United Nations
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International
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Programme

Catalogue of Hydrologic Analysis for Asia and the Pacific

Volume 1

Flood Hazard Mapping

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Flood Hazard Mapping

The UNESCO-IHP Regional Steering Committee for Asia and the Pacific

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Preface

It is our great pleasure to present the first volume of the Catalogue of Hydrologic Analysis for Asia and the Pacific. This volume focuses on flood hazard mapping in Asia and the Pacific and contains six documents from Indonesia, Japan, Republic of Korea, Malaysia, Myanmar and Philippines. It is a new outcome of the international co-operation of the countries which form the Regional Steering Committee for Asia and the Pacific (RSC) under the auspices of the UNESCO International Hydrological Program Phase VIII (IHP-VIII, 2014-2021), which follows the publications of the Catalogue of Rivers in the region.

The objectives of the publication of the Catalogue of Hydrologic Analysis are:

- To promote mutual understanding of hydrology and water resources of the region and of the neighboring countries.
- To promote information exchange among different organizations in each country.
- To share information on water-related issues such as disaster preparedness, water environment conservation, and water resources management in Asia and the Pacific.

In the Asia and the Pacific region, various hydrologic analysis methods have been applied for designing hydraulic structures and river improvement works for rainfall-runoff predictions, flood inundation mapping and other purposes. These hydrologic analysis methods and experiences have different characteristics in terms of climate, topography, and development history of the catchments. Developing a platform to share these experiences and hydrologic analysis methods would help improve the ability for risk estimation and water-related hazard damage reduction; especially for some of researchers and engineers in certain countries and sectors in the region who have limited knowledge and experiences with these hydrologic analysis methods.

To improve this situation and enhance risk estimation ability in research and engineering communities, meetings of the IHP Regional Steering Committee for Asia and the Pacific (RSC-AP) has discussed the formation of a research team and the development of a hydro-informatics platform in the Asia and the Pacific with the objective of realizing hydro-hazard resilient Asia. With the objective enhancing regional capacity for evaluating water-related disaster risks, the RSC-AP decided to develop a Catalogue of Hydrologic Analysis (CHA) through collaboration among researchers and engineers in Asia and the Pacific. The Catalogue collects documents including various experiences and hydrologic analysis methods from practical use to advanced studies for short-term rainfall prediction, rainfall-runoff prediction, flood inundation mapping, hydrologic frequency analysis, eco-hydrology, and more. These resources are freely accessible through the CHA home page.

By developing and sharing knowledge through CHA, RSC-AP provides a platform to improve the ability for evaluating water-related disaster risks, which in turn will strengthen cooperation among researchers, governmental agencies and private sectors; serve to reduce the damage of water-related disasters; and stand as a regional contribution to achieve the targets of SDGs and UNESCO IHP-VIII.

We would like herewith to express our sincere appreciation and due respect to all the individual contributors towards this volume from across the region. We also express our sincere gratitude to the many institutes, agencies and other organizations who have carried out the work reflected in its contents. In particular, we would like to thank the following organizations for providing the necessary support:

- UNESCO Office Jakarta
- The Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, which provides funds to support UNESCO IHP activities in Asia and the Pacific

The editors hope that this volume may serve in various ways to further fulfill related national and regional objectives. Finally, we invite readers to provide critical comments and ideas to improve future volumes of the Catalogue.

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Flood Risk Assessment with High Spatial Resolution for Flood Disaster Mitigation with Climate Change Scenario

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Abstract

One of the important components in flood disaster risk reduction is the availability of spatial information on flood risk that include: flood discharge (q), flood depth (h), flood extent (A), flood duration (t), and the loss value due to flood which could be quantified in the form of damage costs (θ). Change in the value of risk f(h, A, t, θ) was hypothesized to be sensitive to climate change and other environmental factors that exist at a river basin area. Therefore, it is quite important to control the flood disaster risk as a part of adaptation programs to the climate change impacts and to deal with the increasing pressure due to anthropogenic activities. Additionally, to support the action plan and to increase the understanding and awareness related to the flood disaster mitigation, spatial information on flood risk which having high resolution and precision is required. This study aimed to quantify the spatial information of flood risk with high spatial resolution. 2-D flood-modelling system (e.g., rainfall-runoff-inundation), climate change projection and risk assessment have been used as the main method. Furthermore, this study has been focused in the Batanghari River basin, Sumatera and 13 river catchments flowing through Jakarta Capital City, Indonesia. Obtained risk information forms the basis for long term management decisions on improving operational flood risk management, especially in order to cope with impacts of the future climate change.

Keywords: climate change, flood risk, flood disaster mitigation, Batanghari River, Jakarta

1. Introduction

Indonesia, geographically and hydro-topography, is very susceptible to the occurrence of various types of natural disasters especially those related to water related problems such as floods, droughts, and landslides. Indonesia, which has abundant water resources, has approximately 5,590 rivers and 600 of them are potentially at high risk of flooding. In total, the extent of flood prone areas within the main river reaches 1.4 million hectares. National Disaster Management Agency (BNPB) quantify the number of location, frequency and intensity of occurrence, as well as the value of losses from the flood disaster are continue to increase within the last 50 years.

Based on the BNPB information (http://www.satuharapan.com/read-detail /read/tren-bencana-banjir-meningkat-514-korban-setiap-tahun), floods and landslides in Indonesia tend to increase. BNPB mentioned that in 2003 there were 266 incidents of floods and landslides and increased to 822 incidents in 2013. In that period, there are 6,288 events or 572 events per year, cumulatively. The highest number of flood and landslide incidents occurred in 2010, which was 1433 events.

Many studies have demonstrated that there are two factors that cause flooding. First, natural events such as very high rainfall (extreme weather) and sea level rise. This condition is exacerbated by the fact that many people live in locations with topographic conditions lower than the river water levels or below sea level. For example, flood event that occurred in some areas of DKI Jakarta Province due to excessive groundwater extraction process and subsequent land subsidence. Second, human activities that cause excessive pressure on land use demands and later it effects the changes in ecosystem function and environmental degradation.

If there is no more integrated and mitigation effort based on societal participation, then the changes in climate and land use, which will become more intensive in the future, it is hypothesized that it will to continue to contribute to the increase of flood hazard and its risk, especially in river basins that have national strategic value. Therefore, the implementation of adaptation program including disaster mitigation in response to climate change at the river basin scale is urgent to be carried out. In this regard, quantification of risks with a strong scientific basis and a higher level of spatial resolution and accuracy are necessary. Another fact, although climate change-related research is already underway, studies of climate change impact projection on flood risk are still limited in Indonesia. Therefore, this paper presents the concept of spatial quantification of flood risk in river basin scale with high precision by considering the function of climate change and anthropogenic factors.

2. Study area and method

Batanghari River basin (47,479.54 km2) that situated in Sumatera Island, and 13 river basin (6,070.00 km2) flowing through DKI Jakarta Province, the capital city of, Indonesia, are selected as study sites. According to the climate projection analyses which focused on the change of average monthly rainfall depth especially in December (peak of rainy season), these two study sites are hotspot locations that will experience with an increase in the number and intensity of rainfall during the future climate period.

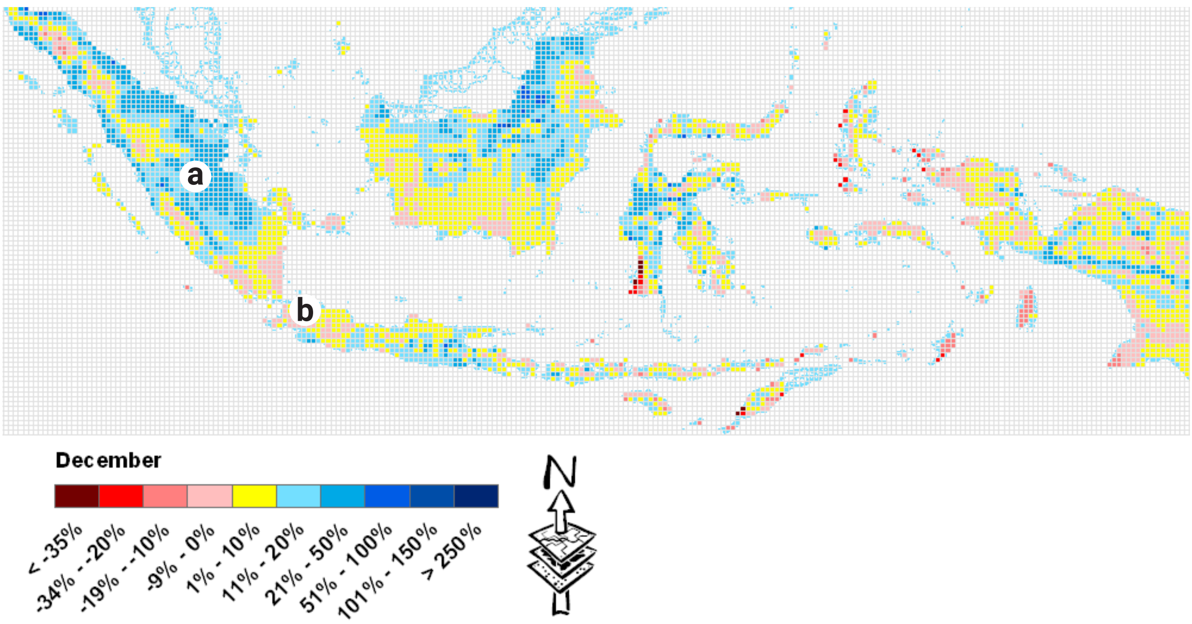

Figure 1 Projected changes in average monthly rainfall (%) for December in the period of 2075-2099 compared to the average rainfall of December in the period 1979-2004; (a) Batanghari River basin and (b) 13 river basins flowing through Prov. DKI Jakarta, the capital city of Indonesia.

The Batanghari River basin represents a large river basin area dominated by forests, plantations, and agriculture land uses. An intensive conversion of land use from forest to agriculture encountered in this basin. Meanwhile, 13 river basins in Prov. DKI Jakarta classified as small to moderate basin area. Type of land cover in this area is dominated by settlements, paddy fields, and moor. Along with the increase in population and economic activity, in these study areas, there has been a significant intensification of land use conversion, especially from agricultural land use to settlements. As a result, the two selected sites have the same relative problem of increasing the intensity and frequency of flood disasters although they have different flood types and characteristics.

The amount of flood risk determines the magnitude of the disaster level and the level of losses. The formulation of flood risk in this study is based on the equation as follows (Tariq et al, 2013):

$$Flood\ Risk = \frac{Flood\ Hazard\ x\ Exposure\ x\ Susceptibility}{Control\ Measures} \qquad (1)$$

Flood risk value is affected by the magnitude of the flood hazard; biophysical condition of river basin which is represented by the vulnerability factor, and; existing flood control measures. Dynamics changes of the flood hazard values are quantified based on the changes of flood dimension that consists of: flood discharge (q), flood depth (h), flood extent (A), and flood duration (t). Flood hazard dimension is strongly influenced by the duration and intensity of extreme rainfall with probabilities of occurrence P. The vulnerability factor of river basin biophysical component can be explicitly determined by the exposure and susceptibility. Nevertheless, in this study both factors were implicitly quantified in the form of damage costs (θ). If flood risk unit given in the form of loss value in terms of rupiah (Rp) then equation 1 can be simplified as follows:

$$Flood\ Risk\ (Rp) = f\left(P(t, q, h, A), \theta\right) \qquad (2)$$

3. Results and discussion

Spatial information of flood risk in Batanghari River basin and DKI Jakarta Province in the form of maps had been made by BNPB in cooperation with several related agencies (Figure 2). Based on Figure 2, it can be seen that the flood risk maps created and used at the present time are inadequate in the following terms: (1) the information provided is qualitative, i.e. in the form of hazard or strength levels categorized in low, medium and high; (2) the spatial resolution is still low, administrative units such as districts or sub-districts generally serve as the smallest unit of risk identification, and (3) climate change factors have not been included as important variables in the flood risk map creation process. In order to provide more detailed flood risk maps, the concept of flood risk quantification conducted in this study will create flood hazard maps with high spatial resolution. The map created in quantitative way based on hydrological process mechanism-flood propagation including climate change aspect.

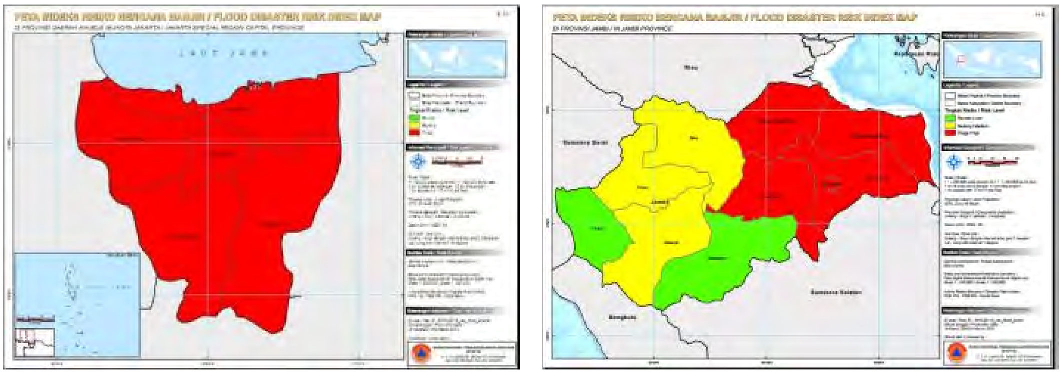

Figure 2 Map of flood disaster risk index for DKI Jakarta (left)
and Batanghari watershed in Jambi Province (right).

Figure 3 shows the concept for quantifying spatial flood risk for selected river basin. Modeling the process mechanism of runoff and flood distribution spatially inside the river basin is the main method for quantifying flood hazard dimensions such as q, h, A, and t. The rainfall-runoff-inundation model is one type of hydrological model suitable for use in the calculation of the flood hazard dimension (Sayama et al., 2012). The smallest unit of area within a model able basin depends on the spatial resolution required, known as grid. For large basin cases like Batanghari River basin, 500 m - 1 km resolution is used, while for 13 DAS in Jakarta smaller resolution (10 m - 90 m) is used. Furthermore, the temporal dynamics of the flood hazard dimension for each location (grid) are converted into the unit of damage values based on the flood dimension relationship curve and the value of losses made based on the data of the inventory of losses generated from the historical flood disaster that ever happened.

In addition, considering the diversity values of soil and topographic properties within the catchment, the quantification of each flood dimension variables is based on the: (1) input of probability data of extreme rainfall events (Hosking & Wallis, 1997) with t-day duration and return period N-year, and (2) land use type which indirectly represents the influence of anthropogenic factors. To find the impact of climate change and anthropogenic factors, at least two climatic periods (Apip, 2014) and different types of land use includes the current conditions and future projection, should be used in the analysis.

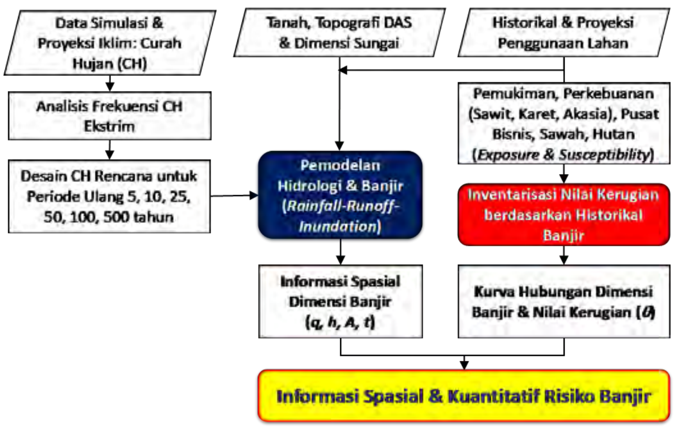

Figure 3 Concepts (frameworks) for spatial quantification of flood risk of watershed scales in scenarios of global climate change impacts and increased anthropogenic factor stresses.

One of the outputs of this research is spatial-temporal information of flood risk. Mathematically, it is formulated as a function of several components, namely: flood flow discharge (q), flood depth (h), flood inundation extent (a), flood duration (t), and economic losses value, which are quantified in the form of damage costs (θ). The q, h, A, and t variables are the three variables that naturally (due to extreme rainfall) affect the flood hazard. Furthermore, the magnitude θ is very influenced by high flood hazard and conditions of vulnerability and resilience of existing biophysical conditions within the watershed, in particular the condition of the community and infrastructure facilities of flood control (exposure & vulnerability components).

For example, the development of spatial flood hazard distributions under climatic change conditions has now been established for both selected sites. The criteria for extreme rain are based on rainfall data that causes major flooding. The flood incident of February 2002 in Jakarta and the flood incident of December 2003 in Batanghari watershed was chosen as the basis for the selection of extreme rainfall category. The spatial and temporal information of extreme rainfall in both locations can be seen in Figures 4 & 5.

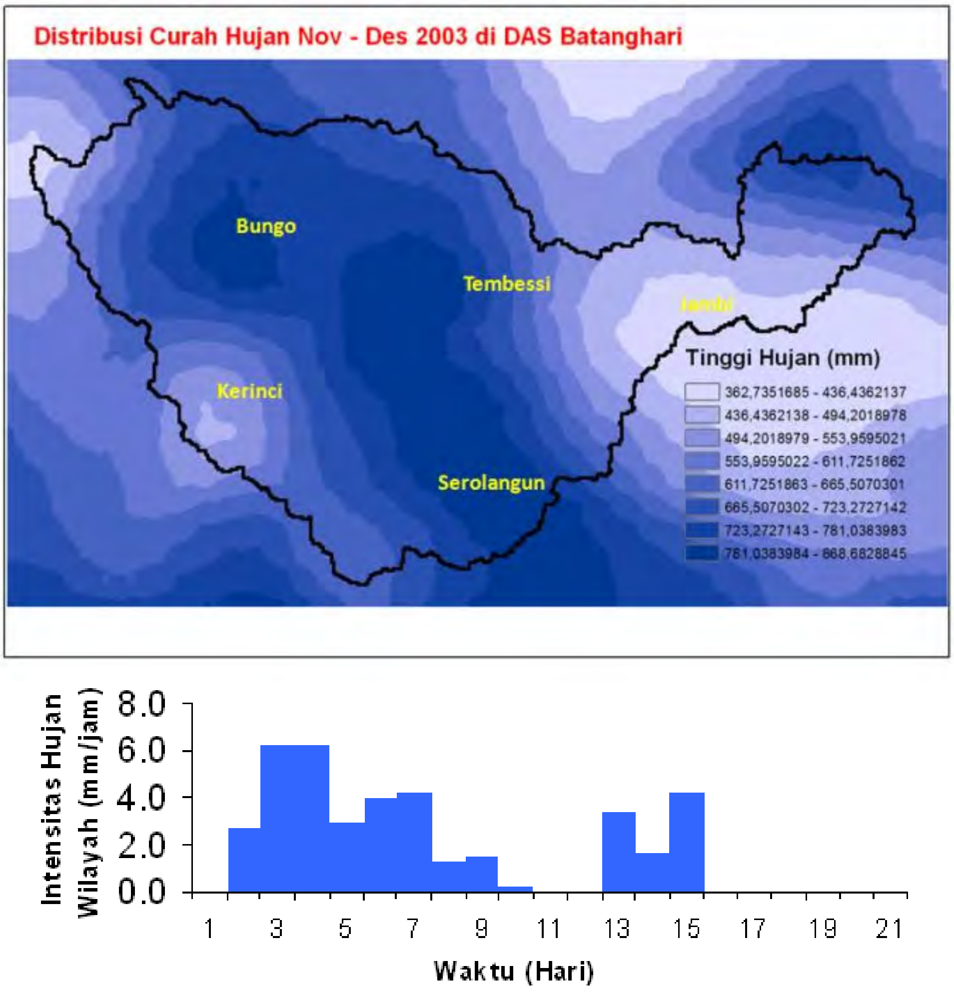

Figure 4 (a) Spatial distribution of cumulative rainfall (mm) during November-December 2003 in Batanghari river basin (above) and (b) The average extreme rainfall design of Batanghari river basin area made based on rainfall during the flood event of December 2003 (below).

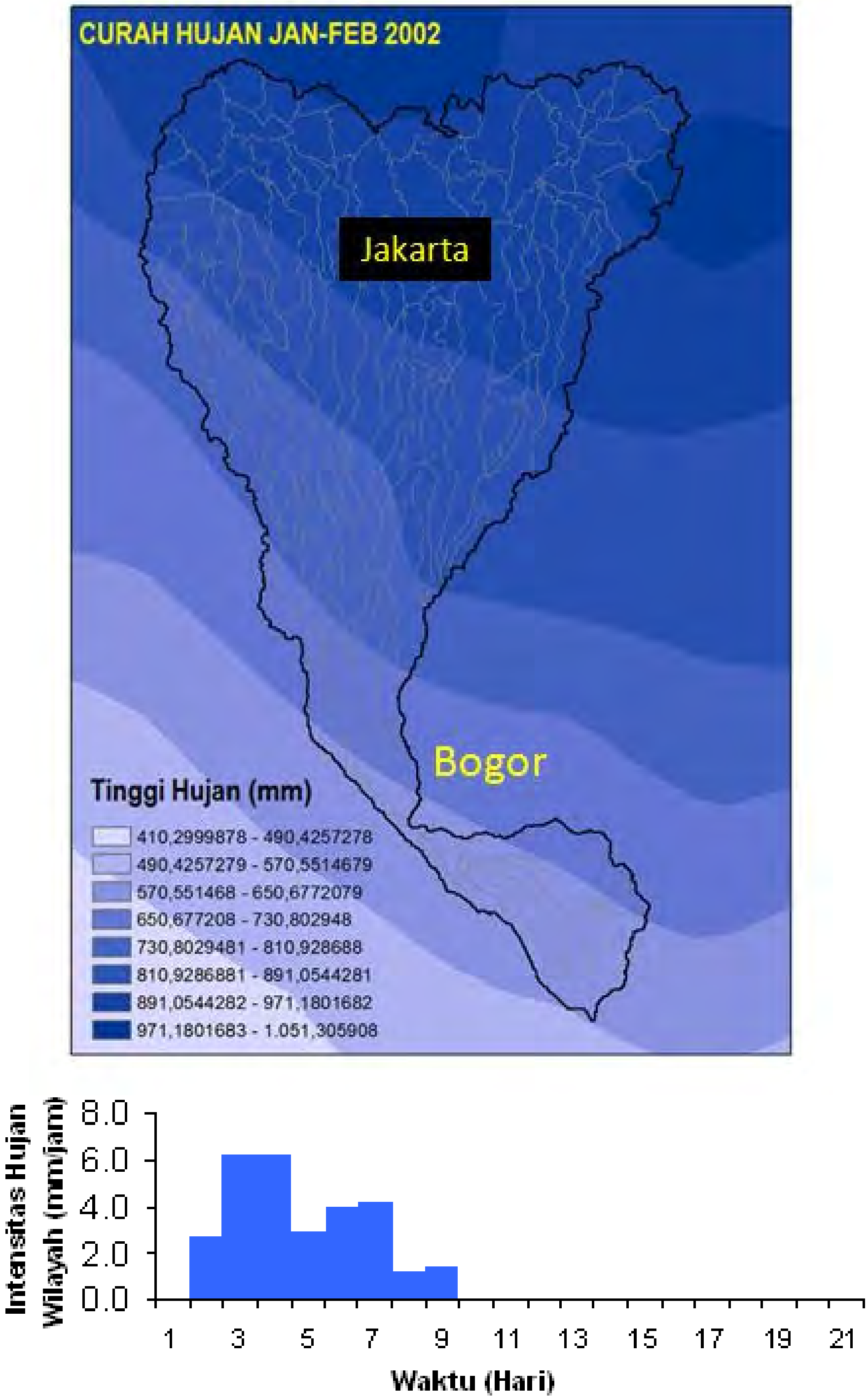

Figure 5 (a) Spatial distribution of cumulative rainfall from January to February 2002 in Jakarta and surrounding areas (above) and (b) The average extreme rainfall design of the area in 13 river basins through Prov. DKI Jakarta made based on rainfall during the flood event in January 2002 (below).

