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Mathematical model of Maan River basin for flood mitigation in Muang Loei urban area

Sakchai Phuangjan

Faculty of Industrial Technology, Loei Rajabhat University, Loei 42000, Thailand

Abstract

This study involved hydrodynamic model of Maan River basin, and was aimed to (1) survey cross sections of Maan River for geometric data; (2) collect hydraulic data for the model; and 3) develop the hydro-dynamic model with HEC-RAS program. The model was one-dimensional with unsteady and subcritical flows. The upstream boundary condition locates at Sta. 14+416 km. (Kh.86) in Baan Ta Taan. The downstream boundary condition was located at Maan River mouth, the outlet to Loei River in Baan Kok Muang Chi. The overall reach length was 14.416 km with 64 cross sections, includes 7 bridges, 2 weirs. Hydraulic data of 5 periods, with flood waves in the river, were chosen from the hourly flow data during 2013-2016.

The model was calibrated by comparing RMSE (Root Mean Squared Error) of the calculated stage hydrographs and the observed ones at km. 03+342 station, with the Sep-2016 flow data. By trial and error method, the optimum value of Manning's n for the model was 0.042. The model was then verified with 4 flow data sets during flood wave periods. This yielded the average RMSE of 0.156 m. and the average r (correlation coefficient) of 0.893, indicating that the model was good for analyzing flows in lower Maan River.

By running steady flow simulations, it was found that the flood wave takes 3 hrs. to travel from Kh. 86 to the urban area in Baan Hae. It sets time limit for warning people and preparing for the incoming flood. The amount of flow that can cause inundation in Baan Hae and the urban area is 200 cms. It was also found that Baan Hae weir obstructs the flow and worsens the flood.

Keywords: floodplain modeling, HEC-RAS, Maan River basin

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1. Introduction

1.1 Background

In mountainous areas of the upper northeastern Thailand, most of the rivers are in Mekong basin. Seasonal floods are common, especially in low river bank areas. In relatively short-length rivers, flash-floods occur within hours, when the heavy rains accompany with high flow in the channels.

In the case of Muang Loei urban area, where Loei River is joined by its tributary, Maan River, floods are caused by both rivers, with different inundations. In 2011, there were major floods in Thailand that were caused by a strong monsoon causing high rainfall across the country and the remnants of four tropical storms [1]. That year, there were 2 flood events in Loei urban area. One in September was caused by Loei River; the other in October was caused by Maan River. Floods caused by Loei River occur in a few areas of low river banks and rarely cover the whole downtown area. On the other hand, floods caused by Maan River inundate the urban area of Muang Loei and could cause more damages to the business district. Maan River is a tributary of Loei River hence less flow. However, floods due to Maan River is less understood and predicted. General public and local governments focus on the floods caused by Loei River, for it is the main river.

The flood in October, 2011 was the most recent flood caused by Maan River. During the time, Loei River level was low, and had no inundations. The flood swept most of the urban area, causing damages to people and businesses substantially. This suggests that, despite less flow, flood inundations due to Maan River need to be taken seriously, and require more understanding. Unfortunately hydraulic and geographic data in Maan River was limited. Inadequate and untimely warning to the public was to blame for the damages that could otherwise be lessened. In such case, flood prediction in terms of time and magnitude is needed. Mathematical floodplain modeling is one tool to predict the flood. This study created a hydrodynamic model in HEC-RAS program, a worldwide program for hydrodynamic modeling. With proper calibration and verification, the model can simulate flood events and predict time and severity (water levels) of the flood with accuracy [2]. Thereby, the flood mitigation and public warning can be planned and executed properly and precisely.

