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Article

Assessment of Flood Dynamics in Lower Mekong Delta Using Modeling Approach

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Abstract. The assessment of flood dynamics is essential in supporting the nation and all stakeholders for the better flood management and adaptation. Climate change and hydropower dam operation pose threat to water resources in the Lower Mekong Delta. Cambodia is vulnerable to the flood impact due to its low adaptive capacity. Historically, flood has big impact on Cambodian society, economics and environment. This research was conducted by using the 2D HEC-RAS Modeling Application to study the flood dynamics under the influence of climate change, hydropower operation and irrigation expansion. The analysis is based on the observed flow and water level of 5 years from 2015 to 2019 and digital elevation model (6 m x6 m). The indices indicated satisfactory performance for the simulation model with the value of NSE between 0.78 and 0.97 and R2 between 0.80 and 0.96. The impact of climate change, hydropower operation and irrigation expansion, on the Cambodian Mekong floodplain area in forms of the flood inundation characteristics using the above well-configured hydraulic model framework. The results show that the flood extent increases around 74% in dry season and decrease around 20% in rainy season. Comparing to the baseline, the results of the scenario study suggest that the study area is likely to experience larger floodplain area in dry season (October to April), and flood extent in rainy season is lesser (May to October). The simulated results will provide important hydraulic information to respond to the future change of flood extent. The increase of water level in the dry season will provide water availability in the water supply sector and agriculture.

Keywords: 2D modeling, flood assessment, HEC-RAS, lower Mekong delta.

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1. Introduction

Located in Southeast Asia, Cambodia has the landscape of a low-lying central plain which is surrounded by mountains, while the Tonle Sap Lake (Great Lake) and Mekong River provide a favorable geography for storing the freshwater. The Mekong River brings yearly floods of about 475 km³, and before flowing downstream, inundating the lowlands and where the floodwaters partially enter the Great Lake and eventually flow down to the lower Mekong and Bassac River [1]. The Mekong basin is one of the richest sites of biodiversity in the world after the Amazon River basin which has the higher level of biodiversity [2]. Mekong is home to approximately 20,000 plant species, 430 mammals, 1,200 birds, 800 reptiles and amphibians [3], and around 850 freshwater fish species including the world largest freshwater fish [4]. Around 80% of the nearly 65 million people living in the Lower Mekong River Basin depend their lives on the river's natural resources [5]. Protein intake of Cambodian people are getting from fish that caught in the Mekong River.

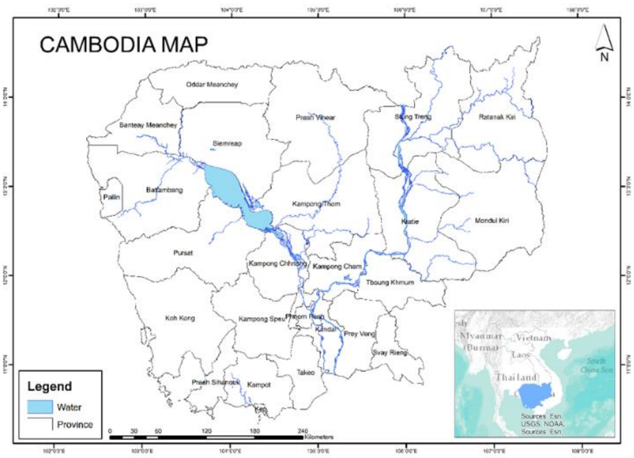

Fig. 1. Map of water bodies in Cambodia.

Flood is the common natural disaster in Lower Mekong Delta. There are three types of floods: Rainfall floods, Dam related floods, and Maritime floods [6]. The weather condition in Cambodia is under the influence of Southwest Monsoon, combined with severe tropical storms. This has been the cause of flood disasters in the Lower Mekong Delta [7]. Any alterations in the duration, amplitude, timing, and rapidity of the Mekong flood pulse that result in changes of floodplain dynamics in the Lower Mekong River Basin can severely impact a wide range of ecosystems and undermine regional food security [8]. Climate change is a long-term change in the average weather patterns that have come to define Earth's local, regional and global climates [9]. Climate change leads to the rising temperatures and extreme rainfall pattern. The unusual turn of wet and dry condition tends to replicate themselves according to a semi-periodic pattern [7]. Flood and drought events in the Mekong River Basin have become more unpredictable, frequent and intense causing devastating damage to the region's livelihood, food security, economies and environment. In addition, climate change, deforestation, agriculture, irrigation and hydropower dam contribute their affects to water resources sector in Cambodia.

