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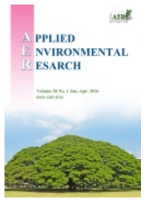

Spatiotemporal Flood Risk Determination and Management for a Large River Basin

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Abstract

The Chao Phraya River Basin (CPRB) of Thailand faces flooding almost every year. The severest flood occurred in the CPRB in 2011 with the highest property damage costs (46.5 billion USD) and the highest casualty (813 deaths). The objectives of this study were thus to (1) determine flood risk indices and categorize them into four risk zones (low, moderate, high, and very high) across 994 sub-districts in the CPRB during the six rainy months (May–October); and (2) propose specific measures for flood risk management for each of the categorized risk zones. The flood risk indices were assessed as the product of two hazard variables (flood levels and monthly cumulative precipitation) and the vulnerability variable (land uses). The findings revealed spatiotemporal variations in flood risk. Spatially, the sub-districts deemed to be in the high or very high flood risk zone were mainly located close to the Chao Phraya River (CPR), where the flood levels reached 1.1 – 4 m in depth; whereas the sub-districts detected in the low or moderate flood risk zone were located further away from the CPR. Temporally, more sub-districts were detected in the high or very high risk zone in September when heavy rainfalls were observed. Specific measures are proposed herein to manage flood risk regarding the categorized zones during three periods. The preventive and mitigation measures should be prepared before flooding; emergency responses should be practically implemented during flooding; and the recovery after flooding should cover both infrastructural and environmental damage and mental/physical illnesses amongst the affected people. Intensive measures are recommended for the sub-districts located in both the high and very high risk zones. These measures may be properly loosened for the sub-districts located in the low and moderate risk zones.

Keywords: Chao Phraya River; Emergency response; Flood risk; Mitigation; Recovery; Thailand

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Introduction

Assessing flood risk is often difficult in areas where flood-related data are scarce [1]. Consequently, field observations and model predictions are commonly used together for assessing the flood risk in an area of interest, particularly where observed data are insufficient or unavailable [1–4]. Flood-related variables are usually interactive with each other [5], e.g., flooding frequency, flood levels, rainfall, geography, land use activities, drainage characteristics, etc. Meanwhile, flood risk assessments at local levels are useful for preparing specific measures/plans to efficiently manage the local flood risk [6–7].

Although flood risk assessment is ideally considered as the product of the probability of the occurrence of a flood event and its consequences on both socioeconomics and the environment [8–10], sufficient data for estimation are often unavailable in some areas of interest [1]. Thus, the assessment aspects of flood risk have been simplified in a superficial way by latter researchers according to the availability of the flood-related data in their study areas and how the data were used [11]. For instance, Shivaprasad et al. [12] assessed the flood risk in the Kopili River Basin of India as the product of flood hazard zonation layers retrieved from satellite data and the vulnerabilities in terms of social, infrastructural, and land use data. Gain and Hoque [13] assessed the flood risk in the eastern part of Dhaka City in Bangladesh as being a combination of flood hazards (in terms of flood depth and duration) and the consequences thereof (in terms of the degree of exposed land uses vulnerable to the flood hazard).

In this study, the Chao Phraya River Basin (CPRB), a major low-lying central floodplain and the rice bowl of Thailand with about 71% of the agricultural area (45% paddy fields, 22% other agricultural areas, and 4% aquaculture) [14–15], was selected as one of the representative river basins in the Asian region for assessing flood risk. The CPRB has faced continuing flood risks (flood risks that remain in both existing and future development areas, [11]) almost every year. In particular, in 2011 the CPRB underwent the severest flood in the latest 50 years with a flood duration of more than five months (from early August 2011 to early January 2012), the highest ever property damage costs (46.5 billion USD), and the unprecedented casualties of 813 deaths from flooding [16–18].

Determining flood risk in the CPRB is challenging because no long-term data of flood hazard variables have been recorded [15]; principally, because it was difficult for the line government agencies to collect data in many local areas in the river basin due to a lack of budget and manpower. Additionally, there were few flood-related studies in the CPRB; and various methodologies were used to attain the research goals [19–21]. To deal with these limitations, flood risk indices were estimated across the CPRB as the product of two hazard variables (i.e., flood levels and monthly cumulative precipitation) and the vulnerability variable (i.e., land uses) that were available in the river basin.

The first objective of this study was thus to determine the flood risk indices (between 0 and 1) and categorize them into four risk zones (low, moderate, high, and very high) across 994 sub-districts during the six rainy months (May–October) in the CPRB. Other than these conventional assessments, the second objective was to propose specific measures on flood risk management regarding each of the categorized risk zones. These results would be useful for both line government agencies and stakeholders in the river basin to improve or prepare more effective flood contingency plans for managing flood risks in their local areas.

Study area

The CPRB (between 13°28′N, 99°33′E and 16°6′N, 101°5′E) covers a 21,604 km^2 area [9] in the 994 sub-districts of 19 provinces. The Chao Phraya River (CPR), a major river situated in the CPRB with the length of 379 km, flows in a north-south direction from the river mouth of the Pak Nam Pho in Nakhon Sawan Province through the river basin to the Gulf of Thailand (Figure 1). The mean monthly discharge of water into the CPR was 12 – 500 million m^3 a month during May–November and 0.6–11 million m^3 a month during December–April (Royal Irrigation Department, unpublished data, [15]).

