Flood Inundation Mapping and Hazard Assessment for Mitigation Analysis of Local Adaption Measures in Upper Ping River Basin, Thailand

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ABSTRACT

Annual monsoon flooding phenomena have caused disastrous impacts on the Upper Ping River basin and its inhabitants over the years. The existing administration set-up for flood mitigation and adaptation measures lacks effective utilization of locally available resources for complete flood protection. This study addressed this gap by flood hazard assessment at a lower administration scale (sub-district level) and performance evaluation of local adaptation measures was performed. 1D and 2D hydrodynamic models were developed and calibrated against observed discharge and water level (1D) and flood extent (2D), respectively. Flood inundation and hazard maps were reproduced and categorized into different classes based on defined critical depths for 2, 5, 10, 25, 50 and 100 years return periods. A maximum flood inundated area of 996.9 km^2 (3.94% of total basin area) was simulated in a 100-year return period. The flood hazard results represent that the largest flooded area categorized under "high hazard", followed by "very high hazard" and "low hazard" categories, and least flooded area was classified under "medium hazard" category. The current administration set-up for flood adaptation and mitigation needs to update based on an integrated flood management approach to improve its effectiveness for future flood protection.

Keywords: Flood hazard; Mitigation; Upper Ping River Basin; Adaptation; Flood inundation

Introduction

Annual pluvial and fluvial floods occurred during monsoon period in Thailand leads to disastrous impacts on people, their properties, government and commercial infrastructure, and socio-economic activities (Gale and Saunders 2013; Jular 2017). Besides these impacts, the floods severely disturbed daily routine life of local people in rural and urban areas at a larger scale. Generally, the flooding phenomena occurs in this region because of heavy monsoon rainfalls, climate change impacts, conventional flood control and management strategies and resources, topographical characteristics of floodplain areas and low level of education and technical training of local residents about flood disaster preparedness (Haraguchi and Lall 2015). Considering local structural and non-structural flood management resources, there is need to improve local flood control and management framework based on available resources in order to improve its effectiveness with the help of combined effort of all available resources.

Upper Ping River basin, a sub-region of Chao Phraya basin located in north of Thailand is home to about ~11.5 million population, rice dominated region with a high economic growth rate. Large fraction of population (~90%) in the basin lives in rural areas and exposed to river flooding due to storage of flood water in rice fields (UN 2003; Reda et al. 2012; Komsai et al. 2016). The flooding in Ping basin is associated to heavy monsoon rainfall, tropical storms, typhoons, and land-use changes (Wood and Ziegler 2008; Gale and Saunders 2013; Komsai et al. 2016; Takata and Hanasaki 2020). Available literature on climate change assessment in the basin though very limited, reports significant increase in temperature extremes and insignificant decrease in mean and extreme precipitation in the basin (Sharma and Babel 2013; Masud et al. 2016; Saengsawang et al. 2017). Several other studies on floods highlight the occurrence of extreme events in past in 1994, 1995, 1996, 2001, 2003, 2005, and 2011 (Wood and Ziegler 2008; Gale and Saunders 2013; Komsai et al. 2016). For example, the 2011 flood in Thailand caused heavy damage to agriculture, transport, fishery, tourism and industry. The overall economic losses in all sectors amount to around $200 million (Taesombat and Sriwongsitanon 2010). Such huge losses necessitate evaluation of the hazard potential to flood depth and spatial extent.

Flood hazard potential can be mapped in multiple ways such as by conducting field surveys for historical flood investigations or using remotely sensed imagery, employing hydrological and hydrodynamic models, or both (Shehata and Mizunaga 2018). However hydrodynamic modeling approach is more promising, it uses terrain data to simulate spatiotemporal variations of depth of flood water (hazard potential) (Yalcin 2020). Hydrodynamic modeling can be one-dimensional (1D) or two dimensional (2D) (Abdessamed and Abderrazak 2019; Mahmood et al. 2019; Nastiti et al. 2018; Masood and Takeuchi 2012). One dimensional is most commonly used for flood hazard mapping however possess one major limitation that it calculates spatial extent of the flood water between two cross-sections using linear interpolation that introduces uncertainty in the interpolated maps (De Kok and Grossmann 2010; Sarhadi et al. 2016; Yin et al. 2013; Zhang et al. 2021). Two dimensional models have capability to overcome this problem using sophisticated numerical methods such as finite difference and finite element. They can calculate flood depth, spatial extent and velocity for each node and time step (Bates and De Roo 2000; Mani et al. 2014; Patel et al. 2017; Farooq et al. 2019).

Flood adaptation and mitigation measures are normally applied under different administration scales (e.g., National Government Level, Local Government Level, Local Community Level) in Thailand and mostly they only work within their jurisdiction. This conventional flood control and management set-up are not effectively working for potential flood risk reduction over the vulnerable floodplain areas, as mostly, one administration department or stakeholder completes his assigned task only, due to which the flood risk is transferred or redistributed to neighboring regions or lower floodplain areas (Lebel et al. 2011; Manuta et al. 2006; Lebel and Sinh 2009; Nikitina 2007). Considering this situation, there is a need to re-think about flood control and management strategies that should cover this deficiency and produce combined effect of all resources for potential flood risk reduction over the region. To cover this gap, this study developed and applied 1D-2D hydrodynamic models for flood inundation mapping and hazard assessment for evaluation of available mitigation options in Upper Ping River basin.

Synthesis of the literature available on flood hazard mapping and evaluation of mitigation options in Ping River basin reveals a major drawback. The scope of almost all the studies was limited to assess flood characteristics using simple rainfall-runoff and 1D hydrodynamic models (e.g., Wood and Ziegler 2008; Mapiam and Sriwongsitanon 2009; Sriwongsitanon 2010; Boonrawd and Jothityangkoon 2015; Komsai et al. 2016) and no study has yet been conducted for flood hazard mapping at sub-district scale for improvement in potential of locally available mitigation options. The authors argue that “integrated flood management framework” is the absolute omission of current flood adaptation and mitigation application system that can mislead future flood mitigation planning and limit the efficiency of flood protection system. This is actually happening in the basin during past one decade and bringing public concerns about the performance of the existing protection measures (Jarungrattanapong and Manasboonphempool 2011). Since integrated flood management approach has potential to boost the current flood protection system and its impacts would be beneficial for local residents for future floods.

Considering its importance this study evaluates the flood hazard potential at sub-district level in Upper Ping River basin using 1D and 2D hydrodynamic models for mitigation assessment of local available flood mitigation resources and recommendations for these resources for improvement in future floods. The paper is divided into five sections; section 1 details characteristics of the Upper Ping River basin; section 2 comprehends materials and methods; section 3 describes results and discussion parts, and section 4 includes conclusions.

Study area and data description

The Ping river is one of the main tributaries among four rivers of Chao Phraya river that originates from Chiang Dao district in the north of Thailand, flows through the central and lower region of Thailand before discharging into the Gulf of Thailand. The Upper Ping River basin is located between Wang and Salween river basin of Myanmar (Jothityangkoon et al. 2013). The Basin covers a catchment area of 25300 km^2 with several mountain ranges in Chiang Mai and Lamphun provinces (Figure 1). The Ping river passes from north to south in the center of Chiang Mai city, the most popular tourist place in the northern region of Thailand. The Bhumipol Dam that is constructed in Tak province, divides the upper and lower ping river basin, has a maximum storage capacity of 13462 million m^3. The basin generates an average annual runoff of 6815 million m^3 (Mapiam and Sriwongsitanon 2009) with average annual rainfall and potential evaporation of 1174mm and 1661mm. Most of the basin’s climate is tropical and has a long rainy season (May – October), and 90% of the annual rainfall occurs during rainy season. The weather of the study basin is influenced by the Southwest and Northeast monsoon. The topography of the basin is based on steep and complex mountainous regions with elevation ranges from 224m to 2575m. The highest proportion of land-use consists of forest (70%), followed by urban (12%), and only 6% area is covered under plantation. Multiple flood episodes have been observed over the last two decades during the monsoon period in the Upper ping basin including 1994, 1995, 2001, 2005, 2009, 2010, and 2011 with the highest flood level of 4.94m in 2011 year at P.1 station (Boonrawd and Jothityangkoon 2015).

