Thai Environmental Engineering Journal Vol. 33 No. 3 (2019) : 27-38
www.eeat.or.th

Flood Risk Mapping Using HEC-RAS and GIS Technique: Case of the Xe Bangfai Floodplain, Khammoune Province, Lao PDR

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Abstract

Xe Bangfai (XBF) is one the main tributaries of the Mekong river in central Lao PDR, where is vulnerable to flooding, was influenced by monsoon in northeastern and southwestern parts of country. The heavy rainfall often occurs over several consecutive days resulting in a rise in the level of the Mekong River. In this study, the flood frequency of different magnitudes was analyzed using the Gumbel's distribution method. The flood depth value was simulated for different return periods using HEC-RAS model and GIS program was used to create the flood risk maps in Xe Bangfai floodplain. It was found that peak flow in each flood frequency of 2, 6 and 35 years return period as 3,746.57, 4,505.99 and 5,877.60 m^3/s respectively. These peak flow in each flood frequencies were selected for simulation of water surface profiles at lower part of XBF. The result from model simulation were used for flood hazard analysis and generated flood risk maps using GIS tool. The flooded areas by 2, 6 and 35 years return flood shown as 49,534.0, 53,800.0 and 56,047.0 hectares respectively. The large vulnerable area for 2, 6 and 35 years return period on crop land were 25,456.00, 28,054.00 and 29,443.00 hectares, respectively and followed by the forest area were 17,588.00, 19,062.00 and 19,852.00 hectares respectively. The vulnerability area analysis was shown that the 2 years return flood inundated 30,000.00, 16,567.00 and 2,889.00 hectares, respectively of crop land, forest and; and water respectively.

Keywords : Flood risk; HEC-RAS; GIS; Xe Bangfai floodplain

Introduction

Natural disasters in Lao People's Democratic Republic (Lao PDR), especially the form of floods and droughts, the most vulnerable areas are the low-lying areas along the Mekong River and its major tributaries. Xe Bangfai (XBF) is one the main tributaries of the Mekong river in central Lao PDR, where is vulnerable to flooding. The flooding occurs due to heavy rain during the rainy season (August to September) when the tributaries of XBF river rising up and also the rising water from Mekong river flowing into the low basin area of XBF [1]. The flooding has impact on the social, economic and environment in this area.

The flood risk assessment [2] requires a clear understanding of the causes of a potential disaster, which includes both the natural hazard of a flood, and the vulnerability of the elements at risk, which are people and their properties. Flood risk assessment therefore consists of understanding and quantifying this complex phenomenon. The assessment of the expected flood damage consists of four primary steps including (1) hydrological frequency analysis; (2) hazard assessment; (3) hazard exposure analysis; and (4) damage assessment. In this methodology, the hydrological frequency analysis is based upon the historical records and provides an estimate of exceedance probability or recurrence interval of the flood of a particular magnitude. The hazard assessment includes the assessment of risks posed by a flood event in terms of tangible and intangible damages. After identifying the potential hazards, the next step in the assessment process includes the estimation of extent and severity of the damages in terms of hazard exposure analysis, usually defined by flood water depth and the velocity. Flood hazards are categorized based on water depth and they are as follows: Low (0-1 m), Medium (1-3 m), High (3-6 m) and very high (>6 m) [3]. The damage assessment involves estimating the impact of the likely exposure in terms of the costs of replacing and restoring the affected areas.

Flood frequency analysis is one of the important aspects of a hydrological study which is based on the frequency distribution of flow data that is used to calculate statistical information (mean values, standard deviation, skewness, and recurrence intervals) and to estimate future its occurrences. This information will provide the likelihood of several discharges as a function of the recurrence interval exceeding a set probability [4]. Flood frequency analysis is essential for providing hazard probability of flood risk assessment as well as for determining design flood for sites along the river such as design the flood control structure (e.g dams, levees, gate, floodways, and channels) to protect the expect flood event [5]. It is a necessary tool for water resources management and water infrastructure design [6]. There are several types of theoretical probability distributions (or frequency distribution functions) that have been successfully applied to hydrologic data. The most popular theoretical probability distributions have been the lognormal, log Pearson Type III and Gumbel distributions [7]. Gumbel's distribution [8] is one of the statistical approaches that is mostly used to analyze flood data. It is also used to predict hydrological events such as flood. It is widely used in flood frequency study. This distribution can be used to represent the distribution of the maximum or minimum of water level, discharge, and other parameters such as precipitation in particular year that there was a list of maximum or minimum values for the past ten years [9].