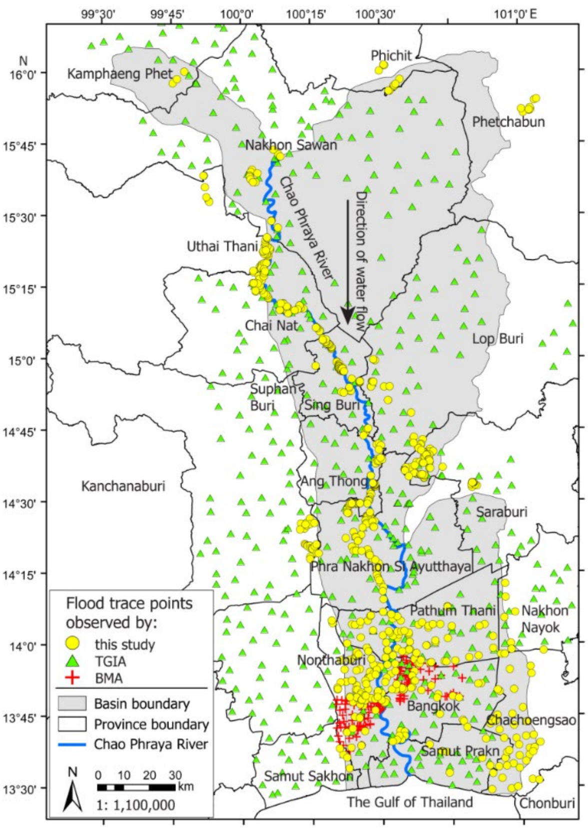

Figure 1 The Chao Phraya River Basin and the 1,379 points of the observed levels of the 2011 flood traces. These included 702 points observed by this study, 556 points observed by the Thai General Insurance Association (TGIA, unpublished data), and 121 points observed by the Bangkok Metropolitan Administration (BMA, unpublished data).

Materials and methods

In theory, a large number of flood hazard variables (i.e., flood-related events, such as precipitation, flood level, land elevation, and so forth) and vulnerability variables (e.g., physical, environmental, and socioeconomic features, land uses, soil types, etc.) should be considered for assessing flood risks in an area of interest [5, 8, 13, 22]. However, in practice, most of the flood-related data were sparse in sizes or unavailable at the local level (sub-district) in the CPRB. Given the data limitation, two flood hazard variables (i.e., flood levels and monthly cumulative precipitation) and one of prominent vulnerability variables (i.e., land uses) were still available for estimating flood risk indices across the CPRB. The data used for determining flood risks and the relevant methods for deriving the data and estimations are described below.

1) Flood level

1.1) Observation

Traces of flood levels (in meters, m) that exist on various objects as a result of the mega flood in 2011 were observed at 1,005 points in the CPRB and 374 points in the areas adjacent to the river basin (Figure 1). Of the total 1,379 points, 702 points were observed in 269 sub-districts in 2016 by this study, 556 points were observed in 500 sub-districts in 2012 by the Thai General Insurance Association (TGIA, unpublished data), and 121 points were observed in Bangkok in 2014 by the Bangkok Metropolitan Administration (BMA, unpublished data). These flood traces remain on those inundated objects that readily absorbed water, such as concrete buildings/walls and electricity poles (Figure 2), after the longest duration of inundation of about 153 days (5 August 2011 – 4 January 2012, [18]). The objects showing distinct traces of flood levels implied that they were inundated at these levels for the longest period of a week or more during the 2011 flood (local administrative officers, personal communications).

1.2) Prediction

The observed flood levels at 1,379 points in and around the CPRB above were used to predict the flood levels at unobserved points across the CPRB using three types of kriging (i.e., ordinary, universal, and empirical Bayesian). The ArcGIS program was used to perform each type of kriging and its cross validation and validation [23]. Cross validation was done using all of the data to estimate the autocorrelation; whereas, the validation was done using the second part of the data (which were not used for testing the model parameters) as the training data set for developing trend and autocorrelation (see details of both validation methods in Johnston et al. [24]). Of the three kriging types, empirical Bayesian kriging (EBK) provided the best prediction based on (1) the standardized mean nearest to zero, (2) the smallest root-mean-square prediction error (RMS), (3) the average prediction standard error nearest the RMS, and (4) the standardized root-mean-square prediction error nearest to one (Table 1) [24]. According to the validation results, the EBK provided a good agreement between the predicted and observed flood levels (R^2 = 0.86) at each of the 501 locations (the training data set) as illustrated in Figure 3. Thus, the EBK was used to predict the flood levels across the CPRB.

Figure 2 The examples of the traces of flood levels on the concrete poles (top right), the temple wall (top left) and the buildings (bottom) located in the Chao Phraya River Basin.