Subsequently, by using the calibrated rainfall-runoff-inundation distribution model, the spatial information of the flood hazard components in unit h is shown in Figure 6 & 7. The initial flood hazard simulation results in both locations show good spatial information. For Batanghari watershed, flood propagation through all areas had been categorized into flood-prone areas with medium-high category. Those areas spread from the middle to downstream of the watershed. Likewise for Jakarta, the propagation of flood hazard dimensions through the usual locations affected by floods, namely the downstream of the watershed, especially North Jakarta, West Jakarta, and Central Jakarta.

The flood dimension relationship curve especially h with the value of losses that may occur for various types of land use is then used to generate spatial flood risk information with unit of loss value, for example in rupiah nominal. More detailed and quantitative information is expected to help the user, especially BNPB, adding detail information flood risk map that has been made previously.

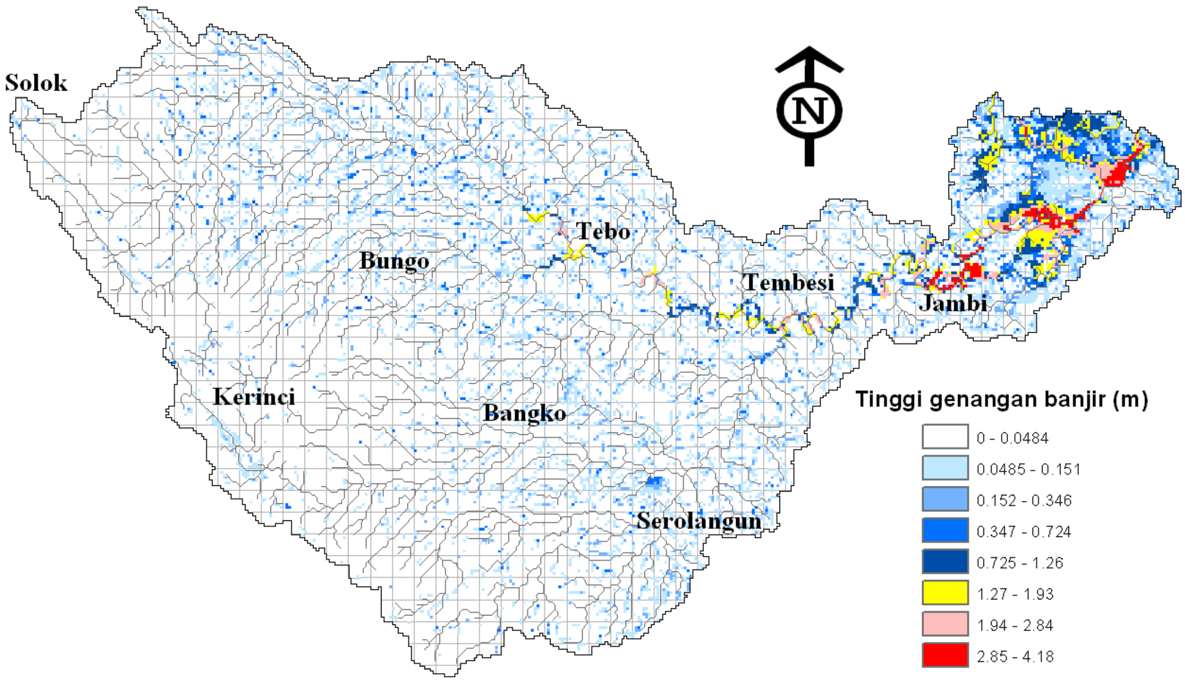

Figure 6 Flood hazard spatial information in Batanghari River basin delineated from the simulated flood inundation depth (m) which occurred in December 2003.

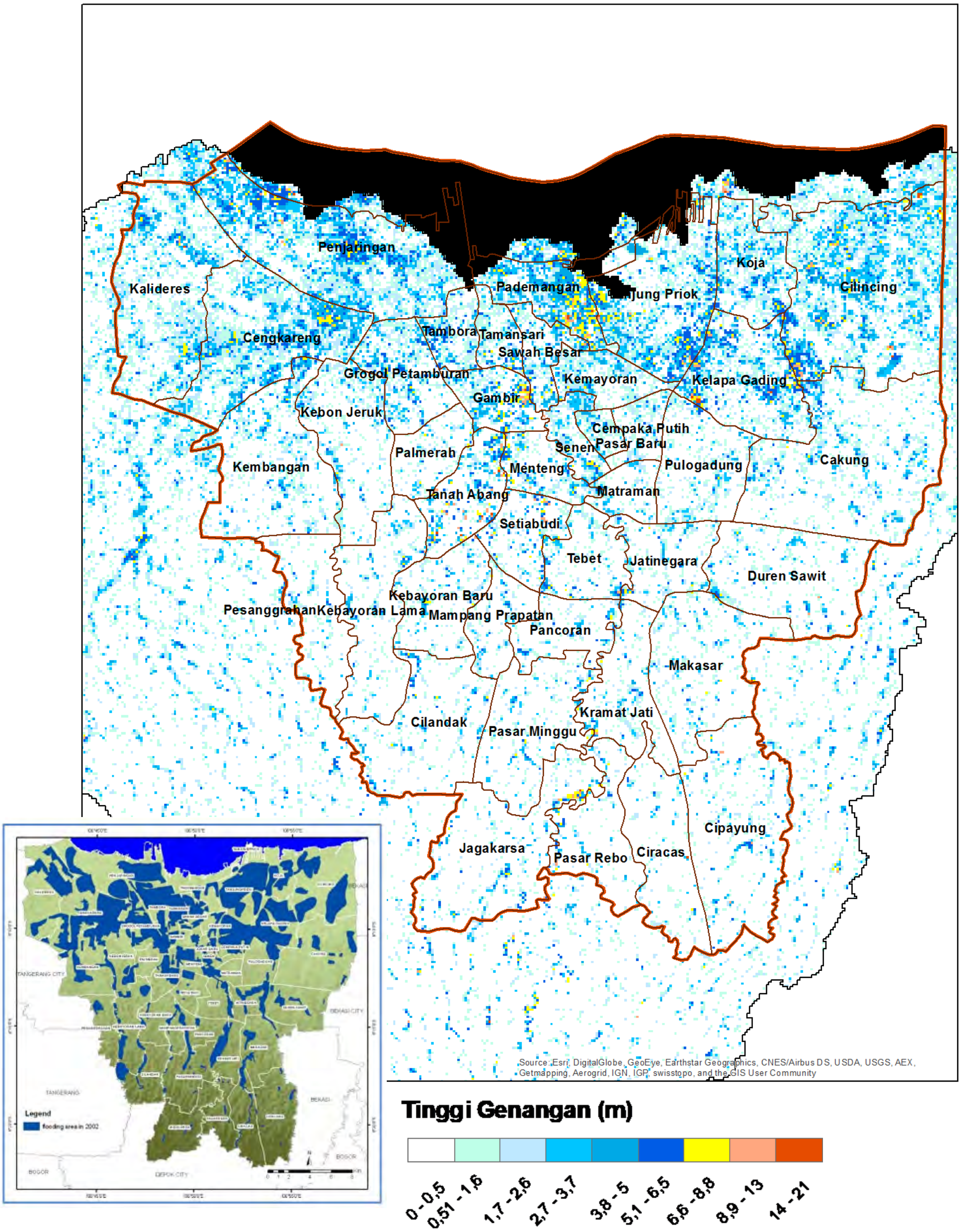

Figure 7 Flood hazard spatial information for the Jakarta Capital City of Indonesia, it was delineated from the simulated flood inundation depth (m) which occurred in February 2002. The spatial information of the inundation pattern can be compared with the observed inundation pattern (observed; bottom left picture).

4. Conclusion

The concept of spatial risk formulation by incorporating aspects of climate change and anthropogenic factors, had been made and applied in the Batanghari River basin and 13 River basins that flow through the Jakarta city. physically-based distributed hydrological modeling system, called rainfall-runoff-inundation model, was used as the main method in quantifying flood hazard dimensions (q, h, A, t). The relationship curve between flood hazard dimensions and its economic loss values were made based on the damage inventory data, collected from the historical flood disaster events. Furthermore, the curve was used for the conversion of flood hazard dimension units in each location (square grid) and land use type into damage costs.

In order to investigate the impacts of climate change and anthropogenic factors, at least two different climatic periods and types of land use, the current conditions and forward-looking results, was used in the analysis.

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Flood Hazard Mapping in Japan

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Abstract

This chapter aims to present the details of flood hazard mapping in Japan. The flood inundation mapping methodology used by Government of Japan is briefly described followed by the explanation on how the flood inundation modeled by MLIT and Prefectural Governments are used to prepare flood hazard maps by municipality/city governments. The uses of flood hazard maps are explained in details for the Kyoto City (as a case of Kyoto Prefecture) and the Omihachiman City (as a case of Shiga Prefecture) in Yodogawa River Basin. Finally, the institutional roles, legal frameworks, good practices and lessons learned about the flood hazard mapping are described in brief.

1. Introduction

1.1 Japan flood disaster statistics

The Infrastructure Development Institute of Japan and Japan River Association estimates about 49% of the population and 75% real estate in Japan are located in alluvial plains exposed to flooding risk [1]. The annual damage amount caused by water-related disasters in Japan from 1966 to 2010 is shown in **Figure 1**. The total flood inundated area was in the range of 100-200 thousand ha during 1966-1985. It shows a declining trend from 1982 onwards as a result of several years of flood control efforts. The annual flood inundated area (mostly with built or residential areas) was slightly above 50 thousand hectares (ha) in 1977. It has decreased over time as a result of various flood damage prevention systems such as widened channels and embankments, detention basins, floodways, and dam, etc. However, the density of property damage (the amount of damaged general assets) in inundated areas shows an increasing trend. The primary reasons are the continued population and general assets growth and increased urbanization-suburbanization in flood hazard areas. To avoid future flood damages in various forms, it is essential to understand the drivers of the flood risk and prevent anticipated damages by planning flood management strategies in advance.

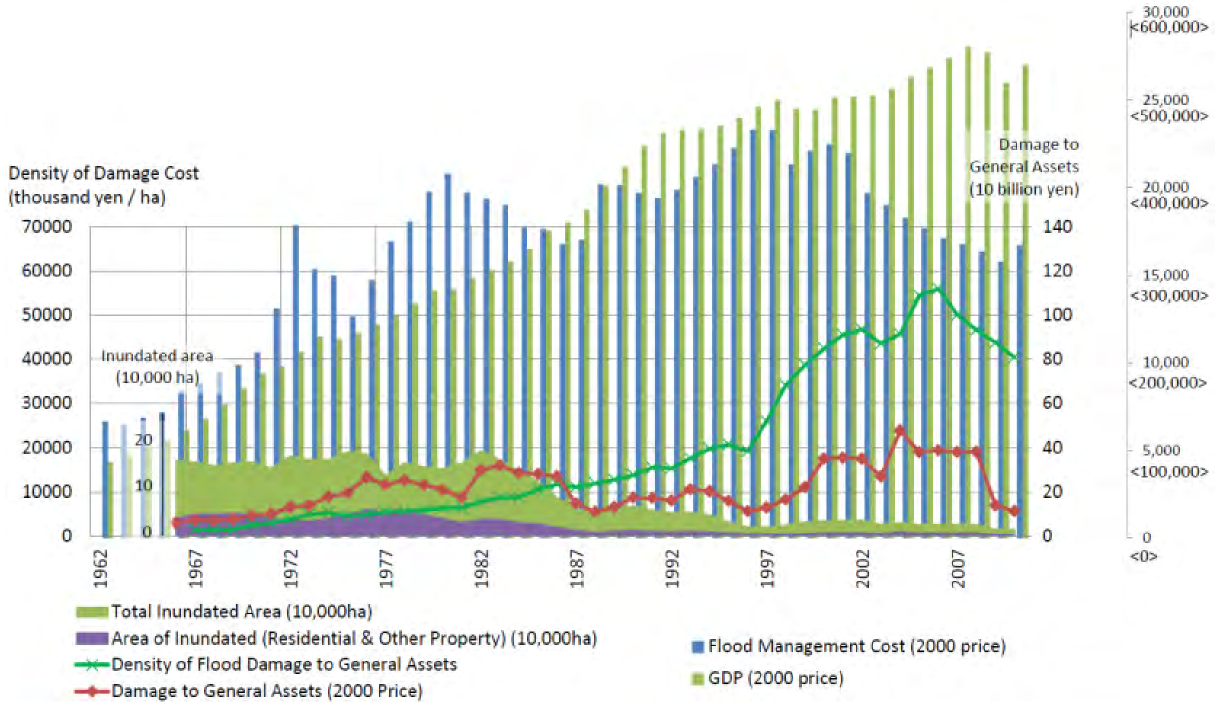


Figure 1 The annual damage caused by water-related disasters in Japan (adapted from [2])

1.2 Purpose of flood hazard mapping

For planning efficient flood management strategies in advance it is important to understand the flood risk. The flood risk is a function of flood hazard (the possibility of extreme flood event), exposure (the population and general assets in flood inundation areas), and vulnerability (the susceptibility of the exposed population and general infrastructure to flood hazard) [3]. The flood hazard in this chapter is defined as the possibility of flood inundation with different scenarios. The flood hazard map is a basis for understanding the exposure and vulnerability components of the flood risk. It provides the spatial information of flood inundation area, inundation depth and duration in a geographical region against the various scenarios of extreme rainfall events and determines the exposure of population, economic assets in the area likely to experience the damage. It serves as a reference tool for decision making, planning and implementation of flood preparedness and management strategies [4]. The flood hazard map is useful for the following purpose:

- To get advanced insights into the likelihood of the future flood events, exposed population, and ability to cope up with the event
- To inform residents about the probability of inundation in advance and raise their awareness
- To design guidelines for residents on how to act during a flood emergency
- To design evidence-based flood evacuation plans and search and rescue operations during a flooding event mainly useful for municipalities

- To estimate expected damages by flood in different areas
- To develop flood management plans and guidelines for infrastructure planning and future investments, etc.

The details of flood hazard mapping in Japan is explained in the following section.

2. Flood Hazard Mapping in Japan

2.1 Methods to develop flood hazard map

In Japan, flood hazard maps are mainly prepared by the Ministry of Land, Infrastructure, and Transport (MLIT) and Prefectural governments (local municipalities) using inundation information. The steps being currently used by MLIT to prepare flood hazard maps in Japan are given in the following sub-sections.

2.1.1 Flood inundation model: Shallow Water Equations

MLIT [5] uses the following shallow water equations (SWE) for the simulation of flood inundations areas:

$$\gamma\frac{\partial Q_x}{\partial t}+\frac{\partial}{\partial x}\left(\gamma\frac{Q_x^2}{h}\right)+\frac{\partial}{\partial y}\left(\gamma\frac{Q_xQ_y}{h}\right)+g\gamma h\frac{\partial(h+z_b)}{\partial x}+g\gamma n^2\frac{Q_x\sqrt{Q_x{}^2+Q_y{}^2}}{h^{7/3}}+\frac{1}{2}C_D'(1-\gamma)\frac{Q_x\sqrt{Q_x{}^2+Q_y{}^2}}{h}=0$$

$$\gamma\frac{\partial Q_y}{\partial t}+\frac{\partial}{\partial x}\left(\gamma\frac{Q_xQ_y}{h}\right)+\frac{\partial}{\partial y}\left(\gamma\frac{Q_y^2}{h}\right)+g\gamma h\frac{\partial(h+z_b)}{\partial y}+g\gamma n^2\frac{Q_y\sqrt{Q_x{}^2+Q_y{}^2}}{h^{7/3}}+\frac{1}{2}C_D'(1-\gamma)\frac{Q_y\sqrt{Q_x{}^2+Q_y{}^2}}{h}=0$$

$$\frac{\partial h}{\partial t}+\frac{\partial(\gamma Q_x)}{\partial x}+\frac{\partial(\gamma Q_y)}{\partial y}=q$$

where, *Qx*, *Qy* are the discharges per unit width in x and y directions, *h* the water depth, z_b the bed elevation, *γ* the porosity, *q* the rainfall, inundation from the sewerage, etc., *n* the roughness coefficient according to the land use, C_D the drag coefficient. The spatial resolution (grid size) for the model simulation of the Yodogawa River Basin is 25 m x 25 m.

2.1.2 Levee breach conditions

The amount of the flow overtopped from the river is estimated using modified Honma's overflow formula (as used in Manual for Economic Evaluation for Flood Control Investment, 2005, MLIT) [6].

a. Honma's front-overflow formula:

For complete overflow (for $h_2/h_1 < 2/3$),

$$Q_0 = 0.35\ h_1\sqrt{2gh_1}\,B$$

For submerged overflow (for $h_2/h_1 \geq 2/3$),

$$Q_0 = 0.91\ h_2 \sqrt{2g\,(h_1 - h_2)}\ B$$

where Q is overflow discharge through structure and h_1, and h_2 are the water depth measured from the bed height of a breached levee.

b. Honma's side-overflow formula:

Inundation discharge (Q) following a levee breach is given by:

For I > 1/1580,

$$\frac{Q}{Q_0} = \left(0.14 + 0.19\ \times \log_{10}\left(\frac{1}{I}\right)\right) \times\ \cos\left(48 - 15\ \times log_{10}\left(\frac{1}{I}\right)\right)$$

For 1/1580 ≥ I > 1/33600,

$$\frac{Q}{Q_0} = \left(0.14 + 0.19\ \times \log_{10}\left(\frac{1}{I}\right)\right)$$

For 1/33600 ≥ I,

$$\frac{Q}{Q_0} = 1$$

where Q is inundation flow, Q_0 is flow volume calculated by Honma's formula, I is bed slope of a river, and B is the width of the crest. The unit of "cos" in the parenthesis is "degree."

2.1.3 An approach to estimate maximum inundation depths

The steps to prepare flow inundation area map using SWE and levee breach conditions are shown in **Figure 2.** In step 1, it is assumed that the levee breach has occurred at two or more locations simultaneously. It is assumed that inundation starts at or above the designed high water level in the river. The levee breach is assumed at a point if the water level in the river is greater than the designed high water level of the river. In step 2, inundation depths are simulated for individual levee breach points. Step 3 overlays the inundation maps (for two or more levee breaches) obtained in step 2 to estimate maximum inundation depths. Finally, in step 4, the maximum inundation depth maps are distributed to local governments, and other stakeholders, etc. The MLIT disseminate flood inundation maps through its 'Hazard Map Portal Site' at https://disaportal.gsi.go.jp/

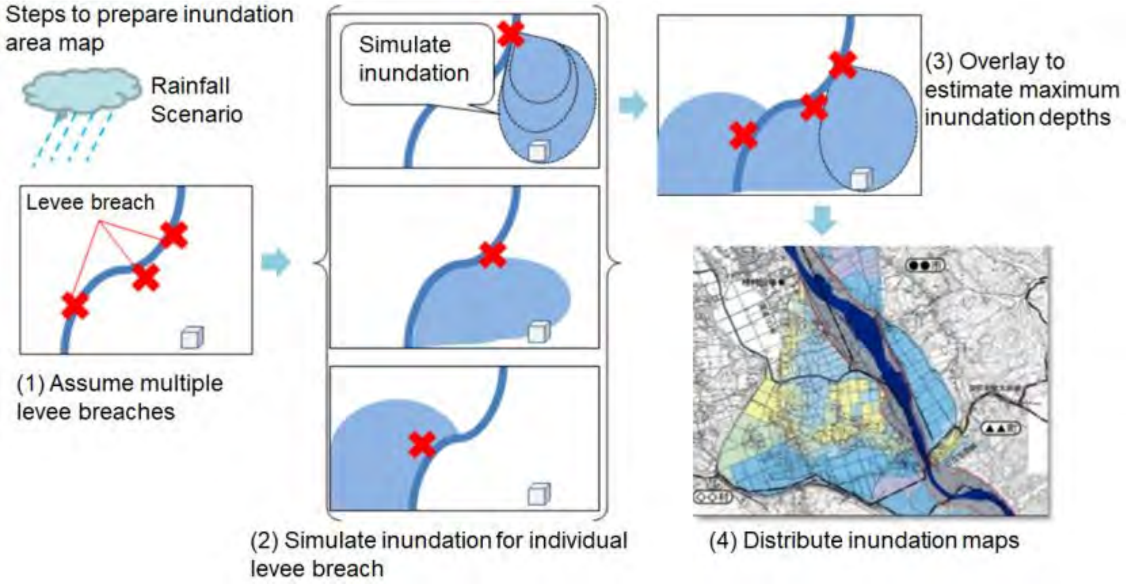


Figure 2 Steps to prepare the inundation area map (Source: MLIT [7])

2.2 Scenarios of external force to develop flood hazard map

According to the Flood Fighting Act (FFA) amended in 2014 the river administrators, MLIT and prefectural governments should design the area that might be inundated during the flooding events. The act specifies that two rainfall scenarios should be considered as inputs to simulate flood hazard (inundation area) maps. The first scenario is to use the design-rainfall used for the river works as input to simulate flood inundation. In case of the Yodogawa River, the design rainfall is assumed equivalent to 200-year return period (261 mm in 24 hours) while the upstream tributaries assume comparatively smaller return periods (150-years): for the Uji River (164 mm in 9 hours), the Kizu River (253 mm in 12 hours) and the Katsura River (247 mm in 12 hours).

The second scenario is to use the largest-scale (worst case) rainfall as input to simulate flood inundation. Based on rainfall patterns, the whole Japan is divided into 15 regions, and Depth-Area-Duration (DAD) analysis is conducted using recorded maximum rainfall in each region. **Figure 3** shows the DAD relationship for the Kinki region. The average basin rainfall can be estimated from DAD analysis and typically exceed or equivalent to 1000-year return period. If the historical maximum rainfall observed is less than the rainfall corresponding to the exceedance probability of 1/1,000 (360 mm/24 hr), then the rainfall corresponding to that exceedance probability is used for the simulation as maximum rainfall in the worst-case scenario. The historical maximum rainfall observed in the Hirakata station (Yodogawa River Basin) is 314 mm in 24 hrs which is less than 360mm in 24 hrs. Hence the rainfall by DAD analysis for the Yodogawa River Basin is assumed to be 360 mm in 24 hours for the simulation, whereas for its major tributaries: for the Uji River is 356 mm in 9 hours; for the Kizu River is 358 mm in 12 hours; and for the Katsura River is 341 mm in 12 hours.