Cambodia is still vulnerable to the flood disaster due to its low adaptive capacity. In Cambodia, floods caused by the Mekong River in 2000 and 2011 killed 250 people respectively, affected 350,000 households of over 1.5 million people, causing 52,000 households to be evacuated, costing the economy of 521 million US dollars which were ranked as the worst natural disasters in Cambodia over the last 70 years [10].

This study aims to investigate the impact of climate change, hydropower operation and irrigation expansion in the upstream basin of Mekong on Cambodian Mekong flood plain area in forms of the flood inundation characteristics. The two-dimension (2D) simulation of the flow dynamics in the Lower Mekong Delta under the influence of climate change, hydropower operation and irrigation expansion will be performed to achieved this. A 2D numerical simulation of the 2015-2019 Lower Mekong Delta with the daily discharge of the Kampong Cham (Mekong River) and Prek Kdam (Tonle Sap River).

The remaining sections are arranged as following section 2 (Methodology) which includes the detailed of study area, the input data to run the application, the overall of the process and model selection and calibration. The performance of model application, the output and result are in the section 3 (The result and discussion) to show the comparison of simulated and baseline result. The last section is a conclusion and the suggestion for the future study.

2. Methodology

2.1. Study Area

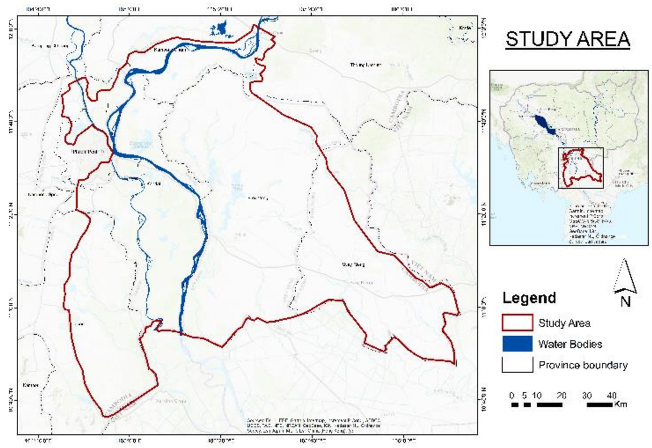

Fig. 2. Map of the study area which is along of Lower Mekong River (LMR) and comprised of 5 provinces and Phnom Penh city with the total area of 31884.1 km².

This study was conducted in the Lower Mekong River catchment of Cambodia starts from Kompong Cham station on Mekong River (11,909 Latitude 105,388 Longitude) and Prek Kdam station on Tonle Sap River

(11,813° Latitude 104,804° Longitude) to Tan Chau station (10,803° Latitude 105,243° Longitude) and Chau Doc (10,707° Latitude 105,133° Longitude). The study area covers 5 provinces, such as Kompong Cham, Kandal, Phnom Penh, Prey Veng, Takeo and Svay Reang and Phnom Penh city with the total area of 31884.1 km^2.

2.2. Data Acquisition

The important data used in this study are topography, bathymetry, and hydrology data that provide information about the river bathymetry, discharge and water level of Mekong, Tonle Sap and Bassac River. The geographic data was based on the Digital Elevation Model (DEM) from the Mekong River Commission (MRC) with the grid resolution of 6 m. Likewise, the Acoustic Doppler Current Profiler (ACDP) was employed to generate the river bathymetry and mosaic with the DEM to form the terrain data.

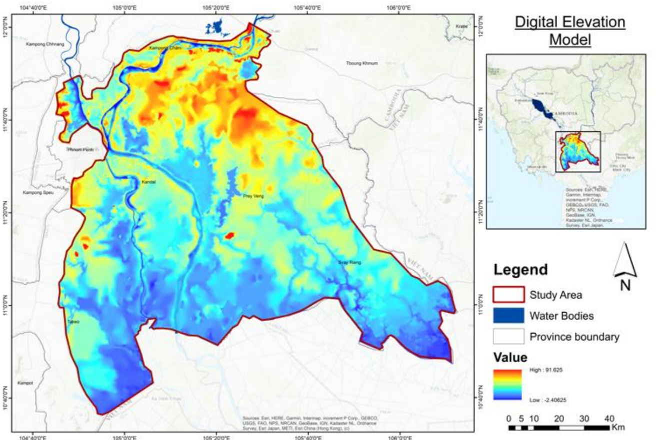

Fig. 3. The Digital Elevation Model (DEM) of the study area which covers the lower Mekong River part of Cambodia.