* Corresponding author; e-mail: sakchph@gmail.com

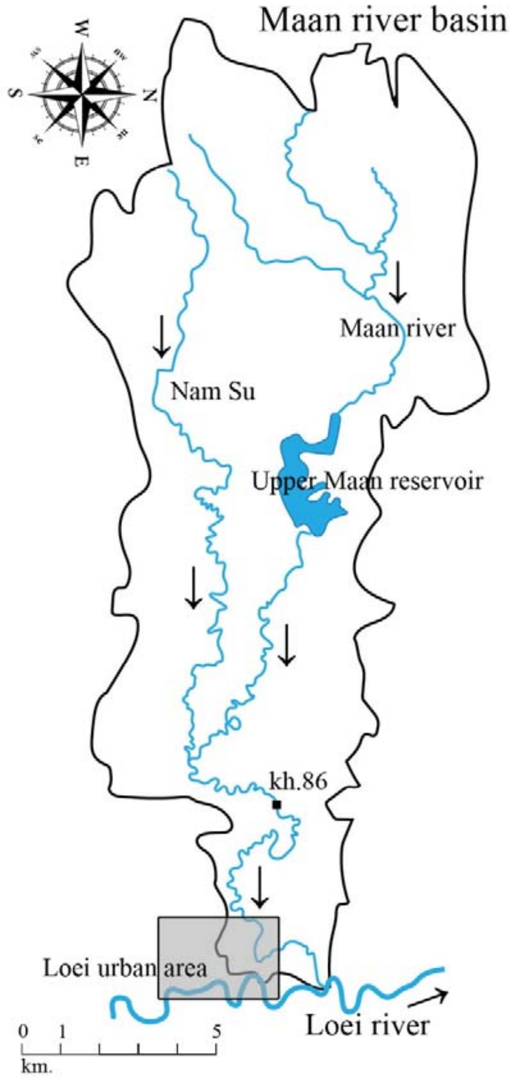


Figure 1 Maan River basin

1.2 Maan River Basin

The major river in Loei province is Loei River, flowing from Phu Luang northward to Mekong in Chiang Kan. Maan River is one of 147 tributaries of Loei River. Maan River is located in the middle of the province, and joins Loei River by slightly north of Muang Loei urban area. Maan River basin covers 189 km^2, only 4.7% of Loei River basin, as shown in Figure 1. Despite the small area, Maan River basin is one of the most important basins in the province, in terms of economic and social values. Its water has fed the entire Loei urban area since Upper Maan River reservoir was built in 1987. Maan River basin consists of three parts: Upper Maan River basin (86 km^2), Nam Su basin (55 km^2), and Lower Maan river basin (49 km^2). The model in this study was based on the last part, starting from station kh. 86, located 2 km. downstream from the Nam Su-Nam Maan junction. The lower tip of the basin narrows down to the river mouth, where Maan River joins Loei River, at Baan Kok Muang Chi. Its catchment area is only 13 km^2, so the flow comes mainly from the channel.

The lower Maan River begins from the junction between upper Maan River and Nam Su River. The river flows toward the city, reaching Ban Hae, and curves to the north to join Loei River at 78+400 km. of Loei River. It is 17 km. long from the junction to the river mouth. In the past, Lower Maan River weir, located at 07+010 km. in Baan Ta Pae, was the main reservoir for agricultural areas of Muang Loei. This part of the river is crucial for flood monitoring and warning, because there is only one gaging station, Kh. 86, located at 14+416 km. This station provides crucial inflow data for the model, so the flood can be predicted. From 04+213 km., the river flows in the urban area, starting from Baan Hae toward downtown at 03+342 km. and bends northward to the river mouth.

2. Materials and methods

The objectives of the study include (1) surveying cross-sections of Maan River for geometric data of the model; (2) collecting hydraulic data for the model; and (3) developing a hydrodynamic model of Maan River in HEC-RAS program. The model employed hydrodynamic analysis in HEC-RAS program to run floodplain modeling in the lower part of Maan River basin. HEC-RAS can analyze both steady and unsteady flows.

For unsteady flows, it uses Saint Venant's equations [3] that include two equations: the continuity equation and the momentum equation.

Continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_1 = 0 \quad (1)$$

where A is the cross-sectional area, t is the time period, Q is the flow, x is the distance along the river, and q_1 is the lateral flow per unit length.

Momentum equation

$$\frac{\partial \mathrm{Q}}{\partial \mathrm{t}} + \frac{\partial \mathrm{QV}}{\partial \mathrm{x}} + \mathrm{gA}\left(\frac{\partial \mathrm{z}}{\partial \mathrm{x}} + \mathrm{S_f}\right) = 0 \quad (2)$$

where V is the velocity, g is the gravitational acceleration, and S_f is the frictional slope.

The program uses implicit finite difference scheme to solve the one-dimensional unsteady flow equations simultaneously. This allows the information from the entire reach to influence the solution at any one point. As a result, the time step set in the program, can be significantly larger than the case of explicit scheme [4].