Table 1 Result comparisons of the ordinary, universal, and empirical Bayesian krigings for the predicted flood levels at unobserved points in the Chao Phraya River Basin

Kriging type	Mean	Std.[1]	RMS[2]	SE[3]	RMSS[4]	Abs(SE – RMS)[5]
Ordinary	0.046	–0.003	63.69	67.89	0.95	4.20
Universal	–1.086	–0.019	63.57	67.95	0.94	4.38
Empirical Bayesian	0.698	–0.001	58.50	58.28	1.01	0.22

Remark: [1]Std. = Standardized mean; [2]RMS = root-mean-square prediction error; [3]SE = average prediction standard error; [4]RMSS = standardized root-mean-square prediction error; [5]Abs (SE – RMS) = the absolute difference between the RMS and SE.

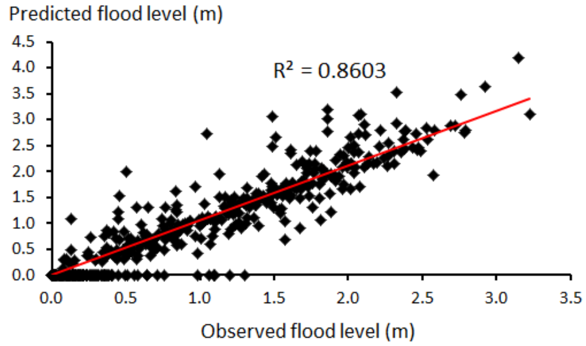

Figure 3 The validation result obtained from the empirical Bayesian kriging showing a good agreement between the predicted and observed flood levels ($R^2 = 0.86$) at each of the 501 locations (the training data set) in the Chao Phraya River Basin.

1.3) Categorization

The ArcGIS program's natural breaks method for classifying a data set with big jumps in data values (e.g., the flood levels in the CPRB) was used to categorize the predicted flood level contours into four levels, i.e., 0 – 0.5, 0.6 – 1, 1.1 – 2, and 2.1 – 4 m. These predicted flood contours are illustrated together with the observed and predicted points of the flood levels in the CPRB (Figure 4: Left). The observed and predicted flood levels in each sub-district were averaged in cases where more than one value for each point was obtained.

2) Monthly cumulative precipitation

The cumulative precipitation data across the CPRB for each of the six rainy months (May–October) over the 15-year period (2005–2019) were retrieved from the database of the Climatic Research Unit [25]. They were monthly averaged for each sub-district and categorized into five ranges (i.e., 131.1–170, 170.1–209, 209.1–248, 248.1–287, and 287.1–326 mm as shown in Figure 5.