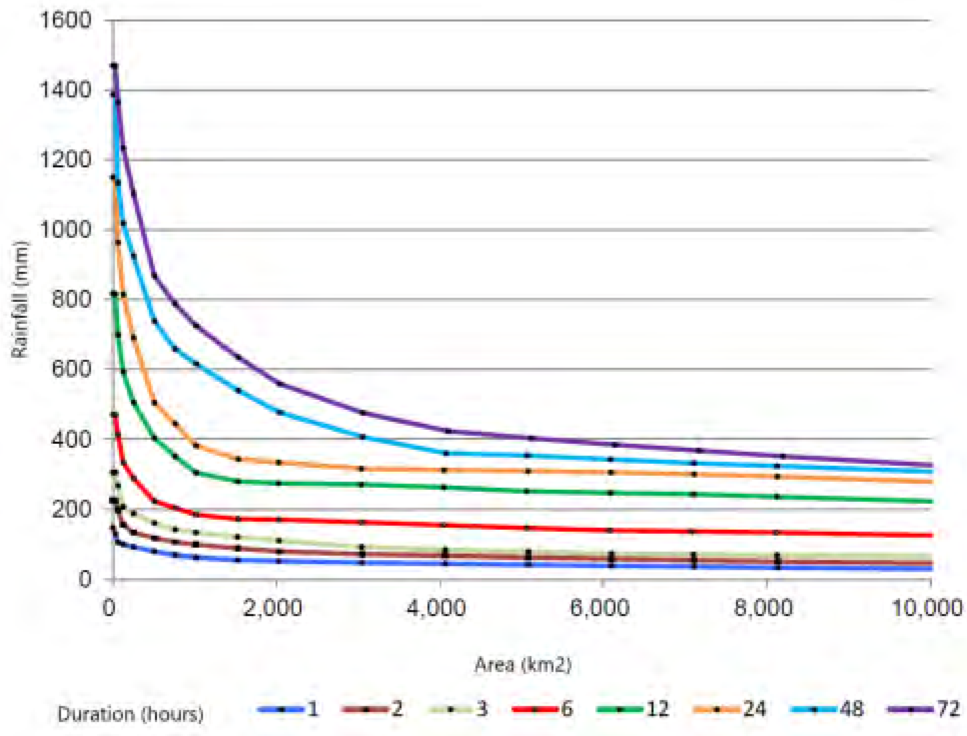


Figure 3. DAD analysis for the largest-scale scenario (e.g., Kinki Region). [8]

The inundation simulation maps are prepared by MLIT using the second scenario in combination with steps in subsection 2.1. The prefectural government may use the flood inundation map (25m X 25m) prepared by MLIT to plan mitigation activities during flood events for decision making, planning, and implementation of flood management strategies. However, the prefectural governments can also develop their own inundation models using different tools. For example, the Shiga Prefectural government uses own model for flood inundation simulation (50m X 50m). In addition to MLIT and prefectural governments' flood simulation models, a list of commonly used flood inundation models in Japan is given in **Appendix A**.

3. Flood Hazard Map of the Yodogawa River Basin

3.1 Location

The Yodogawa River Basin located in the central part of Japan is shown in **Figure 4**. The length of the Yodogawa River is 75 km. It is the seventh largest river basin in Japan with a catchment area of 8,240 km2 [9]. Flowing south out of Lake Biwa, the largest lake in Japan, first as the Seta River and then the Uji River, it merges the Kizu River and the Katsura River near the border between Kyoto and Osaka Prefectures. The Yodogawa River runs through the heartland of the Kinki region and flows into the Osaka Bay. The Yodogawa River basin consists of six sub-catchments, which are the Lake Biwa basin (3,802 km2), the Uji River basin (506 km2), the Kizu River basin (1,647km2), the Katsura River basin (1,152 km2), the lower Yodogawa River basin (521 km2) and the Kanzaki River basin (612 km2). It extends over six prefectures namely Shiga, Kyoto, Osaka, Hyogo, Nara, and Mie [10].

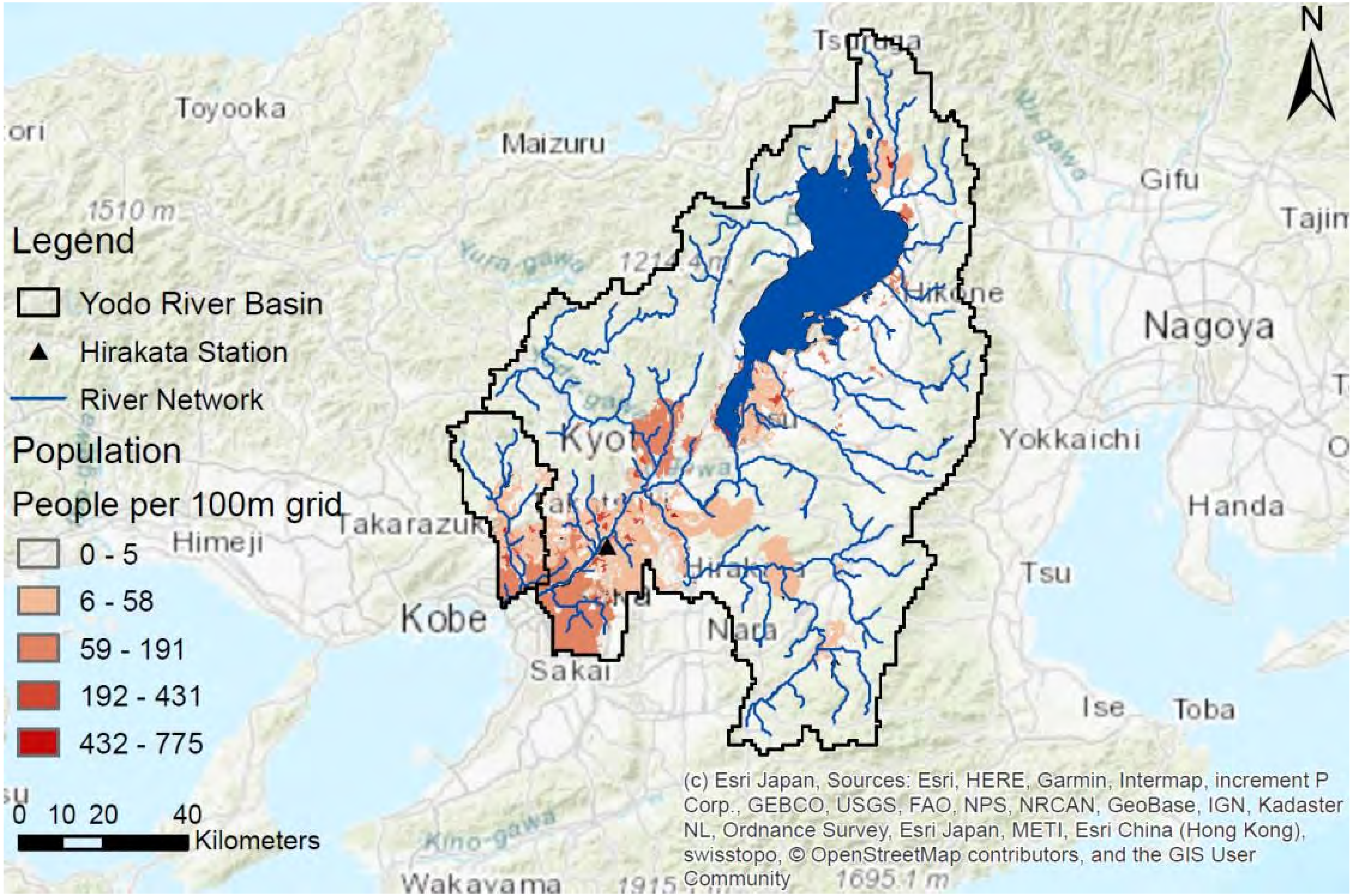


Figure 4 Location of Yodogawa River basin in Japan (The figure is prepared in ArcMap 10.6.1 using data from the Geospatial Information Authority of Japan (GSI), HydroSHEDS, WorldPop [11] and ArcGIS online).

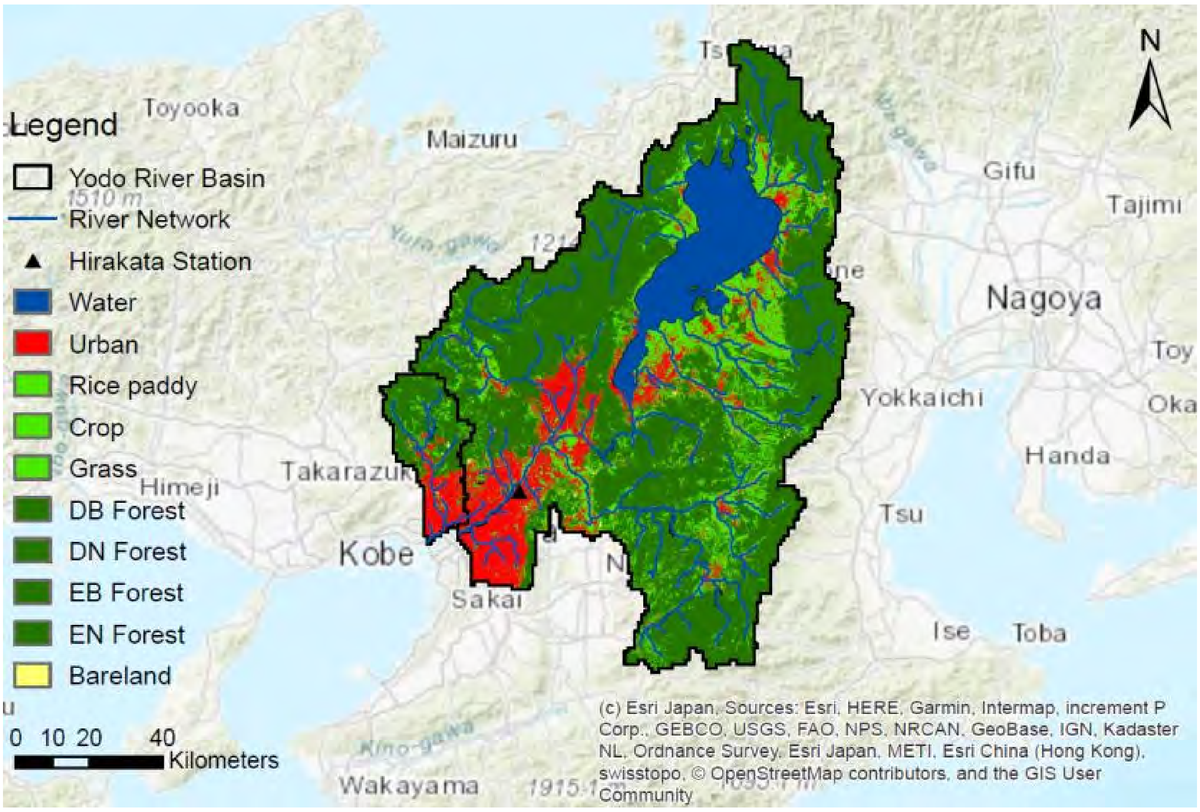
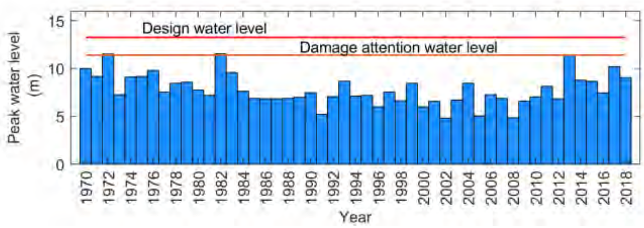


Figure 5 Land use map of the Yodogawa River Basin (The figure is prepared in ArcMap 10.6.1 using data from JAXA EORC [12] and Geospatial Information Authority of Japan (GSI), HydroSHEDS, and ArcGIS online)

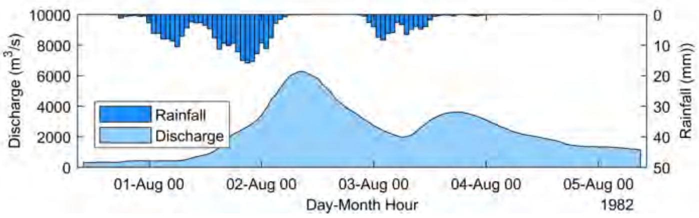
City areas spread throughout the basin as shown in **Figure 5**. Metropolitan areas such as Osaka, Kyoto, and Otsu are located along the rivers. The population in the basin is about 9.30 million in 2015 [11,13]. In the lower Yodogawa River basin, most of the highly populated urban developments are in areas lower than the river water level. In Osaka City, it is estimated that 94.9% of the total metropolitan area is in the flood-prone area [10].

3.2 Hydrologic characteristics

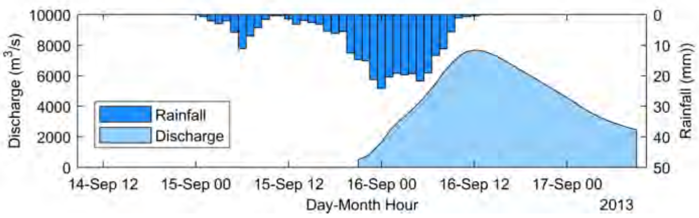
The mean annual rainfall of the Yodogawa River Basin is 1,600 mm. The rainfall in the basin is widely distributed in time and space. The annual precipitation of the Lake Biwa sub-basin, the Katsura River sub-basin, the Kizu River sub-basin, and the lower Yodogawa River sub-basin are about 1,880 mm, 1,640mm, 1,590mm, and 1,400mm, respectively [10]. The major flood events in the Yodogawa River Basin are shown in Figure 6. During 1970 -2018, 1972, 1982 and 2013 the water level at Hirakata station (location shown in Figure 4 and 5) in the basin exceeded the 'Damage attention water level' and caused flooding in the basin.



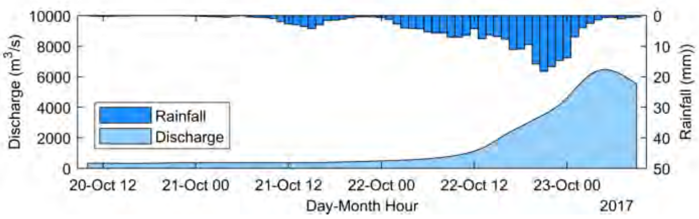
Observed peak water level at Hirakata Station [14]



Hydrograph: Typhoon No. 10 in 1982



Hydrograph: Typhoon No. 18 in 2013



Hydrograph: Typhoon No. 21 in 2017

Figure 6 Major flood events in the Yodogawa River Basin (Rainfall: Average rainfall in the Upper Catchment area above Hirakata station; Discharge: Discharge recorded at Hirakata station. Discharge during 2017 is a temporary estimate) [15].

3.3 Flood hazard map

The simulated flood hazard map of Yodogawa River Basin with 25 m X 25 m resolution is shown in Figure 7. The second scenario of the external force, i.e., the amount of rainfall 360 mm in 24 hours is used to simulate flood inundation depth. The estimated inundation areas cover approximately 144 km2 in Osaka prefecture and 121 km2 in Kyoto prefecture where Osaka City and Kyoto City are major urban areas, respectively. The maximum inundation area is anticipated in Osaka City is about 62 km2 with an average inundation depth 2.4 m ranging from 2.6 to 7.2 m. The maximum inundation depth of 8 m is anticipated in Takatsuki City in the Osaka prefecture. The model simulated about 40.9 km2 inundated area in Kyoto City around Katsura River (and its major tributary Kamo River) and Uji River. The average inundation depth of 2.7m is anticipated in Kyoto City ranging from 1.9 to 7.4m.

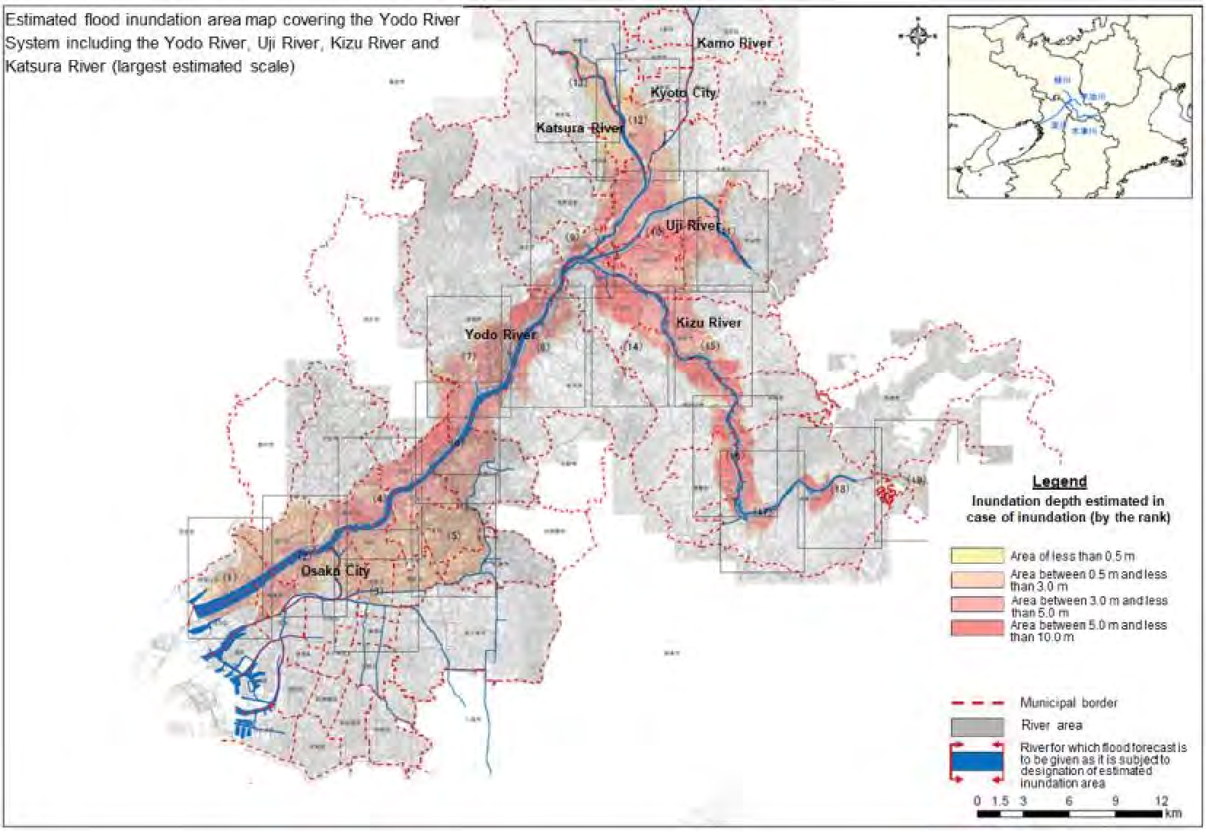


Figure 7 Estimated flood inundation area map of the largest estimated scale of the Yodogawa River Basin (Source: MLIT [16]). Authors have translated the important legend to English.

4. Usage of Flood Hazard Maps

Flood hazard maps prepared by MLIT are useful for the city and prefectural governments to design flood mitigation strategies as explained in the Introduction section. Following are the specific examples of usage of flood hazard maps.

4.1 Flood hazard mapping: Kyoto City in Kyoto Prefecture

Example of the flood inundation map (25m X 25m mesh size) of the largest estimate scale prepared by MLIT for the wards of Kyoto City is shown in **Figure 8**. The Prefectural and City Government use this map as a reference to design flood management strategies.

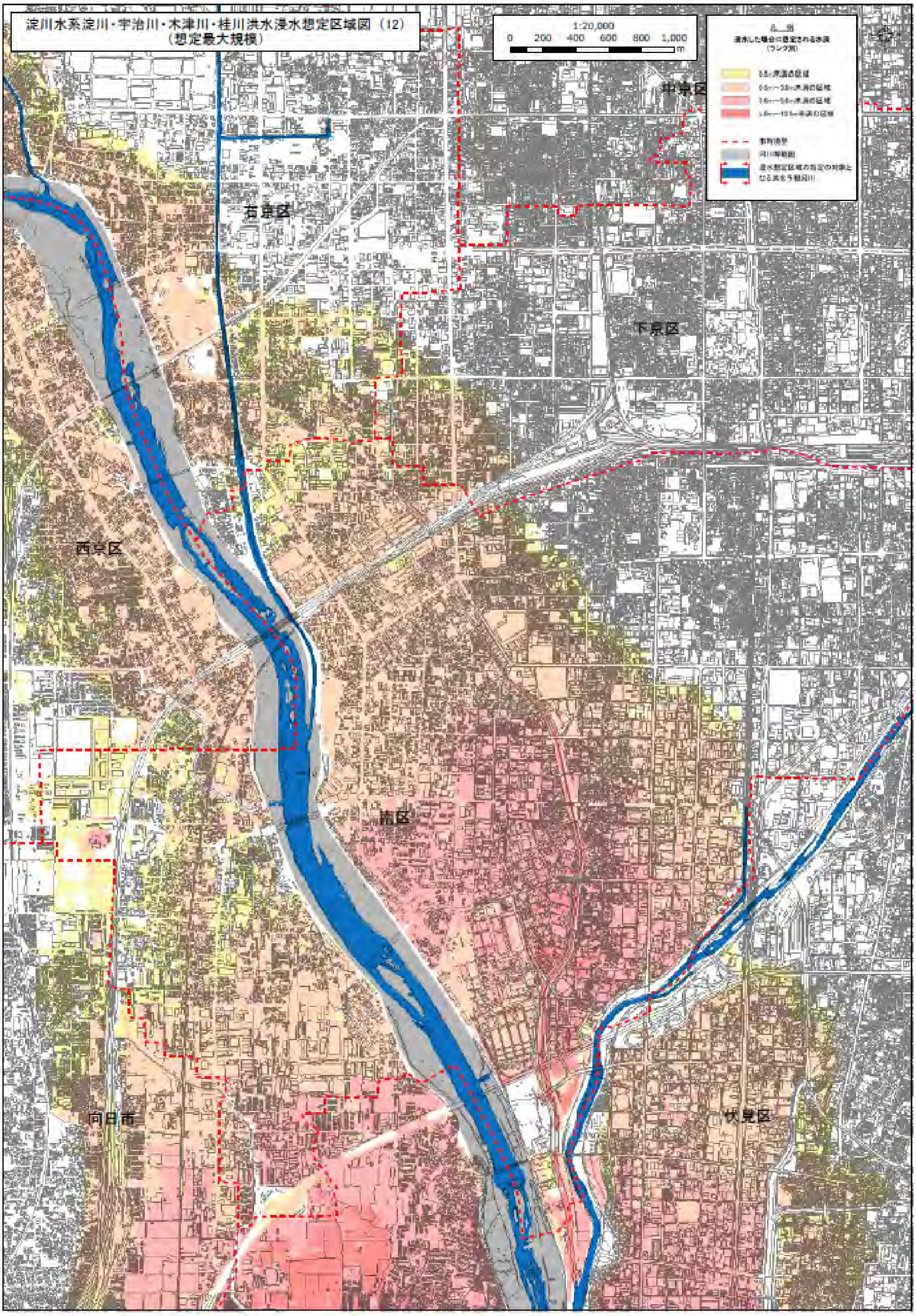


Figure 8 Estimated flood inundation area map of the largest estimated scale (zone 12 in Figure 7) for Kyoto City: Nishikyo-ku, Ukyo-ku, Shimogyo-ku, Minami-ku, & Fushimi-ku (MLIT [16]). Authors have translated the important legend to English

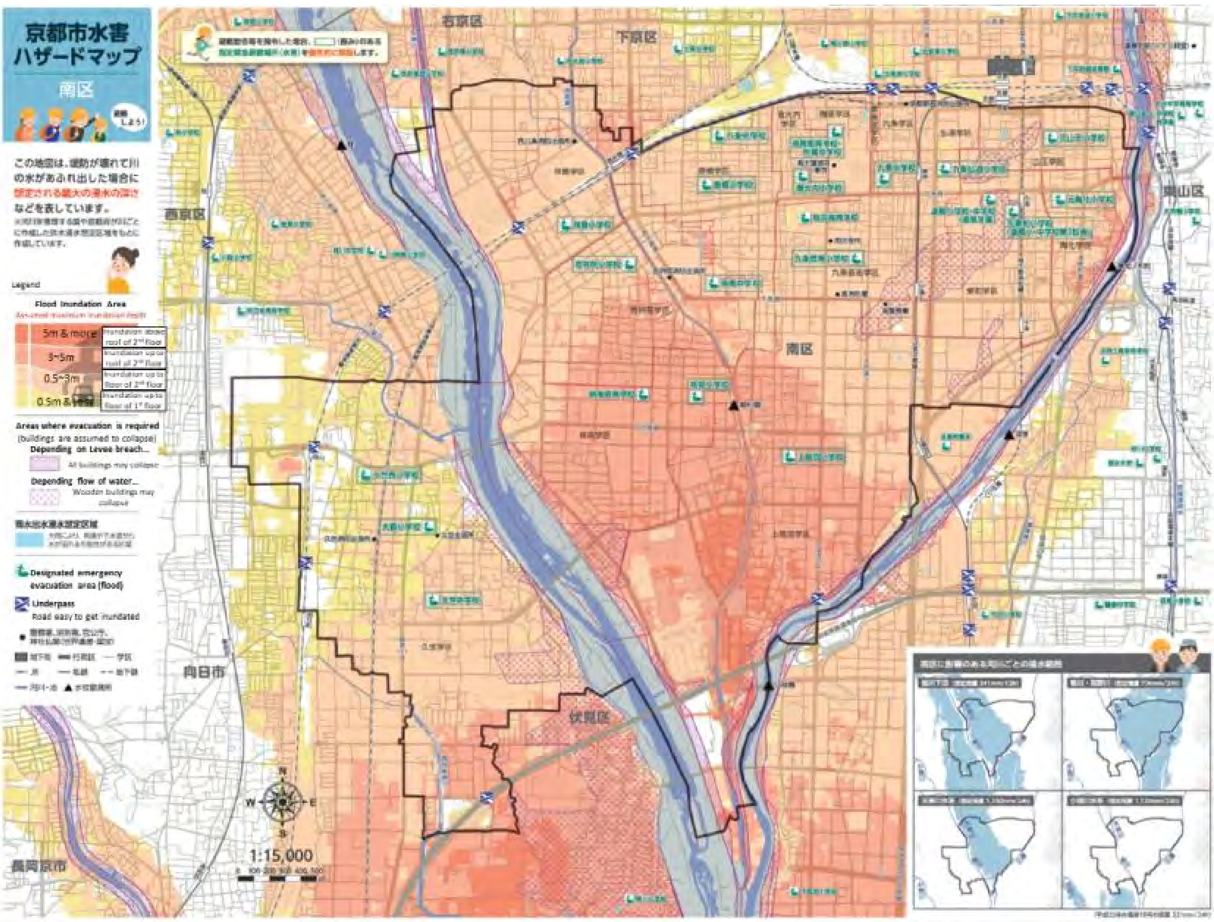


Figure 9 Flood hazard map of Kyoto City, Minami-ku (at the largest estimated scale) by MLIT downloaded from Kyoto City Government Website [16,17]. Authors have translated the important legend to English.

