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Flood Modeling in the Lower Mekong Basin: A 2D Hydrodynamic Approach in Cambodia

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Abstract: *The transboundary floodplain corridor extending from Prek Kdam* Bridge *and Khsach Kandal in Cambodia to the Vietnamese Mekong Delta represents a critical component of the Lower Mekong Basin's hydrological and socio-ecological system. Seasonal inundation within this corridor underpins agricultural production, sustains capture fisheries, and supports the livelihoods of millions of rural households. However, this natural flood regime is increasingly disrupted by multiple interacting pressures, including upstream hydropower development, rapid land use transformation, and the emerging impacts of climate variability. These drivers are reshaping hydrodynamic conditions, intensifying flood risks, and complicating the governance of shared water resources. To examine these dynamics, this study applies a two-dimensional hydrodynamic model (HEC-RAS) to simulate peak flood events in 2022 across the corridor. The model integrates a digital terrain data (12m×12m) with observed boundary conditions to represent key hydraulic parameters, including water depth, velocity, and water surface elevation (WSE). Calibration against observed water levels produced an RMSE of 0.58, NSE of 0.71 and PBIAS of 14.21% demonstrating satisfactory predictive skill and reliability for flood assessment in this complex setting. Simulation results highlight pronounced spatial heterogeneity in flood characteristics. Deep river channels (5–15 m) function as critical aquatic habitats and dry-season refugia but also exacerbate bank erosion and increase exposure to fluvial hazards. Floodplain areas with moderate depths (1–5 m) sustain rice cultivation and sediment deposition processes, yet prolonged inundation in these zones threatens crop yields and rural livelihoods. The results are setting out inundation characteristic hydrodynamic properties of the flood plain.*

Keywords: Bassac River, Flood Risk Assessment, Hydraulic Modeling, Inundation Patterns, Mekong River

1. INTRODUCTION[1]

Flooding in Cambodia is shaped by the interaction of natural hydrological processes and human-induced changes. The Mekong River, Tonle Sap Lake, and the Southeast Asian monsoon system dominate flood regimes across the country [1]. Each year, monsoon rains from May to October raise Mekong water levels [2]. while Tonle Sap experiences its unique reverse flow, expanding the lake and inundating surrounding floodplains. These floods sustain agriculture and fisheries but also threaten infrastructure, communities, and public health [3].

The transboundary floodplain stretching from Prek Kdam Bridge and Khsach Kandal in Cambodia to Châu Đốc and Tân Châu in Vietnam is especially important. This area is a hydrological transition zone linking the Mekong and Bassac Rivers, supporting rice production, fisheries, and cross-border trade. Annual floods bring both benefits (soil fertility, fish migration, groundwater recharge) and risks (displacement, crop losses, and health hazards).

Despite increasing flood challenges, floodplains in tropical deltas like the Mekong remain essential for agriculture, fisheries, and livelihoods, relying on regular flood cycles. However, upstream changes have disrupted flood patterns, threatening food security and ecosystems. Traditional monitoring tools like Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat are limited by low resolution and cloud cover. To improve monitoring, the Water Level–Flood Link (WAFL) method was developed, combining high-resolution Sentinel-1 and Sentinel-2 satellite data with long-term water level records. Applied in the Cambodian Upper Mekong Delta, WAFL has successfully

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reconstructed over 30 years of flood patterns with high accuracy [4]. This makes it a powerful tool for understanding local flood dynamics in data-scarce settings and for informing risk reduction strategies and adaptive management, particularly in vulnerable regions like Koh Thum where traditional monitoring may fall short.

Existing research highlights the value of satellite-based monitoring (e.g., Sentinel-1, Sentinel-2, WAFL method) for reconstructing long-term flood patterns [4]. Studies in the Lower Mekong Basin emphasize the role of floods in sustaining agricultural productivity and fisheries, but also warn of rising risks due to climate change and upstream regulation [5]. However, most previous studies focus either on Tonle Sap or Vietnam's Mekong Delta, with fewer attempts to model cross-border flood dynamics between Cambodia and Vietnam, particularly at Prek Kdam Bridge–Khsach Kandal. This gap limits evidence-based management in one of the basin's most vulnerable regions.

This study seeks to develop a two-dimensional hydrodynamic model using HEC-RAS to investigate the flood dynamics of the transboundary floodplain corridor extending from Prek Kdam Bridge and Khsach Kandal in Cambodia to Châu Đốc and Tân Châu in Vietnam. The model is employed to generate high-resolution spatial outputs of flood depth, flow velocity, and water surface elevation under peak flow conditions, providing a robust basis for characterizing inundation patterns and hydrodynamic behavior. A critical component of the analysis involves identifying flood-prone areas and examining the extent to which land use configurations and floodplain topography shape flood propagation processes. Beyond its methodological contributions, the research addresses a significant knowledge gap in transboundary flood assessment within the Lower Mekong Basin and seeks to inform the development of evidence-based flood risk maps, strengthen early warning and preparedness mechanisms, and support integrated, climate-resilient approaches to floodplain management across national boundaries.