Recently, numerical modeling has applied to study flood (HEC-RAS; ISIS; [10, 11]). Several previous studies have improved the capacity of the flood modelling. The model is used in flood risk mapping and has been developed to simulate flood areas (i.e., [12, 4]). HEC-RAS is a hydrological model [13]. It was developed at Hydrologic Engineering Center (HEC), U.S Army Crop of Engineers. It was designed to perform a one-dimensional steady flow, one and two-dimensional unsteady flow river hydraulic calculations, sediment transport/mobile bed computations, water temperature analysis and generalized water quality modeling [14]. The HEC-RAS system contains four one dimensional river analysis components; 1) Steady flow water surface profile 2) Unsteady flow component 3) Movable boundary/sediment transport computations and 4) Water quality analysis. For HEC-GeoRAS is set of ArcGIS tools specifically designed to process geospatial data for use with the Hydrologic Engineering Center's River Analysis System (HEC-RAS). The extension allows users with limited GIS experience to create an HEC-RAS import file containing geometric data from an existing digital terrain model (DTM) and complementary data sets [15].

The study of flood risk analysis and risk management in lower Xe Done (XD) [4] was shown that he flood frequency analysis was done by using log Pearson type III and Gumbel distribution method to obtain the maximum discharge at the various return periods (2, 5, 10, 50, 100 and 200-year). The results from flood frequency analysis by Log Pearson Type III for 2, 5 and 10-year were a little higher than the results from Gumbel methods but for the other return periods (50, 100, and 200-year) Gumbel provide a higher value. Therefor the Gumbel results were used for model and the results from flood frequency analysis of 2 and 100-year return period were selected as the input to one dimensional hydraulic HEC-RAS model for simulation of water surface profiles at lower part of XD, then used the result from model simulation used for flood hazard and vulnerability, and risk analysis and produced those maps using GIS tools. The objectives of this study were: i) To analyze the flood frequency in Xe Bangfai floodplain area ii) To generate a flood risk map in Xe Bangfai floodplain using HEC-RAS model.

Materials and Methods

Study Area

Xe Bangfai river (XBFR) is the main tributaries of the Mekong river that located in central of Lao PDR. It was located in the latitude 16'40'00'N to 18'0'0' N and longitude 104'20' 0 'E to 106'30'0' E. It has a surface area 10,064 km^2 with length of the main river 360 km. Xe Bangfai bridge station is automatic runoff monitoring station (Figure1). The XBFR was originated at the Lao -Vietnam border at Boualapha district, westward to the Mekong at the border Xebangfai and Nong Bok district in Khammoune province. The catchment of Xe Bangfai covers several districts in Khammoune provinces, namely Boulapha, Gnomralat, Mahaxai, Xebangfay and Nongbok, and cover small part of a few districts in Savanhnaket, namely Xaibouly, Vilabuly and Artsaphone [16]. For the site of study focus on the lower part of XBF in Nongbok and Xe Bangfai district, Khammoune province because this area is prone to floods every year and causing damage to many villages in this area as illustrated in Figure 1.