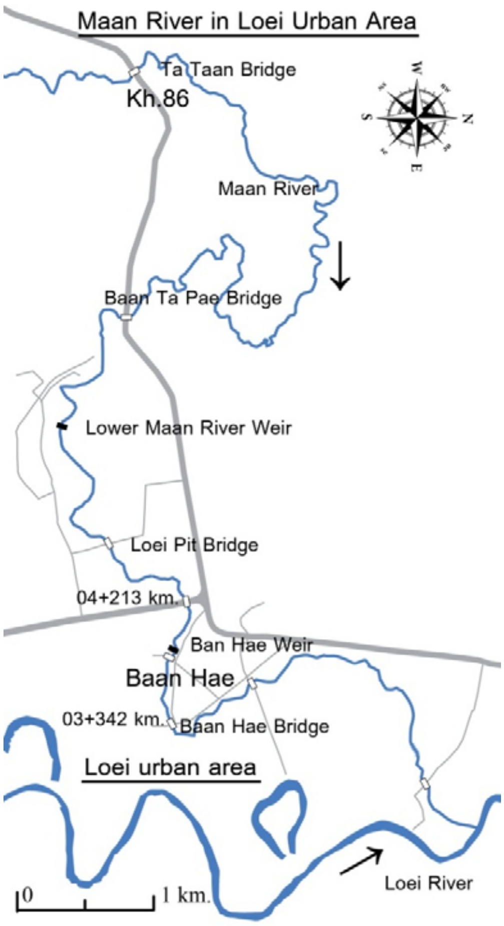


Figure 2 Lower Maan River flowing through Loei urban area

2.1 The scope of the study.

The river reach in the model covered the lower part of Maan River starting from Kh. 86 station at 14+416 km. and ended at the river mouth joining Loei River at Baan Kok Muang Chi, with the total reach length of 14.416 km. The geometric data also included hydraulic structures and inline weirs. The model employed one-dimensional, unsteady and subcritical flow analyses. The hydraulic data included selected hydrographs from 2013-2016. The model evaluation was done by calibration and verification. The accuracy of the model can be found in terms of RMSE and coefficient of correlation.

The procedure of the study includes 5 steps as shown in Figure 3. First, data collection, both geometric and hydraulic data were collected from the field and the documentations. Second, the data were prepared and transformed, so they can be put in the program properly. Third, the model was run and calibrated with a set of hydraulic data, to get the optimum parameter, in this case Manning's n, that yielded minimum errors. Forth, the model was

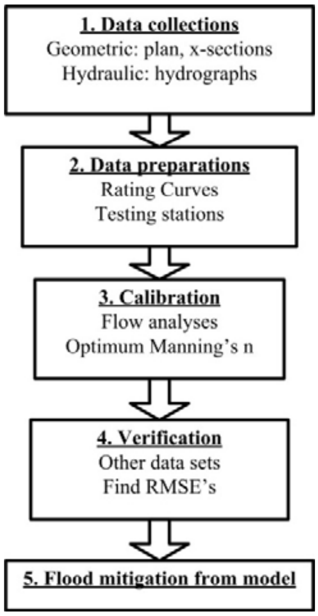


Figure 3 Procedure of creating model in the study

verified with different sets of hydraulic data, to find errors. Finally, the model was run with hypothetical situations to learn and find flood mitigations in Loei urban area caused by Maan River.

2.2 Geometric Data

The geometric data was obtained from field surveys. The river reach in the model was 14.416 m. long covering hillside forests in the upper part and urban areas in the lower part of the reach. Geometric data include the following:

1. River reach. The river reach was 14.416 m. long, ranging from Kh.86 station at 14.416 km. at Ta Taan bridge to the river mouth where it joins Loei River at 78+40 km. in Baan Kok Muang Chi.

2. Plans and cross-sections. There were 64 cross-sections with average distance of 228.84 m. between the sections. The sections are 50-100 m. wide covering left and right banks and the channel. The field surveying was done on foot, with level and measuring tape. The datum was referred at Kh. 86 and Kh. 58A stations.

3. Hydraulic structures. There were 7 bridges along the reach. The dimensions and positions of each bridge were measured from the field.

4. Weirs. There were 2 weirs: Lower Nam Maan weir at 07+100 km., and Baan Hae weir at 03+853 km. The former has been used for irrigation purposes, and the latter was a small weir and is of no obvious use.