This study addresses three principal research questions: first, what are the spatial and temporal patterns of flood depth, velocity, and water surface elevation in the Prek Kdam Bridge –Khsach Kandal to Vietnam corridor under peak flow conditions? Second, how do topography and land use influence flood propagation and the extent of inundation across this transboundary floodplain? Third, what are the implications of the simulation results for flood risk reduction, transboundary water governance, and the development of climate-resilient strategies in the region?

The study applies a 2D hydrodynamic model using HEC-RAS with high-resolution digital elevation data, hydrological inputs from river discharge. Model calibration and validation will use observed water levels and remote sensing datasets (e.g., Sentinel). Scenario simulations will evaluate peak flow conditions, and outputs will generate flood hazard maps (depth, velocity, water surface elevation).

The outcomes of this study are anticipated to advance the scientific understanding of transboundary flood dynamics in a data-limited but hydrologically critical floodplain, offer robust technical inputs for enhancing early warning systems and flood risk assessment, inform evidence-based policymaking and climate-resilient development strategies in Cambodia and Vietnam, and promote strengthened transboundary collaboration and systematic data-sharing across the Lower Mekong Basin.

2. METHODOLOGY

2.1 Study Area

The study area focuses on a transboundary region connecting the Cambodian floodplains to Mekong Delta in Vietnam, extending from Prek Kdam and Khsach Kandal to 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 area is illustrated in Figure 1**.**

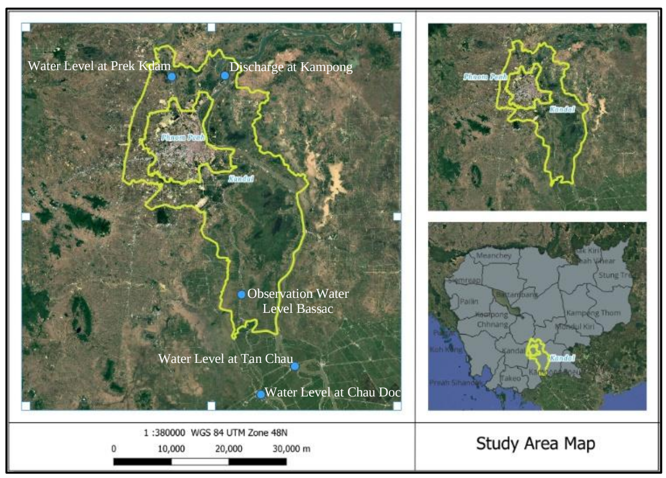

Fig. 1. Map of the Study Area from Prek Kdam and Khsach Kandal to Châu Đốc and Tân Châu

2.2 HEC-RAS 2D Model Setup

In this study, HEC-RAS 2D model was adopted for the hydrodynamics analysis to evaluate the flood extent and dynamic property of the flood plain. HEC-RAS 2D model is a versatile tool [13] which is able to capture spatial and temporal characteristic of study area. This section encapsulates the process and model set up applied in this study the detailed work flow of which is shown in Figure 2.

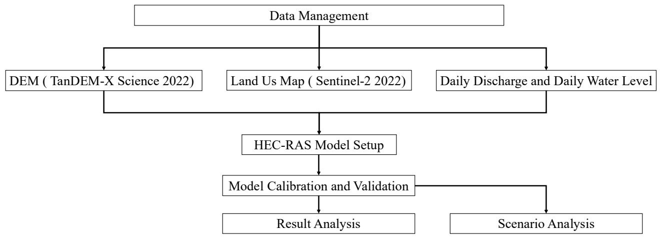

Fig. 2. Flow Chart of Model

2.2.1 Data

The study employed various spatial and temporal datasets to characterize the model in the study area. The main datasets include Digital Elevation Model (DEM), landuse map, daily flow discharge data, and daily water level data (See Table 1).

Table 1. Data For Modelling

Data Name	Date	Spatial Resolution	Source/Url
DEM (TanDEM-X Science)	2022	12m	TanDEM-X Science/https://tandemx-science.dlr.de/cgi-bin/wcm.pl?page=Tdm-Science-Service-System
Bathymetry data	2017	12m	Ministry of Public Works and Transport (2017)
Land Us (Sentinel-2)	2022	12m	Sentinel-2/https://livingatlas.arcgis.com/landcoverexplorer/#mapCenter=154.87343%2C19.47701%2C11&mode=step&timeExtent=2017%2C2023&year=202
Daily Discharge at Kampong Cham Station	2022	N/A	Ministry of Water Resource and Meteorology
Daily Water Level at Tonle Sap Station	2022	N/A	Ministry of Water Resource and Meteorology
Daily Water Level at Chau Doc	2022	N/A	Mekong River Commission
Daily Water Level at Tan Chau	2022	N/A	Mekong River Commission

Digital Elevation Model and River Bathymetry

The study adopted a commercial digital elevation model with a resolution of 12m x 12m from TanDEM-X. The data was used for the terrain processing in the HEC-RAS 2D model for the study area boundary set up.

The study area cover major rivers which are the Tonle Sap, the Mekong, and the Bassac. The bathymetry data is sensitive to the hydrodynamic property of the river. In this study, bathymetry data from river survey was obtained from Ministry of Public Works and Transport (2017) and incorporated into DEM.