The MLIT is responsible for the inundation map of the Katsura River and Kyoto Prefectural government is responsible for the inundation map of the Kamo River. The inundation depths obtained from the MLIT and Kyoto Prefecture Government is used in **Figure 9**. The flood hazard map (largest estimated scale) for the Minami-ku ward of the Kyoto City prepared by Kyoto City Government is shown in **Figure 9**. The major bullet point information shown on the map is summarized as: This map shows the maximum depth of flooding with levee breach assumption. It is based on the flood inundation map created by river management authority (Yodogawa River Bureau – MLIT, Kyoto Prefectural Government). The legend shows the maximum inundation depth assumed. 0.5 m (inundation in the first floor), 0.5-3.0m (flooding to the floor of the second floor), 3.0-5.0 m (Inundation to the roof of the second floor), 5.0m (the flood water level above the second floor). It also shows the areas where buildings are expected to collapse, the sewers where water may overflow, and temporary evacuation shelters during the flooding event, etc.

With reference to the flood hazard map shown in Figure 9, Kyoto City government has prepared the easy to understand evacuation needs and actions as shown in Figure 10. Information on when-, why-, how-, and where- to evacuate is designed using the flood inundation maps.

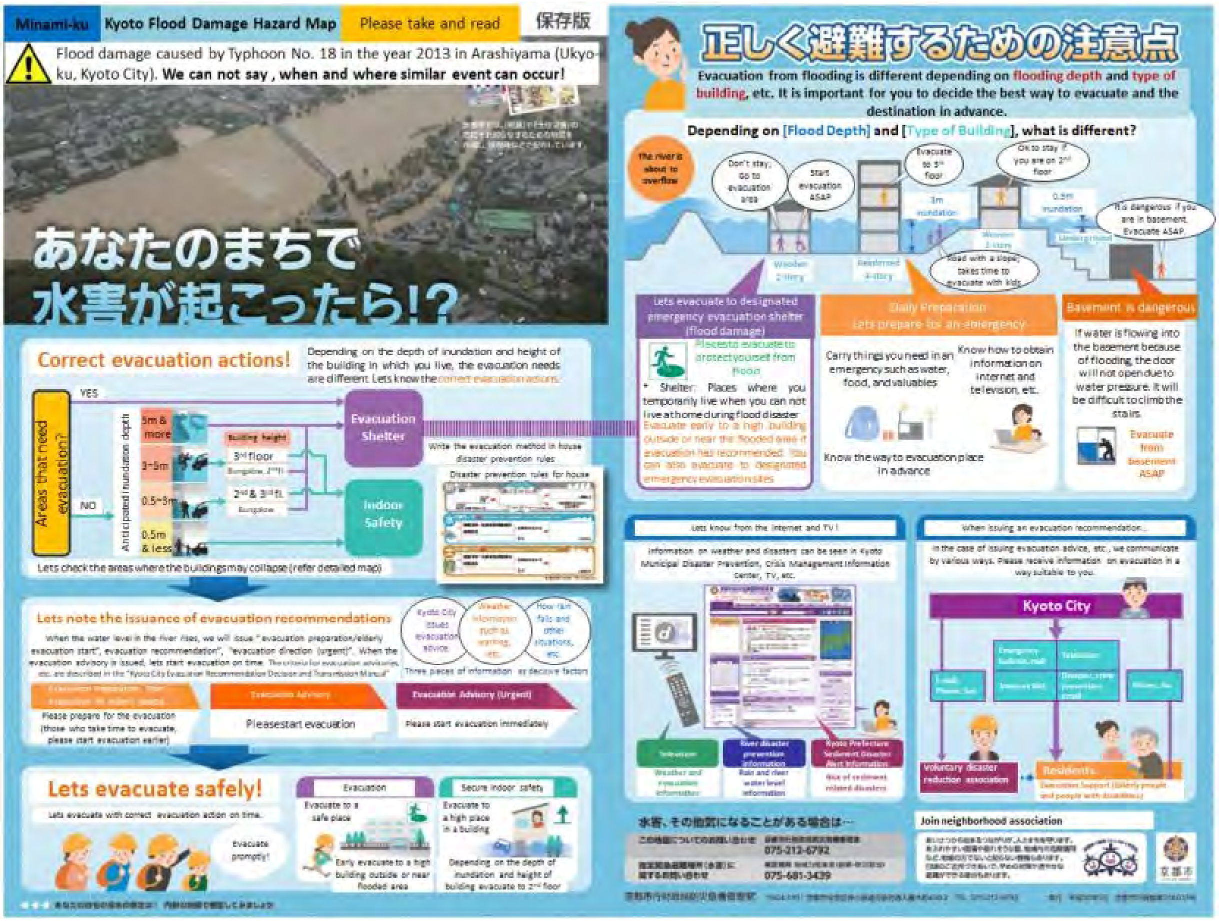
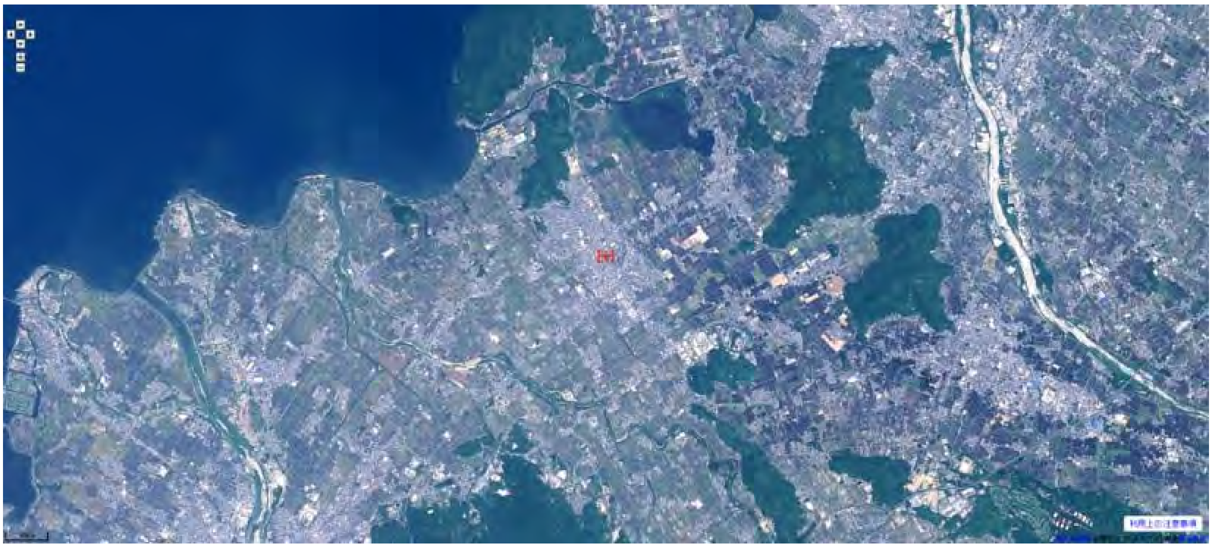


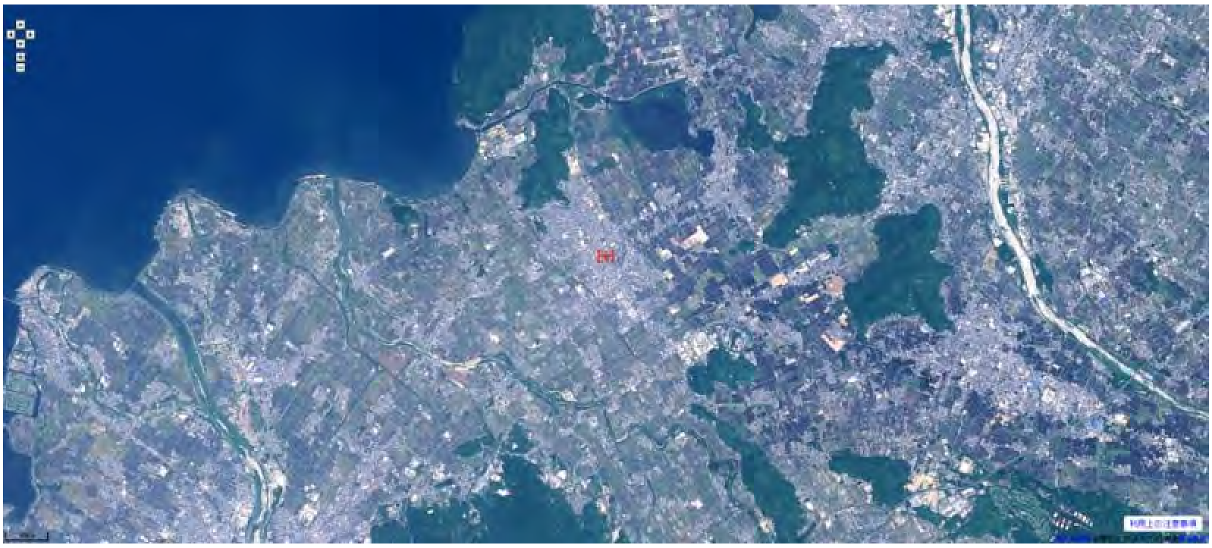
Figure 10 Basic information added to the flood hazard map for safe evacuation by Kyoto City Government [17]. Authors have translated the Japanese version to the English for an easy understanding.

4.2 Flood hazard mapping: Omihachiman City in Shiga Prefecture

The Shiga Prefectural Government has developed a numerical flood simulation model to simulate the flood inundation in 50m X 50m mesh size [18,19]. The model predicts rainfall-runoff, channel flows, overland flow and plain flow considering topping or breach processes. The numerical model details are given in [18]. For inundation simulation, the rainfall 10, 30, 50, 100, 200, 500, and 1000 years return periods assumed uniform over the study area in combination to the three types of levee breach conditions. **Figure 11** (b, c, d) shows the inundation simulation for the Omihachiman City in Shiga prefecture for rainfall input as 10, 100, and 200 years return period. The probability of the inundation above the ground floor (inundation depth > 0.5m) on the flood hazard risk map for the Shiga Prefecture is shown in **Figure 12**.

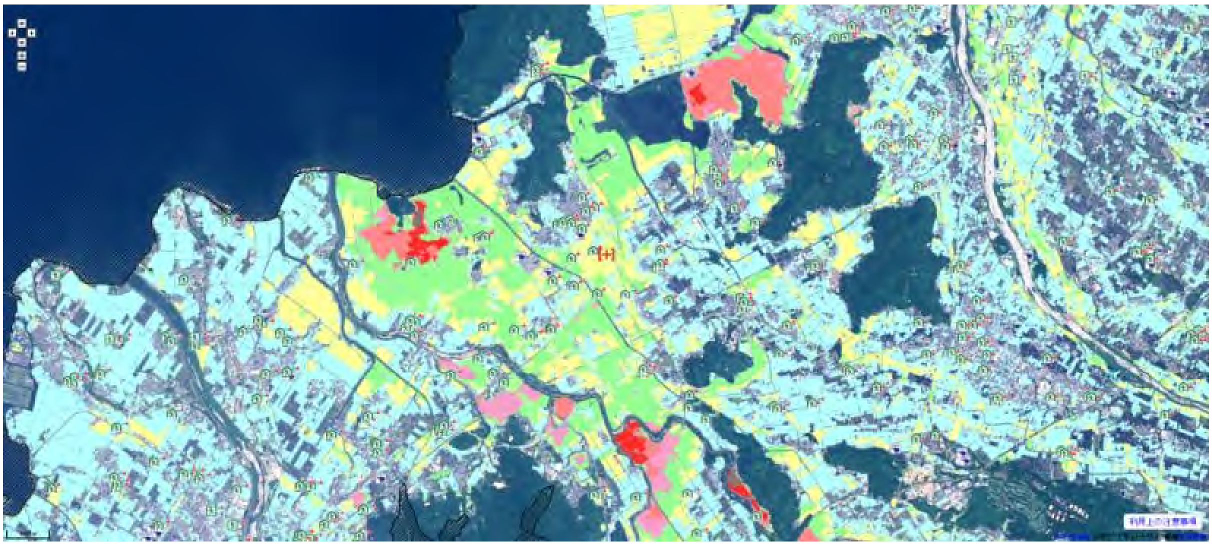


(a) Aerial photograph of Omihachiman City in Shiga Prefecture

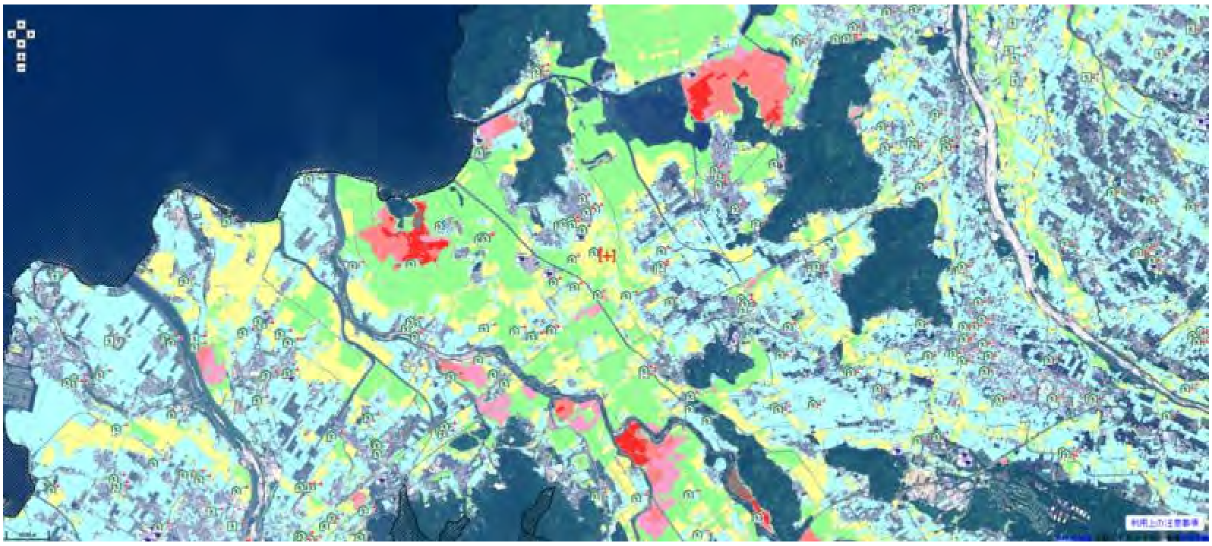


(b) Prob. of maximum inundation depth (50 mm/hr rain; once in 10 years)

Figure 11 Flood hazard map for Omihachiman City in Shiga prefecture (Source: Prepared by authors using screenshots from Shiga Prefectural Government Website http://shiga-bousai.jp)



(c) Prob. of maximum inundation depth (109 mm/hr rain; once in 100 years)



(d) Prob. of maximum inundation depth (131 mm/hr rain; once in 200 years)

Figure 12 Flood hazard map for Omihachiman City in Shiga prefecture (Source: Prepared by authors using screenshots from Shiga Prefectural Government Website http://shiga-bousai.jp)

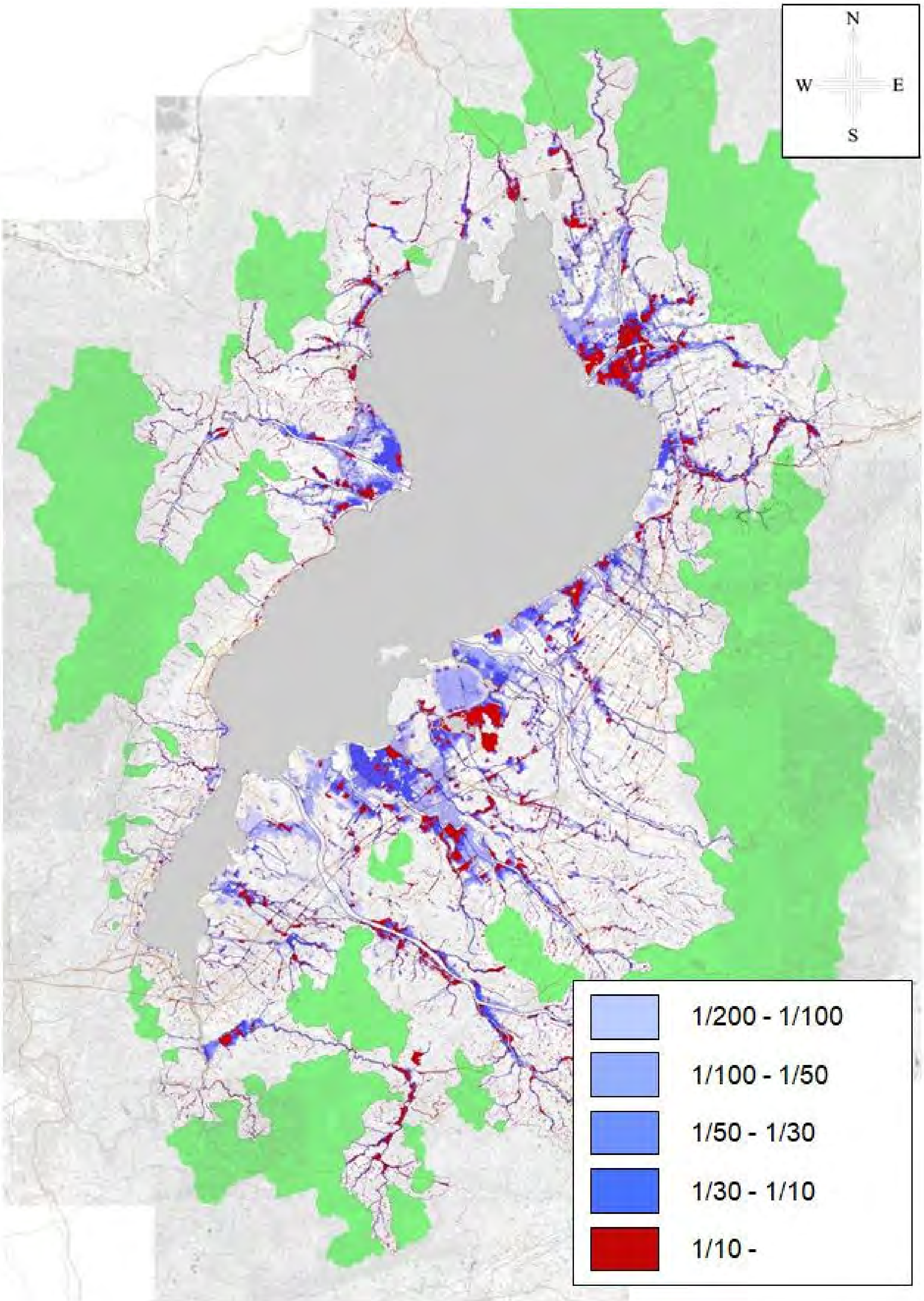


Figure 13 Probability of the inundation above the ground floor (inundation depth > 0.5m) on the flood hazard risk map for the Shiga Prefecture (adapted from [19]).

The flood inundation map with the 100-year return period is used to prepare the flood hazard maps. The example of a flood hazard map for the Omihachiman City in Shiga Prefecture is shown in **Figure 13**.