The daily water discharge data (see in Fig. 2) as an upstream boundary condition (Kompong Cham and Prek Kdam) from 2015-2019, (Prek Tnout) 2019 and the daily water level as a downstream boundary condition (Tan Chau and Chau Doc) 2019 were obtained from MRC. The stage hydrograph in Fig. 4 was entered as the negative value as the downstream boundary.

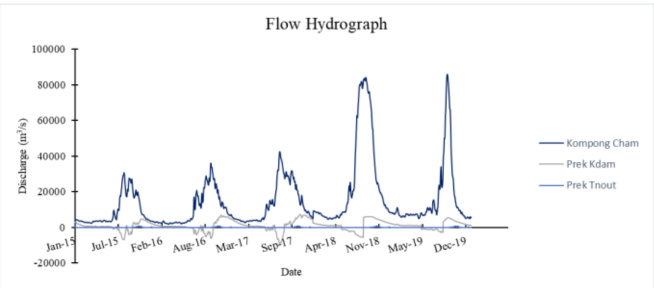

Fig. 4. The Flow Hydrograph (Kompong Cham, Prek Kdam and Prek Tnout stations).

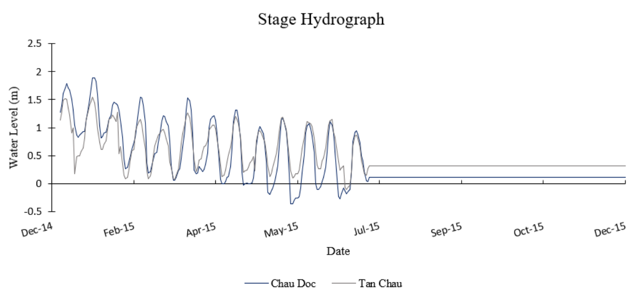

Fig. 5. Stage Hydrograph (Tan Chau and Chau Doc stations).

The water level from 4 stations were used to calibrate and validate the performance of the model with daily water level. Those stations include Chaktomuk, Koh Khel and Neak Leoung (2015-2019) and Chhrouy Chongva (2015-2017). The description of all input data with their sources were presented is presented in Table 1.

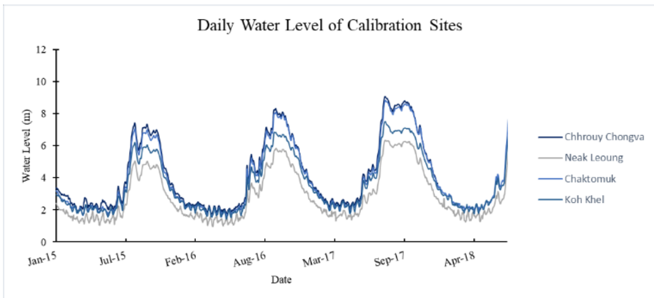

Fig. 6. Daily water level of calibration sites (Chaktomuk, Koh Khel and Neak Leoung and Chhrouy Chongva station).

The data of a recent study [11] were used as the boundary conditions for the best possible scenario of future changes of inflow from upstream part of the Mekong River that took into account of the climate change, hydropower developments and irrigation expansions. The climate change scenario from the above work demonstrated the constantly temperature increase of +1.9 °C (RCP4.5) and +2.4 °C (RCP8.5) in the Mekong River basin based on the climate change scenarios. According to the hydropower dam database of MRC and the Asian Development Bank (ADB), 126 dams will be fully operating around the years 2036–2065. The study employed the irrigation expansion scenarios from the MIRCA (Global Dataset of Monthly Irrigated and Rain-fed Crop Areas around the year 2000) and the global projected irrigation expansion combined with the above scenarios of the future change of discharge under the above three combining factors, the dry season flow (March and April) increased up to +150%, and wet season flow decreased around 10% in June and 25% in July at Kratie station. The monthly percentage changes at Kratie Station [12] was then used to multiply with the discharge of Kompong Cham Station (Fig. 3) in order to obtain the estimated changes between 2036 and 2065 in the Mekong River. In the previous study [12], there is no study of future flow change of Kompong Cham Station in Cambodia, and having both station of Kratie and Kompong Cham to be nearby, this study assumes the similar changes in both station for the future change of flow as well.