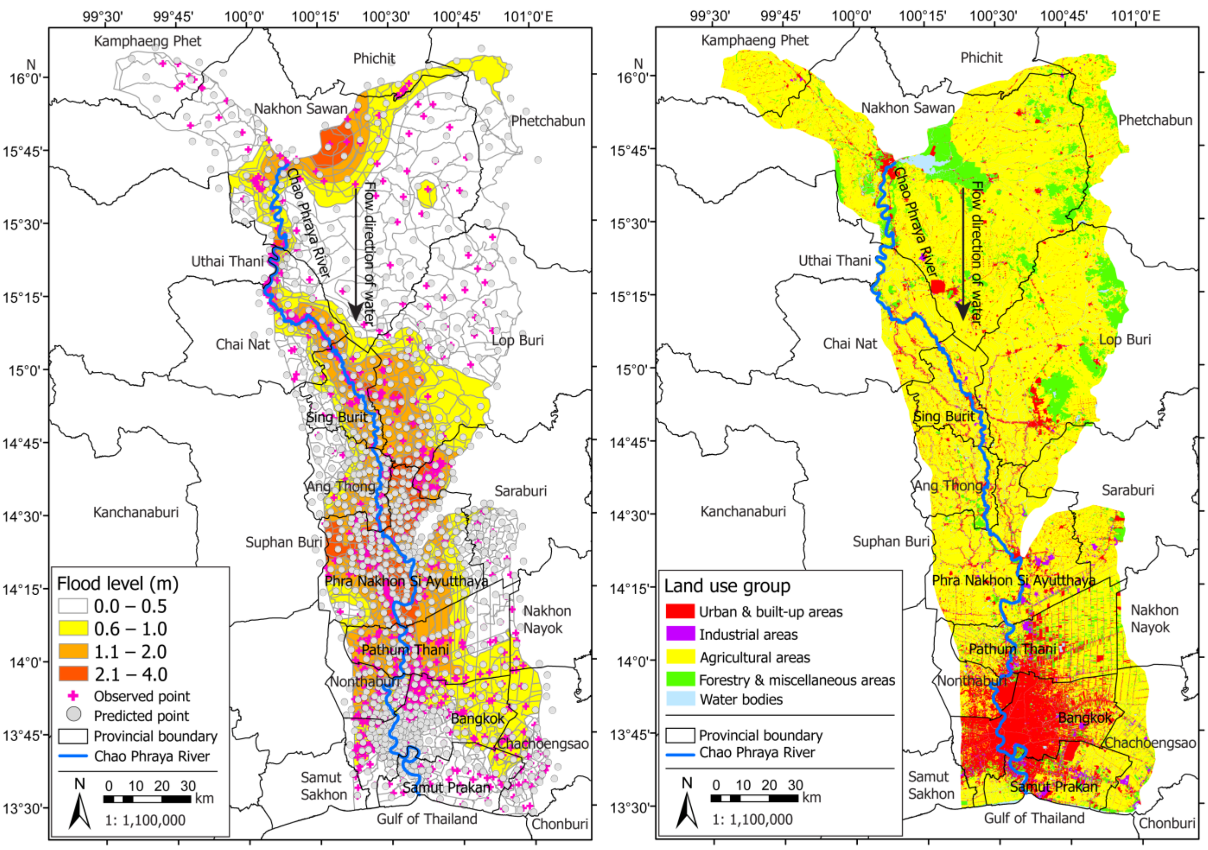

Figure 4 The predicted flood level contour (m) generated from the predicted and observed flood levels in the Chao Phraya River Basin (left) and the land use groups in the river basin (right; Land Development Department, unpublished data).

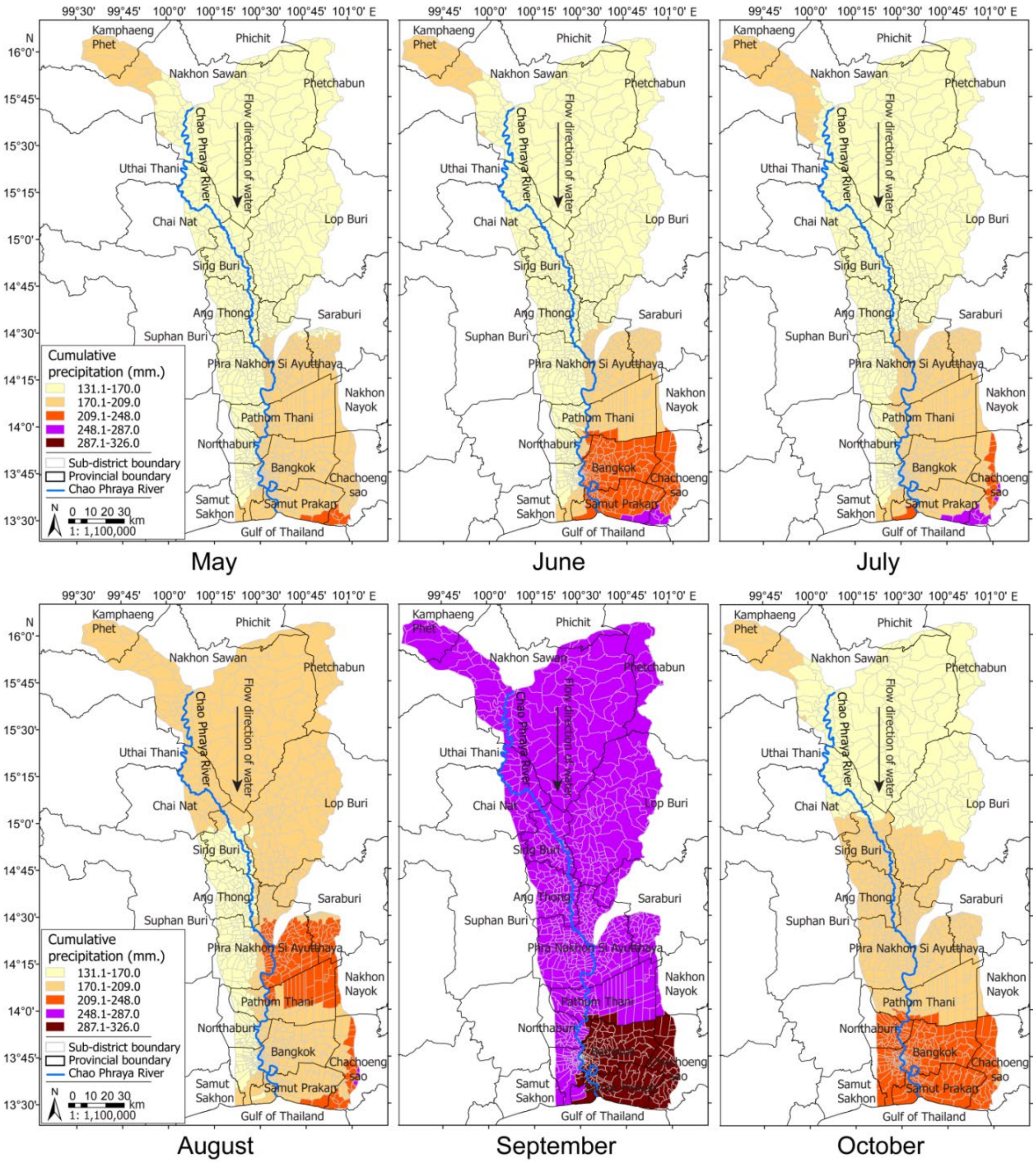

Figure 5 The cumulative precipitation (mm) averaged over a 15-year period (2005–2019) for each rainy month in the Chao Phraya River Basin. The data used for the estimations were obtained from the Climatic Research Unit [25].