The basin has a well-distributed network of rain gauges (90) and streamflow stations (44), but many of them are not functional or do not have sufficient data, and only the meteorological and hydrological data from 17 rain gauges and 2 flow gauges (respectively) have used for the flood hazard assessment and recommendations of appropriate flood mitigation and adaption measures at this region that could be practically implementable considering locally available resources, as represented in Figure 1. The detailed description of meteorological and hydrological stations is mentioned in Table 1 and Table 2. The digital elevation model (DEM), which is used to prepare for floodplain bathymetry for the 2D-hydrodynamic model, is downloaded from https://earthexplorer.usgs.gov/ with a resolution of 30m × 30m. Due to the larger floodplain area and to optimize computational time, the 30m dem resolution was resampled into 85m for the preparation of floodplain bathymetry.

[Figure 1.]

[Table 1.]

[Table 2.]

Methods

Methodological Framework

The methodology of the study based on the development of hydrological and hydrodynamic models, forcing of input data, followed by simulations, calibration and validation, and analysis of post-simulation flood results and its evaluation for further scenarios. The methodological framework consists of three sections (a) 1D-2D coupled model development, (b) 1D and 2D model calibration and validation, and (c) flood hazard assessment and mitigation measures. Figure 2 represents the step-by-step methodological framework adopted in this study.

[Figure 2.]

1D Hydrodynamic Model Set-up

The 1D hydrodynamic model (MIKE 11) applied in this study, which has six editors are mutually interlinked with each other and used for river model development by defining sub-basins, cross-sections, boundary conditions, network layout, hydrodynamic parameters and simulation specifications (Tansar et al. 2020). All editors of the MIKE 11 model are dynamically interlinked and controlled by the simulation editor. Also, this editor used to define simulation specifications including simulation model, simulation mode, runoff and hotstart files, simulation time-period and time-step, and saving time-step. The river network is defined in network editor. In upper ping river basin, the ping river is the main tributary that starts from Doi Thuai in Chiang Dao district, passes from Chaing Mai, Lamphun and Tak provinces and inflowed to Bhumipol Dam. The main rivers including Ping river, Mae Nam Taeng, Mae Nam Rim, Mae Nam NGAT, Mae Nam Kuang, Mae Wang, Mae Klang, Mae Nam Tha and Mae Li's have defined with their total river lengths of 283 km, 155 km, 56 km, 82 km, 115 km, 116 km, 46 km, 78 km and 212 km, respectively. The river geometry is defined as X-Z coordinates (from left bank) in the cross-section editor and the mean distance between two adjacent cross-sections was 2 km. The 19 sub-basins with corresponding rainfall stations (17), and rainfall and evaporation data are defined in runoff editor for runoff generation. The simulated runoff of each sub-basin is laterally distributed along the corresponding river in network editor, where the runoff and network editors are dynamically interlinked by defining sub-basins along with corresponding rivers with upstream and downstream boundaries. The upstream river boundaries as discharge are defined at "0" chainage and only one downstream boundary as water level is defined at the end of Ping river (P.73 station, Figure 1). The hydrodynamic parameters including water depth, discharge, bed resistance, and output parameters with their initial conditions are defined in the hydrodynamic editor. The bed resistance is the main parameter that is defined as local (horizontal and vertical) and global roughness coefficient (Manning' n) for discharge and water level calibration.

2D Hydrodynamic Model Set-up

The floodplain boundary is defined in MIKE 21 model as rectangular bathymetry with 85 m × 85 m resolution, considering the river network and 100-year observed flood extent. With this resolution, the 2D hydrodynamic model simulates discharge and water level at every 85 m distance. Apart from bathymetry as the main input parameter, several other parameters including boundaries, simulation specifications, initial surface elevation, flood and dry depths, resistance and eddy viscosity and infiltration are required for flood inundation simulation. Only the flood plain resistance as roughness coefficient (n) of 0.04 was used for flood extent calibration and remaining parameters were considered as default. The simulation time step and results saving time step were 5 seconds and 12 hours, respectively.

1D-2D Coupled Modeling Package

The calibrated 1D-hydrodynamic model (MIKE 11) and 2D-hydrodynamic model (MIKE 21) are dynamically coupled through MIKE Flood to reproduce flood inundation results. In order to capture flood inundations in MIKE Flood, the weir equation is defined at the lateral links between both river banks (left and right) and floodplain, and the flood volume is overflowed to the floodplain through these links when the water level rises over the bank elevation in the 1D-hydrodynamic model. The flood extent and depth are based on the magnitude of flooded volume, overflow location and topography of floodplain located around both river banks. In addition, the overflow can travel from river to floodplain and vice versa in MIKE Flood based on the topographical characteristics of the river banks, floodplain and the magnitude of flooded volume.

The detailed theoretical background of 1D-hydrodynamic model (MIKE 11), 2D-hydrodynamic model (MIKE 21) and coupling package (MIKE Flood) are explained in Tansar et al., 2020.

Flood Frequency Analysis

The Gumbel probability distribution was applied on meteorological, hydrological and water level data of past 30 years to find the extreme values for different return periods. The gumble distribution was selected among other probability distributions (e.g. normal, log-normal, Pearson type-III, log-

Pearson Type-III and extreme value Type I (EV I) because of its better performance and it has been extensively applied and reported over the last few years in different published case studies of Thailand (Tingsanchali and Karim 2010; Shrestha and Lohpaisankrit 2017; Tansar et al. 2020)

Gumbel Distribution

The cumulative distribution function (cdf) of the of Gumbel distribution (maximum) is defined as represented in Eq. (1).

$$\boldsymbol{F(x) = exp[-\exp(-y)] = e^{-e^{-y}}} \; ...(\mathbf{1})$$

Where function $\boldsymbol{F(x)}$ denotes the probability distribution function of random variable $\boldsymbol{x}$ and y represents the reduced variable.

Eq. (2) denotes the relation between probability of exceedance of excluded events and return period (T).

$$\boldsymbol{F_1\,(x) = 1 - F(x) = \frac{1}{T}} ...(\mathbf{2})$$

Eq. (3) is established by following Eq. (1) and (2).

$$\boldsymbol{\frac{1}{T} = 1 - e^{-e^{-y}}} ...(\mathbf{3})$$

The reduced variable $\boldsymbol{y}$ is calculated by using Eq. (4).

$$\boldsymbol{y = -ln\left\{ln\left[\frac{T}{(T-1)}\right]\right\}} ...(\mathbf{4})$$

The statistical variate is computed with Eq. (5).

$$\boldsymbol{y = \overline{y_n} + K.\sigma_n} \; ...(\mathbf{5})$$

Eq. (6) is applied to calculate frequency factor (K) in which $\overline{y_n}$ is a Gumbel's reduced mean variable and $\boldsymbol{\sigma_n}$ is the standard deviation.

$$K = \frac{y - \overline{y_n}}{\sigma_n} = \frac{\left(-ln\left\{ln\left[\frac{T}{(T-1)}\right]\right\}\right) - \overline{y_n}}{\sigma_n} \ldots (6)$$

More technical details of Gumbel distribution method and its application can be found in Onen and Bagatur 2017.

Design Peak Hydrograph

Design peak hydrographs of meteorological and hydrological data of different return periods are derived based on the annual maximum values estimated by frequency analysis of past 30 years of measurements. The design peak flood hydrographs of different return periods (2, 5, 10, 25, 50, and 100-year) are developed based on non-dimensional hydrographs (Tingsanchali and Karim 2010). The 2011 flood year is selected for the development of designed hydrograph. A single annual maximum value is provided by frequency analysis of selected flood year that is used to generate the continuous time series of the entire flood year. The time series of selected flood year is divided by maximum observed value to normalize the non-dimensional hydrograph. Following this procedure, the peak of the non-dimensional value should be equal to unity. The time series of non-dimensional hydrograph is multiplied with the annual maximum value to generate the designed peak flood hydrograph. The same procedure was repeated for each return period for the hydrographs' construction of all stations and boundary conditions (Brunner et al. 2016; Mediero et al. 2010).