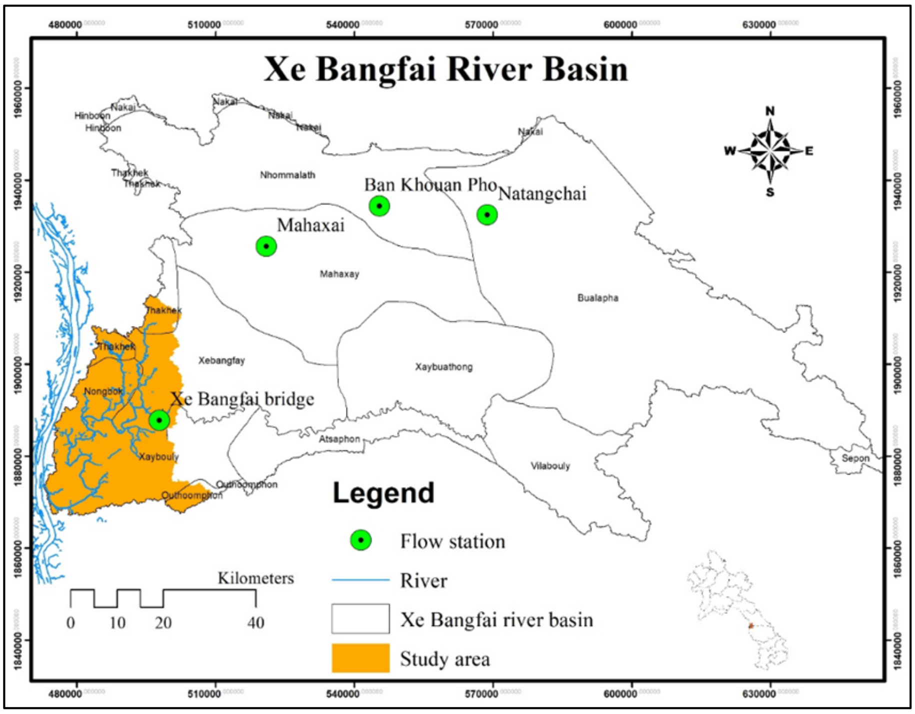


Figure 1 Location of the study area

Methods

There are three main parts of methodology for flood frequency analysis and flood risk mapping which shown in the conceptual framework (Figure 2). The details are follows as;

Data Collection

Input data was required for HEC-RAS model are daily rainfall, DEM, cross section, flow direction and stream banks. The daily rainfall, daily water level data and daily runoff data from 1994 to 2014 year were collected from Department of Meteorology and Hydrology (DMH). There are 77 cross-sections that surveyed by Department of Meteorology and Hydrology which covers floodplain area starting from Xe Bangfai bridge station to outlet and digital elevation model (DEM) with 10 x 10 m resolution was collected from Natural Resource and Environment Institute.

Flood frequency analysis in Xe Bangfai floodplain

Flood frequency analysis is important in a hydrological study and uses the frequency distribution flow data to calculate statistical information and estimate future possibility of occurrences. This information will predict the likelihood of several discharges as a function of recurrence intervals or exceeding probability. This study, flood frequency analysis of different magnitudes (2, 6 and 35 years return period) was calculated using Gumbel's distribution and the maximum observed river flow records at Xe Bangfai bridge station which has a recent period from 1994 to 2014. After calculated, the comparison peak flow in the past of observe river flow records at Xe Bangfai bridge station with flood flow of different magnitudes (2, 6 and 35 years return period) then to selected the representative of normal, medium and high peak flow to use for model in order to simulated flood event in future.

Model application for flood risk mapping in Xe Bangfai floodplain

1. **HEC-GEORAS and GIS application**

HEC- GEORAS is set of ArcGIS tools specifically designed to process geospatial data for use with the Hydrologic Engineering Center's River Analysis System (HEC-RAS). The extension allows users with limited GIS experience to create an HEC-RAS import file containing geometric data from an existing digital terrain model [17]. For this study, it was used for pre-processing geometric data (RAS GIS import file). The RAS geometric menu was used for pre-processing geometric data to create the RAS layers of XBF river, the RAS layer was created from DEM 10 x 10 m. The RAS layers were used for geometric data development. The ArcGIS was used to extract the complete geometric dataset (stream centerlines, river banks (both left and right), the flow path centerlines, cross section cut lines and storage area of XBF river.

2. **HEC-RAS application for runoff calculation**

HEC-RAS is a widely used software application that perform one-dimensional and two-dimensional hydraulic calculations for a full network of natural and construction channel, floodplain areas, etc. The HEC-RAS system contains four one dimensional river analysis components [18]:

- Steady flow water surface profile
- Unsteady flow simulation
- Sediment transport computations; - water quality analysis.

Water surface profiles ware computed from one river cross section to the next section using the energy equation (1):

$$Y_2 + Z_2 + \frac{a_2 v_2^2}{2g} = Y_2 + Z_2 + \frac{a_2 v_2^2}{2g} + h_e \qquad (1)$$

Where Y_1, Y_2 is depth of water at cross sections; Z_1, Z_2 is elevation of the main channel inverts; V_1, V_2 is average velocity; a_1, a_2 is velocity weighting coefficient; g is gravitational acceleration and h_e is energy head loss.

(1) Development and running of HEC-RAS to calculate the surface water profile

The geometric data of XBF river (RAS import file) created by HEC-GEORAS was imported in the geometric data editor in HEC-RAS as shown in Figure 2.