Landuse Data

The landuse data (2022) was obtained from Sentinel-2. In the study area, the landuse includes Developed - High Intensity, Mixed Forest, Developed - Open Space, Pasture-Hay, River, Grassland-Herbaceous, Developed - Low Intensity, Evergreen Forest (see Fig. 3). In the model setup, the landuse is associated to the model which provide the roughness coefficient for the flow simulation (see Table 2).

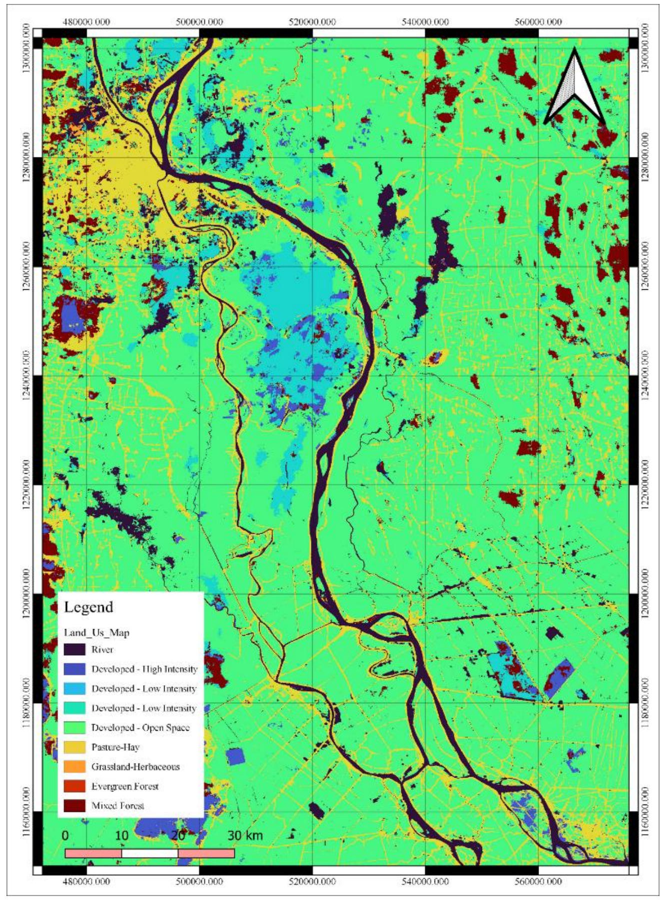

Fig. 3. Land Us Map

Table 2. Land Use / Land Cover

Name	Mannings (n)
Developed - High Intensity	0.015 – 0.030
Mixed Forest	0.080 – 0.150
Developed - Open Space	0.030 – 0.060
Pasture-Hay	0.035 – 0.050
River	0.025 – 0.035
Grassland-Herbaceous	0.030 – 0.050
Developed - Low Intensity	0.030 – 0.050
Evergreen Forest	0.100 – 0.200

Observed Water Level and Discharge

In this study, boundary conditions include: i) daily discharge derived from Kampong Cham station; ii) daily water level data at Prek Kdam station; iii) daily water level data at Tan Chau, and iv) daily water level data at Chau Doc. The flow hydrograph and stage hydrograph of the above stations are shown in Fig. 4 to Fig.7.

Fig. 4. Daily Water Level of Tole Sap River at Prek Kdam Station (01 Jan to 31 Dec 2022)

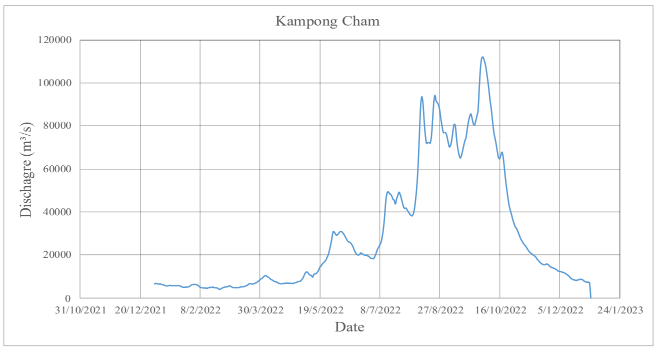

Fig. 5. Daily Discharge of Mekong River at Kampong Cham Station (01 Jan to 31 Dec 2022)

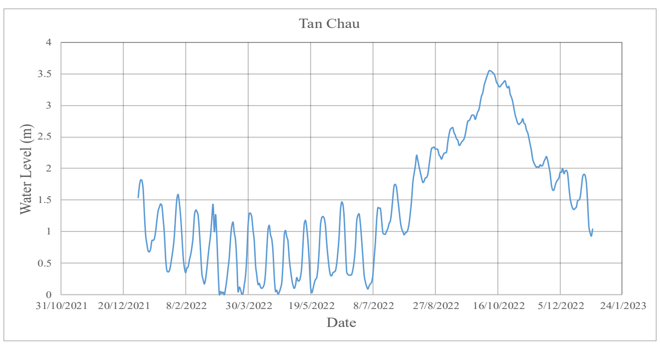

Fig. 6. Daily Water Level of Mekong River at Tan Chau Station (01 Jan to 31 Dec 2022)