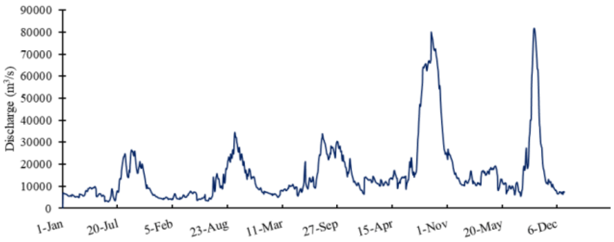

Fig. 7. Future change of daily discharge at Kompong Cham Station under influences of climate change, hydropower operation and irrigation expansion scenarios.

The Manning's *n* values from a study [13] were used in the model to define roughness for the whole catchment. To get *n* value, the water bodies and floodplain are defined. The composition of the riverbed is sand and gravel, and thus the *n* is reasonably ranged from 0.03 to 0.036. For the floodplain, the *n* value was initially set at 0.03 in this study based on the riverbend composition criteria. The n value was considered as calibrated parameter.

Table 1. Data input description and sources.

N	Data	Duration	Description	Source
1	DEM	-	6m-cellsize	MRC
2	Geometry	-	Catchment	-
3	Discharge	2015-2019	3 stations	MRC
4	Water level	2015-2019	4 stations	MRC
5	Cross section	2002,2018,2019	River bathymetry	MPWTP, MOWRAM and MRC

2.3. Model Selection

There are numerous models and choice to be considered when it comes to the hydraulic modeling. In 1991, 65 known hydraulic models existed, but the number has risen [14] incredibly with new technology afterward. Hydraulic modeling is very important for flood hazard assessment since it has the ability to show the magnitude of flood with a convincing exceeded probability [15]. The 2D modeling has become useful and popular as the computing power increase and data retrieval becomes more practical. The 2D modeling is generally employed when there is no well-defined channel and flow path. The Hydrologic Engineering Center's River Analysis System widely known as HEC-RAS is considered as the most suitable application for this study as mentioned in 2.4.1.

This research study is conducted by using 2D HEC-RAS model application. HEC-RAS is an open-source software with a friendly interface which is commonly used to perform flood simulation with just the terrain and discharge data in new features two-dimensional for the large study area.

2.3.1. 2D HEC-RAS

HEC-RAS is an open-source software with the friendly interface that has been using frequently by researchers and experts in Cambodia for the flood study since it could give a valid output both affected area and flood depth. For flood study from 2000 until 2013 and also 10-year return period flood, the outputs both flood extent and flood depth including the river [16]. HEC-RAS is good to perform flood simulation with only the terrain and discharge data in new two-dimensional feature for the large study area. HEC-RAS model can be used to simulate flood extent and flood depth characteristics and provide a satisfied result with higher performance.

In HEC-RAS, the 2D flow modeling is capable of performing (1) 1D, 2D and combined of 1D and 2D modeling. (2) Full Saint Venant or Diffusion Wave Equations in 2D. (3) Implicit Finite Volume Solution Algorithm. (4) 1D and 2D couped solution algorithm. (5) Unstructured and structured computational meshes. (6) Detailed Hydraulic Table Properties for Computational Cells and Cell Faces. (7) Detailed Flood Mapping and Flood Animations. (8) Multi-Processor Based Solution Algorithm. (9) 64 Bit and 32 Bit Computational Engines [17].

2.3.2. Diffusion wave equation

In general, most typical flood modeling employed the 2D Diffusion Wave equations since it can allow faster computation time and more stable even it is less accurate than the 2D Full Saint Venant equation. Local and advective acceleration, viscosity and Coriolis terms of the momentum equation can be disregarded to arrive at a simplified version called diffusion wave [18].

$$g\frac{\partial H}{\partial x} + Cfu = 0 \quad (1)$$

Flow moment was driven by the barotropic pressure gradient balanced with bottom friction equation Cf to the manning's formula and simplified the momentum equation resulted in the simplified Diffusion Wave equation [18].

2.3.3. 2D computational time step selection

Computational runtime is depending on the cell size, simulation duration and computation equation selected. There are two new options available in HEC-RAS Version 6.0. The first option is a variable time step based on monitoring Courant numbers (or residence time within a cell). The second variable time step option is a method that allows users to define a table of dates and time step divisors.

The Courant numbers as high as 5.0 can provide enough accuracy and stability when using the Diffusion Wave computational method. The 2D diffusion wave computational method is the default solver and allows the computations to run faster with greater stability. The smaller the interval, the more data is written to the HEC-RAS analysis results file. This can have a significant impact on computational runtime. Courant Number can be derived as follows:

$$C = \frac{V \times \Delta T}{\Delta X} \leq 2.0\ (with\ a \max C = 5.0) \qquad (2)$$

where:
C = Courant Number
V = Velocity of the Flood Wave (m/s)
T = Computation Time Step (s)
X = the average cell size (m)

In this study, the computation interval was selected to be 10 minutes and 1 day for mapping output interval, hydrograph output interval and detailed output interval.