The modification and edition were done in this stage to improve the model. For each cross section had been modified, the measured flow and water level data were at Xe Bangfai bridge station entered using the unsteady flow data editor as upstream and downstream.

(2) Calibrated and validation

Calibration was done by adjusts the model's parameters mainly for roughness (Manning's η values). These values were adjusted to reproduce each stage hydrograph until the desired results are achieved. In general, for a free-flowing river, roughness decreases with increased water level and flow. Validation was

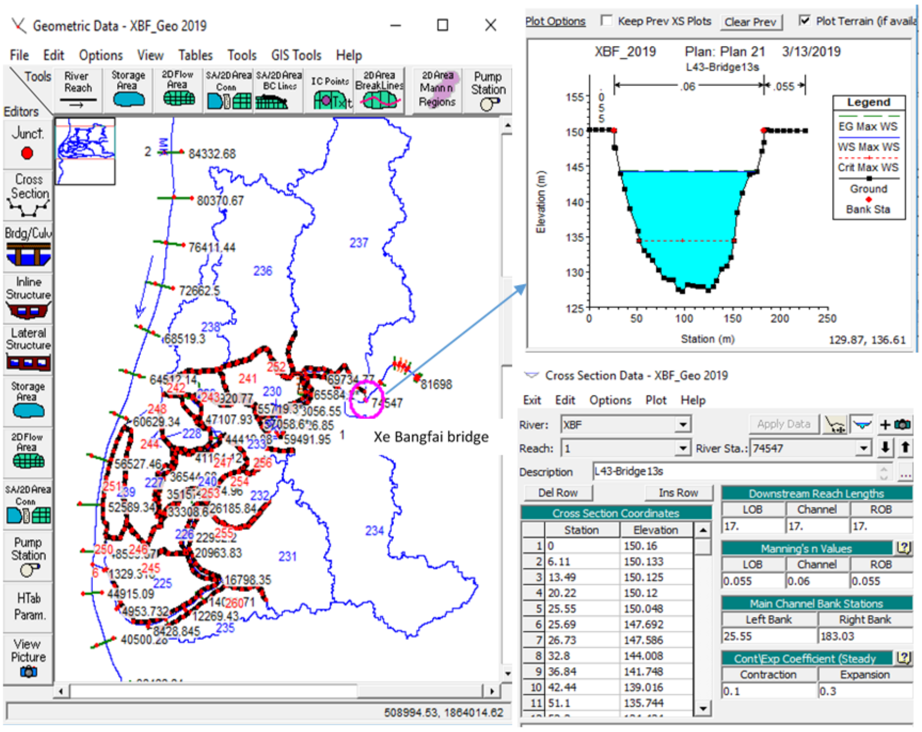


Figure 2 Model schematization of XBF model (Left) and HEC-RAS Floodplain cross section (Right)

done by using the hydrograph of the observed water level data in the year 2011 at Xe Bangfai bridge station used the daily observed water level data at Xe Bangfai at bridge station. The Coefficient of Determination (R^2) and Nash-Sutcliffe efficiency (NSE) were used for validation, to assessed the model's performance.

(3) Simulation of flood flow for 2, 6 and 35 years return periods

After the model has been calibrated, the flood flow for 2, 6 and 35 years return periods were entered in the steady flow data editor. Flood flow data and boundary condition was entered from upstream to downstream. Then running the model to calculated the water profile of XBF floodplain

(4) Post processing and flood risk mapping

Post processing is floodplain delineation base on the data contain in the HEC-RAS-GIS output file (name for the analysis, RAS GIS export file, TIN, output directory, output geodatabase, dataset name, and raster cell size). Using HEC-GEORAS functionalities, The RAS result datasets contain the cross section cut lines and bounding polygon for each water surface profile were used further in the analysis after being successfully created. Post-processing of RAS results was generated GIS layers for inundation and other parameters mapping.

Results and Discussions

Flood frequency analysis in Xe Bangfai floodplain

The results of 2, 6 and 35 years return period flood frequency analyze based on maximum peak flow recorded at Xe Bangfai bridge from year 1994-2014 (21 years) using the Gumbel's Distribution. Flood frequency shown that the peak flow for 2, 6, and 35 years return period provide a value as 3,746.57, 4,505.97 and 5,877.60 m^3/s respectively. The comparison peak flow in the past of observed river flow records and these peak flows indicated that 2 years is representative of low - normal peak flow, 6 years is representative of medium flow and 35 years is the high peak flow. Therefore, these results were used for model in order to simulate flood event in future.