Categorization of Flood hazard Assessment

The flood hazard has been classified into different categories for spatial flood risk assessment, and this information leads to in-depth understanding of severity of flood problems that can be avoided in future by following proper flood mitigation and adaptation measures (Shrestha and Lohpaisankrit 2017). Multiple factors such as flood depth, duration of flood and flood velocity are considered for estimation of flood hazard assessment during flood study. These parameters are considered based on the topographical characteristics of study area, especially of floodplain regions and also flood conditions. The present study only consider flood depth for classification of flood hazard as the topography of flooding region is quite flat and flood wave velocity can be negligible.

The detailed classification of flood hazard categories along with their indexes and description has been presented in Table 3. The critical flood depths 0.8, 1.0 and 3.5m that applied for classification of flood hazard assessment established based on the floor level of local buildings, neighboring commercial infrastructure, and also elevation of single-storey building (Tingsanchali and Karim 2005, 2010). The present study adapted liner scale among linear, geometric, and exponential scales for hazard classification as the linear scale has performed the best among others and also has been recommended by previous published research studies. Eq. (6) is used to calculate hazard factor $\boldsymbol{H_F}$.

$$\boldsymbol{H_F}(\mathbf{i}) = \left(\sum_{j=1}^{N_D} \boldsymbol{A}(\boldsymbol{i},\boldsymbol{j})\boldsymbol{H_I}(\boldsymbol{j})\right) / \sum_{j=1}^{N_D} \boldsymbol{A}(\boldsymbol{i},\boldsymbol{j}) \ldots(7)$$

Where, i, j, N_D and $\boldsymbol{H_I}$ represent land unit identification number, depth category, total number of depth categories and hazard index, respectively, whereas $\boldsymbol{A}(\boldsymbol{i},\boldsymbol{j})$ belongs to land unit i under depth category j.

[Table 3.]

Model Performance Evaluation

The study considers some of the most commonly used statistical parameters for the model's performance evaluation. The hydrological model performance for discharge simulation was evaluated using the Coefficient of Correlation (R), Nash Sutcliffe Efficiency (NSE), and Root Mean Square Error (RMSE), and hydraulic model performance for the water level simulation was evaluated using the Coefficient of Correlation (R), Relative Peak Error (RPE) and Volume Bias (VB). Further detail on these statistics is reported in Shrestha and Lohpaisankrit 2017; Leta et al. 2018.

Results and Discussion

Calibration of 1D-hydrodynamic model

Discharge and water level in 1D-hydrodynamic model were calibrated and validated for the period of 4 years (2006-2009) and 2 years (2011-2012), respectively. The discharge and water level stations located along main river (Ping river) are represented in Figure 1. The calibration parameters presented in Table 4 tuned to improve hydrological model performance, and global and local manning's 'n' values were adjusted for improvement of model's hydraulic performance. The global and local manning's 'n' values are differentiated based on their "effecting scale", the adjustment of global value has uniform effect on all river network~~,~~ however, the local manning's 'n' values are defined for adjustment of flow by changing the roughness of specific rivers or section of river. The manning coefficient was adjusted between 0.29-0.50 during model calibration and validation. Table 5 represents three statistical parameters (R, NSE, RMSE) for performance evaluation of 1D hydrodynamic model for discharge simulation, and model' performance was reasonably acceptable for calibration and validation at both stations, P.1 and P.67. The discharge calibration and validation results are shown in Figures 3a and 3b, and 4a and 4b, respectively. Generally, the simulated discharge hydrograph is well-matched with observations at both locations (P.1 and P.67) for low and high periods during calibration, however, simulated discharge peak was relatively underestimated for 2006 and 2009 years at both locations. Similar results pattern was noticed at both locations during discharge validation. In case of water level calibration and validation results, the model performance was relatively better at P.1 station compared to P.67, as statistical parameters can be seen in Table 6. It might be because P.67 station is located at just downstream of Mae Nam NGAT channel that starts at downstream of NGAT Dam, so the simulated water level at P.67 station may not fully capture the controlled flow's pattern as it was in real condition. However, the model performance is still quite acceptable and reliable for flood inundation modeling at a larger scale considering limited data availability with coarser river geometry. The water level calibration and validation results have been represented in Figures 3c and 3d, and 4c, and 4d~~,~~ respectively. Multiple sources of uncertainties that exist and affect the accuracy of river modeling results have been previously discussed for particularly in this region by the author in Tansar et al., 2020.

[Figure 3.]

[Figure 4.]

[Table 4.]

[Table 5.]

[Table 6.]

Calibration of 2D-hydrodynamic model

The 2D-hydrodynamic calibration was performed for the flood year 2011 by using MIKE Flood. The 1D-2D hydrodynamic models were simulated for a period of 13 days (September 27, 2011 to October 10, 2011) to reproduce flood inundation maps. The remotely sensed observed flood map of 2011 year obtained from the Geo-Informatics and Space Technology Development Agency (GISTDA), Thailand and compared with simulated inundation extent, as shown in Figure 5. The area of observed and simulated flood inundation extent was 550.6 km^2 and 489.6 km^2, respectively. Generally, the observed and simulated flood inundation extent reasonably matched well throughout the inundated area. The flood inundations produced along the river network including Ping river, Mae Nam NGAT, Mae Nam Taeng, Mae Wang, Mae Klang and Mae Nam Tha have represented satisfactory better performance against the observed flood map. However, there are some differences noticed between the observed and simulated extent around the lower section of Mae Nam Kuang river and the observed flood extent relatively has a larger inundation area compared to the simulated. It is reasonable to explain that the area along Mae Nam Kuang river in Ban Thi and Mueang Lamphun districts also have a small network of small streams, located along the Mae Nam Tha river that transferred the monsoon flow from the north-eastern part of this region to the south-western areas. Occasionally, these streams also flooded during the monsoon period and it might be possible that the simulated flood extent which does not cover by the overflow of Mae Nam Tha river occurred because of these local streams. In addition, some cross-sections of the rivers were taken from DEM (30m resolution) that could also lead to produce uncertainty in flood inundation results. During this calibration process, the flood depth could not be calibrated in the floodplain because of the unavailability of flood depth measurements. The average flood depth of all floodplain was 1.86m.

[Figure 5.]

Flood inundation mapping

The flood inundation maps of return period 2, 5, 10, 25, 50 and 100 years are analyzed to compare spatial distribution of flood extent and depth in different districts located in upper ping river basin, as represented in Figure 6. The total flooded area against return period 2, 5, 10, 25, 50 and 100 years are 601.8 km^2, 743.0 km^2, 811.4 km^2, 878.3 km^2, 935.6 km^2 and 996.9 km^2 (3.94% of total basin area), respectively, as represented in Table 7. Based on flood inundation results, some plain areas are inundated along with the Ping, Mae Nam NGAT and Mae Nam Taeng rivers in upstream districts (Chaing Dao, Phrao, Mae Taeng and Mae Rim) for the above-mentioned return periods and the flood extent did not substantially expand during simulation of higher return periods (25, 50, 100 years), but the significant increase in flood depth was observed. It happened because the topography of the neighboring areas around the river is plain and surrounded by mountains. The major flood inundations took place in central part of upper ping river basin, and flood extent and depth also significantly increased during higher return periods. The Ping and Mae Nam Kuang rivers and some local streams located in central region overflowed and caused flooding in nine districts (Mae Rim, San Sai, Hang Dong, San Pa Tong, Mueang Lamphun, Saraphi, Ban Thi, San Kamphaeng), including in Chiang Mai district which is a major tourist place in northern part of Thailand. The Ping river passes at the center of Chaing Mae district and the community and local tourist spots are highly vulnerable to flood risk during peak monsoon period~~,~~ especially, when the upstream areas of upper ping basin receive continuous rainfall events followed by local rainfall events in central regions. In such situation, the capacity of Ping river is unable to hold the flood volume within the embankments and the neighboring areas are inundated. In case of lower part, the substantial increase in flood extent and depth was observed from lower to higher return periods. Approximately, the river Mai Li's was not flooded in lower return periods (2 & 5 years) in Ban Hong and Li district and inundations made in neighboring areas with about 1m depth during higher return periods. The famous bigger Doi Tao lake is located in Hot and Doi Tao districts, in the lower region of upper ping river basin. The flood volume that passed from central region to lower region stored in Doi Tao lake with higher flood extent and depth (more than 4.5m) and this area is almost less populated and not as much of susceptible to economic losses because of flooding.