3) Land use

The land use in 2016 (Land Development Department, unpublished data) across 994 sub-districts in the CPRB was classified into five groups including urban and built-up areas (LU1), industrial areas (LU2), agricultural areas (LU3: paddy fields, other agricultures, and aquaculture), forestry and miscellaneous areas (LU4), and water bodies (LU5) (Figure 4: Right). A weight was assigned to each land use group ($LU_{weighted}$) to reflect the degree of susceptibility to damage from flooding in the relevant land use area if it was flooded. LU1 was weighted the highest at 1 as they represent the dwelling and working places of people; and if these areas were flooded, the loss of life and property (the direct damages) would be the primary area of concern [12, 26–27]. The second priority was LU2 with an assigned weight of 0.8 regarding the financial loss in this land use area. The flooding damage cost (in monetary units) on the industrial sector in the CPRB during the mega-flood of Thailand in 2011 ranked second after housing [16, 28]. A weight of 0.5 was assigned to LU3, which covers about 71% of the CPRB. Although casualties from flooding might be low in the agricultural areas, these flooded areas could indirectly affect the livelihood of local people, especially farmers, in the river basin. The lowest weight of 0.1 was assigned to LU4 as people and properties are rarely located in these areas. However, some tree species might have perished if they had low tolerance to flooding or were flooded for a long time period; and these might have indirectly affected the health of the ecological system. The zero weight of flooding impacts was assigned to LU5 (e.g., rivers, streams, canals, swamps, etc.) that are reservoirs of floodwater.

4) Flood risk determination

Flood risk was determined for each sub-district as the product of hazard variables (i.e., flood level and monthly cumulative precipitation) and a vulnerability variable (i.e., weighted land use groups; [12, 29]). To obtain the dimensionless index (between 0 and 1 and without unit), the estimated flood risk for each sub-district was divided by the maximum flood risk detected in the CPRB. For instance, the estimated flood risk index in May (F_{RI-May}) for the Subphudsa Sub-district of Phetchabun Province using equation 1 (Eq. 1) is shown below.

$$F_{RI-May} = \frac{F_{R-May}}{F_{R_{max}}} \quad \text{(Eq. 1)}$$

$$= (3,871.48/53,315.45)$$

$$= 0.07 \text{ (dimensionless)};$$

where; F_{R-May} = the flood risk in May = $(F_L \times P_{May}) \times LU_{weighted}$ = (0.59 × 157.54) × 41.7 = 3871.48 (m·mm·%)

F_L = the flood level over the longest duration of flooding = 0.59 m

P_{May} = the cumulative precipitation in May averaged over the 15-year period (2005–2019) = 157.54 mm

$LU_{weighted}$ = the weighted percentage areas of five land use groups = 41.7% of the total land use of 17,392,200 m^2 in the sub-district, it contains 3.25% of LU1, 0% of LU2, 71.96% of LU3, 24.71% of LU4, and 0.08% of LU5. Thus, $LU_{weighted}$ for this sub-district is [(3.25 × 1) + (0 × 0.8) + (71.96 × 0.5) + (24.71 × 0.1) + (0.08 × 0)] = 41.7%

F_{Rmax} = the maximum flood risk in the river basin. It was detected in the Bang Prok Sub-district of Pathum Thani Province in September. = 53,315.45 (m·mm·%)

The estimated F_{RI} for each of the remaining 993 sub-districts in each of the six rainy months was done using a similar method. The ArgGIS's natural breaks method was used to categorize the varied indices of flood risk across the CPRB into four spatial zones in each of the six rainy months. They included low, moderate, high, and very high flood risk zones with associated F_{RI} of 0–0.15, 0.16–0.3, 0.31–0.5, and 0.51–1, respectively. These were for the purpose of specific measures suggested by this study to manage flood risk in each categorized risk zone.

Results

The four categorized zones of flood risk varied in space (across 994 sub-districts) and time (across six rainy months) in the CPRB as shown in Figure 6. In May, most of the total 994 sub-districts were detected in the zone of low or moderate flood risk. The zone of very high flood risk this month covered nine sub-districts in Pathum Thani (4 sub-districts), Phra Nakon Si Ayutthaya (4) and Nonthaburi (1) provinces. The zone of high flood risk covered 166 sub-districts located along the river banks of the CPR (Figure 6: May), where the flood levels were mainly 1.1–2 m deep and some between 2.1 and 4 m deep (Figure 4: Left). The land use groups presented along the river banks were urban and built-up areas and industrial sector, particularly in Pathum Thani, Nonthaburi, Bangkok, and Samut Prakan provinces (Figure 4: Right). The cumulative precipitation was 131.1–170 mm in 408 sub-districts of many provinces, 170.1–209 mm in 404 sub-districts of 11 provinces, and 209.1–248 mm in 7 sub-districts of Chachoengsao and Samut Prakan provinces (Figure 5: May).