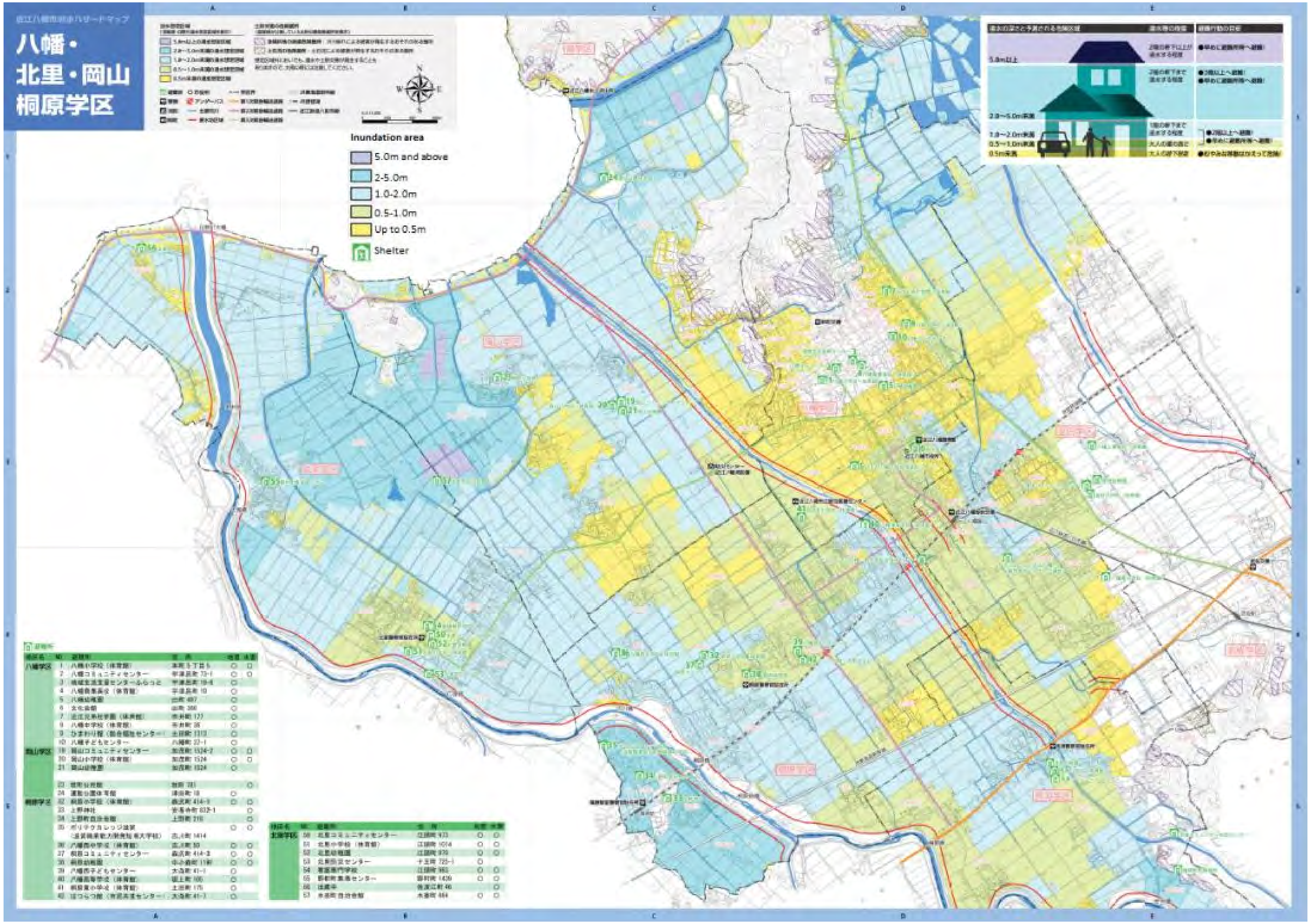


Figure 14 Flood hazard map for the Omihachiman City in Shiga Prefecture. The major legends are shown in English. (Map prepared using the 100-year return period) Source: [20].

5. Institutional and Legal Frameworks for Flood Hazard Maps

5.1 Institutional and legal frameworks

The scope of flood hazard mapping falls under the MLIT River Bureau, Prefectural Governments, and Municipal (City) Governments activities. According to the Flood Control Act (FCA) amended in 2014 [21], the Minister of MLIT and prefectural governments should design the area that might be inundated during a flooding event (Article 14) as shown in **Figures 7, 8, 11,** and **12**. The municipal (City) governments are responsible for the design and dissemination of information in the form of flood hazard maps to residents (Article 15). The examples are shown in **Figure 9** and **13**.

5.2 Dissemination of flood hazard map

Flood hazard maps are widely disseminated in various ways (mainly, pamphlets, online publishing). The MLIT disseminate flood inundation maps through its 'Hazard Map Portal Site' at

https://disaportal.gsi.go.jp/

The flood inundation maps for the Yodogawa River Basin are available at the following website:

http://www.kkr.mlit.go.jp/yodogawa/activity/maintenance/possess/sotei/index.html

Local municipal/prefectural governments' show the maps and evacuation area on their website homepage. Kyoto City provides the Kyoto City flood hazard maps on the following website:

http://www.city.kyoto.lg.jp/gyozai/page/0000237021.html.

The Shiga Prefectural Government provides flood hazard maps on the following website:

http://shiga-bousai.jp/dmap/map/index?l=M_r_k_risk_map&z=&lon=&lat=

6. Good Practices and Lesson Learned

6.1 Good practices

The flood hazard map (or flood hazard risk maps) developed by the city is used for land use and building regulations. For example, the areas in Shiga Prefecture whose estimated inundation depth is greater than 0.5m with ten-year flood return period are prohibited from inclusion in the urbanized promotion area stipulated by the City Planning Law [19]. Also, the Prefectural Flood Management Ordinance stipulates that the real-estate agencies must inform their customers appropriate flood risk information before making a real estate transaction.

The latest hazard mapping is done at a higher spatial resolution (25 m X 25 m mesh grid) with multiple rainfall scenarios and levee breach conditions. In addition to the flood inundation, inundation duration time and house collapse hazard zones are proposed in latest inundation area estimates which are useful for designing the flood hazard map (particularly identify the areas where early evacuation is necessary and location of evacuation shelters).

The information on evacuation routes and shelters is disseminated in advance by using easy to understand hazard maps. The information is also made available through websites and mobile applications.

Depending on the depth of water and type of building, area-specific modes of evacuation, i.e., horizontal and vertical evacuation needs are explained in the flood hazard map.

6.2 Lesson learned, gaps/challenges

The flood hazard maps are a vital tool for future flood preparedness. The Mabicho town of Kurashiki City in Okayama Prefecture experienced the worst flood on July 7, 2018. The flood hazard map designed by Kurashiki Municipal Government before the flood disasters show a good agreement with the areas and depths of the flood occurred on July 7, 2018 [22].

There is a need to increase people's awareness about flood hazard map. It has been found that the people who have not seen the flood hazard map take more time to evacuate (about 1 hour more [23]) than the people who have seen flood hazard map in advance. Hence it is important to increase the individual's awareness of flood hazard-prone areas and evacuation options. In addition to increasing individual awareness, the improvement in reliability of flood hazard maps is essential.

People moved to a new city and prefectures are often unaware of the historical flood information in the region. Hence, the real-estate agencies should inform their customers about appropriate flood risk information prior to the transaction.

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Appendix A

Examples of software used for flood inundation simulation in Japan

1. Rainfall-Runoff Inundation (RRI)

   The RRI model is a two-dimensional model capable of simulation the runoff and flood inundation using rainfall, digital elevation model (DEM), land cover, and river cross section [24,25].

   Website: http://www.icharm.pwri.go.jp/research/rri/index.html

2. Nays 2D Flood

   Nays 2D Flood is a two-dimensional flood flow simulation model [26].

   Website: https://i-ric.org/en/download/

3. DioVISTA

   DioVISTA flood simulator developed by Hitachi Ltd. [27]

   Website: http://www.hitachi-power-solutions.com/en/products/product12/p028.html

Flood Hazard Map of Korea

Joo-Heon Lee[1)], Yongwon Seo[2)], Sung-Sik Park[3)], and Hyo-Seob Cho[3)]

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[2)]Yeungnam University, Republic of Korea
[3)]Water Resources Information Center, Han River Flood Control Office, Republic of Korea

1. Introduction

1.1 Flood disasters of Korea

South Korea have been suffered from flood year by year despite all the investment and efforts for flood prevention or mitigation. The total flood damage during the last hundred years from 1916 to 2015 is up to 43 billion USD and the annual average flood damage is up to 498.9 million USD in Korea. During the new millennium, the flood damages are even unprecedented and summed up to 24 billion USD from 2000 to 2015 primarily due to unexpected and extreme severe heavy rainstorms and typhoons. Accumulated flood damage for last 10 years are most severe in Han River Watershed followed by Nakdong River, Geum River, Seomjin River, and Yeongsan River. The flood damage of Han River Watershed was greatest for six years during last 10 years among other watersheds. The flood damage of Nakdong River Wastershed was greatest for four years during last 10 years compared to other watershed. For last 10 years, flood damages were 93.5% of total damages (65.3% from heavy rainstorms and 28.1% from typhoons) and 99.5% of total casualties from natural disasters.

In addition, a recent analysis for flood-prone areas showed that 26.6% of total damages was due to river overflows, whereas 73.4% was due to other causes such as low elevation (22.01%), insufficient drainage capacity (14.23%), insufficient pumping capacity (14.11%), overflows from manhole (13.48%), and insufficient conduit capacity (11.22%).

1.2 Concept of flood hazard map

Flood hazard map provides fundamental information of expected flood depths and extents in case of river flood and urban flood inundation in forms of paper or electrical maps. The production of flood hazard maps includes flood hazard maps for each river due to river flooding (or overflowing) and flood inundation hazard maps for important urban areas due to rainfall events that exceed the design criteria and drainage capacity. The spatial range of river flood hazard map includes all river intervals, connected tributaries and expected flooding areas depending on flood scenarios. In contrast, the spatial range of flood inundation hazard map includes total drainage zones and flooding areas due to exceeding rainfall events, water level rise in river, and pump failures and so forth depending on scenarios.

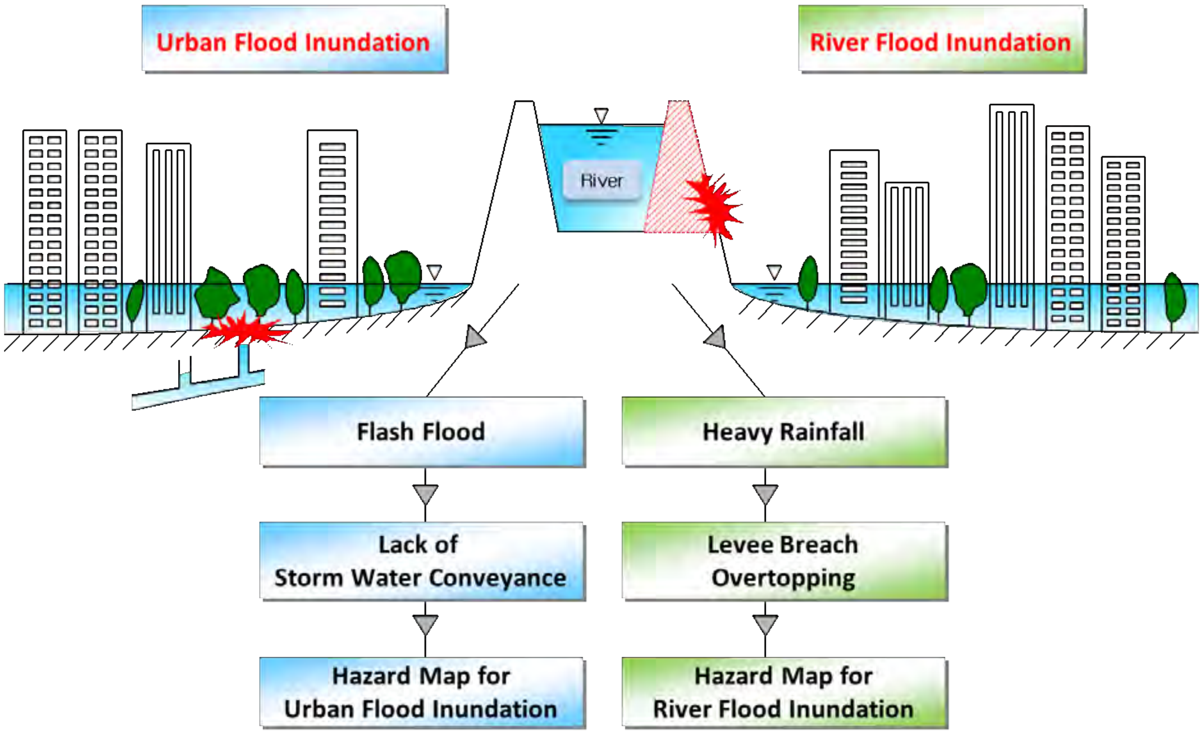


Figure 1 Conceptualization of river flood and urban flood inundation

1.3 Practical use of flood hazard map

As mentioned earlier, flood damages are constantly increasing due to changing environments. Flood prevention measures can be divided into structural measures such as levee, dam and detention/ retention reservoirs and nonstructural measures such as flood forecasting, floodplain management, flood insurance, and flood hazard map. Structural measures are important but uncertainties of their effect keep increasing due to increasing flood risks and changing environment such as rapid urbanization and climate change and so on.

Flood hazard map as one of nonstructural flood mitigation measures is to overcome the limitation of structural measures. The purpose of flood hazard map provides some of the basic information of potential flooding areas as a form of maps to regional governments and relevant authorities for effective disaster prevention such as evacuation, flood insurance, land use regulation and so forth.

2. Flood Hazard Mapping

2.1 Flood hazard mapping methodology

The process of flood hazard map includes site survey, topological data construction, flood scenario, inundation analysis, and map production and DB construction. The site survey includes collecting basic hydraulic and hydrologic information, relevant plans, flood damage history and existing survey data for the target river or drainage areas. The topological data construction is a process to obtain topological information such as ground elevation for inundation analysis and, hence, it should guarantee the required accuracy and precision for inundation analysis. A flood scenario consists of catchment condition, flood scale, and inundation scenarios. Flood and inundation analysis is performed based on flood scenarios with a methodology determined by land use and land cover. Flood inundation results are obtained by validation and revision process comparing historical flood records such as depth and water elevations. These results are mapped as a flood hazard map or flood inundation hazard map and kept in a DB system.

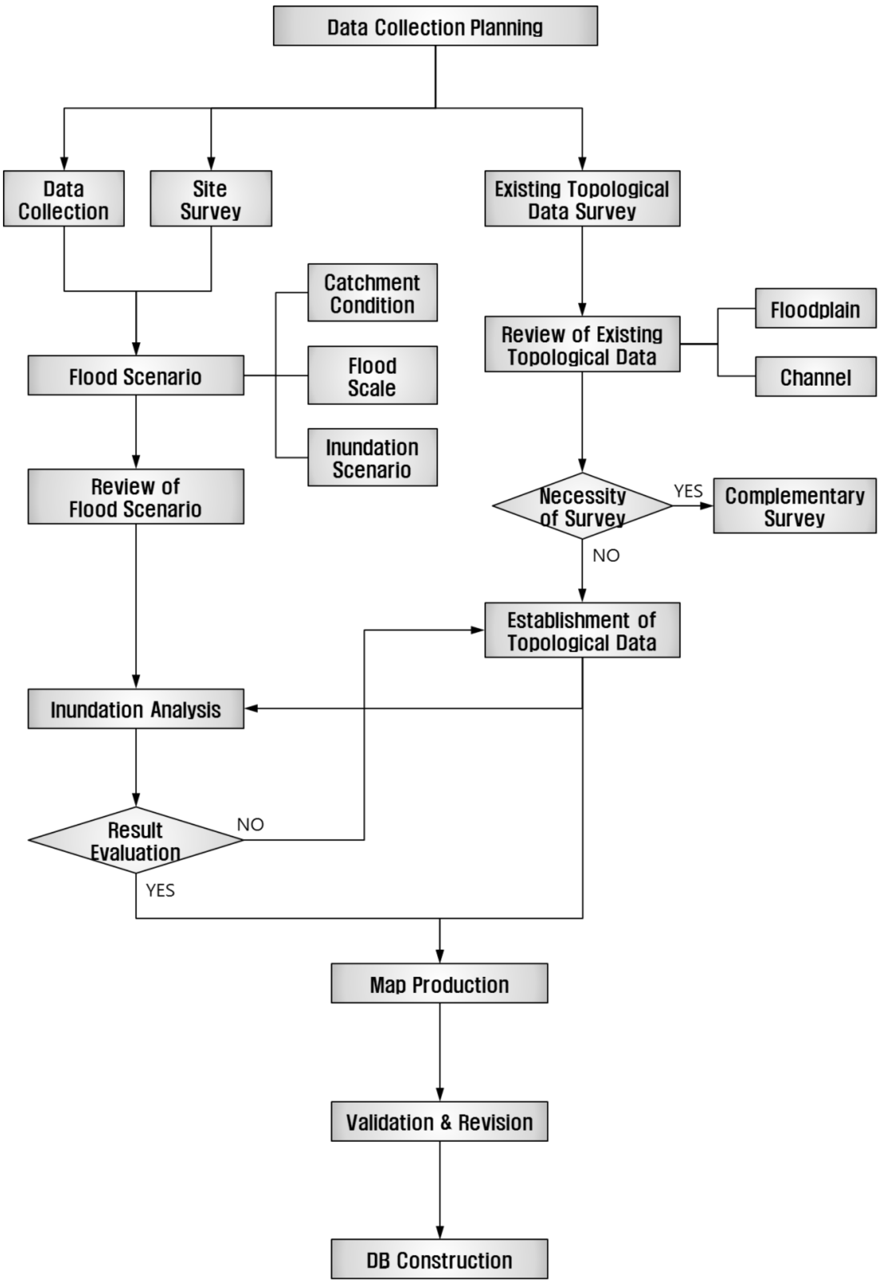


Figure 2 Mapping process for river flood inundation

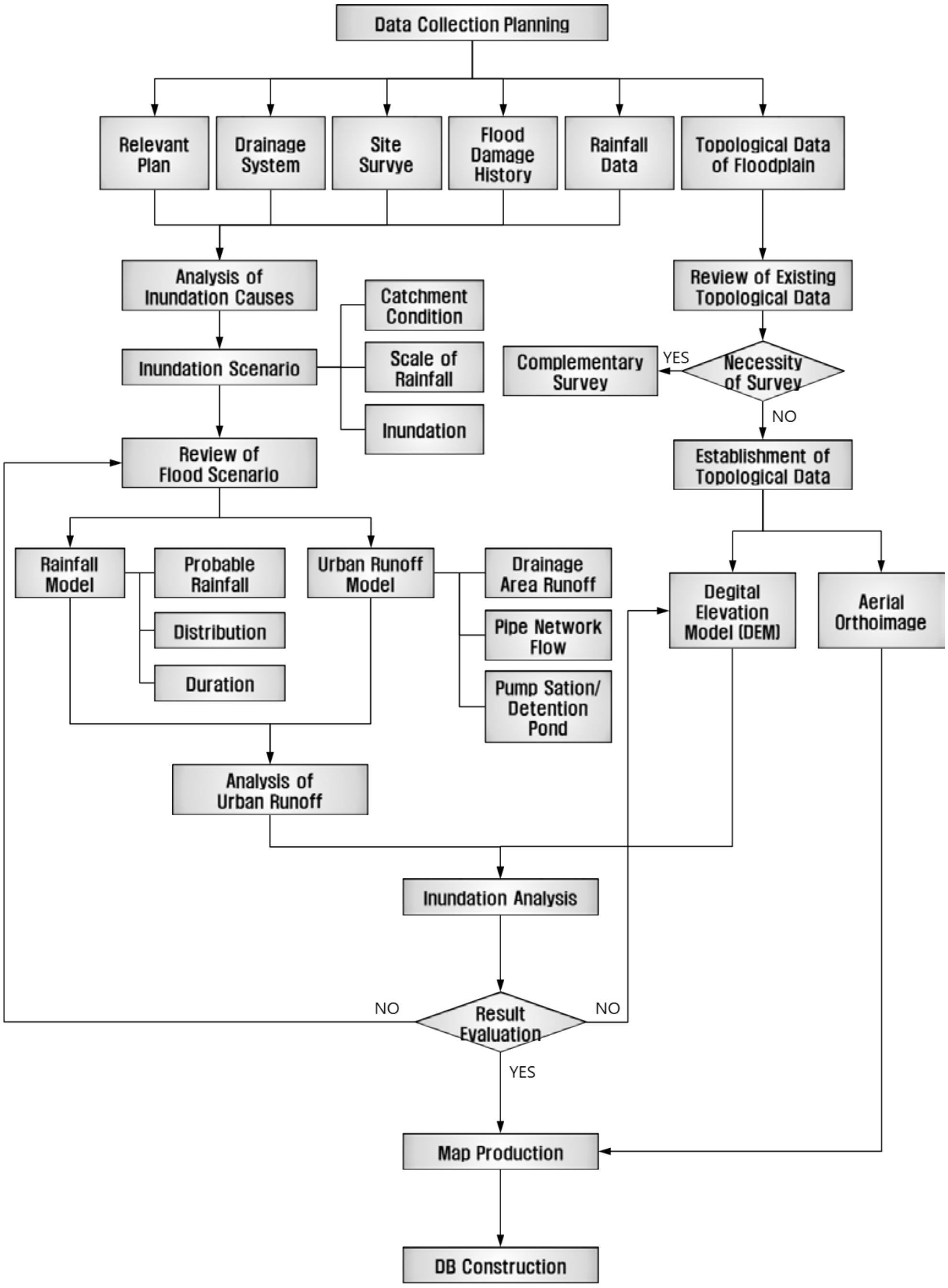


Figure 3 Mapping process for urban flood inundation

2.2 Geometry for mapping

Topological data collection is a most important procedure for the inundation analysis. It can be collected from previous data and additional survey. The collection procedure can be different depending on which areas are targeted. Topological information for river flood mapping is divided into channel and floodplain. The topological data for channel is obtained from bathymetry survey and the data for floodplain is obtained from high-resolution and high-accuracy digital elevation model (DEM). The accuracy tolerance for the DEM is ±0.5 m in Korea. For the areas outside the primary urban areas, DEM (5 m×5 m) from National Geographic

Information Institute (NGII) can be used. For the purpose of urban flood inundation, additional information is required for the analysis such as drainage network, pumping stations and storages.

2.3 Scenarios for flood hazard mapping

Flood scenarios determine the proper conditions of maximum inundation or flooding based on objective reasoning for the target areas. The scenarios can be divided into three types depending on the procedures as follows:

2.3.1 Watershed scenario

- Overall conditions that affect flooding such as land cover, land user plans, flood mitigation measures
- Separate a target area as a zone considering land use and geography such as tributaries for river flooding analysis
- Separate target areas as a drainage zone considering drainage systems and characteristics

Figure 4 Zoning flooding area effected by given flood event

2.3.2 Flood magnitude scenario

In case of river flood inundation analysis, it is required to calculate flows for each return period, which is the same for urban flood inundation analysis considering river flows.

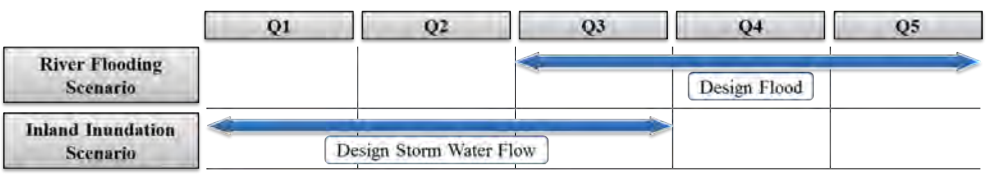


Figure 5 Scenario of flood magnitude

2.3.3 Flood inundation scenario

Flood inundation scenarios consist of river flood inundation (external causes) and urban flood inundation (internal causes). Design of scenario does not just mimic the previous flooding but comprises all possible conditions that result in potential flooding depending on the purpose of flood hazard map. Moreover, the scenario aims to delineate the flood-prone low land areas considering various conditions of flooding.

- River flood inundation assumes,
  - Overflows
  - Levee breach
  - Categorizing inundation types depending on analysis tools
- Urban flood Inundation assumes,
  - Exceeding pipe (conduit) capacity
  - Confluence of low lands
  - Drainage failure due to higher river water level
  - Pumping station failure

2.4 Hydraulic modeling for estimation of expected inundation area

In general, flood inundation caused by river flooding (external flooding) and urban flooding due to drainage issues (internal flooding). In case of external causes, the flooding is divided into three types: advection type, storage type from one-dimensional (1-D) analysis, and diffusion type from two-dimensional (2-D) analysis, which are caused by overflows or breaches. In case of internal causes, the flooding depends on its causes such as drainage issue, pumping station failure, insufficient conduit capacity, and so forth.

For one-dimensional analysis, HEC-RAS is utilized in Korea and the application procedures are depicted in Figure 6.