[Figure 6.]

Flood hazard assessment

The flood hazard categories are classified based on criteria of the critical depths, as introduced by Tingsanchali and Karim 2010, and a detailed description of flood hazards has been described in Table 3. The flooded area of 2, 5, 10, 25, 50 and 100 years return periods are categorized under different flood hazard levels in Table 7. The classification of flood results represents that the overall major flood extent occurred under the "high hazard" category during all return periods, followed by "very high hazard" and "low hazard" categories, and the least flooded area was classed under "medium hazard" category. Besides the "very high hazard" category, the flood extent of other categories was not significantly changed during all return periods, however, the major increase in the flood extent area of "very high hazard" category observed from lower return period (2-year) towards higher return period (100-year). During a 100-year return period, about 1.74 % (439.8 km^2), 1.51% (382.9 km^2), 0.54 % (137.6 km^2) and 0.14 % (36.6 km^2) of the total flooded area are classified under very high hazard, high hazard, low hazard, and medium hazard category, respectively. Based on the flood hazard description in Table 3 and flood hazard results, most of the local community and property existed in flood inundated areas are highly vulnerable to flood damages during all return periods, and following by the inundated areas that can have severe flood damages during higher return periods floods, because the flooding depth would be greater than 3.5m, classified as "extreme danger zone". In case of low and medium flood hazard levels, the flooding water can enter surrounding buildings and can affect the daily routine activities of local residents. In case of Thailand, the local administration departments, department of drainage and sewerage, and department of disaster prevention and mitigation together with local residents take some preliminary actions before monsoon season to avoid flood hazards and reduce the flood damages to local infrastructure. However, the potential of such flood mitigation measures is limited and can only help to reduce the flood impacts of low and medium hazard levels and need to improve further for mitigation of higher hazard levels. The government needs to plan and implement the state-of-the-art telemetry system in northern areas of Thailand that can help in flood early warning system, real-time flood forecasting and decision support system for dissemination of flood warning alarms to local community before flooding, as a precautionary step for flood mitigations.

Figure 7 represents the flood inundation area against 2, 5, 10, 25, 50 and 100 years return periods. The flood inundation area is linearly increased against return periods from lower to higher return periods floods.

[Table 7.]

[Figure 7.]

Flood hazard classification at sub-district scale

The 159 sub-districts located in upper ping river basin of Chiang Mai, Lamphun and Tak provinces are classified into different flood hazard categories based on average flood depth of each sub-district. Figure 8 represents the flood hazard zoning at sub-district scale (the smallest administration unit in Thailand) for 2, 5, 10, 25, 50 and 100 years return periods. Overall, the maximum sub-districts lie under "high hazard", followed by "very high hazard" and "medium hazard" categories, and very few sub-districts classed under "low hazard" category during all return periods. Generally, the assessment of classification concludes that most of the region in upper ping river basin might be expected to face flood depth of 1-3.5m followed by more than 3.5m, and the flooding probability of less than 1m is may possibly be less during monsoon season. Specifically, the 122 sub-districts classified under high hazard category for a 2-year return period and the number is gradually decreased to 104 for 100-year return period. In contrast, the number of subdistricts increased from 2 to 37, for 2- to 100-year return period. However, the classified sub-districts for low and medium hazard levels remained almost constant during all return periods, and subdistrict numbers varied from 5 to 9 in low hazard and 10 to 15 in medium hazard category.

All sub-districts located along ping river categorized under high hazard level during each return period. In case of higher return periods, the flood depth in neighboring areas of ping river (upper, central and lower section) increased and the classification of sub-districts changed from high hazard to very high hazard category. Further, the sub-districts located along with Mae Nam Tha and Mae Li's rivers were less anticipated to flooding and categorized under low and medium hazard levels. It is also reasonable to explain that there was no flooding observed at the downstream side of upper ping river basin during lower return periods (2 & 5 years). Based on these results, the community and property existed along the ping river, especially in upper, central, and lower sections, are highly vulnerable to flood risk during the monsoon season. In particular, Chiang Mai city and its surrounding areas are also classed under high hazard flood; as this city is received a lot of tourists during the whole year and most of the economic activities in this region are directly or indirectly interlinked with tourism. The fluvial and pluvial flooding has also been reported in recent years in Chiang Mai city (Bicksler 2019). Comparatively, the probability of flooding in distant areas is very less.

[Figure 8.]

Capacity assessment of flood adaptation and mitigation measures

This section evaluates the potential of local flood mitigation and adaptation measures at three administration scales (1) National Government Level (2) Local Government Level (3) Community Level (Table 8) and discusses various gaps that existed in flood adaptation measures at institutional level and community scale. Also, future flood management recommendations are suggested for the study area considering flood inundation and hazard results described in previous sections.

Multiple structural and non-structural flood mitigation measures are applied under each administration level during flooding period to reduce the flood impacts in rural and urban areas, however, the upper ping river basin is still severely facing flooding problems in monsoon period. The maximum capacity of Ping river at P.1 station is 460 m^3/s, and additional discharge at this location in monsoon period leads to flooding in downstream region especially Chiang Mai city and its neighboring areas. However, to mitigate this problem, the "Ping River expansion project" has been recently completed with its total length of 6km in Chiang Mai city. Indeed, the city municipality has only considered river's length within their jurisdiction because of fund limitation and technically the flood risk now has been redistributed to downstream areas (Jarungrattanapong and Manasboonphempool 2011). Based on river capacity and floodplain topography assessment in 1D-2D hydrodynamic model, it is suggested to further expand Ping river's capacity of 16km following previous improved river length to potentially reduce future flood risk in this region.

The flood prediction capacity of currently available forecasting system is "seven hours" before it hits the Chiang Mai City, and Hydrology and Water Management Center (HWMC) dissimilate flood warnings to relevant government and communities (Jarungrattanapong and Manasboonphempool 2011). However, the current system needs sufficient improvement with state-of-the-art real-time flood early warning system with high prediction accuracy and larger flood forecasting capability. Following this, the flood alerts system also needs to be modified for faster dissemination of flood warnings to all relevant stakeholders and local residents.

[Table 8.]

Flood adaptation gaps and future recommendations

Multiple gaps found in previous flood mitigation planning and management procedures of government and local departments, and local stakeholders. Each department or community completed their assigned tasks on an individual basis, either it is short-term or long-term, however, now there is need to re-think and establish an integrated flood management framework in which combined potential from all level of resources should be systematically managed and applied. Moreover, the local community involvement is highly recommended and would be beneficial in flood mitigation and adaptions process as their previous real flood experiences can help to develop technically sound, practically applicable, socially acceptable, and economically viable structural and non-structural flood mitigation strategies.

As local community now is habitual of annual floods, so sometimes they do not take flood warnings seriously and also do not prepare themselves for disaster, resultantly, more tangible and intangible flood damages have been occurred in past flood events. Moreover, some local residents do not participate in individual and collective adaptation activities as they think that it is the government's responsibility to protect people from flooding; there is need to educate and train local community through disaster awareness and preparedness workshops to involve full human resources potential during flood mitigation periods. A detailed practical research study is recommended in future for the development of an integrated flood management framework with the consideration of availability and limitation of local resources, administrative priorities and conflicts, and preferences of local community' concerns. The study could provide guidelines to update current administrative flood adaption and management set-up into an improved version for better performance in future flood risk reduction.