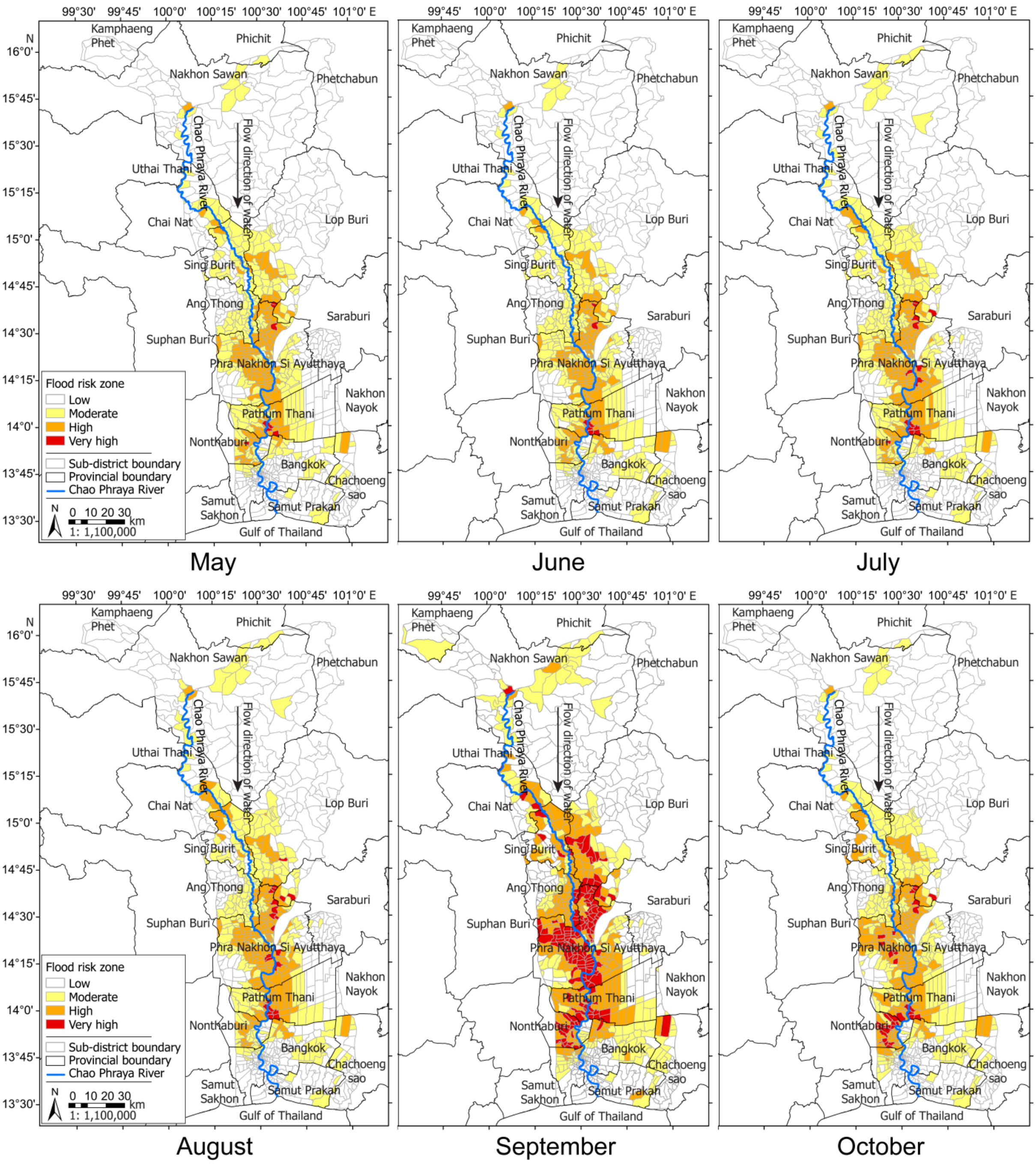

Figure 6 The categorized zones in association with the estimated flood risk indices (F_{RI}) across 994 sub-districts and six rainy months (May – October) in the Chao Phraya River Basin. These include low (F_{RI}: 0 – 0.15), moderate (F_{RI}: 0.16 – 0.3), high (F_{RI}: 0.31 – 0.5), and very high (F_{RI}: 0.51 – 1) risk zones.

In June, the categorized zones of flood risk were similar to those in May. That is, many sub-districts were detected in the low or moderated risk zone. Seven sub-districts in Pathum Thani (5) and Phra Nakhon Si Ayutthaya (2) were detected in the zone of very high flood risk; and 160 sub-districts were detected in the zone of high flood risk (Figure 6: June). The cumulative precipitation was still mainly detected in the ranges of 131.1–170.0 mm in 570 sub-districts, 170.1–209 mm in 231 sub-districts, and 209.1–248 mm in 186 sub-districts. However, higher range of the cumulative precipitation (248.1 – 287 mm) was additionally detected in 7 sub-districts (Figure 5: June).

In July, the number of sub-districts detected in the low and moderate risk zones decreased (compared to that in June) but the number of sub-districts detected in the high (186 sub-districts) and very high (16 sub-districts) risk zones increased (Figure 6: July). In addition, the sub-districts with the cumulative precipitation in the ranges of 170.1–209 mm (430 sub-districts) and 248.1–287 mm (13) were more than those in June (Figure 5: July).