2.4. Overall Workflow of Modelling Approach

To achieve the objectives the study herein, the modeling set up and data analysis approach need to be clearly designed. The flowchart in Fig. 7 shows the overall process of modeling set and data analysis in this study. We divided overall process into three main steps: pre-processing, processing, and post-processing.

The study area was defined within the Cambodian Mekong River catchment from Prek Kdam (Tonle Sap River) and Kompong Cham (Mekong River) to Tan Chau and Chau Doc (Lower Mekong Delta). The boundary conditions were set at the inflow and outflow boundary and the break lines were set as well around the Chaktomuk River that divides the flow from Tonle Sap and Mekong River into Bassac river and Mekong delta. The DEM from MRC was clipped within the study area and mosaic with 74 cross-sections interpolation to get the new DEM raster of 6m resolution. The cross-sections were interpolated to create river bathymetry. The second part was processed in the HEC-RAS application. RASmapper was used to perform the data preparation for the simulation as a window to create the terrain data, land-cover data and geometry data. Manning's n = 0.08 was provided for all main river and floodplain. Then, the flow data and water level were input in the boundary condition.

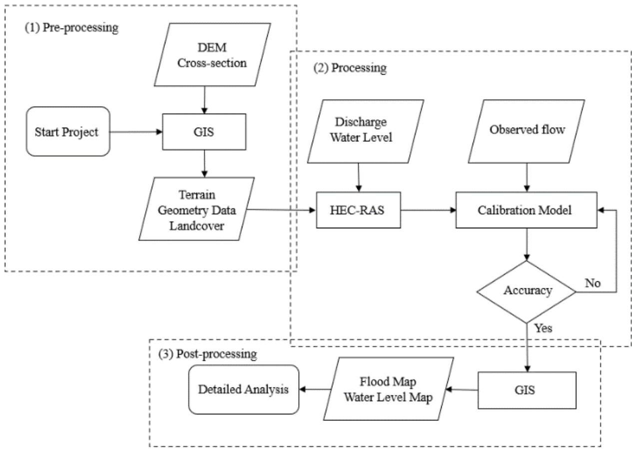

Fig. 8. The flowchart of modelling approach.

2.5. Model Calibration

The performance of the model was assessed graphically and by Nash–Sutcliffe efficiency (NSE) and the coefficient of determination (R^2).

The Nash–Sutcliffe efficiency coefficient (NSE) is a normal statistic used to assess the predictive skill of hydrological models [19], and has the formula as the following:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(H_{obs_i} - H_{sim_i})^2}{\sum_{i=1}^{n}(H_{obs_i} - H_{obs_{mean}})^2} \qquad (3)$$

where:
H_{obs} = the observation water level (m)
H_{sim} = the water level that got from simulation (m)
H_{mean} = the average of water level from observed (m)
n = the total number of observation and simulated data

Table 2. Criteria of Performance Rating [20].

Performance Rating	NSE
Very good	0.75<NSE<1
Good	0.65<NSE<0.75
Satisfactory	0.5<NSE<0.65
Unsatisfactory	NSE<0.5

R^2 is measure that represents the proportion of the variance for a dependent variable that's explained by an independent variable or variables in a regression model.

$$R^2 = 1 - \frac{RSS}{TSS} \qquad (4)$$

where:
RSS = the Sum of Squares of Residuals
TSS = the Total Sum of Squares

3. Results and Discussion

3.1. Model Performance

The hydrologic model was calibrated for the years 2015-2019 for 3 hydrological stations (Chaktomuk, Neak Loeung and Koh Khel) and 2015-2017 for a station (Chhrouy Chongva) on Mekong River. The simulation result of the model was assessed by comparing the daily water surface elevation of simulation with observed water level. As a result, the Manning's n Value is set to 0.08 which produced a great simulation performance as follows. Based

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on the guideline of performance evaluation criteria for models as in Table 2, very good model performance is obtained for all the stations with the value of NSE between 0.78 and 0.97 and R^2 between 0.80 and 0.96.

Table 3. Performance of HEC-RAS model daily water level simulation.