Conclusion

Flood inundation mapping and hazard assessment of the Upper Ping River basin performed for different return periods with 1D-2D coupled hydrodynamic modelling approach to categorize flooded areas into different hazard levels at the sub-district scale (the smallest administration unit in Thailand). This study contributes to better utilization of flood adaption and mitigation measures taken by multiple administration authorities before, during, and after floods for the protection of local people, their properties, and other infrastructure.

The flood inundation and hazard analysis results represent that the sub-districts located around Ping River are highly vulnerable to future floods, during low or high return periods in monsoon season. The maximum flood inundation occurred at an area of 996.9 km^2 (3.94% of total basin area) during the 100-year return period. The sub-districts are classified under "high hazard", followed by "very high hazard" and "medium hazard" categories, and very few sub-districts classed under "low hazard" category during all return periods. The severity of flooding problems reduced for those sub-districts located at distant places from the river and vice versa.

Considering the flood problems, topographical characteristics of the basin, and locally available flood mitigation resources, the current national and local administration needs to find an integrated flood management approach with the better utilization of local resources to improve the current flood protection system. The potential of existing flood early warning and information dissemination systems needs to upgrade with state-of-the-art real-time flood forecasting and the latest dissemination system.

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Figures

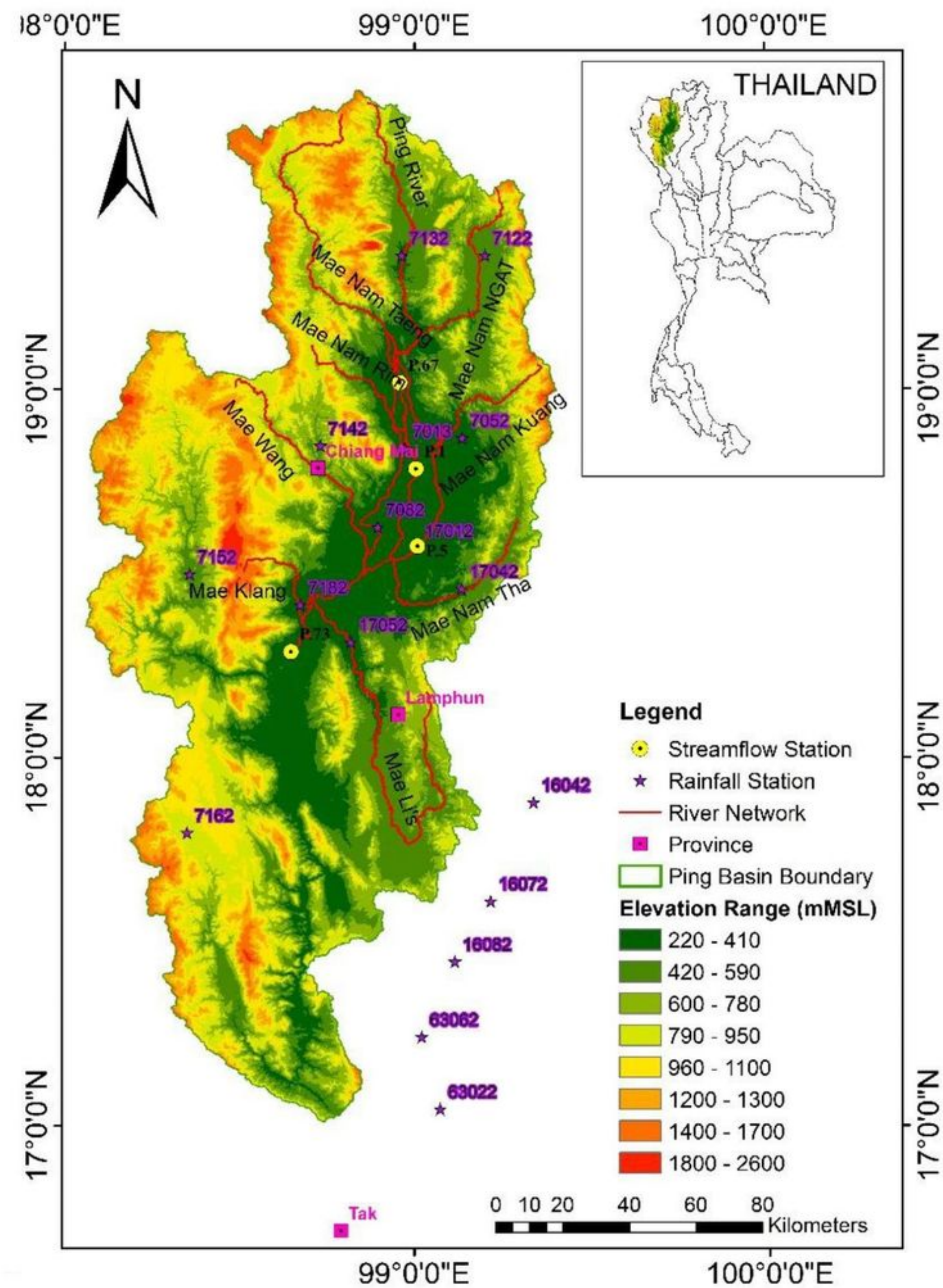

Figure 1

Figure 1

Location map of study area with hydro-meteorological stations in Upper Ping River Basin, Thailand Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