In August, more sub-districts were detected in the high (192 sub-districts) and very high (24 sub-districts) risk zones than those in July, whereas the remaining sub-districts detected in the low and moderate risk zones were similar to those in the previous three months (Figure 6: August). Likewise, the cumulative precipitation was 170.1–209 mm in 563 sub-districts (more than half of the river basin); and it was 209.1–248 in 160 sub-districts, and 248.1–287 mm in 6 sub-districts (Figure 5: August).

In September, many sub-districts were detected in the high (214 sub-districts) and very high (175) risk zones (Figure 6: September). Consistently, heavy cumulative precipitation of 248.1–287 mm was detected in almost of the entire river basin (covering 798 sub-districts). The remaining 196 sub-districts showed the highest cumulative precipitation of 287.1–326 mm (Figure 5: September).

In October, the number of sub-districts detected in the high and very high risk zones declined; and this pattern was similar to that in August (Figure 6: October and August). The cumulative precipitation was in the range of 170.1–209 mm in 502 sub-districts and 209.1–248 mm in 303 sub-districts (Figure 5: October).

Discussion

Two hazard variables (flood levels and monthly cumulative precipitation) and the vulnerability variable (land uses) influenced the variations in flood risk [4, 30–31] in the CPRB. Overall, the sub-districts detected in the zone of high or very high flood risk were mainly located close to the CPR (Figure 6), where the flood level was 1.1 to 4 m deep (Figure 4: Left). The sub-districts detected in the zone of low or moderate flood risk were located further away from the CPR (Figure 6). However, these patterns were exempted in Samut Prakan Province, whose many sub-districts were located near the mouth of the CPR. The flood levels detected in this province were shallow (0–0.5 m, Figure 4: Left). This might be due to the major fact that floodwaters were disallowed to flow as per normal circumstances through inner Bangkok (where a lot of economic and shopping centres, government offices, academic institutions, important temples, palaces, etc. are located) to Samut Prakan, which is located downstream of Bangkok. The large amounts of floodwater in the CPRB in 2011 were diverted out of Bangkok before they would flow through Bangkok to Samut Prakan [32]. Consequently, many sub-districts in Samut Prakan were not flooded or were flooded at a shallow level.

As the flood vulnerability variable, the major land use group in the CPRB is agriculture (including paddy fields, other agricultures, and aquaculture), which covers about 71% of the river basin area [15]. Most of the farming area is paddy fields, which are located in low-lying land or flood drainages in the river basin. Urban and built-up (15% of the CPRB) and industrial (2%) areas are also mainly located in the low-lying land in the provinces of, e.g., Phra Nakhon Si Ayutthaya, Pathum Thani, Nonthaburi, and Samut Prakan (Figure 4: Right). These land use groups contributed, more or less, to the varied flood risk [22, 33] in the sub-districts located in the river basin. Meanwhile, in concordance with previous studies [12, 22, 34], the precipitation, one of the two selected hazard variables in this study, noticeably influenced the variations in flood risk across the six rainy months particularly in September, when heavy rainfalls were mainly observed in the CPRB (Figure 5). Consequently, the sub-districts detected in the zone of high or very high flood risk in September were more than those in the rest rainy months.

In this study, specific measures are proposed to manage flood risk in relation to each of the four categorized zones in the CPRB during three periods as provided in Table 2. Intensive flood risk management measures are recommended for the sub-districts located in the high and very high risk zones; the measures may be implemented with a light touch for the sub-districts located in the low and moderate risk zones. During the first period (before flooding), all of the sub-districts located in every risk zone should have good preparedness on flood risk management, which is more effective and cheaper for reducing flooding impacts than recovery. For example, a local plan at the sub-district level should emphasize non-structural and progressive measures [35], particularly for the sub-districts situated in the zone of moderate, high, or very high flood risk during the rainy period. The important preparation measures in relation to the zones of flood risk are, e.g., flood education, flood evacuation training, land use planning and zoning, and flood contingency plan (Table 2: Before flooding).

For the second period (during flooding), a practical emergency response to flooding is an important feature of the flood contingency plan for a sub-district situated in the zone of moderate, high, or very high flood risk. Although most of the emergency response measures (e.g., people evacuation rehearsals, evacuation routes and shelters, etc.) should be prepared in advance, details of the plan and flood-related information should be reiterated to the communities through local broadcast channels, e.g., village loudspeakers, community radio, and so forth [35]. The local flood watch volunteers and networks should be set up to monitor the flooding conditions in their communities. Residents who live in high and very high flood risk areas should have flood kit luggage at home, so that they can leave their houses with the sustenance luggage any time a flash flood occurs in or around their residential areas (Table 2: During flooding).

In the final period (after flooding), the local recovery should cover both infrastructural and environmental damage and mental/physical illnesses of those affected. Meanwhile, flood-related studies should be conducted; and the flood damage in all aspects (e.g., life, property, and environment) should be assessed [11, 35] in all sub-districts located in all zones of flood risk with varied experiences of flood impacts. These data will be useful for improving the categorization of flood risk zones over time. The local flood contingency plan and mitigation measures should be updated as well based on the results of the latest flood-related studies (Table 2: After flooding). Community consultation and participation [11, 35] are the most important attributes in all three periods of the measure preparations on flood risk management. Local communities should involve in the processes of flood contingency plan preparations, emergency response, recovery, flood-related studies, and so forth. Community involvement is helpful to facilitate the flood risk management measures to be more effective at the local level [11, 32, 35].