2.3 Flow Data

Most of the flow data were obtained from Office of Water Management and Hydrology, Royal Irrigation

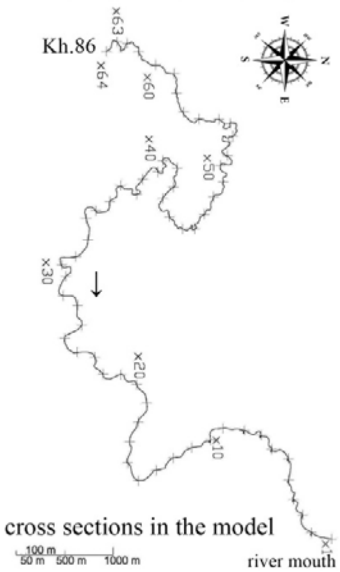


Figure 4 Positions of the cross sections in the model

Department. Some were collected from the field where there was no flow data. Since the model employed unsteady flow analyses, they required flow hydrographs of selected periods to run the models. There were 5 periods of flow selected from 2013 to 2016. Each period contained at least one flood wave, starting before the rising leg, and ended after the falling leg of the wave. Five sets of flow data from five periods were the followings:

- Jul. 2013, from Jul. 10^{th}, 2013 to Jul. 18^{th}, 2013 (181 hrs.).
- Sep. 2013, from Sep. 26^{th}, 2013 to Oct. 5^{th}, 2013 (231 hrs.)
- Oct. 2013, from Oct. 14^{th}, 2013 to Oct. 19^{th}, 2013 (135 hrs.)
- Oct. 2014, from Oct. 22^{th}, 2014 to Oct. 26^{th}, 2014 (100 hrs.)
- Sep. 2016, from Sep. 24^{th}, 2016 to Oct. 6^{th}, 2016 (277 hrs.)

Downstream Boundary Condition. The stage hydrographs at Kh. 58A station in Loei River were used as downstream boundary condition of the model. The station is close to the river mouth, and located on Baan Fag Loei bridge, upstream of the river mouth.

Upstream Boundary Condition. The inflows at Kh. 86 station were used for upstream boundary condition of the model. They were converted from stage hydrographs by rating curve at the station.

Rating curves. To convert water level to flow data of each measurement, rating curve is frequently used. Royal Irrigation Department of Thailand has rating curves ready for every gaging station in Loei. For convenience and accuracy sake, the curve representing the relation between water levels and flows could be transformed

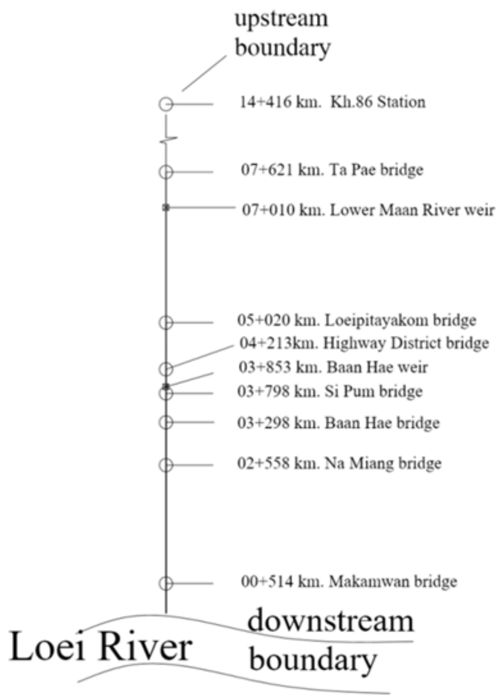


Figure 5 Schematic Model of the river reach

into an equation. The U.S. Geological Survey suggests the empirical equation [5] for discharge ratings with 3 parameters. With that, Phuangjan [6] transformed 7 rating curves in Loei River to corresponding equations by Least Square method, using the solver in Microsoft Excel to find the parameters in the equations. One of them was the rating curve equation at Kh. 86 station used in this study as follows:

$$Q = 7.706(G - 250.234)^{1.850} \qquad (3)$$

where Q is the flow rate, G is the water level.

Testing station. Along the entire reach, there was one gaging station located at the upstream boundary, namely Kh. 86. To evaluate the model by finding the errors from the calculation, there had to be another gaging station, so the observed water levels at which could be compared with the calculated ones. The testing station was located at 03+342 km., close to Baan Hae bridge where the water level is crucial for flood situation in the city. The stage hydrographs during the 5 periods of data sets were collected at the station.