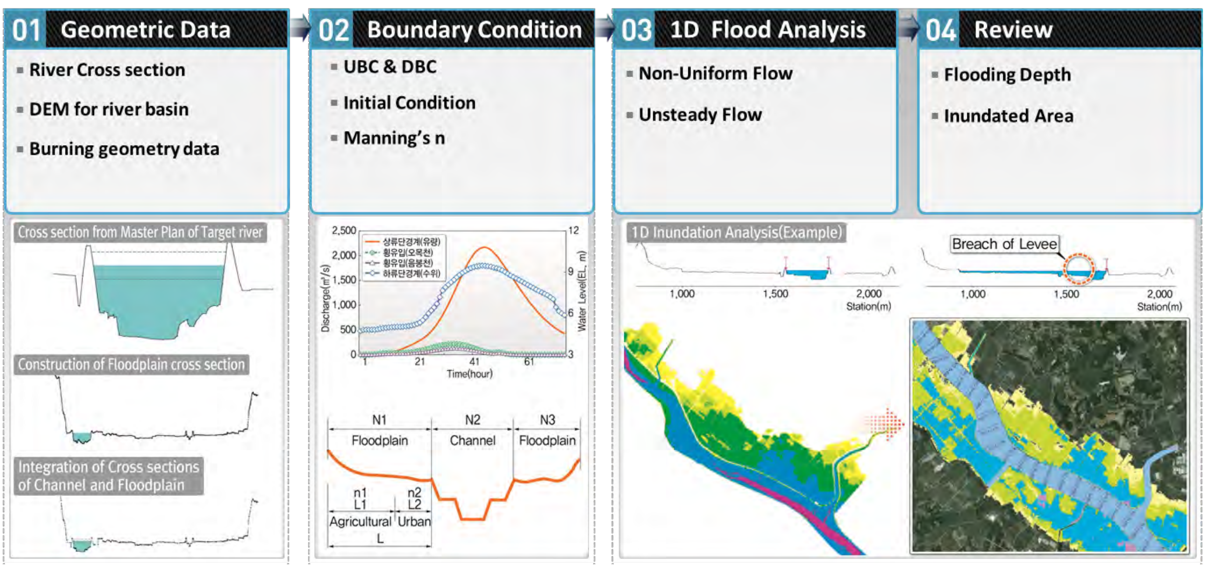


Figure 6 1-D hydraulic modeling for estimation of expected river flood inundation area

External flooding requires two-dimensional unsteady simulations considering channels and floodplains simultaneously. However, channels and floodplains can be separately modeled with appropriate modeling techniques for the purpose of modeling efficiency. In Korea, FLUMEN is utilized for two-dimensional unsteady flooding simulation and the procedures are described in Figure 7.

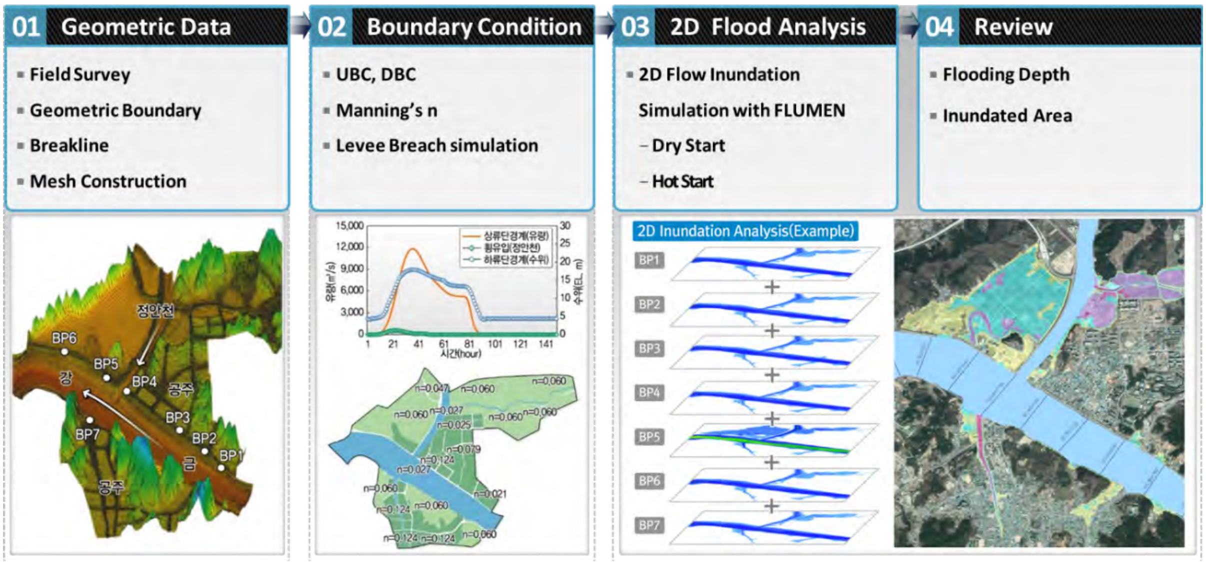


Figure 7 2-D hydraulic modeling for estimation of expected river flood inundation area

In case of internal flooding analysis, two-dimensional unsteady analysis can be adopted to simulate tributary flooding and inundation. Typically, flooding volume is calculated considering drainage networks and pumps capacities, which leads to flooding depth analysis with urban flooding modeling schemes.

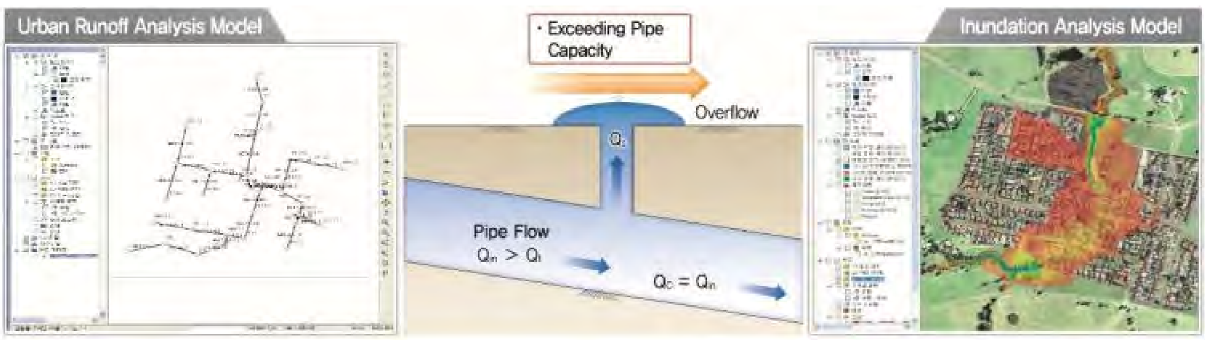


Figure 8 Urban drainage modeling for estimation of expected urban flood inundation

3. Dissemination of Flood Hazard Map Information

Flood hazard maps are distributed to central and regional governments for the purpose of flood prevention/mitigation policies and activities. Ministry of the Interior and Safety (MOIS) utilizes flood hazard map as a basis for hazard map, flood insurance map, life safety map, and so forth. Regional governments utilizes flood hazard map as a basis for flood insurance map, flood-prone area management "Countermeasures against Natural Disasters Act" and "Storm and Flood Insurance Act. Flood hazard map can provide basic information for natural disaster management policies and reduce the budget and effort at the same time.

Moreover, relevant authorities such as research institutes can utilize flood hazard map for research purposes and even people can identify flood risk areas based on flood hazard maps. Currently, announcement to public is quite limited due to secondary causes such as complaints. However, more notification is expected in the future through the form of life safety guidance. Basin information of flood hazard map is distributed as a form of paper map or electronic map with all the results from the production processes.

Table 1 Sharing and dissemination of flood hazard map information

Index		Relevant task	Resource
Government	Central (MOIS) and regional	• Disaster map • Storm and Flood insurance map • Regional risk assessment • Insurance rates • Natural disaster mitigation plan • Preliminary natural disaster assessment • Flood risk areas and management • Flood forecasting • Structure management	• Flood hazard map • Analysis results • Electronical DB for target areas
Research institutes		• Flood risk map • Natural disaster research	
Public		• Identification of flood prone areas	

Flood hazard map has a form of paper map and system (electronical) map. The map overlays flood risk areas over existing maps, which provides integrated information to readers. Paper maps follows a standardized form including map structure, revision frequency and other information. Electronical maps provides two ways: one from a web-based and the other from standalone systems.

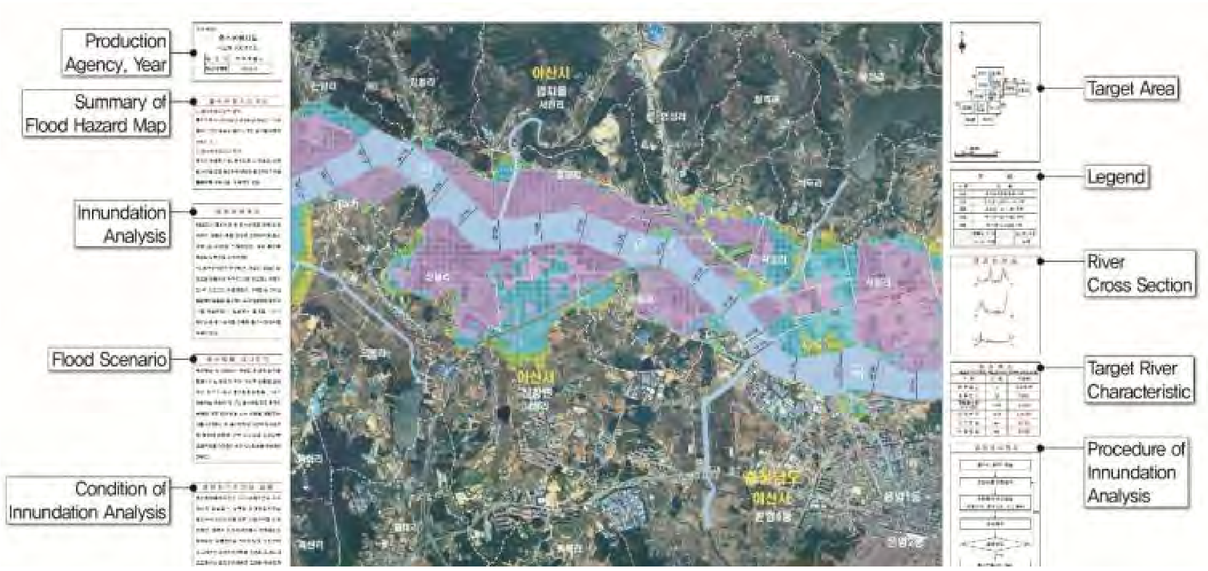
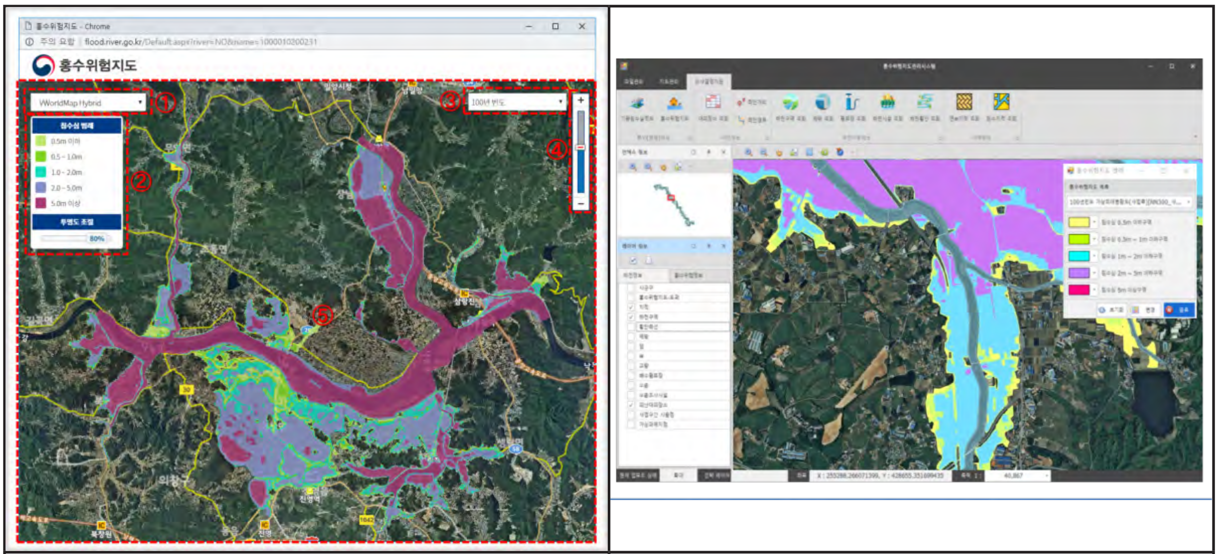


Figure 9 Flood hazard map (sample)



Web system	Stand alone

Figure 10 Management system of flood hazard map

4. History of Flood Hazard Map Project of Korea

	Period	Master planning Project	Flood Hazard Mapping Project
Stage 1 Introduction Stage	1999	Decision of Flood Hazard Mapping	
	2001	Basic investigation for Flood Hazard Mapping	
Stage 2 Development Stage	2002		Pilot project for the Han River basin
	2003		Pilot project for the Anseong River basin
	2004		Flood Hazard Mapping for the Nakdong River basin (1st)
	2005		Flood Hazard Mapping for the Nakdong River basin (2nd)
	2006		Flood Hazard Mapping for downstream of the Nakdong River basin
	2007		Flood Hazard Mapping for upstream of the Nakdong River basin
Stage 3 Sattlement Stage	2008	Master planning for Flood Hazard Mapping (1st)	
	2009		Flood Hazard Mapping for the Yeongsan River basin
	2012		Flood Hazard Mapping for the Han River basin
	2016		Flood Hazard Mapping for the Seomjin River basin
Stage 4 Expansion Stage	2016	Master planning for Flood Hazard Mapping (2nd)	
	2018		Flood Hazard Mapping for regional river and urban areas in the Han River basin

Figure 11 History of flood hazard mapping of Korea

In 1999, the Flood Disaster Prevention Planning Board decided to produce flood hazard map as one of nonstructural measures for flood mitigation. Basic investigation started in 2001 and the completion of the flood hazard map for national rivers was 2016 for 62 sites and 2,332 km lengths nationwide. Han River Flood Control Office (HRFCO) continues to produce flood hazard maps for regional river and urban areas and expects to complete the map production for entire rivers in Korea by 2021. Rivers in Korea are divided into “national” and “regional” rivers depending on management authority. The total lengths of 3,776 regional rivers nationwide are up to 26,872 km. Moreover, HRFCO established a guideline for flood hazard map production to ensure the map quality and regularly revise considering the most up-to-date technologies and methodologies.

Table 2 Contents of Guideline for flood hazard mapping of Korea

Chapters	Contents
Chapter 1. Overall rules	• Purpose • Application scope • Relevant regulations • General Terms
Chapter 2. General guidelines	• Institute • Project Scope • Project Duration • Expert council and advices • Consultation with relevant authorities
Chapter 3. Data investigation	• Hydrologic data collection • Relevant planning • Flooding history • Site survey • Other investigation
Chapter 4. Survey and topologic data collection	• Accuracy tolerance • Existing data collection and applicability • Survey scope • Methodology • Topologic data collection
Chapter 5. Flood scenario	• Catchment condition scenarios • Flood scenarios • Inundation scenarios
Chapter 6. Flood and inundation analysis	• 1D modeling for river flood inundation • 2D modeling for river flood inundation • Urban flood inundation
Chapter 7. Map production and quality control	• Terms on reports • Terms on map production • Quality control
Chapter 8. Database and system	• DB • Flood Mapping Web System
Chapter 9. Utilization	• Emergency action plan • Disaster map • Natural insurance management map • Integrated planning of natural disaster mitigation and management • Other applications

5. Administrative, Legal and Institutional framework

Flood hazard map in Korea is produced following Article 7 “Act on the Investigation, Planning and Management of Water Resources” to promote management before and after a flood event for the mitigation of casualties and property losses as much as possible. Flood hazard map can be utilized to produce hazard maps specified by “Countermeasures against Natural Disasters Act”, of which purpose is to support evacuation primarily. The authority in charge of production of flood hazard map is the minister of Ministry of Environment and, if necessary, a head of a regional government can produce flood hazard maps for the extents of jurisdiction and notify the results to the minister and relevant authorities’ heads.

Table 3 Administrative, legal and institutional framework for flood hazard mapping of Korea

Index		Act on the Investigation, Planning and Management of Water Resources	Countermeasures against Natural Disasters Act
Act and ordinances		• Act: Article 7 (Investigation of flood/drought damage) • Ordinance: Article 5 (Production of flood risk map/ drought vulnerability map)	• Act: Article 21(Various types of maps production and utilization) • Ordinance: Article 18(Types of disaster maps)
Authority		• Ministry of Environment	• Ministry of Interior and Safety

Flood	Before	• Production of flood hazard map
		• Distribution and utilization of flood hazard map
			• Production and utilizationof disaster information map
			  • Evacuation/disaster informative/ education
			• Flood forecast map
			  • Flood risk map/coastal flood map

	After	• Investigation and analysis of flooding
		  • Flood depth, duration, area
			• Flood marks investigation/map production and reservation
			  • Site flood marks management map (electronic form)

6. Good Practices, Lessons Learned and Gaps

6.1 Utilization of flood hazard map in regional areas

HRFCO investigates utilization rate of flood hazard maps every year targeting regional governments. The results showed that the utilization rate is 69.8% in 2018. The results shows more than half of the regional government utilized flood hazard maps and the rate keeps increasing yearly. Recently, MOIS started to utilize the maps for the production of natural disaster insurance management map and life safety guidance map services. The investigation showed that 25.52% of the regional governments utilized the maps to establish integrated natural disaster mitigation plans. 17.24% of the governments answered that they utilize the flood hazard map for preliminary natural disaster assessment, 14.48 % for designation of flood-prone areas, and 13.10% for production of disaster information maps.

The reasons for not utilizing the flood hazard maps include insufficient notification for the map production (37.27%), insufficient notification for relevant acts and regulations (24.55%) and emotional complaints from residents (15.45%). Mostly, regional government required the production expand to regional rivers and urban flood inundation or flood maps. After the completion of flood hazard maps in 2021, the utilization rate is expected to keep increasing.

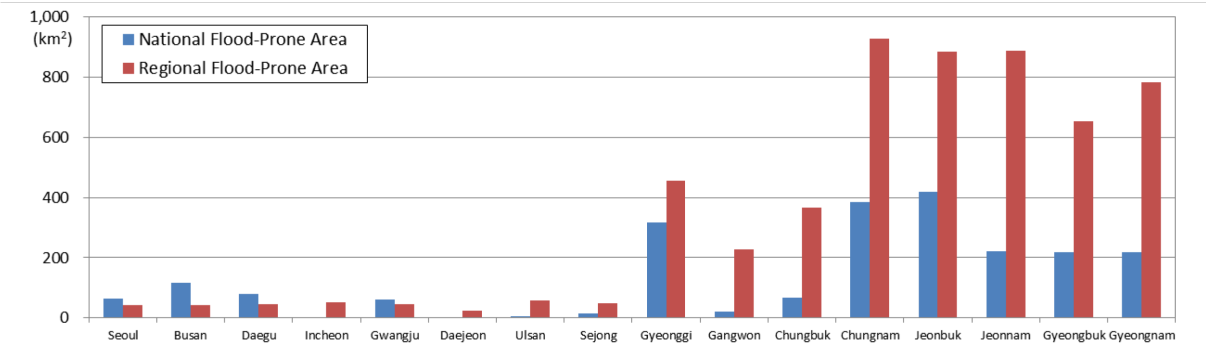


Figure 12 Regional flood-prone areas of Korea

6.2 Public disclosure of flood hazard map information

Institutionally, the utilization of flood hazard map is limited by worries about public complaints about disclosure of flooding information. The flooding information of flood hazard maps has been provided to regional government but limited to public. However, the request for disclosure of information keeps increasing due to highly developed information society, public right to know, and ensuring safety. Moreover, extreme hydrologic events potentially by climate change start to threaten the safety standard of existing structural measures such as levees and dams, which require all the citizen to identify flood risks nearby exactly.

However, the disclosure of flood information should be done gradually based on agreement and understanding of the public. It is necessary to make citizens understood that the flood information is useful and beneficial to them. Therefore, the flood information provided by flood hazard maps can be categorized by characteristics and delivered to the citizens when they actually need it. This would help to change the public understanding of flood slowly but steadily. For example, practical maps such as life safety maps or life sympathy maps provided by various authorities and governments can be an excellent platform to present the flood information more friendlily. Especially, more practical purposes such as traffic information considering flooding areas can be a good example to provide flood information.

Recently, MOIS started to provide hazard information as a form of life safety maps to promote citizens to identify and prepare themselves more actively. The safety information provided by life safety maps includes traffic, disaster, public order, facilities, industry, hygiene, accident information. The safety maps also provide disaster information such as flooding, coastal flooding, landslide, earthquake information. Currently, flood hazard maps provide flood risk information as one of disaster information to the public in forms of web services and mobile application services.

	
Safety map web service for Living Environment	Safety map mobile application service for Living Environment

Figure 13 Information system of flood hazard map

7. Future Plans for Flood Hazard Map Usage

7.1 VWORLD service and flood hazard map

Currently, the Ministry of Land, Infrastructure and Transport (MOLIT) provides the VWORLD map service where geographic information is categorized into land, life/safety, culture/tour, transportation/aviation, industry, environment, agriculture/forestry, and marine. Especially, life/safety category map service provides safety map, protection facility map, pedestrian priority, and landslide risk information. The information from flood hazard map can be integrated into a VWORLD category to support policy makers and decision makers in terms of national water resources management and planning.

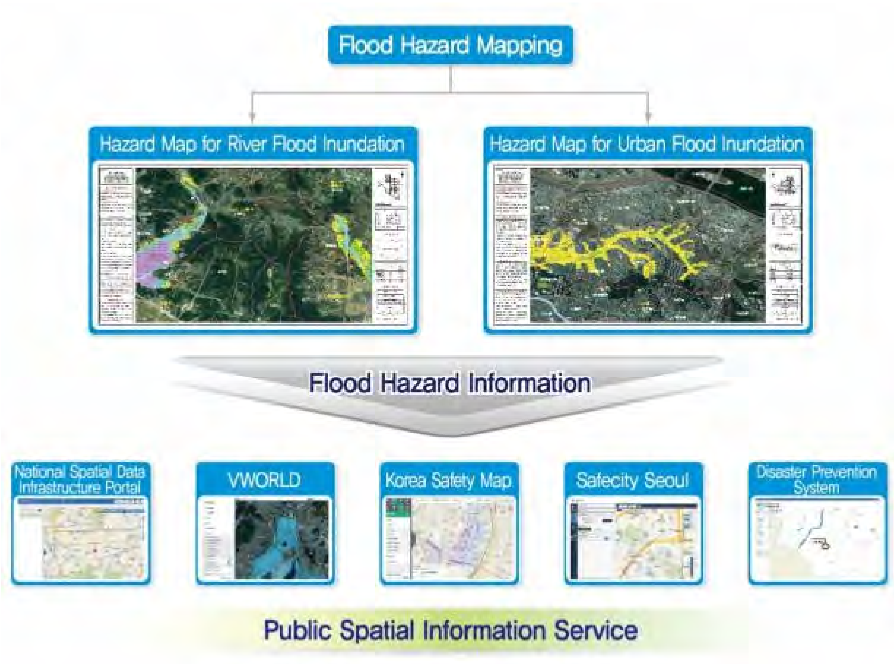


Figure 14 Incorporating public geographic information service with flood hazard maps

7.2 Road inundation information

Number of flooding roads keeps increasing due to convectional summer storms potentially due to climate change. It is important to identify and distribute information about flooding roads beforehand and flood hazard map can be utilized in this. In Korea, insurance companies built road information systems by themselves that provide flooding information especially for flood-prone areas. Central and regional traffic information centers provides traffic safety information about changing road conditions to relevant authorities and organizations through a traffic information management system. Flooding information, such as flood-prone areas and real-time weather information, belong to the traffic safety information that the system provides. However, the information from flood hazard maps is not currently utilized and not even recognized by the system builders and managers. Therefore, the information provided by flood hazard maps can be combined into road information system of the insurance companies to improve the system performance by feedback from both sides such as real time flood depth forecast based on expected amount of potential rainfall.