Flood risk analysis and mapping in Xe Bangfai floodplain

1. **Unsteady flow simulation**

After simulating the flow in HEC-RAS model by unsteady flow analysis, the model performs the relationship between stage (water level) and flow of Xe bangfai simulated data. The result from model the stage maximum value as 145.34 meters (including mean sea elevation), the average mean sea level was 123.55 MASL, flow value as 5185.12 m^3/s, the period at max in August as present in Figure 3.

2. **Calibration and validation**

The Manning's η values were chosen for model calibration. For Manning's η values for different land use values between 0.022-0.06. The calibration of XBF floodplain was increased in the Manning's η value indicates that the water levels have increased some locally at the upstream. For validation was done by using the hydrograph of the observed data from 1/1/2011 to 31/1/2011 (1 year). The validation result show that the comparison between the simulated daily water level and the observed data is well as presented in Figure 4 and scatter plot in Figure 5.

The simulated daily water level matches the observed value for the validation period with Coefficient of Determination (R^2) value as 0.96 and Nash-Sutcliffe efficiency (NSE) value as 0.88, the performance of observed and simulated daily water level for the calibrated period was considered very good [9]. However, the daily simulation in some months was slightly underestimated and some month overestimated with water level more than 2.5 maters in some location of reached.

3. **Flood risk map for 2, 6 and 35 years return period**

After model was calibrated and validated, the flood flow imports in HEC-RAS, the simulation was done by steady flow simulation. After modelling and simulation steps, flood risk mapped using HEC-GEORAS. The results of flood risk assessment based on model simulation of observed flow in year 2011, 2, 6- and 35-years flood return period in XBF floodplain were summaries in Table 1.

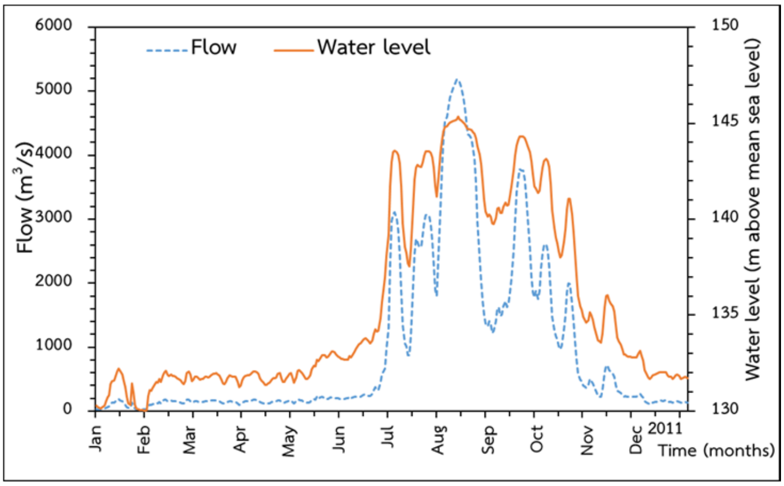


Figure 3 Relationship of stage and flow at Xe Bangfai floodplain

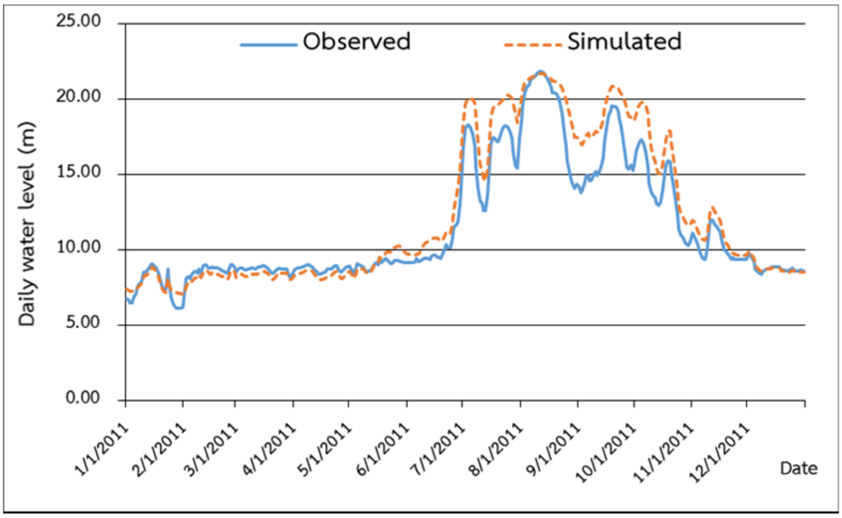


Figure 4 Comparison of measured hydrograph with HEC-RAS simulated time series for the validation period