Lateral inflow. The studied area is located at the downstream tip of the basin, so the catchment area covers only 13 km^2, or 6.8% of the total basin area of 189 km^2. Therefore, the lateral flow that depends on the catchment area is relatively small. It was not included in the model.

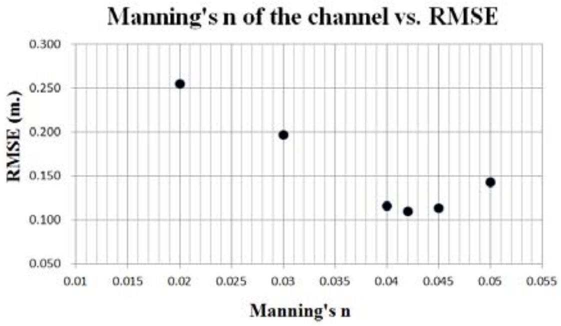


Figure 6 Finding optimal n that yields the least RMSE for the model calibration

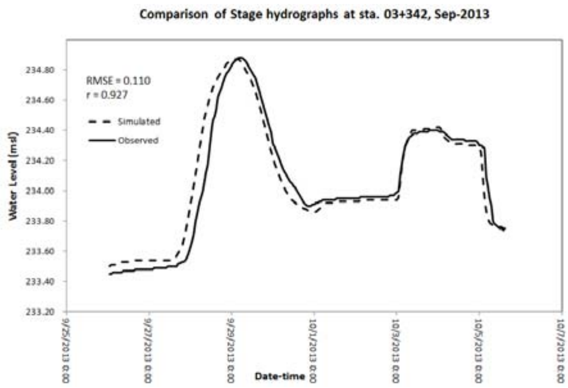


Figure 7 Comparison between the observed and simulated stage hydrographs with Sep. 2013 flow for model calibration