The traffic safety information provided by the central and regional traffic information centers can be improved by the results of expected flooding areas based on flood hazard maps. The flood forecasting system can be combined with the traffic information system to support real time flooding forecasts that can be delivered to the public, organizations and relating authorities. Moreover, flood hazard map can contribute to improve accuracy of real time road flooding information or risk index based on real time rainfall amounts. Integrating spatial geographic information and flooding depth also can contribute to the flood hazard monitoring system.

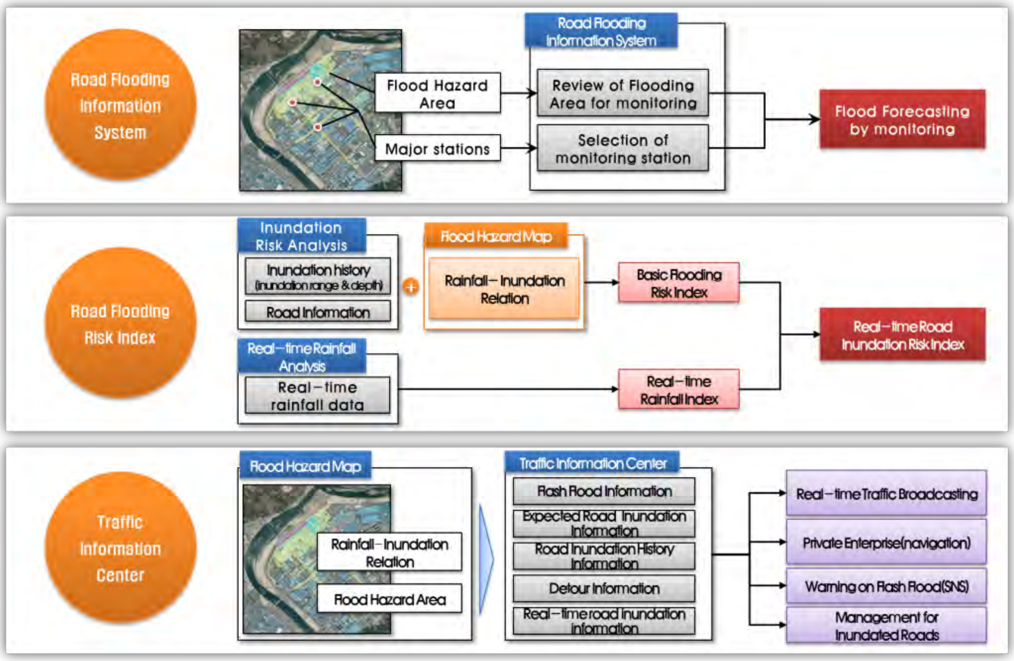


Figure 15 Road inundation information based on flood hazard maps

7.3 Improvement of flood forecasting system

Flood hazard map can contribute to improve the flood forecasting system by spatial presenting real time flood area forecast by spatial flood forecasting system. Spatial flood forecast can be divided into spatial flood forecast based on scenarios and dynamic spatial flood forecasting based on real time flooding analysis. Flood hazard map can contribute to improve the scenario-based spatial flood forecast because the production of flood hazard map is based on a scenario-based procedure. The database built for flood hazard map can be directly used to improve the spatial flood forecasting based on scenarios shortly.

In addition, real time spatial flood forecasting can be obtained by real time flood simulation and analysis in a long term. However, current computing power limits the application of real time flood simulation due to long simulation time, which deteriorates three factors of flood forecasting including accuracy, proper timing and reliability. It is expected that substantial amount of technical advances and infra are necessary to accomplish this.

Currently, the scenario-based spatial forecasting system, combined with river flood hazard maps and urban flood risk maps, is regarded as the best alternative for improving flood forecasting system. It is expected that real time dynamic spatial flood forecasting system would be possible in near future with technical advances.

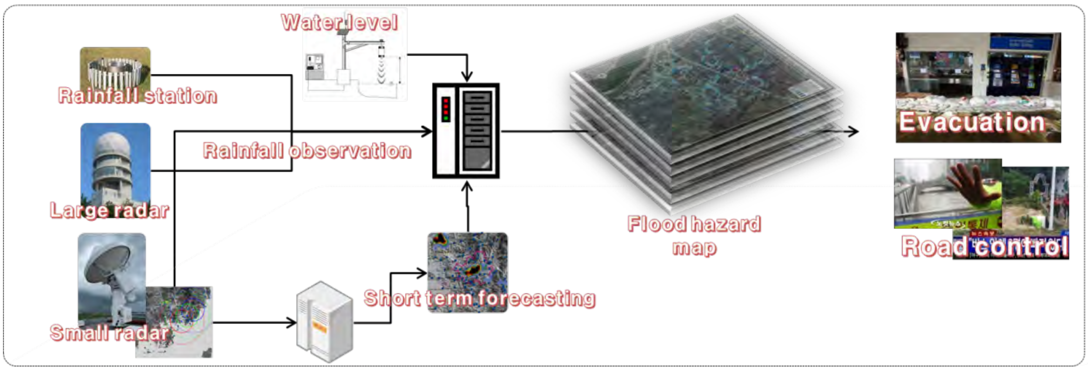


Figure 16 Improvement of flood forecasting system

Table 4 Comparison of spatial flood forecasting methodology

Flood forecast	Scenario-based spatial flood forecast	Real time simulation-based spatial flood forecast	Remarks
Summary	• Utilizing existing information from flood hazard maps	• Dynamic spatial flood forecasting based on real time simulation	
Buildup	• Integrating existing flood hazard map information • River flooding: WSE-flood extent • Urban flooding: Rainfall-flood extent	• Combined modeling of rainfall runoff modeling and flood inundation modeling • Improved technical background	
Pros and Cons .	• Quick evaluation of flood extent utilizing existing information • Limitation of scenario-based modeling	• Computing power limitation • Uncertainties for forecast	
Evaluation	• Short term improvement of spatial flood casting based on flood hazard map information	• Long term improvement of spatial flood forecasting based on real time simulation	

7.4 Integrated toolkit for river management

Flood hazard map is a special form of a map that provides flood inundation information, such as flood depth and extents, combined with catchment's geographical information. Flooding is divided into external and internal flooding depending on its causes. Flood hazard map for each river illustrates flooding area extents by levee overtopping or breaches. In contrast, urban flood inundation map illustrates flooding areas extents by insufficient drainage system capacities. The management of a river system has been focused on river structures such as levees so far but not much focused on urban areas that can be potentially affected by river flows.

Levee is a structure along river protecting urban areas. Understanding the characteristics of each urban area protected by levees is essential for effective flood mitigation and river management. These areas have their original conditions and characteristics affecting flood. In this regard, river flood hazard maps and urban flood inundation maps is considered as a flood map in a narrow sense or a basic system to expand river management from rivers (lines) to protecting areas (areas) in a broad sense at the same time, which enables us to combine all the information provided by flood hazard maps, such as structures, assets under flood risks, flood vulnerability, casualties and so forth, in order to provide integrated river flood management. In addition, the information provided by flood hazard map can be utilized as a basis for the assessment of flood mitigation measures and alternatives.

Figure 17 Integrated river flood management

8. References

MOLIT (2008) Basic planning for flood hazard maps, revised (2nd)

MOLIT (2008) Guidelines for flood hazard map production

MOLIT (2016) Basic planning for flood hazard maps, revised (3rd)

MOE (2018) Flood hazard map for regional urban rivers in Han River Watershed

Flood Hazard Mapping in Malaysia: Case Study Sg. Kelantan river basin

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Abstract

One of the critical issues in Malaysia, which is mostly reflected in the Sg. Kelantan river basin, is flooding which occurs almost every year. This paper aims to present the result of the study on developing flood maps consisting of flood hazard map, flood evacuation map, and flood risk map. The contents will describe the development, calibration and validation of a flood model for the 100 ARI design flood. Calibration and validation involved comparison between observed and model simulated discharge hydrographs, as well as observed and model simulated flood inundation extents. The use of hydrodynamic model using InfoWorks 1D and 2D techniques and utilizing DEM data from IFSAR significantly improve the results. The hydrodynamic model was applied to reconstruct the recent flood events, as well as to simulate flood inundation due to rainfall events of varying recurrence intervals. The generated flood inundation map helps the preparedness for disaster agency to have proper planning and early evacuation during monsoon flood season. Meanwhile, the flood risk maps will be used as guidance to local government for planning guidelines in line with national development policies and planning principles.

1. Introduction

1.1 Flood disaster statistics

Floods are known as one of the world's most frequent and devastating events including Malaysia (Osti et al., 2008). A substantial amount of the nation's annual expenditure has been allocated to the development of strategies to reduce the effects of flooding. In particular, the impact of flooding in terms of infrastructure damages, human causalities, and long-term economic downturn has been rapidly increasing. This scenario is brought about by the ballooning global population, unsystematic urbanization, and climate change in the form of higher sea levels and more intense cyclones weather systems and precipitation (Sanders, 2007). The damage on agriculture, households, and public utilities caused by floods amounts to billions of dollars each year worldwide, in addition to the loss of human and animal life (Sharma and Priya, 2001).

In Malaysia, floods occur almost every year, especially in areas located in flood plains. These annual flood events have been classified as normal flood which occur during the northeast monsoon season between November and March. Normal flood often inundates the lowland areas in the east coast of Peninsular Malaysia. Meanwhile, major floods occur once every few years, and sometimes, even consecutively, like the 1970 and 1971 flooding in Pekan, Pahang (Chan, 1997). The major flood in Johor (located at the southern part of Peninsular Malaysia) involved more than 110,000 evacuees and 18 casualties. The damages from these disasters amounted to RM 1.5 billion (excluding losses caused by the economic downturn) (Sulaiman, 2007). The flooding in Johor has been classified as "abnormal" as it occurred twice in two months, namely, in December 2006 and January 2007.

Meanwhile, based on Department of Irrigation and Drainage, Malaysia in 2012, about 33,298 km2 or 10.1 percent of the country is prone to flooding. It represent 5.67 million of peoples affected and annual loss more than RM 1 billion. The amounts of losses substantially increase once major flood occurred. As reported, December 2014 flood which hits badly in three states namely Kelantan, Terengganu and Pahang cause more than 500,000 peoples evacuated, 25 casualties and RM2.85 billion losses (not include intangible loss). Malaysia laid on equator and has been categorized humid-tropic region, flash flood almost occurred every month which is in 2018, 450 floods event recorded and 90% is flash flood.

1.2 Purpose of flood hazard mapping

There are various methods to mitigate the damages caused by floods, such as flood prevention, flood protection, flood preparedness, and emergency response. These methods must be objectively approached to reduce the effect of floods and subsequently avoid the loss of human life and damages to infrastructure and agriculture. In Malaysia, flood control has been managed through structural and nonstructural measures. The structural measures concentrated on building dams, reservoirs, embankments, levees, and artificial channels. Major rivers, where building structures are not economically suitable, are widened and deepened through dredging. However, dredging is expensive and resources are not always available.

Another structural measure to protect rivers for short periods is creating a wall out of concrete, bamboo, or wood. For low-lying areas along rivers, a retention pond is built to store floodwater temporarily. The stored water is released only after the river flow returns to its normal level. The retention pond also serves as a multifunctional pond where a certain volume of water is permanently stored. The riverine habitats in the pond could improve the quality of the remaining floodwater, as well as the other habitats in the area. In flood-prone areas where floodwater remains for very long periods, water pumps can be strategically installed along the rivers or flooded areas. These water pumps can either be mobile or permanently installed depending on the volume of floodwater.

While most structural methods attempt to control floods, nonstructural methods largely focus on preventive efforts. Currently, the Department of Irrigation and Drainage (DID) has emphasized the strengthening of a nonstructural approach by introducing more comprehensive solutions to manage flooding. A new Urban Storm Water Management manual (MSMA), published by DID in 2000 (Sulaiman, 2007). This manual emphasizes the management of peak discharge using the concept of "control at source," which means that the time before the runoff water enters the river is lengthened. Therefore, the existing river capacity can accommodate floodwater, eliminating the need for exorbitant-costing structural remedies.

There are others non-structural flood control measures such as flood forecasting and warning system and flood hazard mapping. Conceptually, four stages of flood hazard mapping requires includes flood map, flood hazard map, flood evacuation map and flood risk map. Flood map or flood inundation map defines the location of flood or area of flooding drawn on a map. It draws based on the records of flooding occurred through field observation or satellite imaginaries.

Meanwhile, flood hazard map generated using the hydrodynamic flood model which contains the map of likelihood of the future flood events, which is normally based on Average Recurrence

Interval (ARI) of floods. The flood hazard map output includes flood area, flood depth, flood velocity and flood extent. These results will help to generate flood evacuation maps at the particular flooding area. Although, the flood evacuation map subject to time of updated information of evacuation centre and the accessibility of roads during the flood events, this will give guidance on how to act once floods occurred.

The existence of flood hazard map will further enrich with flood risk map. Flood risk is the combination of the probability of a flood event and the potential adverse consequences to human health, the environment and economics activities associated with a flood event. To generate flood risk maps, three components involved which is the value of risk at probability scenarios, the probability of exposure and the vulnerability of objects at probability scenarios. The main target output for flood risk map is to obtain assets information at zone of risk. Flood risk map also used to assist local peoples and governments to develop effective methods of reducing flood-related damages in the community over the long run. It is clear that the least costly and most effective solution is to adopt a preventive approach which emphasizes longer range planning in flood prone areas. Measures such as zoning by-laws, building codes and subdivision regulations can be used to control and direct land use within the flood hazard areas.

2. Flood Mapping

The Department of Irrigation and Drainage, Malaysia responsible to prepare flood map in inundation area at the whole country. Currently, there are 39 flood hazard maps and 3 Flood Risk Maps has been established and this paper will present the methodology for developing the flood maps at Kelantan River Basin (Sg. Kelantan).

2.1 Catchment Background

Kelantan river basin covers an area of about 13,000 km2 together with its other tributaries, namely Sg. Lebir, Sg. Galas, Sg. Pergau and Sg. Nenggiri. The Kelantan river is approximately 105 km and it includes Lebir and Galas River at Kuala Krai. Kelantan river passes through the several urban areas namely Kuala Krai, Tanah Merah, Pasir Mas and Kota Bharu. Downstream of Kelantan river has a population around 0.5 million which can be in a medium level of population. The river is the principal cause of flooding because it is constricted at its lower reaches. The capacity of the river at downstream area is less than 10,000 m3/s, therefore flood that exceeds this capacity will overspill the banks and inundation flood water at land surface area and finally moving to the sea. Since 1965, there have been more than 20 floods that exceed the capacity limit. During December 2014 flood events, it was reported that the total damage cost to property, agriculture and infrastructure amounted to more than RM 1 billion, with 319,156 people evacuated and 14 deaths counted. In term of hydrological records, the total rainfall occurs in 10 days about 1898 mm had made this the wettest December on record for the state. This amount is almost 50% of the total annual rainfall (4,000 mm) and a clear indication that the rainfall received during the period was extreme.

2.2 Method to develop flood maps

The study method consists of four stages as below:
Stage 1 – Data preparation and analysis of catchment characteristics;

Stage 2 – Hydrological analysis;
Stage 3 – Hydrodynamic analysis; Stage 4 – Flood Hazard Map;
Stage 5 – Flood Evacuation Map; Stage 6 – Flood Risk Map

2.2.1 Stage 1 – Data preparation and analysis of catchments characteristics.

The study is focused on compilation the availability of documents and pre-existing data that collected from multiple sources including federal and local agencies. There are includes topography and hydrological data, river morphology, spatial data and landuse for current and future scenario. Details of the types of data as follow:

Table 2.1: Details Types of Data for Analysis

No.	Type of Data	Description
1.	Previous study reports	• Hydrological Procedure for Design Rainfall and Design Flow (HP1 (2010), HP11(1976), HP27(2010) • DID Manual (Flood Management) (2008) • Urban Storm Water Management Manual for Malaysia (2010) • Flood Hazard Mapping, FEMA (2015) • Handbook on Good Practices for Flood Mapping in Europe (2007) • Integrated Flood Risk Analysis and Management Methodologies – Review of Flood Hazard Mapping (2008)
2.	Flooding reports	Flood reports 2000 to 2015
3.	Rainfall, water leveland streamflow, evaporation records	Hydrological data between 2000 to 2015
4.	Tidal information	Kuala Kelantan tidal gauge
5.	Flooding extents andlists	Flood extents for extreme flood event 2011, 2012, 2013, 2014
6.	River cross-section	Various interval between 400, 500, 1000 meter
7.	Topographic maps	20m- interval contour line and IFSAR
8.	Soil Map	Hydrological Soil Group and soil type
9.	Landuse map	Current land use and future landuse in 2020
10.	Satellite imaginaries	Archive data 2000 to 2013
11.	On-site observe data collection	Flood mark and water assets
12.	Climate Change Factor	Technical guide-Estimation of Future Design Rainstorm under the Climate Scenario in Peninsular Malaysia; National Hydraulic Institute Malaysia (NAHRIM)

For the purpose to delineate the catchment and sub-catchment boundary and slope, DEM data at 20m interval and IFSAR data has been used. Analysis to merge all data has been carry out using ArcGIS software. The IFSAR data was merged with the interpolated DEM points result from contour line for the area is not covered by IFSAR. There are 13's Ground Control Point (GCP) stations used for model comparison using RMSE to measure the accuracy. It was found DEM dataset is 4.5 meter more lower compare to IFSAR. Therefore, raster adjustment has been done in order match IFSAR data. In term of river cross section, Sg. Kelantan carry out recent survey and provide cross section data at 400, 500 or 1000 meter interval subject to the river morphology and the existence of river facilities such as bridges, water intake, weir, pump house on the others.

2.2.2 Stage 2 – Hydrological analysis

The purpose of carrying out the hydrological analysis is to investigate in detail the response of the catchment to rainfall and to derive the design flood hydrographs with reasonable accuracy using an appropriate rainfall-runoff model from the rainfall data. This design flood hydrograph will be routed through a model of river channels in order to evaluate the conveyance capacity of the river concerned. The resulting flows from Sg. Kelantan will then be used in the derivation of flood inundation area.

All rainfall, water level, streamflow and rating curve data had been obtained from the Water Resources Management and Hydrology Division of DID. For the rainfall data set, a quality assessment was conducted by plotting double mass curves for all stations and identifying stations which are not suitable for analysis. The double mass plot/curve is commonly carried out to verify the integrity and consistency of the rain gauge data recordings. As for the water level and streamflow data, a yearly plot was conducted to assess and identify large gaps of missing data.

The hydrological modeling was completed by utilizing the InfoWorks ICM Software, using SCS Synthetic Unit Hydrograph Method. This was then calibrated with 8 extreme rainfall events. A flood frequency analysis of the streamflow data had also been completed. For the purposes of this Study, an adopted rainfall temporal pattern was used as Hydrological Procedure No. 1 (HP1). The design rainfalls obtained were then applied onto the calibrated rainfall-runoff model in order to produce design flood hydrographs of various return periods and durations for present and future land use conditions. These hydrographs would later serve as input boundary conditions of the hydraulic model.

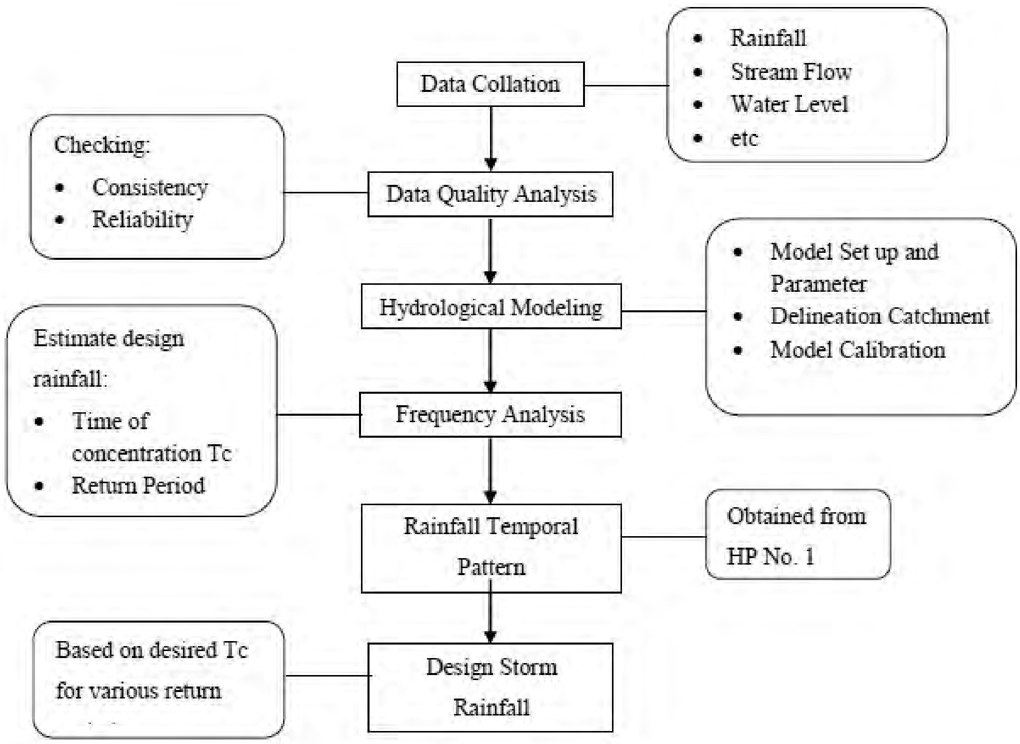


Figure 2.1: Flow diagram of the Hydrological Analysis

2.2.3 Stage 3 – Hydraulic and Hydrodynamic analysis

The hydrodynamic analysis in this study was carried out to evaluate the capacity and the conveyance of the existing Sg. Kelantan river system for various input hydrographs obtained from the hydrological analysis. Hence, the main purposes for the hydraulic analysis are:

- To obtain the design discharges of Sg. Kelantan river system using the input flood hydrographs at various Average Recurrence Interval (ARI) from the Rainfall Runoff (RR) model.
- To obtain the design water surface profiles along the rivers

The flood simulation modeling software used in this study is InfoWorks Integrated Catchments Model (ICM). In preparing the flood maps and deciding the best flood mitigation solution, integrated use of one-dimensional (1D) and two-dimensional (2D) hydrodynamic models is utilised as this can simulate the river and flood plain interaction. InfoWorks ICM enables hydraulics and hydrology of natural and man-made environments to be incorporated into a single model. "The 2D engine used in InfoWorks ICM is based on the procedures describes in Alcrudo and Mulet-Marti (2005). The shallow water equations (SWE), that is, the depth-average version of the Navier – Stokes equations, are used for the mathematical representation of the 2D flow. The hydrological output data and the cross-sections derived from digital terrain model were used in the hydraulic analysis. The SWE assume that the flow is predominantly horizontal and that the variation of the velocity over the vertical coordinate can be neglected". (ICM Help, 2015). Bridges, low weirs and river confluences along the river were also used as inputs in the model to simulate the real conditions. The hydraulic model was also calibrated to the 2013 flood event, and subsequently validated to the 2011, 2012, 2013 and 2014 events.