Station	Performance Evaluation	
	NSE	R^2
Chaktomuk	0.80	0.90
Chhrouy Chongva	0.97	0.96
Koh Khel	0.78	0.80
Neak Leoung	0.80	0.89

3.2. Simulated Monthly Flood Maps

The 0.3 m of depth is defined as flood depth threshold in this study, and thus the flood depth that is less than 0.3 m was deduced for map generation. In the rainy season, both figures (Fig. 8 and Fig. 9) have demonstrated the increasing flood depth and flood area for baseline and scenario study respectively. A noticeable behavior of flood is that the water depth has risen in the left side of the river bank (Bassac River) first. Then it enlarges to the right side (Lower Mekong River) of the catchment, which precisely corresponds to the terrain topography. In the early dry season, specifically in November and December, the wetted area remains almost the same as that of the rainy season especially in August, and September but the water depth started to shrink rapidly compared to the flood area (Fig. 8).

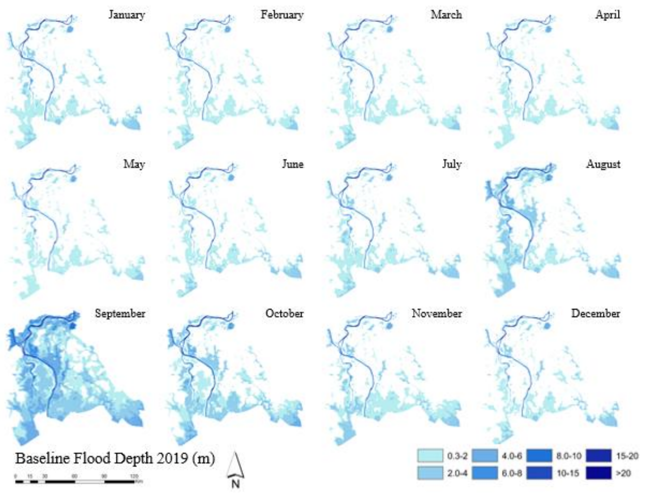

Fig. 9. Map result of monthly baseline flood depth in 2019.

Under the influences of climate change, hydropower operation and irrigation expansion (hereafter refer to as "Scenario" in this report), the flood extent is considerably different from the baseline (Fig. 9). The increasing in discharge at the boundary conditions during the dry season is the main factor contributing to the increase of water depth and as well as the flood extent. In March and April, the flood area is expanding and water depth is rising; however, the water depth is less than that of the baseline (Fig. 8 versus Fig. 9) in July and August.

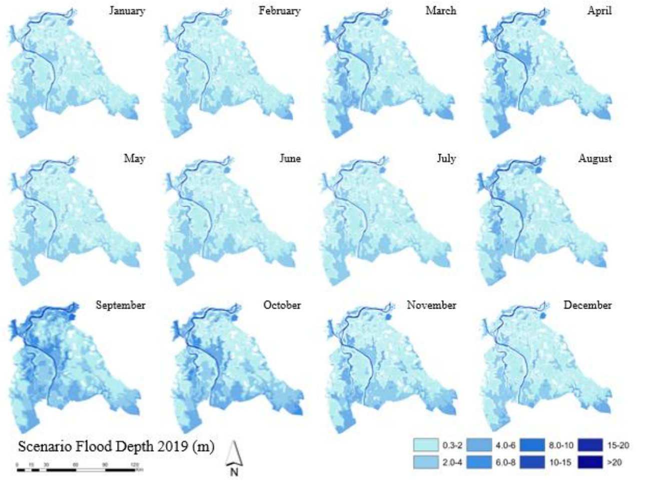

Fig. 10. Map result of monthly scenario flood depth in 2019.

3.3. Flood Map Comparison of Baseline and Scenario

The months of April and July were selected to compare the flood extent between the baseline and scenario because of the most future significant change of the discharge in Mekong River. Comparing to the baseline, the results of the scenario study suggest that the study area is likely to experience larger floodplain area in dry season (October to April), and flood extent in rainy season is considerably smaller (May to October). The simulation results also show that the flood area expands around 40% in April compared to that of the baseline (Fig. 10). In contrast, the flood extent decreases around 19% in July (Fig. 11).