3. Results

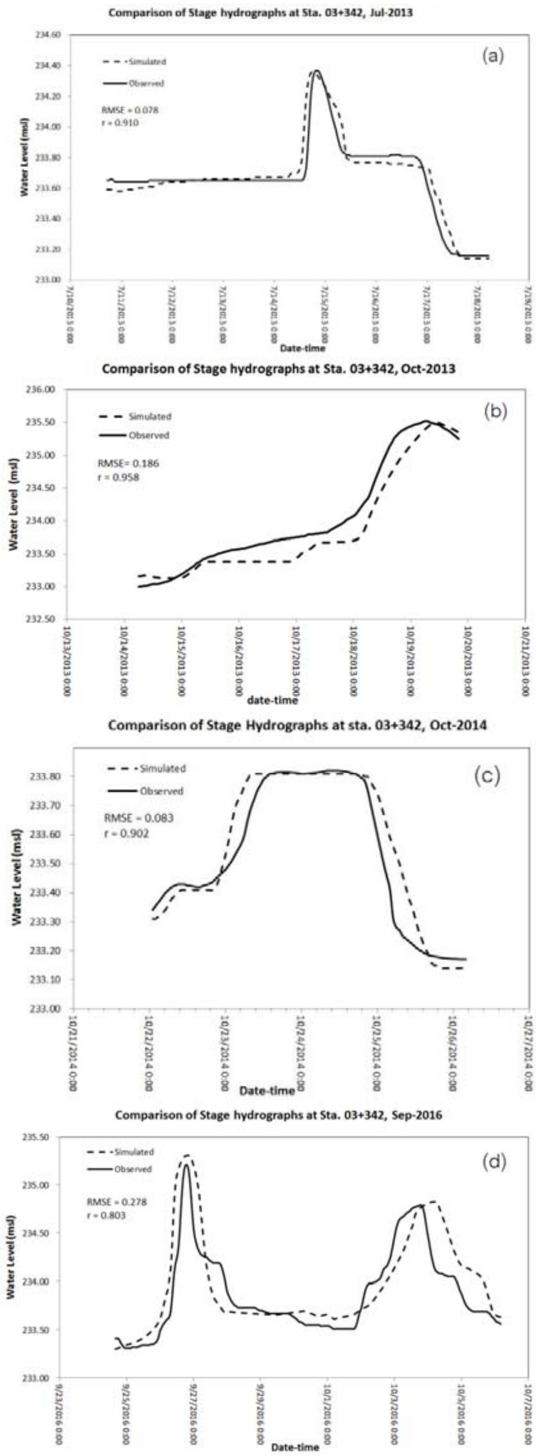
3.1 Model Calibration

When each set of data were put in the program, the model was ready to run with one-dimensional, subcritical, and unsteady flow analysis. However, to make sure that the model yielded the result with the least error, it had to be calibrated by trying different values of parameters to get the optimum result. The parameter used for calibration was Manning's n in the channel. By trial and error method, each value of n yielded different stage hydrographs at the testing station at 03+342 km. By comparing the calculated results with the observed ones, the errors can be found.

With the time-series set of result for each calculation, the error can be represented in terms of RMSE (Root Mean Squared Error). It can be found from the following equation:

$$\text{RMSE} = \sqrt{\left(\frac{\sum(g_m - g_c)^2}{n}\right)} \qquad (4)$$

where g_m is the recorded water levels, g_c is the calculated water levels, and n is the number of data in the set.



(d)

Figure 8 Comparison between the observed and simulated stage hydrographs for model verification: (a) Jul. 2013 flow; (b) Oct. 2013 flow; (c) Oct. 2014 flow; and (d) Sep. 2016 flow

Table 1 RMSE's and r's from four data sets for model verification at station 03+342

Data sets	RMSE (m)	r
Jul. 2013	0.078	0.910
Oct. 2013	0.186	0.958
Oct. 2014	0.083	0.902
Sep. 2016	0.278	0.803
average	0.156	0.893

The data set used for the model calibration was the period from Sept. 26th, 2013 to Oct. 5th, 2013. After trying 6 values of n from 0.020 – 0.050, the optimumal n that yield the least error was 0.042 with the least RMSE of 0.110 m., as shown in Figure 6.

3.2 Model Verification

After obtaining optimumal Manning's n, the model was verified by analyzing different data sets to see how accurate the model was in terms of RMSE. The less RMSE, the more accurate the model is. This study used 4 flow data sets for model verification. Each set contained at least one flood wave in the hydrograph. Figure 8 compares the observed and the simulated stage hydrographs for the four data sets at the testing station 03+342 km. In addition, the agreement between the calculated and observed result was also found in terms of the correlation coefficients (r). The RMSE's and r's for each data set were shown in Table 1.

Table 1 suggests that the RMSE's range from 0.078 to 0.278 m. at the testing station, with the average of 0.156 m. The correlation coefficients range from 0.803 to 0.958, with the average of 0.893.

By comparing the observed and simulated water level for each data set of flow with the scatter plot, as shown in Figure 9, most of the cases reveal that the simulated results are higher than the observed water levels. This is probably caused by the fact that the program created a virtual vertical wall by both ends of the floodplain in the situations that the water levels are above the bank level. The water in the model, therefore, remains between the walls instead of spreading further and could be higher than the observed ones.

3.3 Using the model for flood mitigation in Loei urban area.

Provided that the causes of the flood by the channel flow without flash flood, the model considers only the flow in the main channel. Flood inundation in October 2011 of Loei urban area reminded us that the flood due to Maan River can cause major damages to the city, even though, the flow was far less than that of Loei River. The main reason was that Maan River basin was closer to the city, hence less time for the flood wave to travel, and the channel capacity in urban area was less.