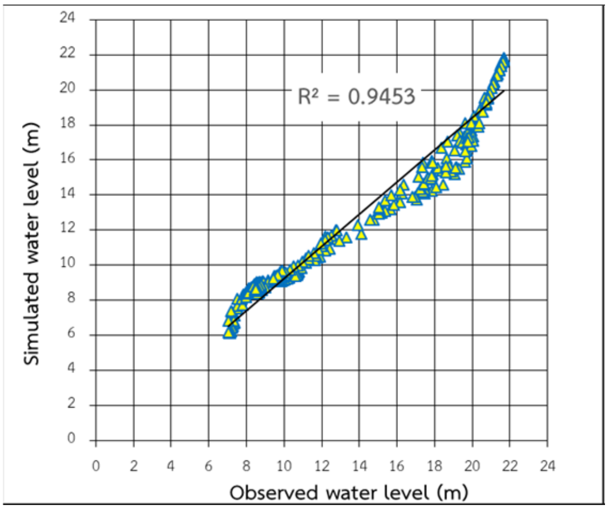
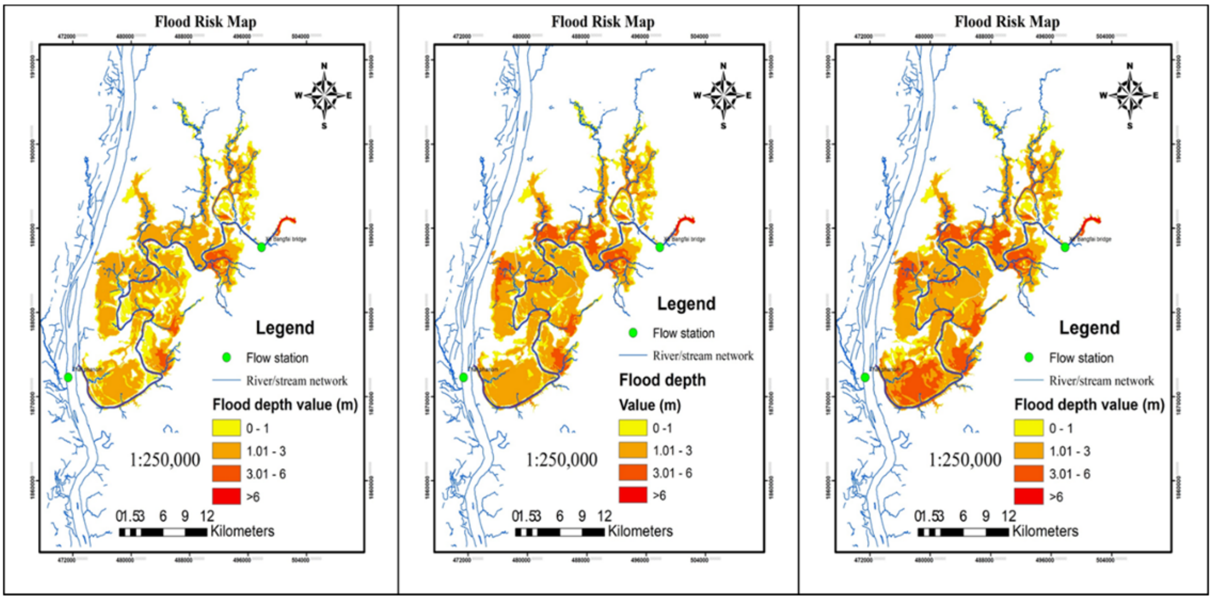


Figure 5 Scatter pots of observed and HEC-RAS simulated daily water level time series for the validation period

Table 1 Classification of flood depth and areas according to flood hazard

Flood depth range (m)	Flooded area (ha) in each return periods		
	2 Years	6 Years	35 Years
Low (0-1)	10,362	8,012	7,237
Medium (>1-3)	19,517	22,060	21,295
High (>3-6)	3,692	7,077	10,352
Very high (>6)	15,963	16,651	17,163
Total	**49,534**	**53,800**	**56,047**