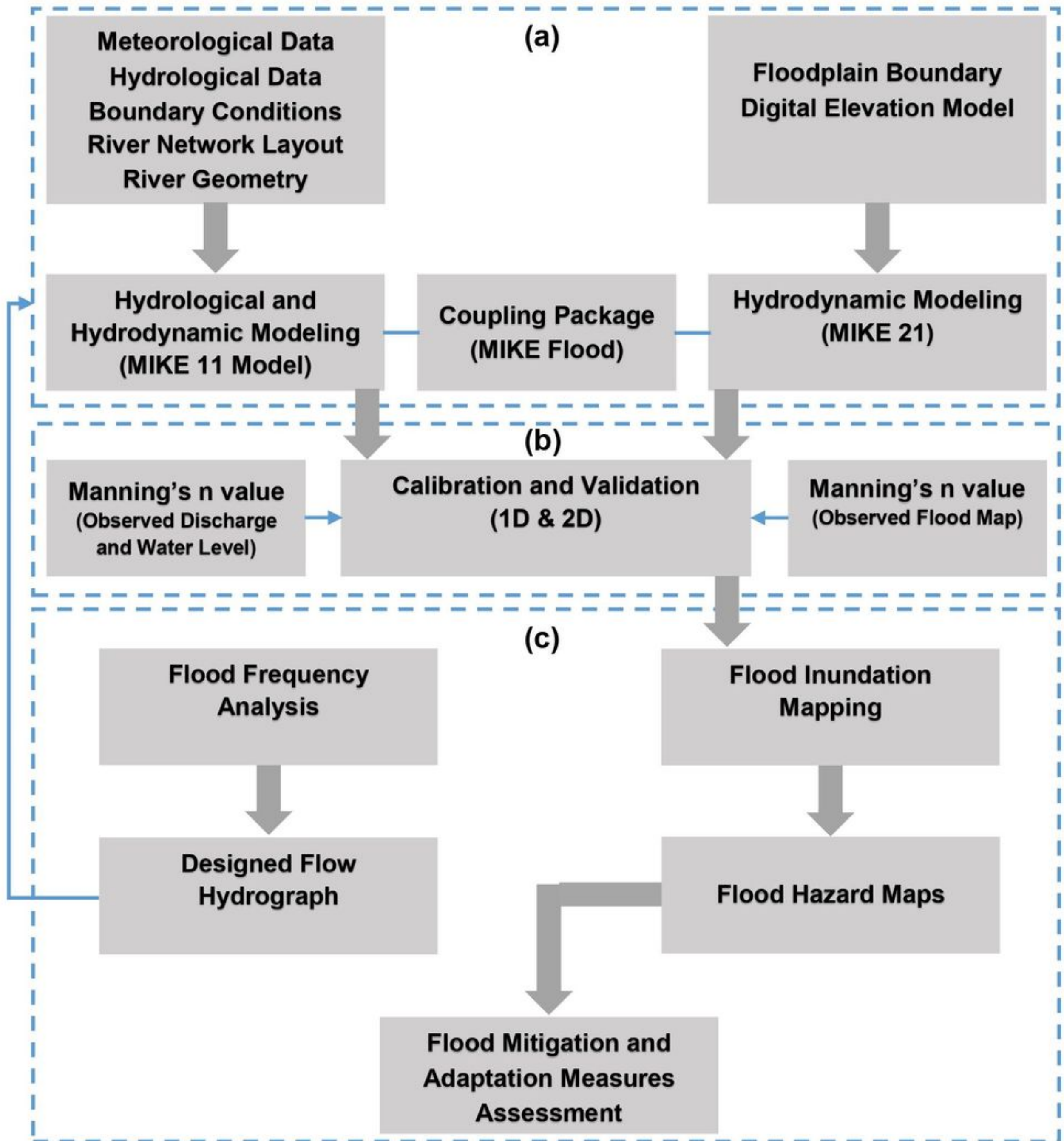

Figure 2

Figure 2

Methodological Framework for flood hazard assessment and adaptation measures

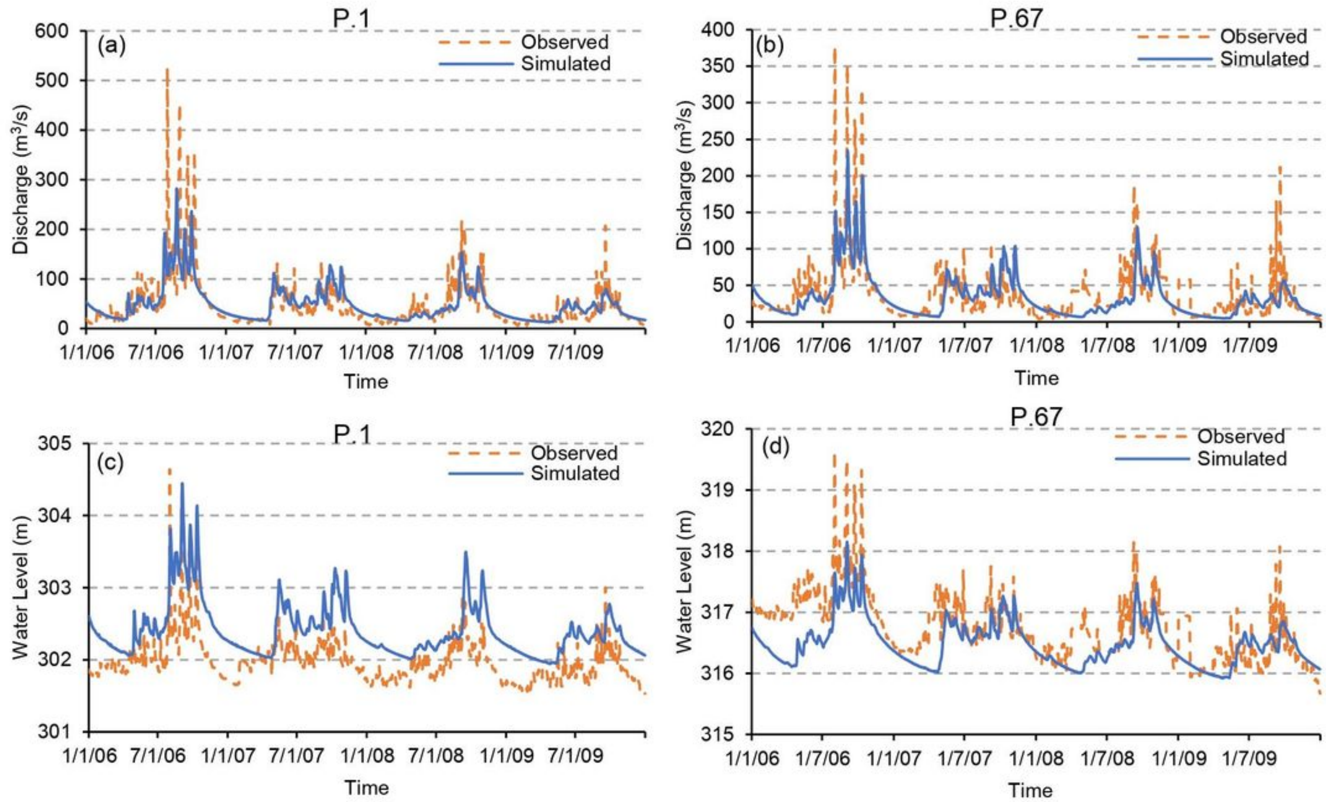

Figure 3

Figure 3

Calibration results of discharge at (a) P.1 and (b) P.67 and water level at (c) P.1 and (d) P.67

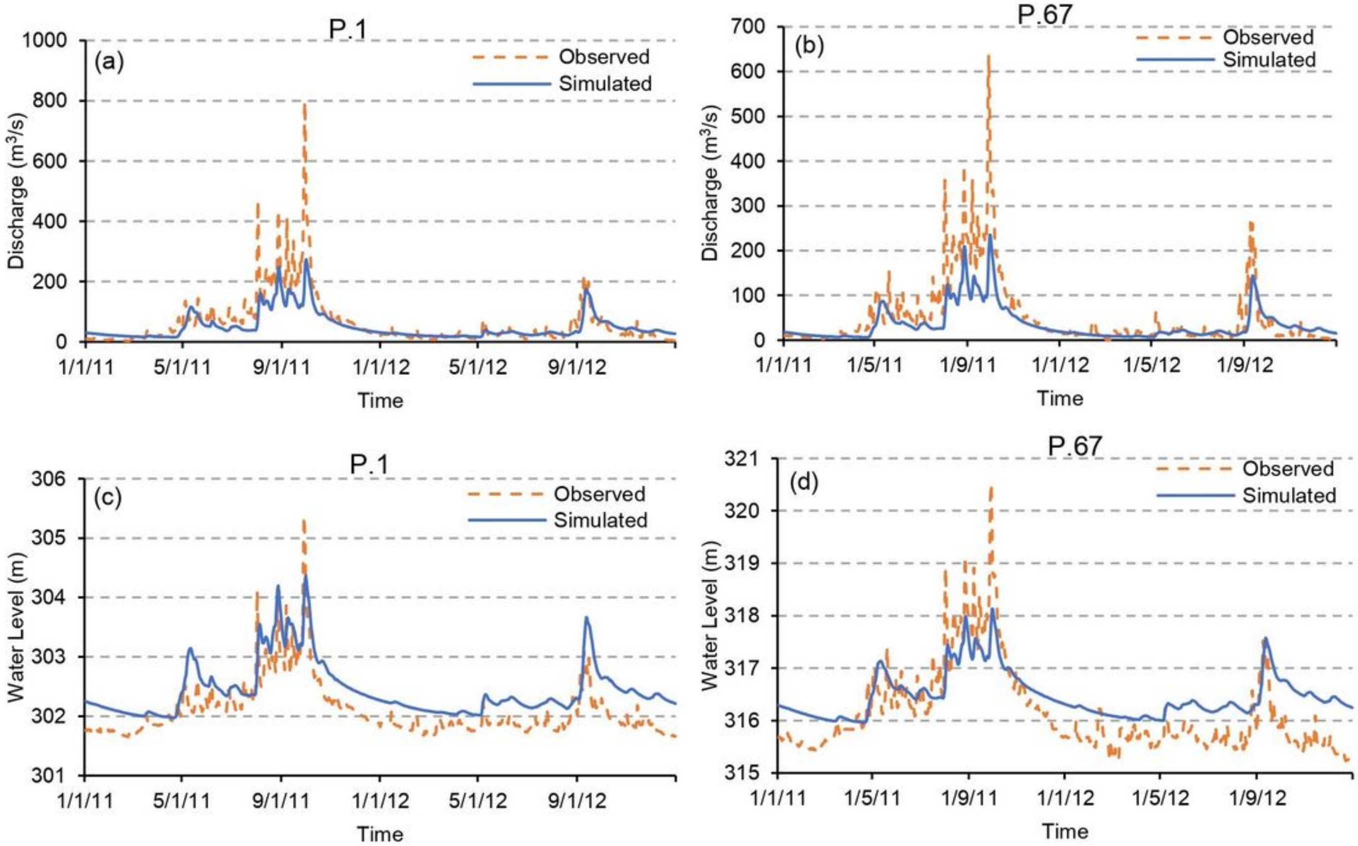

Figure 4

Figure 4

Validation results of discharge at (a) P.1 and (b) P.67 and water level at (c) P.1 and (d) P.67

