Very Good
0.65 – 0.75	Good
0.50 – 0.65	Fair
< 0.50	Poor

Percent Bias (PBIAS) is a widely used statistical metric to assess the agreement between simulated and observed data in hydrological modeling. It measures the average tendency of the simulated values to be larger or smaller than their observed counterparts, expressed as a percentage [11].

$$PBIAS(\%) = \frac{\sum_{t=1}^n (w_{Ob,t} - w_{Sim,t})}{\sum_{t=1}^n w_{Ob,t}} \quad (\text{Eq. 2.3})$$

Table 5. Following commonly used thresholds [11]

NSE (m)	Model Performance
< $\pm 10\%$	Very Good
$\pm 10\% - \pm 15\%$	Good
$\pm 15\% - \pm 25\%$	Fair
$\geq \pm 25\%$	Poor

- n = number of data points
- W_{ob} = observed value at point (Ob)
- W_{sim} = predicted model value at point (Sim)

III. RESULTS AND DISCUSSION

3.1 Model Performance Assessment

The HEC-RAS 2D model demonstrated strong reliability and predictive skill through both the calibration (January 1 to June 30, 2022) and validation (July 1 to December 31, 2022) phases (Figures 8 and 9). The performance statistics confirm that the model is suitable for detailed flood simulations in this complex environment. The NSE values (0.71 and 0.69) both fall within the "Good" range (≥ 0.65 to ≤ 0.75), indicating that the model successfully captured the overall shape and magnitude of the observed hydrographs. The PBIAS values (14.21% and 13.83%) confirm no systematic bias, falling within the "Good" range ($\pm 10\%$ to $\pm 15\%$).

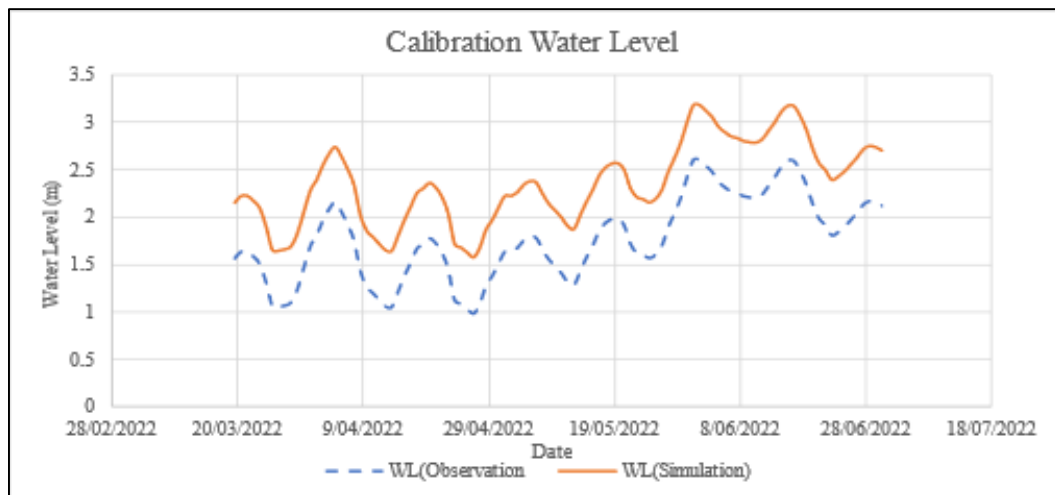


Figure 8. Water Level Calibration from 01 Jan to 30 Jun 2022.