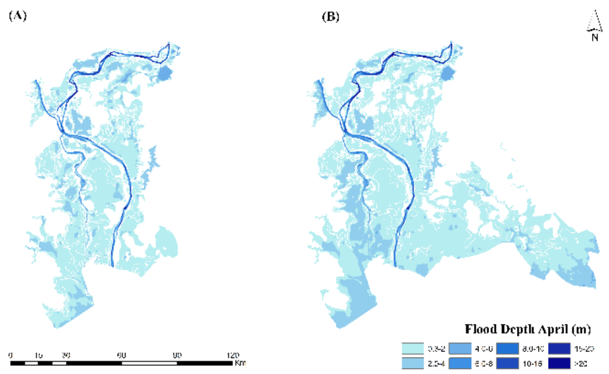

Fig. 11. Flood map comparison of Baseline (A) and Scenario (B) during Dry Season.

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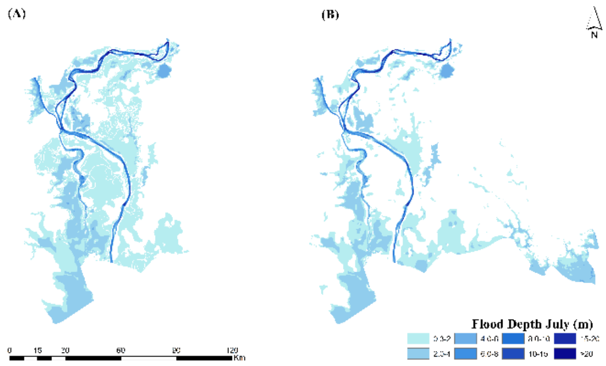

Fig. 12. Flood map comparison of Baseline (A) and Scenario (B) during Rainy Season.

3.4. Comparison of Flood Area, Water Depth and Water Level

The flood extent included both river and floodplain area. The total flood area of the baseline is around 4600 km² in January till May (Fig. 12), and it increases gradually to the peak of 7000 km² in October which is the rainy season in Cambodia. The inundation area, however, decrease as the dry season begins. In the same figure (Fig. 12), the red column represents the flood extent of the scenarios of future change. As it can be seen, the flooded area increased drastically in January to June from around 4600 km² to almost 8000 km² corresponding to +74% change. Interestingly, the flood extent of scenario study decreases in July from approximately 5000 km² to around 4000 km² corresponding to -20% change. This significant drop occurs since July is the early period of wet season which corresponds to the result finding the previous study [11].

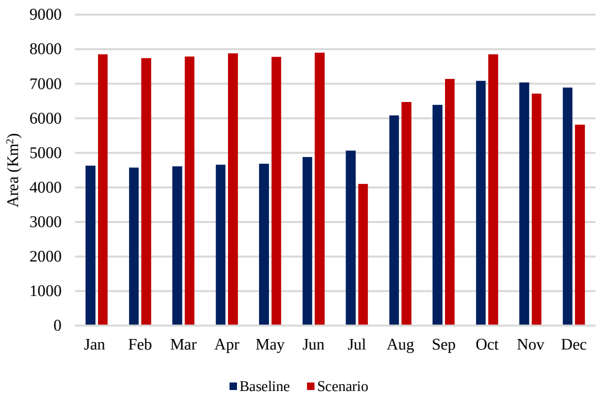

Fig. 13. Comparison of Flood area between Baseline and Scenario.

Comparison of Flood area cannot capture the whole view of the change of flood characteristics, and thus the raster calculation of difference was performed to demonstrate the change of flood depth between the baseline and scenario. Figure 13 shows the results of this calculation as spatial variation of the changes. The positive values (1 or 2) indicate that the scenario water depth is higher than that of the baseline, while the negative values indicate that the scenario water depth is lower than that of the baseline, and the 0-values indicate that the water depth remained the almost same between the scenario and the baseline flood map. The inundated area has occurred in almost every month throughout the year and excessively from May to November except the October. The highest increase of water depth is in September and November. Even most of the area are wetted in June, July, August and November yet it also dried up in some other part as well.

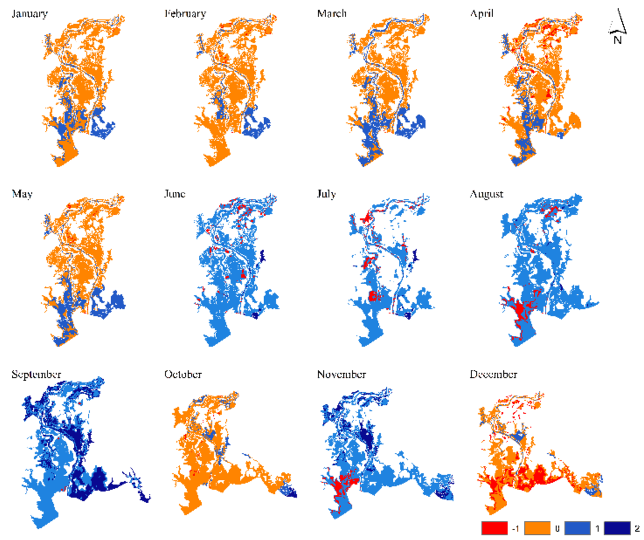

Fig. 14. Map of the change of water depth of the study area using raster calculation between Baseline and Scenario flood area.