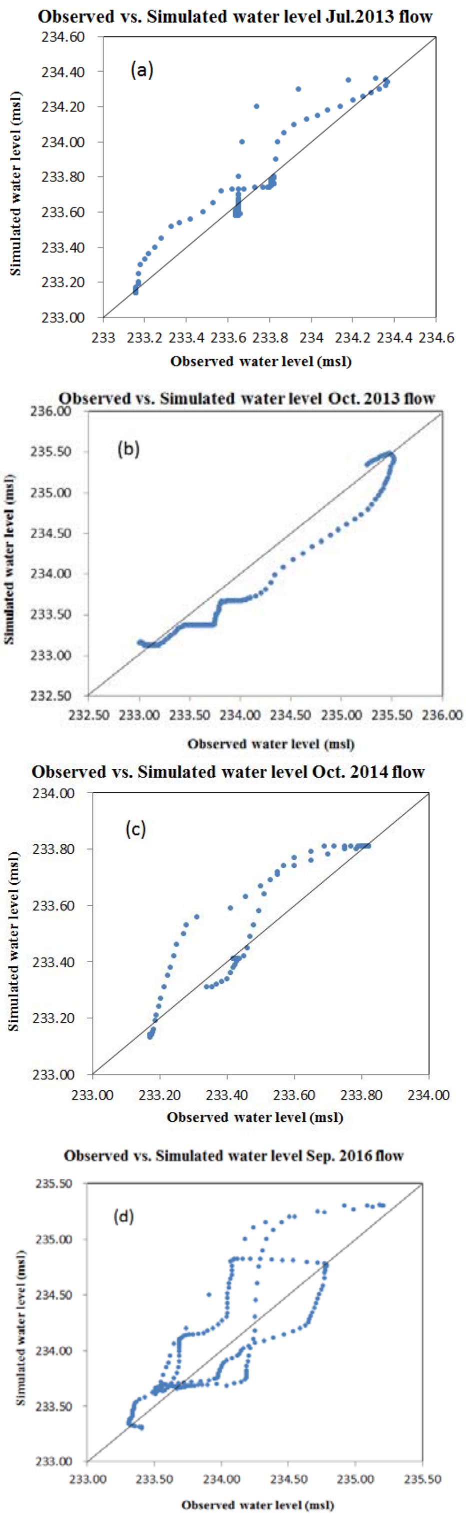


Figure 9 Scatter plots of the observed and simulated water level: (a) Jul. 2013 flow; (b) Oct. 2013 flow; (c) Oct. 2014 flow; and (d) Sep. 2016 flow

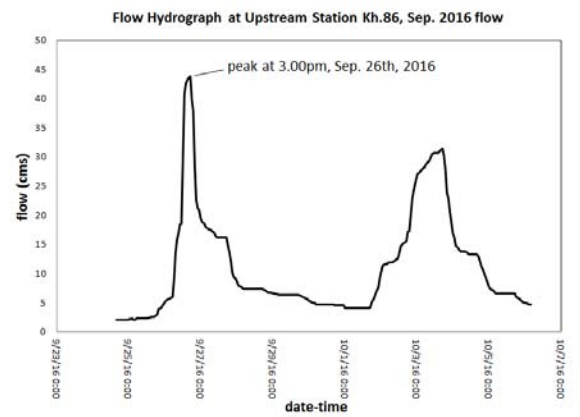


Figure 10 Flow hydrograph at Kh. 86 of Sep. 2006 flow showing peak flow at 3:00pm

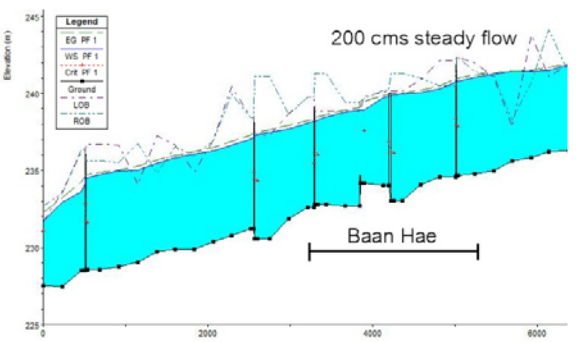


Figure 11 Water level profile of 200 cms steady flow in Baan Hae proximity

Maan River flows from the mountain area in the west toward the city downstream. It runs through sub-urban agricultural area and enters the city at Baan Hae. If the inundation occurs in Baan Hae, the flood can affect the urban area too. The hydrodynamic model created in this study helps us understand how the flood wave in Lower Maan River brings about the inundation in the city, in terms of travel time and flood causing flow.

Flood wave traveling time.

From the model verification process, take the data set of Sept. 2016 for example, the peak of the first flood wave passed Kh. 86 at 3.00pm of Sep. 26th, 2016 and passed the testing station at 6.00pm on the same day, as shown in Figure 8(d) and Figure 10.

It took the flood wave 3 hours to travel from Kh. 86 to the urban area. This information is useful for planning emergency warning and flood announcement, by using Kh. 86 as a trigger. People can be informed the approximate time of arrival at Baan Hae, so they can make plans to prepare for the incoming flood.