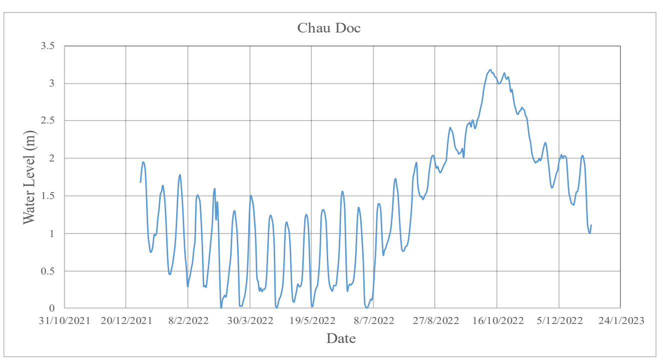

Fig. 7. Daily Water Level of Bassac River at Chau Doc Station (01 Jan to 31 Dec 2022)

2.2.2 HEC-RAS 2D Model Setup Process

Terrain Processing

In HEC-RAS 2D, the DEM is incorporated into the model through the RAS Mapper tool, which establishes the study area boundary and manages the associated spatial layers. To enhance the representation of river channels within the 2D hydraulic model, bathymetric data were integrated into the DEM using the HEC-RAS terrain preprocessing workflow. First, the original DEM was imported into HEC-RAS, and then the elevations along the river channel were edited by replacing them with surveyed bathymetric measurements. This process produced a hydraulically conditioned terrain model with accurate channel depth and slope, which was subsequently used as the terrain input for the HEC-RAS 2D flood simulation.

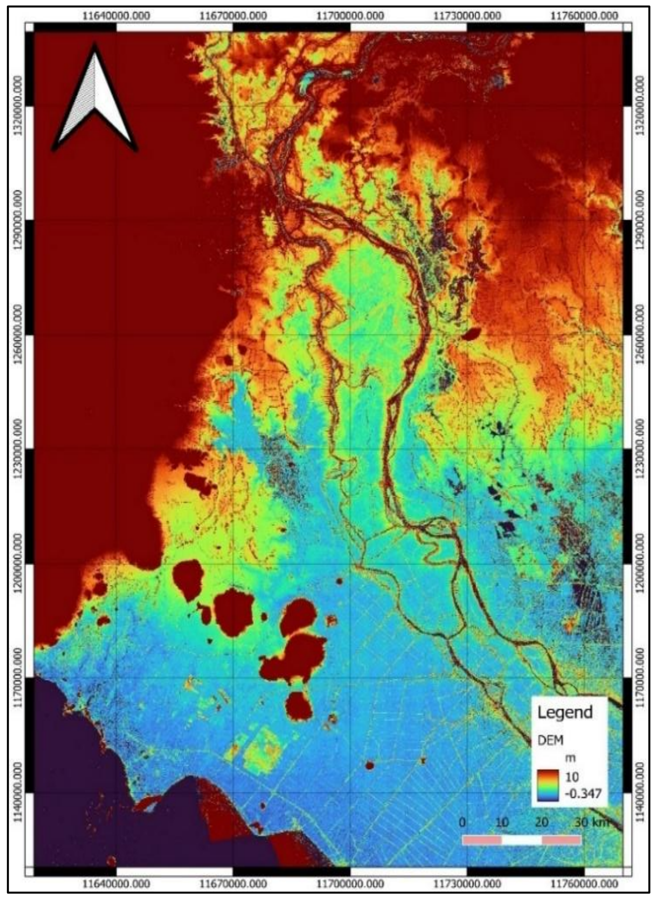

Fig. 8. Digital Elevation Model

Landuse Layer Association

The flood routing process in HEC-RAS requires both channel flow and overland flow the process of which is strongly associated with the roughness of the terrain. Land use layer determines the resistance of the flow in the grid level.

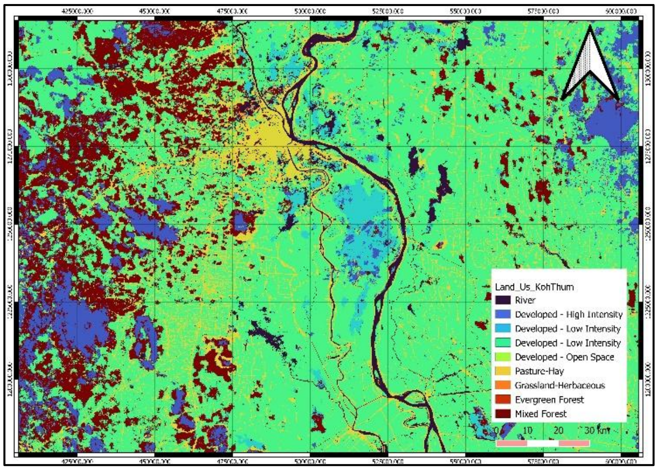

Fig. 9. Land Us Map from RAS-Maper

Table 3. Land Use / Land Cover

Name	Mannings (n)
Developed - High Intensity	0.03
Mixed Forest	0.15
Developed - Open Space	0.06
Pasture-Hay	0.05
River	0.035
Grassland-Herbaceous	0.05
Developed - Low Intensity	0.05
Evergreen Forest	0.20

Boundary Condition Setup

In this analysis, four boundary conditions are incorporated into the model. The upstream boundary conditions are the water discharge derived from Kampong Cham and the water level at Prek Kdam station while the two downstream boundary conditions are water level at Tan Chau and Chau Doc. The stage hydrograph and flow hydrograph of the boundary conditions are shown in Fig.10.