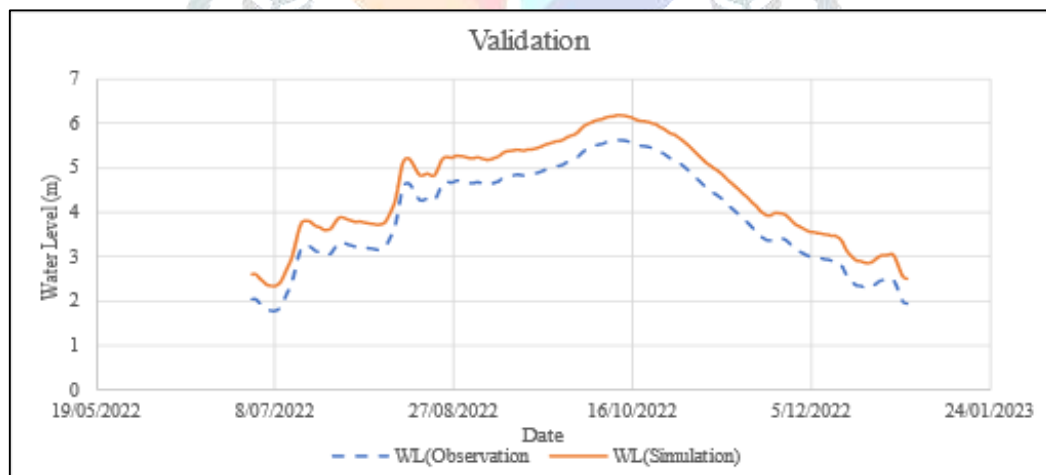


Figure 9. Validation of Model from 01 Jul to 31 Dec 2022.

3.2 Simulated Flood Depth

The simulation of the peak flood on October 2, 2022, revealed significant spatial variation in flood depths (Figure 6). This variation has direct implications for both ecology and infrastructure:

- Deep Inundation (5–15 m): Primarily confined to the main channels of the Bassac River and its tributaries. These areas function as critical aquatic habitats and dry-season fish refugia but simultaneously represent zones of high erosion risk and fluvial hazard to bankside infrastructure.
- Moderate Depth (1–5 m): Widespread across surrounding agricultural floodplains. This depth range is crucial for supporting seasonal rice cultivation, wetland regeneration, and sediment deposition [5]. However, the simulation indicates that prolonged inundation in these zones threatens crop yields and can lead to habitat fragmentation.
 - Shallow/Marginal Depth (<1 m): Found on higher terrain or urban fringes. While these areas experience less structural damage, they are prone to stagnation, which can degrade water quality and elevate risks of water-borne diseases.

3.3 Simulated Flow Velocity

Flow velocity outputs (Figure 7) highlight the dynamic nature of the flood wave propagation.

- High Velocity (0.5–2 m/s): Observed primarily within the main river channels, particularly upstream. High velocities are essential for driving sediment transport and nutrient replenishment, which maintains delta fertility. However, these zones also carry the greatest risk of structural damage to bridges, embankments, and bank erosion.
- Low Velocity (<0.3 m/s): Characterizes the broad, low-lying floodplains used for agriculture and wetland habitats. While these areas act as vital water storage zones, the low flow rates can induce stagnation, which is detrimental to water quality and ecosystem resilience when prolonged.

3.4 Simulated Water Surface Elevation (WSE)

The simulated Water Surface Elevation (WSE) map (Figure 8) provides a clear visualization of the peak flood extent relative to the established datum. The WSE is a fundamental parameter for civil engineering and planning, directly informing the minimum safe elevation for infrastructure and settlements. The map effectively delineates lower-lying areas that experience deeper and more persistent flooding (shown by higher WSE values relative to the ground) from areas of higher elevation, offering essential input for the development of accurate flood hazard maps for the transboundary region.

3.5 Discussion

The results from the high-resolution HEC-RAS 2D simulation provide valuable, spatially explicit insights into the hydrodynamic regime of the Cambodia-Vietnam transboundary corridor, directly addressing the knowledge gap identified in the introduction. The model's "Good" performance metrics ($NSE \approx 0.7$) validate its application for reliable flood hazard assessment in this complex deltaic setting.

The pronounced spatial heterogeneity in flood depth and velocity confirms and quantifies observations made in broader regional studies [5, 12]. The simulated deep inundation zones (5–15 m) along the Bassac channels reinforce their role as vital dry-season refugia for fisheries [12], but simultaneously quantify the corresponding hazard: the steep hydraulic gradients heighten the risk of riverbank erosion, a critical factor often missed in lower-resolution studies. Conversely, the moderate-depth flooding (1–5 m) in agricultural areas validates the reliance on flood-recession agriculture [5]. However, the unsteady flow model highlights the key vulnerability here as the duration of inundation, where prolonged persistence directly threatens crop loss and delays harvests. The flow velocity results provide a crucial link between upstream dynamics and localized impacts: high velocities in main channels are necessary for sediment transport and maintaining deltaic fertility, while the contrasting low-velocity areas (<0.3 m/s) on broad floodplains maximize water storage but pose a direct threat of stagnation and reduced water quality to aquaculture and health [2].