The water level for both the Scenario and Baseline as the output of HEC-RAS is then compared in two stations, namely Chaktomuk (Fig. 14) and Neak Leoung (Fig. 15). The hydrographs in both stations show similar pattern. In general, the water level of the scenario in the rainy season (May to October) increases slightly compares to the baseline, and the water level during the dry season more increase compared to that of dry season. This indicates the different tendency of water level compared to the flood extent and flood depth. The water level of Chaktomuk and Neak Loeung Station are relied from the inflow of the Kompong Cham Station and its catchment rainfall. The higher flow from the upstream due to the hydropower operation in dry season will cause the increasing of water level. The water level in Chaktomuk is not only correlated with the Mekong River alone, it has an interconnection with the Tonle Sap's Lake as well. Despite the geography, the Mekong River's water volume has been creating a reversal flow of Tonle Sap River to fill in the Tonle Sap's Lake in rainy season [21]. Therefore, this phenomenon will also happen during the dry season as the accumulation of water level and it might have an ecological disturbance in Tonle Sap's Lake especially the flooded forest.

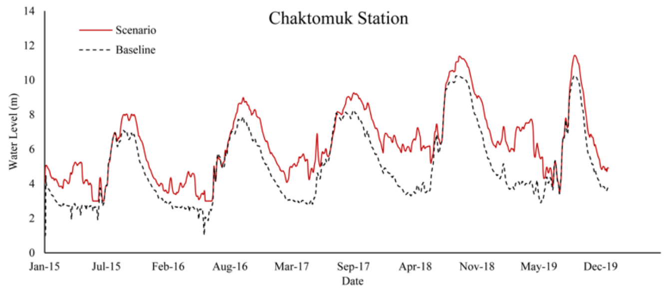

Fig. 15. Comparison of water level between Baseline and Scenario at Chaktomuk Station.

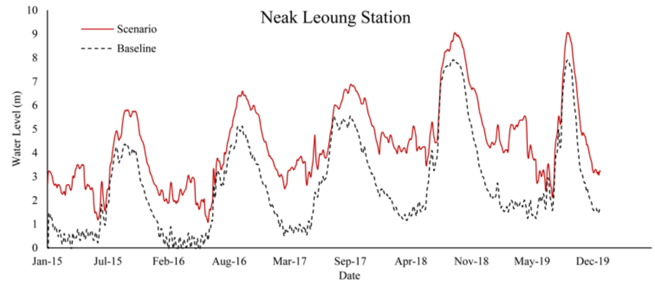

Fig. 16. Comparison of water level between Baseline and Scenario at Neak Leoung Station.

4. Conclusion

This research study has shown the capability of 2D HEC-RAS in performing simulation of the flow dynamics in Lower Mekong Delta with the value of NSE between 0.78 and 0.97 and R2 between 0.80 and 0.96. By running the scenario of future change in flow, this study provides the hydraulic information of the flood such as water depth, water surface elevation and location where water begins to overflow in Cambodian Mekong flood plain. The impact of climate change, hydropower operation and irrigation expansion on the Cambodian Mekong floodplain area in forms of the flood inundation characteristics using the well-configured hydraulic model framework. The vast change between the baseline and scenario can have both positive and negative impacts. The flood extent increases around 74% in dry season and decrease around 20% in rainy season. Comparing to the baseline, the results of the scenario study suggest that the study area is likely to experience larger floodplain area in dry season (October to April), and flood extent in rainy season is lesser (May to October). The increase of water level in the dry season will provide water availability in the water supply sector and agriculture.

However, there were few assumptions for the study such as the infiltration, evaporation phenomena, and the agriculture and domestic water use were ignored. The lack of data for this study also contributes to the uncertainty of model results herein; for example, the vast gap between each cross-sections create inaccurate river bathymetry such as contraction and expansion. Despite the assumptions and uncertainty, the study provides maps and satisfied hydraulic information that are insightful for the future development, adaptation and disaster management. It can be concluded that 2D HEC-RAS modeling application is an important and useful tool for future flood studies.

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