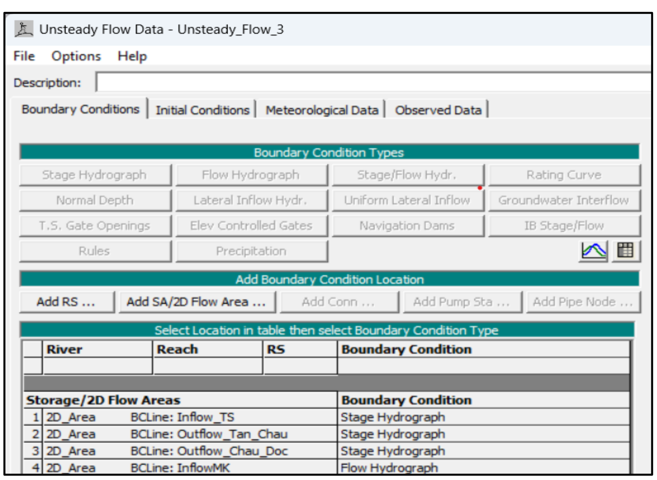

Fig. 10. The stage hydrograph and flow hydrograph of the boundary conditions

Statistical Analysis

The performance of the analysis is evaluated by the following statistical parameters, i.e. Root mean square error, Nash-Sutcliff, and Pbias. The mathematical expression of the parameters are shown as follows:

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

$$NSE = 1 - \frac{\sum_{t=1}^{n}\left(w_{Ob,t} - w_{Sim,t}\right)^2}{\sum_{t=1}^{n}\left(w_{Ob,t} - \overline{w}_{Ob}\right)^2}$$

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

Table 4. Root Mean Square Error (RMSE) and Model Performance Classification RMSE [6] :

NSE (m)	RMSE (m)	NSE (m)	Model Performance
≥ 0.75	< 0.30	< ±10%	Very Good
0.65 – 0.75	0.30 – 0.60	±10% – ±15%	Good
0.50 – 0.65	0.60 – 1.00	±15% – ±25%	Fair
< 0.50	> 1.00	≥ ±25%	Poor

2.3 Scenario Analysis of Model

Model performance was verified using strategically distributed water-level observations along the study boundary to capture spatial variability in hydraulic conditions. After baseline calibration, two sensitivity scenarios were conducted to assess the hydraulic response to boundary forcing: Scenario 1 (Upstream +20%) increased upstream discharge and water level by 20% relative to the baseline while downstream conditions remained unchanged, and Scenario 2 (Symmetric +20%) applied a uniform 20% increase to both upstream and downstream discharges and water levels, allowing evaluation of impacts on water surface elevations, flow distribution, and inundation patterns.

3. RESULTS AND DISCUSSION

3.1 Results

The simulation period from 1 January to 30 December 2022 was selected to represent peak monsoon conditions in Cambodia, characterized by maximum rainfall, river discharge, and flood occurrence. Within this period, 2 October 2022 was identified as the peak flood event, exhibiting the highest recorded water surface elevation, flow velocity, flood depth, and inundation extent. This date reflects the most severe flooding conditions during the study period and was therefore chosen for worst-case flood scenario analysis. Simulating flood dynamics during this critical event enabled a detailed assessment of overbank flooding and inundation patterns based on key hydraulic parameters, including water depth, flow velocity, and water surface elevation. Model calibration and validation for the Bassac River were conducted using reference data provided by the Coastal and Wetland Environmental Research Laboratory.

3.1.1 Calibration of Model

The water level calibration shows strong agreement between observed and simulated values, confirming the model's reliability. The RMSE of 0.58 is below the threshold of 0.60, indicating satisfactory model performance. The NSE of 0.71 falls within the "Good" range, and the PBIAS of 14.21% is within ±15%, showing no systematic bias. These results indicate that the model is calibrated and be able to perform analysis.

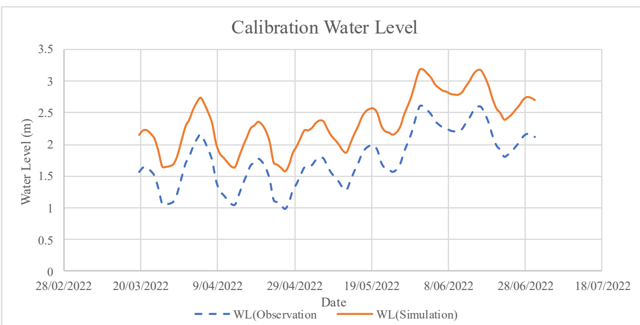

Fig. 11. Water Level Calibration from 01 Jan to 30 Jun 2022

3.1.2 Validation of Model

The model validation shows strong agreement between observed and simulated water levels. With an RMSE of 0.56, NSE of 0.69, and PBIAS of 13.83%, the results is representing the physical property of the system.