Table 2 The specific measures of flood risk management are proposed by this study to each of the four categorized zones of flood risk in the Chao Phraya River Basin

Measures	Risk zones[1]			
	L	M	H	VH
Before flooding (Preparation)				
• Educate local communities about flood risks and relevant impacts in their areas.	√	√	√	√
• Dredge canals, conduits, and water sources for efficiently storing and draining floodwaters to rivers or the sea.	O	√	√	√
• Promote public awareness on flood impacts and reduction of littering and clogging of drainage systems.	√	√	√	√
• Zone flood risk areas out of urban and built-up and industrial areas. These areas should be planned for activities with less flood impacts, e.g., lakes or water parks.	√	√	√	√
• Install early flood warning systems in local communities, which are located along the riverbanks or tend to be flooded during the raining months in their areas.	O	O	√	√
• Prepare a sub-district's flood contingency plan. This plan should cover measures about people evacuation, evacuation routes, shelters, etc. Community participation and consultation are required in preparing the local plan.	O	√	√	√
• Prepare evacuation routes and shelters as indicated in the contingency plan.	O	√	√	√
• Train local officials and volunteers to proper evacuate people, pets, and some property to safe places in case of flooding. Instruments and vehicles for evacuation should be available for prompt and timely use.	O	√	√	√
• Perform local rehearsals about the evacuations of people, pets, and some property from flooded areas to shelters following those indicated in the contingency plan.	O	√[2]	√[3]	√[3]
• Prepare leaflets containing monthly flood risk maps of each sub-district during the rainy period (May–October) and distribute them to local officials, village heads, and people who are at risk or other stakeholders.	O	√	√	√
During flooding (Emergency response)				
• Broadcast daily flood conditions to local communities through local channels (e.g., village loudspeakers, community radio, or Facebook), so that people can promptly and efficiently access the flood-related information and know how to prepare or respond to flooding; as well as, how to ask for assistance or emergency rescue, etc.	O	O	√	√
• Set up local flood watch networks to monitor flooding conditions in and around their communities.	O	O	√	√
• Provide flood kit luggage for residents who live in high and very high flood risk areas, so that they can be equipped to evacuate in a timely manner. The luggage should contain necessary belongings for one's sustenance for a week, such as: - clear and concise instructions about what are included in the luggage and how to use each item. - important food stuffs and other accessories, e.g., dry food, soap, toothpaste, 2-3 sets of quick drying and lightweight clothes that are easy to wash, a towel, slippers, matches, flashlights and batteries, and recommended medicines, etc. - a small tent and lightweight blanket.	O	O	√	√

Table 2 The specific measures of flood risk management are proposed by this study to each of the four categorized zones of flood risk in the Chao Phraya River Basin (*continued*)

Measures	**Risk zones[1]**			
	L	**M**	**H**	**VH**
- lists of telephone numbers of local government agencies and their responsibilities on flood emergency responses.				
- leaflets showing maps and details of shelters or safe places provided for staying in during a flood event and how to get there.				
- suggestions for self-help whilst waiting for assistance, evacuation, etc.				
After flooding (Recovery and flood-related studies)				
• Recover both infrastructural and environmental damage and mental/physical illnesses amongst the affected people.	√	√	√	√
• Conduct flood-related studies and assess the flood damage in all aspects for improving the estimated flood risk severities in the flooded areas.	√	√	√	√
• Update the flood contingency plan based on the latest flood-related studies.	O	√	√	√

Remark: [1]Risk zones: L (low), M (moderate), H (high), and VH (very high); [2]Once, [3]twice before the rainy season; √ = Suggested, O = Unnecessary.

Conclusions

The spatial variations in flood levels and land uses and the temporal variations in the cumulative precipitation across the rainy period contributed to the varied indices of flood risk in association with the four categorized risk zones (i.e., low, moderate, high, and very high) in the CPRB. The sub-districts detected in the zone of moderate, high, or very high flood risk were situated close to the CPR (the major river in the CPRB), where the flood levels were mainly 1.1–2 m deep and some between 2.1 and 4 m deep. To mitigate impacts of prospective flooding in the CPRB, the specific measures on flood risk management regarding each of the four categorized risk zones are suggested during three periods (i.e., before, during, and after flooding). Overall, the preventive and mitigation measures should be well prepared before flooding; emergency responses should be practically implemented during flooding; and the recovery after flooding should cover both infrastructural and environmental damages and mental/physical illnesses of the affected people. Intensive flood risk management measures in these three periods are recommended for the sub-districts located in the high and very high risk zones; whereas the measures may be properly loosened for the sub-districts located in the low and moderate risk zones. Because most of the flood-related data in the CPRB were unavailable for including in this study; thus, relevant flood studies should be further conducted when more data are available. These would be useful for improving the estimation of flood risk indices and updating the associated risk zones in the river basin.

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