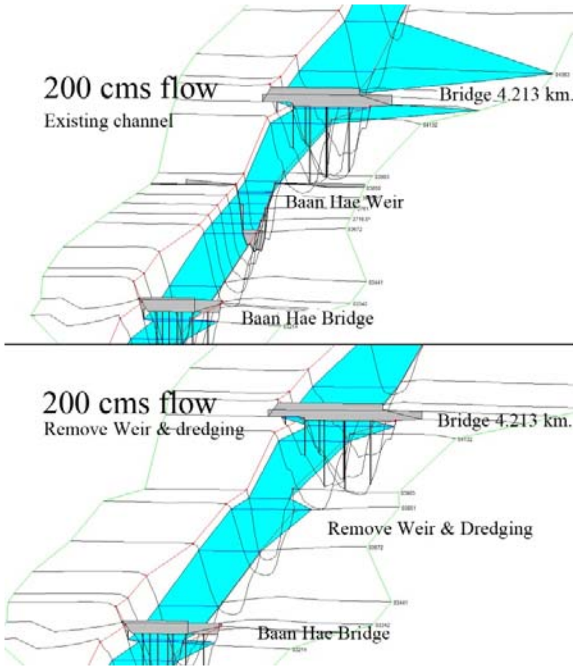


Figure 12 Comparison between the cases with Baan Hae weir vs. without the weir with dredging

Amount of flow that causes inundation.

By running steady flow simulations in the model, with various hypothetical flows from 180 – 220 cms., it was found that with the flow of 200 cms., the inundation started to occur upstream of the bridge at 04+213 km. Figure 11 also shows that, at the 200-cms steady flow the water levels in Baan Hae area were close to the river banks of both sides. This sets the alarming amount of flow at 200 cms. that can cause flood inundation in the city. When the incoming flow of 200 cms at the upstream gaging station Kh. 86 is reached, it can be predicted that the urban area is at risk of flood in 3 hours. With higher flows, the water levels can also be calculated by the model, to find the severity of the flood from the water level at Baan Hae.

Flow obstructing weir.

Currently, the weir at 03+853 km. in Baan Hae has no obvious use. It causes sedimentation upstream of the weir and induces the channel shallower. The steady flow simulations suggest that it raises the water level upstream of the weir and could make the inundation even worse. Figure 11 shows the comparison between the hypothetical 200 cms steady flow cases: with and without Baan Hae weir. In the case of weir removal and channel dredging from the weir to the 4.213 km bridge, there is no inundation caused by the 200 cms.-flow. On the other hand, the existing condition with weir, there is inundation at the bridge, and the urban area can be affected with flood.

4. Discussion

This study developed a hydrodynamic model for the lower part of Maan River basin. The model main parameter is Manning's n in the channel. It was found in the calibration process that the optimum n of Maan River for the part in the study is 0.042. Comparing with other studies of hydrodynamic model in other floodplains with similar characteristics, the values of n are close. For example, n's for the channel in Loei River from different studies were 0.040 [6], and 0.035-0.050 [7]. Considering that Maan River is a tributary of Loei River, and their physical characteristics are alike. USCE [8] suggests that the roughness coefficient of the natural streams with clean, winding channels, some weeds and stones may range from 0.030 – 0.050. For other rivers in the near areas, the Manning's n of hydrodynamic models are also close, such as, Nan River (0.035) [9], Lao River (0.035) [10].

The accuracy of the model was evaluated in terms of RMSE that suggested errors. For this model, RMSE's range from 0.078 to 0.278 m. with the average of 0.156 m. There are several causes of the errors [11], gauge reading error, distances between cross sections, hydraulic structures close to the gaging stations, effects from nearby tributaries, and looped rating curves. Comparing with RMSE's from other studies, such as Nan River [9] 0.35-0.87 m., Loei River [7] 0.204-0.676 m., the RMSE for this model is relatively low, possibly due to shorter reach length and less hydraulic structures.

5. Recommendations

For reduction of flood losses due to Maan River, a proper and precise flood prediction and warning is required. The flood causing flow of 200 cms at Kh. 86 station and the flood wave travel time of 3 hrs. should be used as the alarming sign for flood announcement to the public.

There is a small weir in Baan Hae at 03+853 km. This weir has no practical use either in dry or rainy season. Instead, it can make the flood worse by raising the water surface level upstream of the weir and causing more damages. It is recommended that the weir should be removed.

Acknowledgements

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