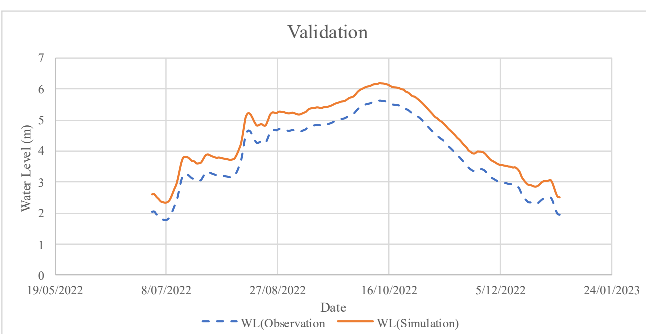

Fig. 12. Validation of Model from 01 Jul to 31 Dec 2022

3.1.3 Flood Depth

Flood depth results for the peak flood event of 2 October 2022 reveal pronounced spatial variability across the transboundary floodplain corridor from Cambodia to Vietnam. Deep inundation zones, with water depths ranging from approximately 5 to 15 m, are primarily concentrated in natural depressions, floodplain storage areas, and local ponded zones adjacent to the main river system. These areas function as key floodwater retention zones during peak monsoon conditions. Moderate inundation depths, typically between 1 and 5 m, are widespread across surrounding agricultural floodplains. These areas play a crucial role in supporting seasonal rice cultivation, wetland regeneration, and fish spawning. However, despite their ecological and agricultural importance, such flood depths also pose vulnerabilities, including habitat fragmentation, delayed planting schedules, and prolonged waterlogging, which can negatively affect crop productivity and rural livelihoods. Shallow flooding, generally less than 1 m, occurs mainly on relatively higher terrain and along urban and peri-urban fringes. Although inundation depths are limited, these zones are susceptible to water stagnation, reduced water quality, and increased risks of vector-borne diseases, particularly when floodwaters persist for extended durations.Flood-prone settlements and critical infrastructure, especially along the Bassac River corridor, are exposed to elevated water levels ranging from 2 to 5 m during peak flooding. Such conditions significantly disrupt transportation networks, damage residential structures, and isolate communities, highlighting the substantial socio-economic impacts associated with high flood depths during extreme monsoon events.

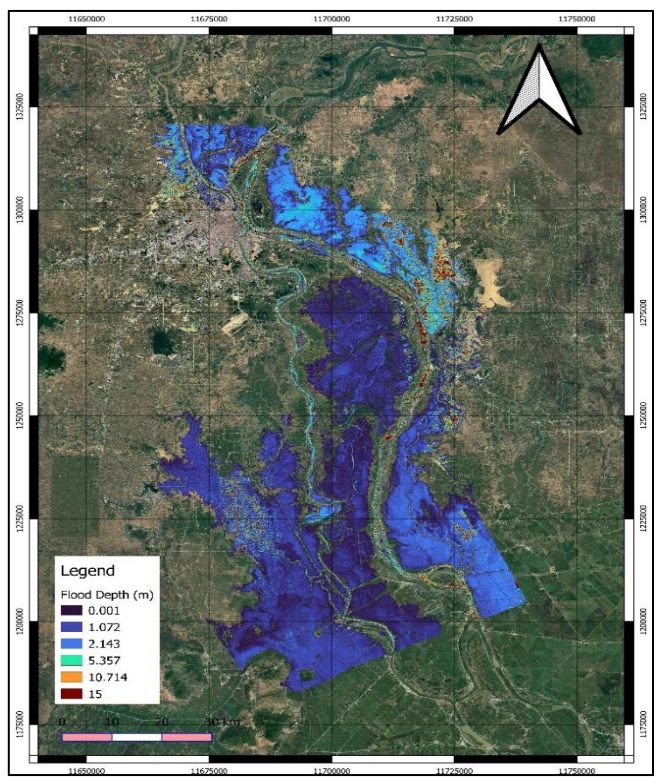

Fig. 13. Simulated flood depth map for the flood on 02 October 2022

3.1.4 Flood Velocity

The flood velocity distribution along the floodplain corridor from Prek Kdam Bridge and Khsach Kandal (Cambodia) to the Vietnam border exhibits pronounced spatial variability. During peak flooding, simulated velocities ranged from <0.1 to approximately 2.0 m/s. The highest velocities (0.5–2.0 m/s) occurred within the main river channels, particularly along the Bassac River upstream, where channel confinement promotes higher flow energy. Downstream toward Vietnam's wider floodplains, flood velocity decreased markedly, with values generally between 0.3 and 1.5 m/s as floodwaters spread laterally and hydraulic gradients diminish. Extensive agricultural and wetland areas experienced very low velocities (<0.3 m/s), reflecting low-energy flow conditions favorable for sediment deposition and floodwater storage. Localized zones of increased velocity were identified near river bends, narrow reaches, and infrastructure crossings, indicating potential areas of enhanced erosion. The results reveal a clear transition from high-velocity, confined upstream channels to low-velocity downstream floodplains, emphasizing the floodplain's role in attenuating flood energy.