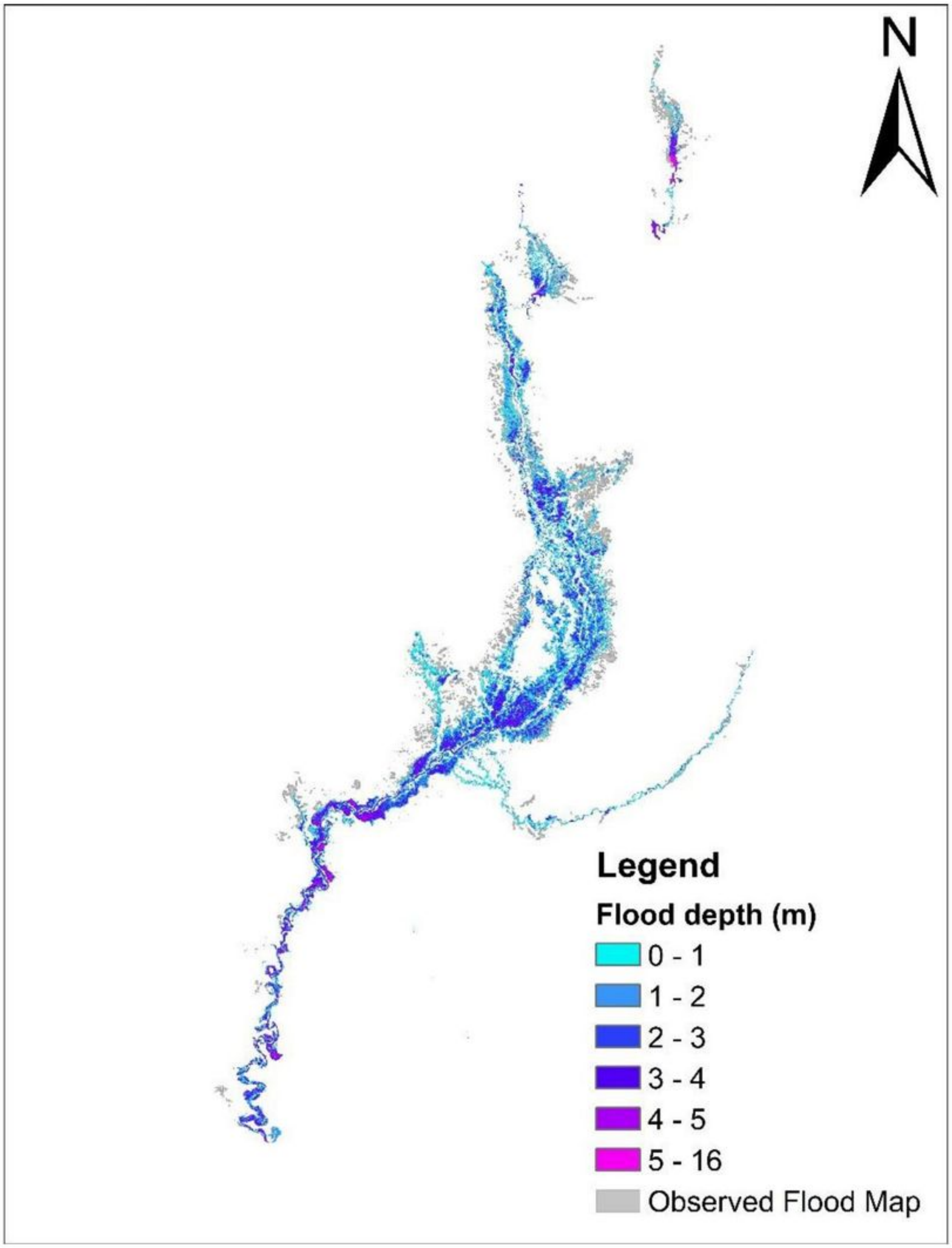

Figure 5

Figure 5

Calibration results of 2D-hydrodynamic model Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

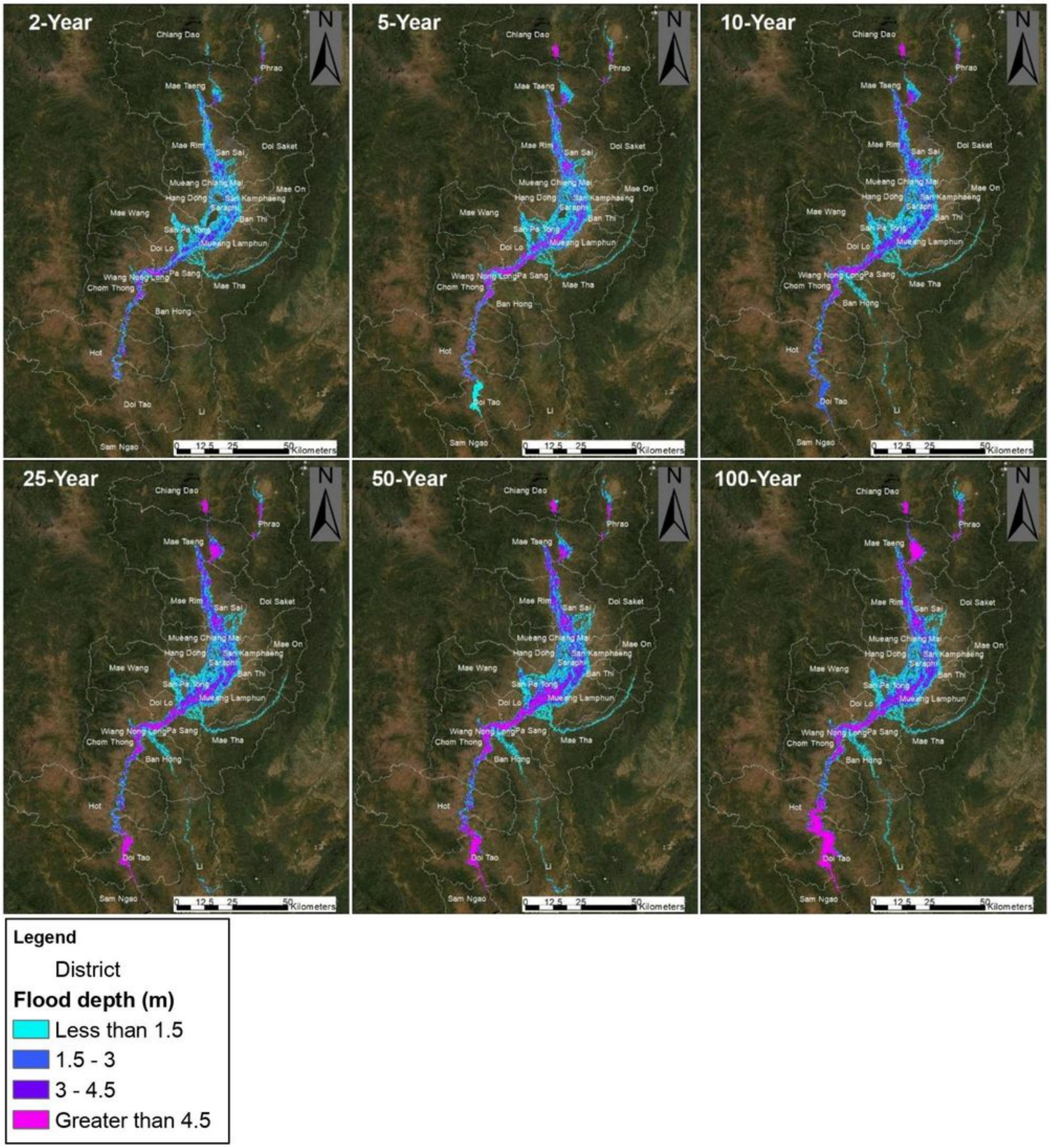

Figure 6

Figure 6

Flood inundation depth for different return periods Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