From Table 1, the flood highest damage area in medium level >1-3 meter and every return period. The flooded areas at low (0-1) flood depth tend to decrease from 2 to 35 year return period due to 2 year return flood was frequent occurred with the demonstrated near the main Xe Bangfai river, a long length river with a low channel slope, and land area surrounding is very flat where can be damaged large area. In contrast, the return flood of 6 and 35 years indicated that the flood area that showed high water level (>3-6), it can be extreme damage large area because high volume of flood. It was observed that even if there were not different of flooded area in each return period but, it showed that the flooded area in 2 years return period will frequency damaged in the same area as illustrated in Figure 6.



(a) (b) (c)

Figure 6 Flood mapping area on 2 years (a), 6 years (b) and 35 years (c) return period

Figure 6 shows flood risk maps of 2, 6 and 35 years return period with effects 49,534.0, 53,800.0 and 56,047.0 hectares respectively. From map of 6, 35 years return period were indicated that the flood area that shown high water level (>3-6 m) was demonstrated near the main Xe Bangfai river. It can be extreme damage large area because high volume of flood.

Flood vulnerability areas were prepared based on the intersection of land use with flood area boundaries for each flood event simulation. The vulnerability analyzes results in Table 2 shown that 2 years return flood inundated 30,000.00, 16,567.00 and 2,889.00 hectares, respectively of crop land, forest and; and water respectively. It mostly has a high proportion of crop land especial paddy rice, inundated by 2, 6 and 35 years return flood respectively. These areas mostly covered by paddy rice where the local people rely on, it is important for further consideration for flood mitigation. The flood risk map provides information of flood risk areas include flood depth, flooded area. Thus, it can be presenting and understanding of the risk and vulnerability that can be utilize to planners and decision-makers lead to improved project planning for flood risk management.

Table 2 Classification of flood risk according to flood hazard area with vulnerable land use in 2015

Land use types	Flood Depth (m)	Flooded area in different return periods (ha)		
		2 yrs	6 yrs	35 yrs
Forest land	0-1	8,046	9,048	3,470
	1.01-3	5,332	5,380	9,717
	3.01-6	3,113	3,500	4,768
	>6	76	239	1,069
	Total	**16,567**	**18,167**	**19,024**
Crop land	0-1	17,524	19,512	6,325
	1.01-3	8,015	8,067	20,409
	3.01-6	4,255	4,833	7,042
	>6	206	228	235
	Total	**30,000**	**32,640**	**34,011**
Wetland	0-1	828	711	130
	1.01-3	765	767	971
	3.01-6	1,257	1,405	544
	>6	39	21	1,258
	Total	**2,889**	**2,904**	**2,903**
Settlements	0-1	27	32	39
	1.01-3	18	22	30
	3.01-6	8	12	8
	>6	0	1	7
	Total	**53**	**67**	**84**
Other land	0-1	12	12	4
	1.01-3	8	7	14
	3.01-6	4	4	6
	>6	1	1	0
	Total	**26**	**24**	**24**

Conclusion

This study, the flood frequency analysis for Xe Bangfai floodplain using 21 years' annual peak flow at Xe- Bangfai bridge station which was performed that the highest peak flow occurs in the period from July till early October. The 2011 flood record was assessed to have a return period of 2, 6 and 35 years, these years return period were representative of low, medium and high peak flow.

The flooded areas by 2, 6 and 35 years return flood shown as 49,534.0, 53,800.0 and 56,047.0 hectares respectively. The large vulnerable area for 2, 6 and 35 years return period on crop land were 25,456.00, 28,054.00 and 29,443.00 hectare, respectively and followed by the forest area were 17,588.00, 19,062.00 and 19,852.00 respectively. The flood risk maps, 2, 6- and 35-years' flood indicated that the flood highest damage area in medium (>1-3) and some area with the water depth greater than 6 maters in XBF floodplain. Flood vulnerability areas were almost in paddy rice area in every return periods magnitude.

Acknowledgement

I would like to express my sincere gratitude to Thailand International Cooperation Agency (TICA) for finical support for this study. My sincere thanks go to the Modeling Research and Development Division, Natural Resource Research and Environment Institute, Vientiane, Laos for providing data to successfully complete this study.

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