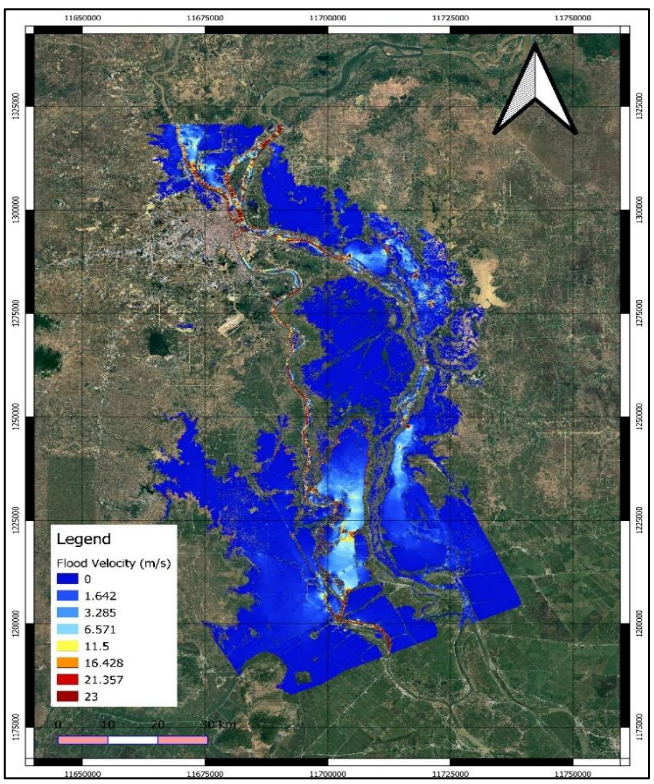

Fig. 14. Simulated flow velocity map on 02 October 2022

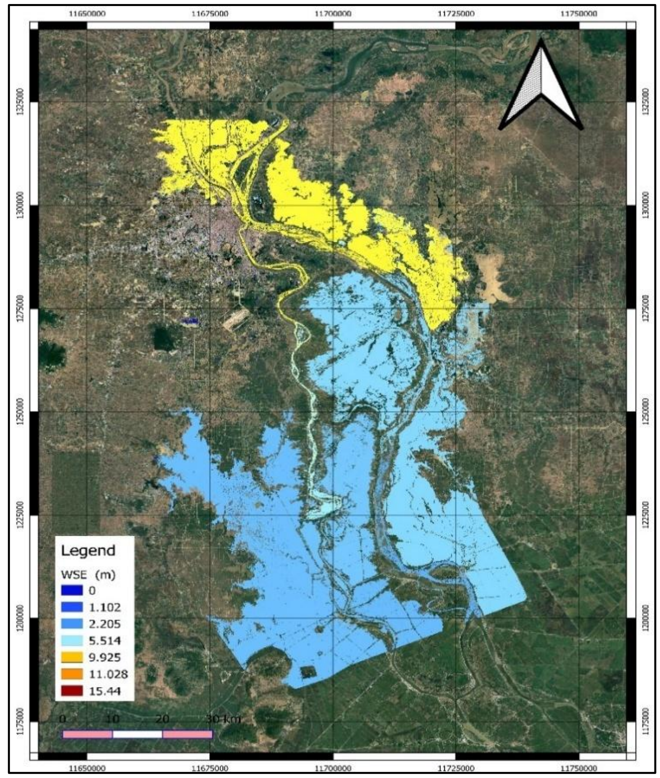

Fig. 15. Simulated Water Surface Elevation (WSE) map on 02 October 2022

3.1.6 Scenario Analyses of Model

Scenario analysis was conducted to evaluate how changes in upstream inflow and downstream water levels influence flood behavior in the Bassac–Prek system. These scenarios represent realistic hydrological variations caused by extreme monsoon rainfall, upstream hydropower regulation, and tidal backwater effects from the Mekong Delta. The analysis helps identify the sensitivity of the system and assess the most critical drivers of flooding.

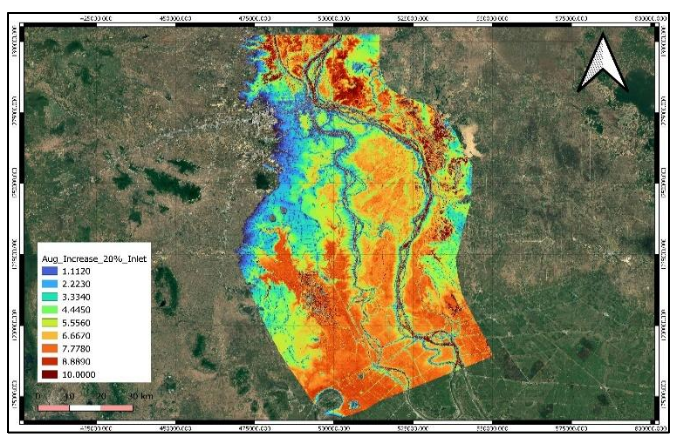

Fig. 16. Simulated Scenarios (+20% Upstream Boundary Conditions)