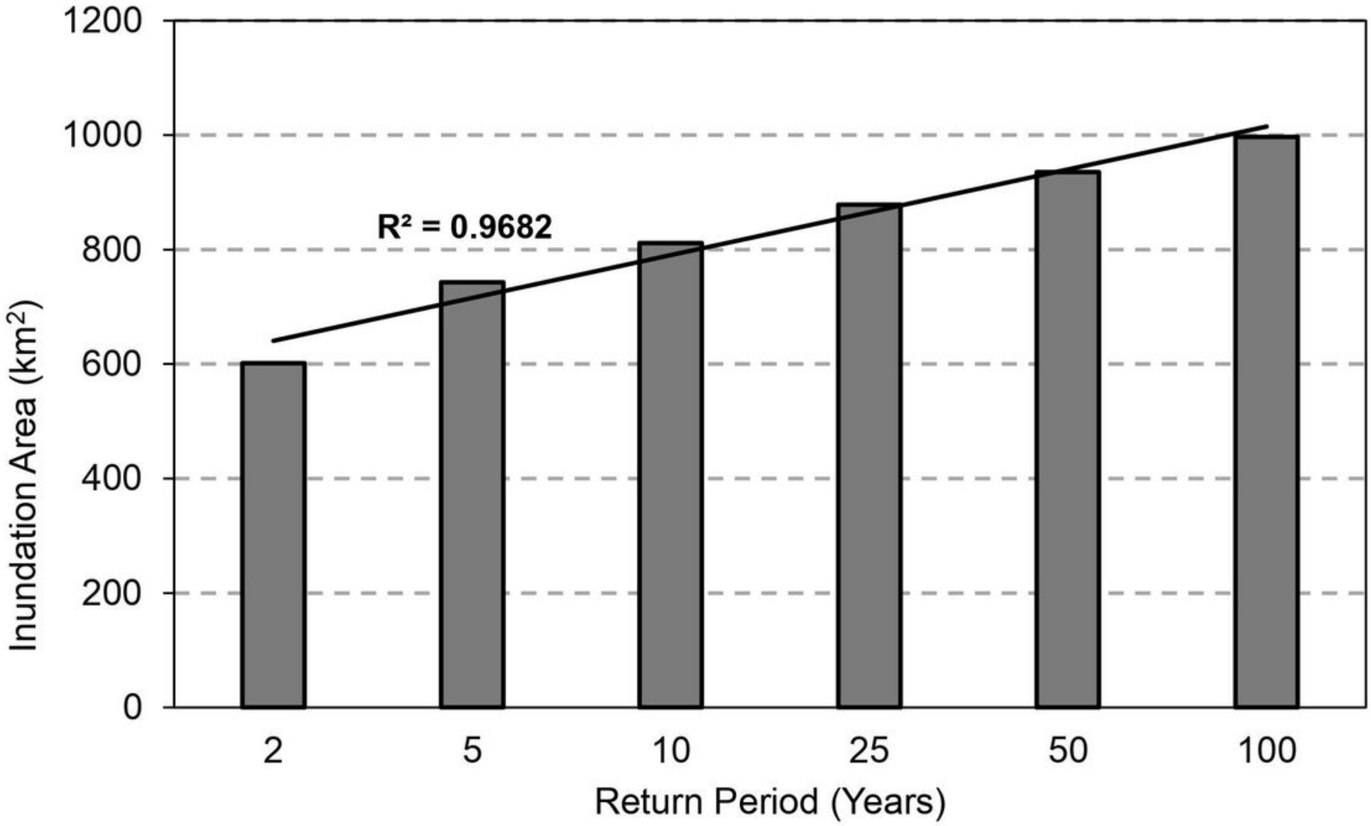

Figure 7

Figure 7

Comparison of inundation area against different return periods

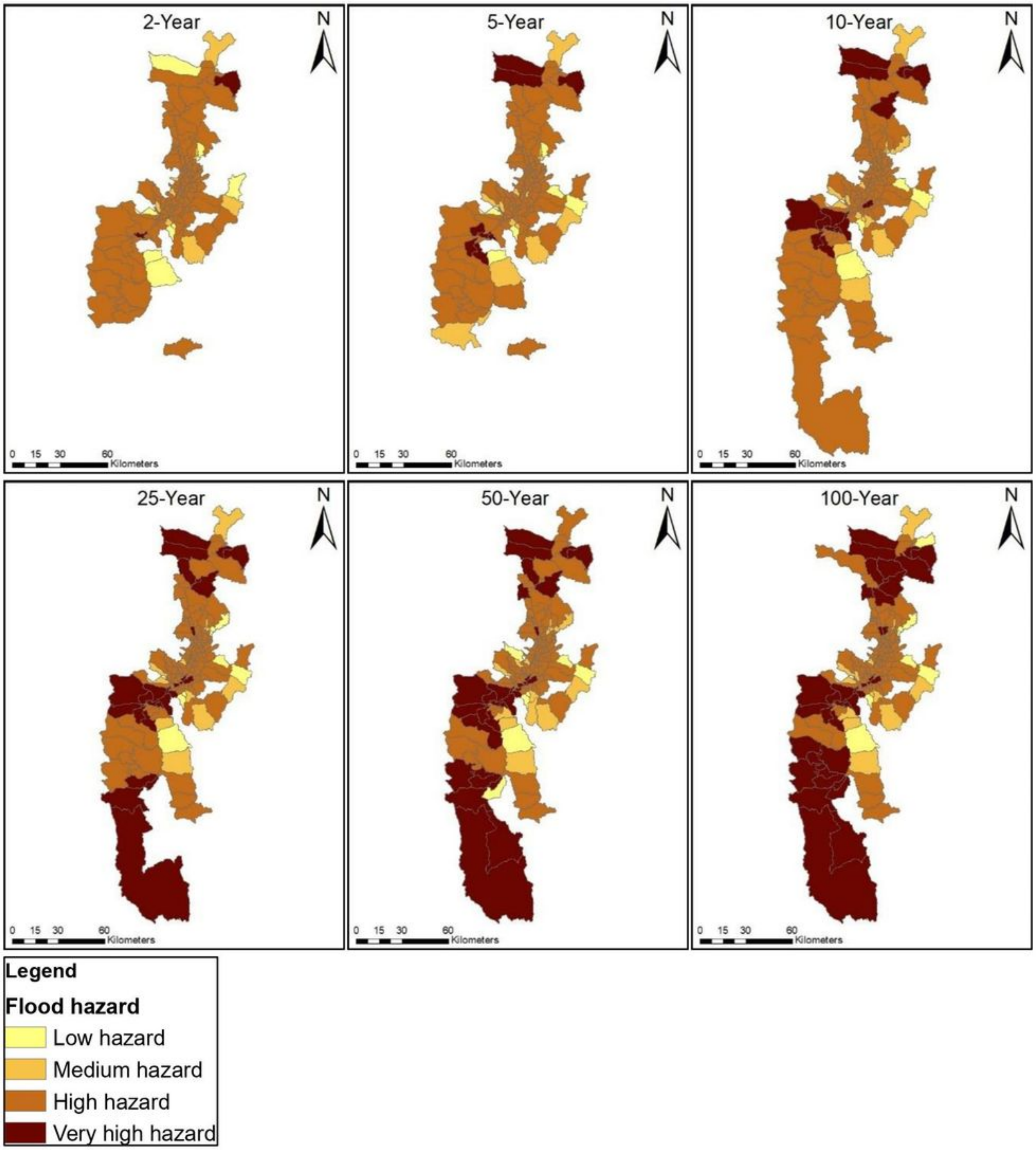

Figure 8

Figure 8

Flood hazard assessment of sub-districts for different return periods Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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