This detailed, high-resolution interpretation highlights the superior value of the 2D HEC-RAS methodology over traditional monitoring approaches like WAFL [4]. While remote sensing excels at historical flood extent, the 2D model provides three indispensable parameters for engineering and governance that remote sensing cannot: flow velocity, accurate WSE, and the ability to simulate future scenarios. Crucially, the 2D formulation captures the lateral momentum transfer and complex overland flow paths across the low-lying, interconnected transboundary borderlands. This level of detail is essential for: 1) Infrastructure Planning (determining minimum safe WSE elevation), and 2) Transboundary Governance, as the model quantitatively links Cambodian upstream inputs to Vietnamese downstream outcomes. This framework serves as a robust technical foundation for systematic data-sharing and coordinated early warning systems between Cambodia and Vietnam, confirming the urgent need for integrated floodplain management that addresses the trade-off between hazard mitigation and ecosystem preservation.

IV. CONCLUSIONS AND RECOMMENDATIONS

This HEC-RAS 2D model reliably simulated cross-border flood dynamics ($NSE \approx 0.7$), providing high-resolution depth and velocity maps. Findings confirm the flood pulse's dual nature: essential for ecosystems but also posing risks like erosion and stagnation. We recommend strengthening transboundary data sharing and implementing adaptive zoning based on these 2D hydraulic outputs to enhance climate-resilient water governance in the Lower Mekong Delta.

V. ACKNOWLEDGMENT

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REFERENCES

- [1] S. Chea, R. Sith, and L. Kim, "Assessment of Flood Dynamics in Lower Mekong Delta Using Modeling Approach," EJ, vol. 26, no. 10, pp. 1–10, Oct. 2022.
- [2] S. D. X. Chua, X. X. Lu, C. Oeurng, T. Sok, and C. Grundy-Warr, "Drastic decline of flood pulse in the Cambodian floodplains (Mekong River and Tonle Sap system)," Hydrol. Earth Syst. Sci., vol. 26, no. 3, pp. 609–625, Feb. 2022.
- [3] "Annual Mekong Hydrology, Flood and Drought Report 2019: Drought in the Lower Mekong Basin," Mekong River Commission Secretariat, Vientiane, Lao PDR, Dec. 2021.
- [4] C. Orieschnig et al., "A Multi-Method Approach to Flood Mapping: Reconstructing Inundation Changes in the Cambodian Upper Mekong Delta," Journal of Hydrology, vol. 610, p. 127902, July 2022.
- [5] D. D. Tran, L. H. Huu, L. P. Hoang, T. D. Pham, and A. H. Nguyen, "Sustainability of rice-based livelihoods in the upper floodplains of Vietnamese Mekong Delta: Prospects and challenges," Agricultural Water Management, vol. 243, p. 106495, Jan. 2021.
- [6] P. Spor, Y. Paşa, and E. Doğan, "Evaluation of Simulation Results of HEC-RAS Coupled 1D/2D and 2D Modeling Approaches Through Scenario-Based Analysis," Water, vol. 17, no. 8, p. 1163, Apr. 2025.
- [7] K. Vashist and K. K. Singh, "HEC-RAS 2D modeling for flood inundation mapping: a case study of the Krishna River Basin," Water Practice & Technology, vol. 18, no. 4, pp. 831–844, Apr. 2023.
- [8] G. Dahal, R. K. Regmi, and S. Adhikari, "Optimization of Model Parameters of HEC-RAS 2D Model on Flood Inundation Mapping: A Case Study of Kankai River Basin".

- [9] A. Juárez, A. Adeva-Bustos, K. Alfredsen, and B. O. Dønnum, "Performance of A Two-Dimensional Hydraulic Model for the Evaluation of Stranding Areas and Characterization of Rapid Fluctuations in Hydropeaking Rivers," *Water*, vol. 11, no. 2, p. 201, Jan. 2019.
- [10] P. V. Timbadiya, P. L. Patel, and P. D. Porey, "Calibration of HEC-RAS Model on Prediction of Flood for Lower Tapi River, India," *JWARP*, vol. 03, no. 11, pp. 805–811, 2011.
- [11] D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith, "Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations," *Transactions of the ASABE*, vol. 50, no. 3, pp. 885–900, 2007.
- [12] S. D. X. Chua, X. X. Lu, C. Oeurng, T. Sok, and C. Grundy-Warr, "Drastic decline of flood pulse in the Cambodian floodplains (Mekong River and Tonle Sap system)," *Hydrol. Earth Syst. Sci.*, vol. 26, no. 3, pp. 609–625, Feb. 2022.