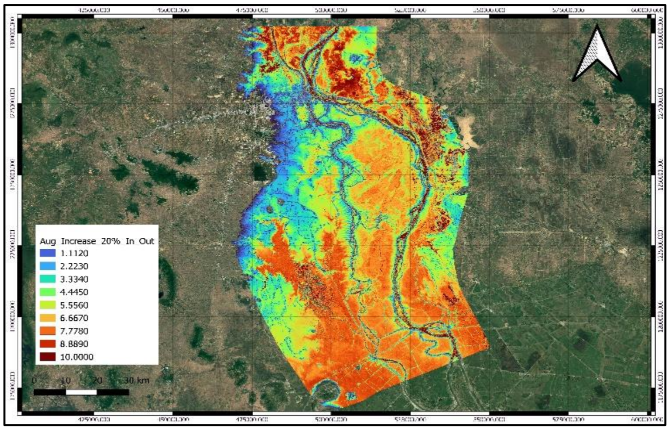

Fig. 17. Simulated Scenarios (20% Upstream–Downstream Boundary Conditions)

Both scenarios were simulated using the same calibrated and validated HEC-RAS 2D model. Only the boundary conditions were modified while maintaining identical terrain, mesh resolution, roughness coefficients, and simulation dates. Hydrodynamic outputs, including water surface elevation (WSE), flood depth, flow velocity, and flood extent were extracted for comparison. Increasing upstream discharge resulted in a 0.12–0.25 m rise in WSE along the Bassac corridor. Flood depths increased by 0.10–0.30 m, particularly near Prek Kdam and Khsach Kandal. Flow velocity increased inside the main channel but remained stable in the floodplain, indicating that the system can partially absorb additional discharge under moderate conditions. The combined upstream and downstream increase produced significantly larger impacts, with WSE rising by 0.25–0.48 m and flood depth increasing by 0.20–0.55 m. Backwater effects slowed channel flow, expanded flood extent in agricultural zones, and prolonged water retention in the Prek canal system. This scenario generated the highest hazard conditions of all simulations.

3.2. Discussion

This study examined flood depth, velocity, and water surface elevation during the 2 October 2022 peak event, assessed the influence of topography and land use on flood propagation, and evaluated implications for flood risk and transboundary management. The simulated results directly reflect the hydrodynamic behavior of the Bassac–Prek floodplain system under extreme monsoon conditions.Deep inundation (5–15 m) was concentrated within the Bassac River channel and adjacent low-lying depressions, indicating strong channel confinement and the activation of floodplain storage areas during peak discharge. These patterns are consistent with observed flooding behavior in Cambodian floodplains, where channel morphology and depression storage dominate peak-stage conditions [2,4]. In contrast, moderate flood depths (1–5 m) extended across agricultural floodplains between Khsach Kandal and the Vietnam border, reflecting widespread overbank flow that supports rice cultivation and sediment deposition but also increases exposure to prolonged waterlogging and crop damage during extreme floods [4,5]. Flow velocity results further demonstrate the role of floodplain geometry and roughness in controlling flood dynamics. Peak velocities exceeding 1.5–2.0 m/s were confined to the Bassac channel, while velocities decreased to below 0.3 m/s across downstream floodplains as flow spread laterally and hydraulic gradients weakened. This marked reduction in flow energy confirms the floodplain's function as a natural attenuation zone, consistent with previous HEC-RAS 2D applications in large lowland rivers [7,8]. Scenario simulations highlight the importance of transboundary boundary conditions. While a 20% increase in upstream inflow produced moderate increases in water surface elevation (0.12–0.25 m), the combined upstream–downstream scenario generated larger rises (0.25–0.48 m) and expanded inundation due to backwater effects propagating from the Mekong Delta into the Prek canal system. This demonstrates that downstream controls play a critical role in flood severity within Cambodian floodplains, reinforcing the need for coordinated transboundary flood management [2,4]. However, the close agreement between simulated flood characteristics, observed hydrological behavior, and published studies supports the reliability of the model and its applicability for flood risk assessment, early warning support, and integrated floodplain management in the Lower Mekong Basin.

4. CONCLUSIONS

This study developed and applied a two-dimensional hydrodynamic model using HEC-RAS to simulate flooding across the transboundary corridor from Prek Kdam Bridge and Khsach Kandal in Cambodia to Vietnam.The model produced high-resolution maps of flood depth, flow velocity, and water surface elevation (WSE) for peak flood conditions, offering valuable insights into spatial flood dynamics, risk areas, and environmental impacts.The results show varied flood characteristics across the region. Deep river channels support ecosystems and aquaculture but raise erosion and infrastructure risks. Moderate-depth floodplains are vital for rice farming and wetlands, but are vulnerable to prolonged flooding and poor drainage. Flow velocity differences influence sediment transport, which is essential for fertility but can cause erosion if mismanaged. The study highlights the need for integrated, site-specific flood management that preserves natural storage, ensures sediment delivery, and maintains water quality. It also emphasizes stronger cross-border cooperation between Cambodia and Vietnam through shared warning systems, data exchange, and coordinated planning. The 2D hydrodynamic model provides a strong technical foundation for collaboration, sustainable management, and climate adaptation.

Overall, this research contributes to improved understanding of cross-border flood dynamics in the Lower Mekong Basin and demonstrates the value of advanced hydraulic modeling for supporting disaster risk reduction, infrastructure planning, and ecosystem resilience in one of Southeast Asia's most flood-prone and socioeconomically important regions.

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