"The 2D mesh is generated using Shewchuk Triangle meshing functionality. Heights at the vertices of the generated mesh elements are calculated by interpolation from a specified Ground Model. A single mesh element may be made up of more than one triangle, if a triangle has an area less than the minimum element area specified for the 2D Zone. Triangles will be aggregated with adjacent triangles until the minimum area is met. The ground level for a mesh element is calculated by sampling the ground model within 2D triangles making up the element and then taking the average of the sample point levels". (ICM Help, 2015)

"The number of sample points for each triangle is determined by subdividing the triangle until the minimum element area or, (when using a Gridded Ground Model), the ground resolution model resolution is reached. The sample points are the centroids of the resulting triangles. If a triangle is smaller than the minimum element area or ground model resolution, the centroid of the triangle will be the only point sampled. The same method is used when recalculating mesh element ground levels by resampling elevations from a different model." (ICM Help, 2015).

In the model setup for hydrodynamics analysis, the basic formulae used in 1D Hydrodynamics Models are based on the one-dimensional unsteady state gradually varies flow equations, which are termed as "the St. Venant Equations". In the modeling of floods, flows often take short cuts through flood plains where the 1D description may become quite inaccurate. For this reason, the 2D shallow water equations are introduced. The hydraulic analysis will be done using the combination of 1D and 2D hydrodynamic modeling. The basic data required are river cross-section, structural details and digital terrain model. The setting up the basic 1D hydrodynamic modeling uses the river cross-section surveys data. For 2D floodplain modeling, comprehensive dot grid with grid spacing of digital terrain model namely IFSAR will be used instead.

The following assumptions used in this study:

i. Design flood hydrographs – All the inflow hydrographs into the Sg. Kelantan river system were obtained from the hydrographs derived the rainfall - runoff model. Two catchments conditions were evaluated: the present and future land use conditions:

ii. Since the survey cross-sections were limited within the river channels, floodplains that have substantial influence on the flood levels and flow discharges could not be ignored in the simulation. The floodplains located on both riverbanks and the widths of the floodplains were based on IFSAR survey, aerial photographs and flood maps available from the JPS records.

iii. Channel and Flood Plain Roughness – The channel roughness n of 0.035 and 0.05-0.07 were assumed for all main river channels and floodplains respectively from the model calibration and validation results.

iv. Tide Levels – Hydrodynamics modeling using Infoworks (ICM) model and for reaches under tidal influences required tidal information at the river mouth. Tidal data was obtained from the Royal Malaysia Navy at Kuala Kelantan secondary port;

v. River Mouth Tail Water Level – the Mean Higher High Water (MHHW) was used as the design tail water level for floods of various ARIs due to its fairly frequent occurrences as compared to the Highest Astronomical Tide (HAT)

vi. River Mouth Tail Water Level for Critical Velocity – for evaluating bank erosion potential where the critical parameter is the flow velocity, the Mean Lower Low Water (MLLW) was used as the design tail water level at the river mouth

vii. In all cases, tide cycle was adopted as the tailwater at the rivermouth instead of water level. Possible rise in the sea level due to storm surge was considered to be negligible and hence ignored in the analysis. Other causes such as greenhouse effect that may increase the sea level etc. were also ignored; and

viii. It was assumed that rainstorm of the same ARI and duration occurred simultaneously over the whole river basin for all simulations.

ix. The critical storm duration has been determined to be 3 and 5 days.

Figure 2.2: Sub-catchments division of Sg. Kelantan

2.2.4 Stage 4 – Flood Hazard Maps

The generation flood hazard maps for Sg. Kelantan based on flood hazard degree. The flood hazard maps include the details of flood extent with flood depth classification and the Point of Interest (POI). Table 2.2 shows the classification of flood hazard degree.

Table 2.2: Classification of flood hazard degree

Degree of Flood Hazard	Flood Depth (m)	Desciption
Low	< 0.5	**Caution** “Caution: Flood zone with shallow flowing water or deep standing water” Note: It is still possible to walk through the water.
Moderate	0.5 – 1.2	**Dangerous** “Danger: Flood Zone with deep or fast flowing water”. Note: The ground floor of the buildings will be flooded and inhabitants have either to move to the first floor evacuate.
High	1.2 – 2.5	**Dangerous for all (Level 1)** “Extreme Danger: Flood zone with deep fast flowing water: Note: The ground floor and possible also the roof will be coveredby water. Evacuation is a compulsory action.
Very High	> 2.5	**Dangerous for all (Level 2)** “Extreme Danger: Flood zone with deep fast flowing water: Note: The ground floor and possible also the roof will be covered by water. Evacuation is a compulsory action

Flood hazard maps were produced based on 5, 10, 20, 50 and 100-year ARIs at the scale of 1:25,000 for present and future land use conditions. The flood hazard maps for the specified ARIs must clearly indicate:

a. Flood depth; and
b. Flood extent

The flood depths were denoted by the colour scheme below;

Colour	Flood Depth	Colour Name	R	G	B
	0 – 0.5 m	Sodalite Blue	190	232	255
	0.5 – 1.2 m	Big Sky Blue	0	197	255
	Above 1.2 m	Lapis Lazuli	0	92	230

- The hardcopy of Size : A1 printed maps
- Scale: 1:25,000
- The flood extent shall be overlaid on top of the cadastral maps, river network, transportation network and flood evacuations centres" locations
- The flood hazard map clearly mark the major towns, flooded areas and point of interest.

2.2.5 Stage 5 – Flood Evacuation Maps

The flood evacuation maps for the Sg. Kelantan river basin were drawn based on the flood hazard maps of 100 year ARI for present and future land use conditions. Among the important details included in the maps are:

a. Flood extent (with flood depth classification)

b. Location of primary evacuation centres

c. Maximum capacity of the evacuation centres

d. Major towns

e. Emergency contact numbers

f. Transportation network

g. Point of Interest (POI)

h. Size of inundation area

i. Estimated number of people affected

The flood evacuation centres are denoted by the colour scheme below:

Colour	Category	Colour Name	R	G	B
●	Flood evacuation centre	Mars Red	255	0	0

The standards as set by DID for the production of flood evacuation maps are:

- Size : A1 printed maps
- Scale: 1:25,000
- The flood extent shall be overlaid on top of the cadastral maps, river network, transportation network and flood evacuations centres’ locations
- The flood evacuation map shall clearly mark the major towns, flooded areas and point of interest.

2.2.6 Stage 6 – Flood Risk Maps

In development flood risk maps, flood damage assessment is crucial to obtain the losses value once flood occurs. The flood damage will include direct and indirect tangible damages. Among the important details included in the maps are:

a. Flood risk zone

b. Flood extent

c. Location of primary evacuation centres

d. Major Towns

e. Transportation Network

f. Point of Interest (POI)

The flood risk zones are denoted by the colour scheme below:

Colour	Flood Risk Class	Colour Name	R	G	B
	Very Low Risk	Grey	178	178	178
	Low Risk	Sky Blue	135	206	235
	Medium Risk	Yellow Green	154	205	50
	High Risk	Orange	255	170	0
	Very High Risk	Red	255	0	0

The standards as set by DID for the production of flood risk maps are:

- Size : A1 printed maps
- Scale: 1:25,000
- The flood extent shall be overlaid on top of the cadastral maps, river network, transportation network and flood evacuations centres’ locations
- The flood risk map shall clearly mark the major towns, flooded areas and point of interest.

Development of Risk index

Flood risk is a measure of the statistical probability of flooding combined with the adverse consequences of the flooding. The practical determination of future flood risk is made up of four major components: (i) the probability of flooding (ii) the exposure of the receptors-at-risk to different flood characteristics (iii) the value of receptors-at-risk and (iv) the vulnerability of these receptors-at-risk. This brief information outlines the procedure on how the flood risk can be computed and mapped out using GIS software.

In its most general form, flood risk can be computed using the following formula:

$$\mathrm{R} = \sum_{i=1}^{n} \frac{1}{i} D_i$$

Where,

R = Flood Risk
i = Return Period (2- , 5-, 10-, 20-, 50- and 100-year ARIs)
D_i = Damage for Return Period i

The computation and mapping of flood risk involves 6 steps. For each flooded pixel (location), say 100m x 100m, the following computational steps can be adopted in order to produce the flood risk map.

i. Step 1 – Determine the unit damage rates that are relevant for each pixel.
The unit damage rates were calculated based on applicable rates covered under 11 different categories and their applications depend on the relevant characteristics and features of each pixel.

ii. Step 2 – For each return period (2-, 5-, 10-, 20- and 100-year ARIs) multiply the computed unit damage rates with the relevant damage factors to produce the estimated damage for each pixel.
The damage factors to be applied shall include flood depth, duration and strata (rural and urban). In this sense the application of the appropriate factors depends on the flood characteristics / severity.

iii. Step 3 – Multiply the estimated flood damage for each return period (2-, 5-, 10-, 20-, 50-and 100-year ARIs with the probability occurrence.
The probability occurrence is, equal to 1/Return Period. For each return period, multiply the probability with the corresponding estimated flood damage.

iv. Step 4 – Sum the results of the multiplication in step 3 to produce the weighted average damage for each pixel.
Sum the product of probability of occurrence and estimated flood damage computed in Step 3 to produce the weighted average damage.

v. Step 5 – Classify the estimated damage into several flood risk classes.
Five risk classes are proposed : Very Low, Low, Medium, High and Very High.

vi. Step 6 – Colour-code the classes to produce flood risk map.
Produce flood risk map by colour-coding the risk classes into 5 categories. The proposed ranges to be adopted are as described in step 5.

In general, the flood risk map that eventually be produced provides a graphical representation of the magnitude of potential impact of floods by combining the probability of occurrence and size of damage.

The explanation in flood risk category is being described in Table 2.3 below.

Table 2.3: Flood risk classification

Risk Class	Index Range	Representative Description of Typical Areas
Very Low	< 50	• Oil palm or rubber land that are infrequently and less severely flooded • Any type of land use with very low probablity of occurenceand very low damage
Low	51-1,000	• Rice fields or sparsely populated rural areas that may be subjected to frequent, but low severity flood • Any type of land use with potentially moderate damage when flood occurs
Moderate	1,001-5,000	• Moderately dense rural residential areas with good infrastructure that are subjected to frequent floods • Any type of land use with potentially moderate damage when flood occurs
High	5,001 – 25,000	• Densely populated areas with good infrastructure that are subjected to frequent floods. • Any built up area with potentially high damage when flood occ
Very High	>25,000	• Densely populated urban areas with plenty of commercial/industrial establishments and served by extensive infrastructure with frequent flooding of various magnitude and occasionally very severe flood • Any built up area with potentially very high damage when flood occurs

3. Results and Application of Flood Hazard Map

3.1 Hydrodynamic Simulation

The hydrodynamic (HD) model was calibrated by comparing model simulation results of the existing conditions with measured data. In this case, the December 2013 Kelantan flood event was chosen for the model calibration. The model parameters were then adjusted to give the best estimates. The HD model was calibrated using measured water level at Sg. Nenggiri at Jambatan Kusial stations. Predicted tidal levels time series at the river mouth of Sg. Kelantan tidal stations served as the downstream boundary condition. Figure 3.1 shows the comparison between simulated and measured river levels at recorded water level station for December 2013 flood.

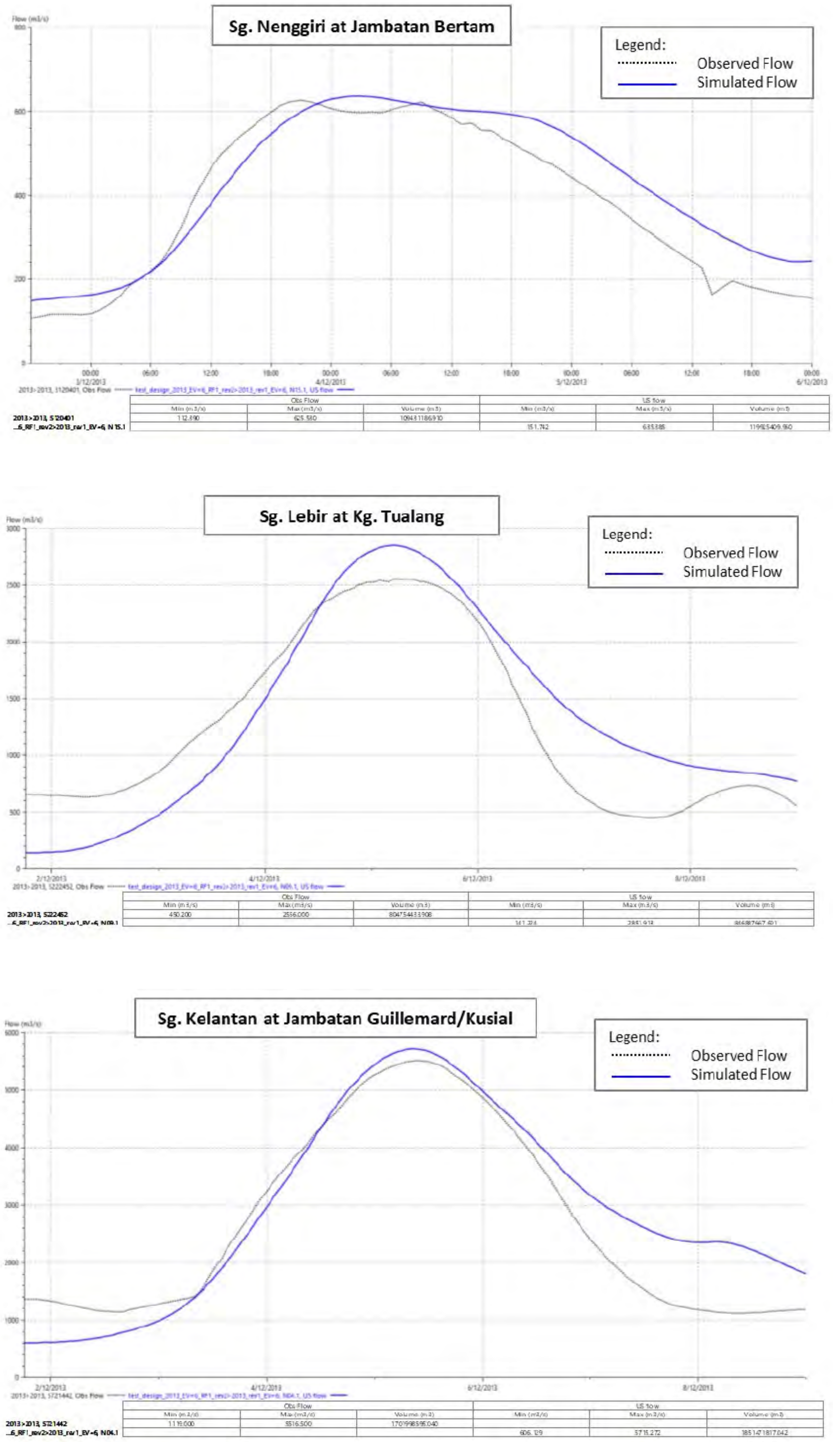
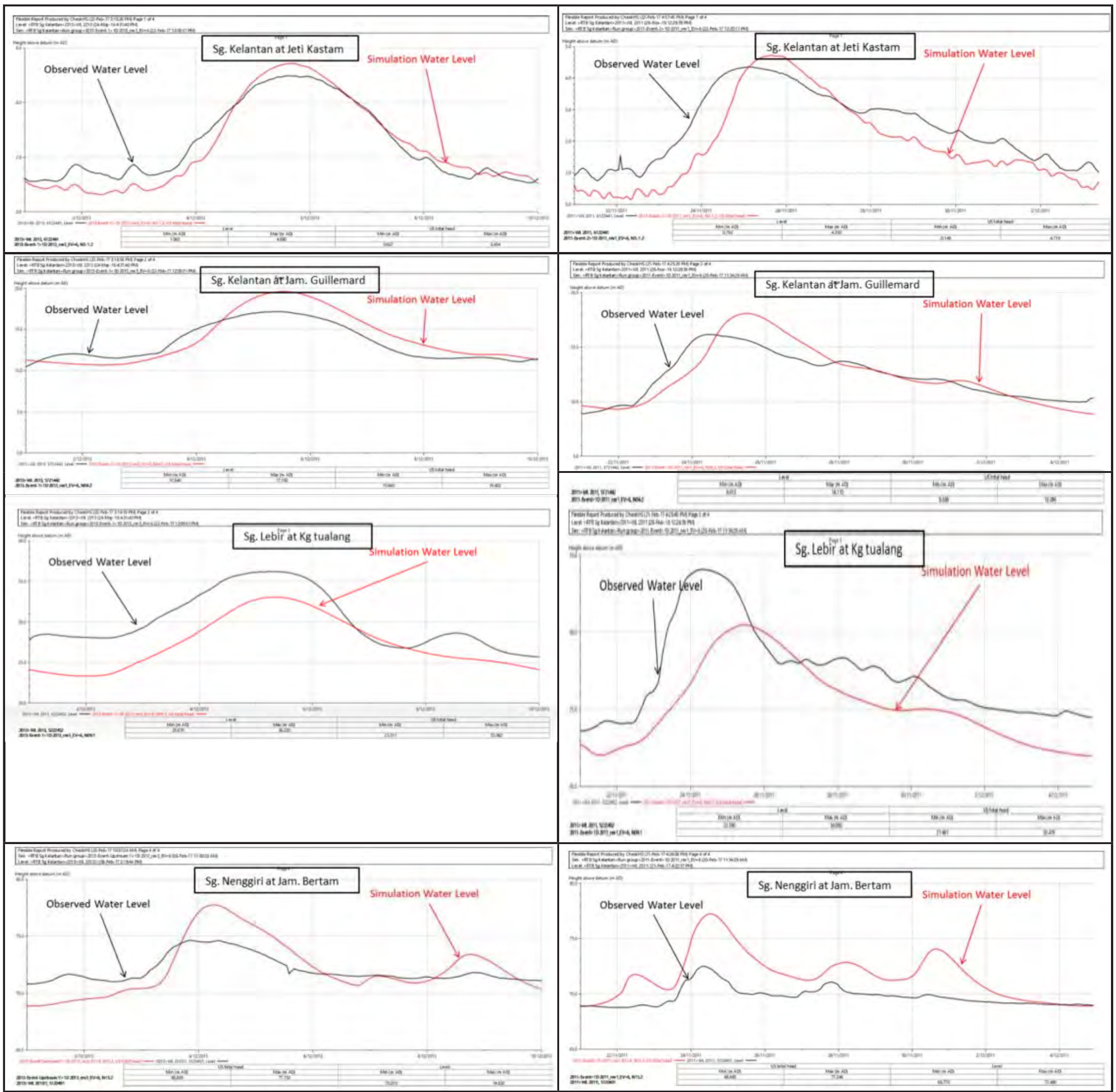


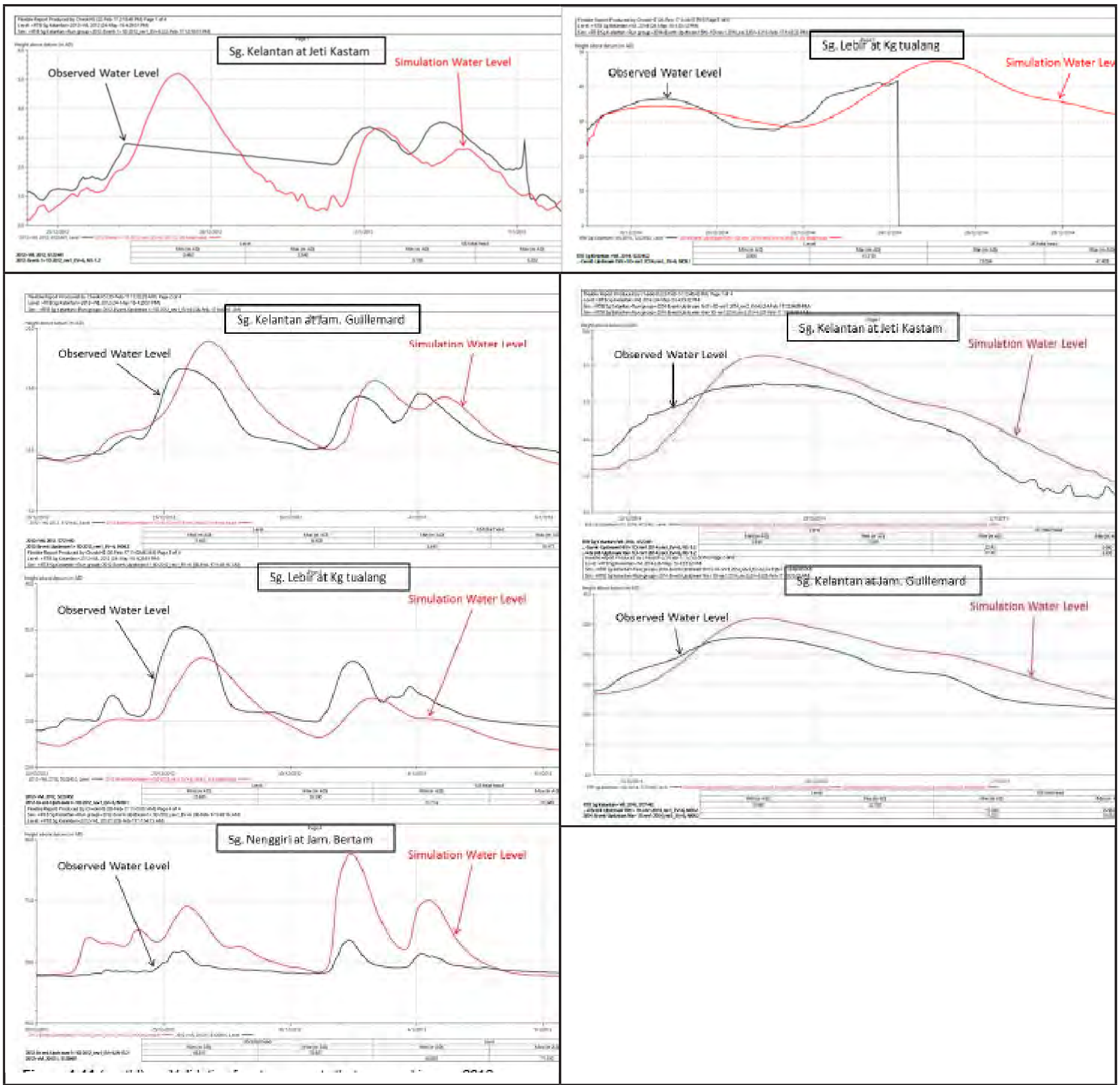
Figure 3.1: Calibration hydrograph for hydrodynamics analysis

The hydrodynamic model was then, being validated using measured water level data for different flood records. In this case, data from 1st to 9th Dec 2013, data 21st Nov to 2nd Dec 2011, data 20th Dec 2012 to 9th Jan 2013 and data 22nd Dec 2014 to 6th Jan 2015 were used for model validation.



1st to 9th December 2013 flood events	21st November to 2nd December 2011 flood events

Figure 3.2: Validation hydrographs for December 2013 and December 2011 flood events



20th December 2012 to 9th January 2013 flood events	22nd December 2014 to 6th January 2015 flood events

Figure 3.3: Validation hydrographs for January 2013 and December 2014 flood events

From the calibration and validation analysis, it shows the model give reasonable results particularly for the hydrograph peak but less accurate for the time of peak.

3.2 Flood Maps

The calibrated hydrodynamic model was used to simulate various scenario of flood condition at multiple design flood condition which consists of 2, 5, 10, 20, 50 and 100 ARI. The flood maps for Sg. Kelantan river basin was divided to 17 box plot to represent appropriate scale of map area. The flood hazard map, flood evacuation map and flood risk map for 100 ARI current conditions at H3 Grid location presented in Figure 3.4 to Figure 3.6. Other maps for 100ARI condition at current and future condition were include in Appendixes;

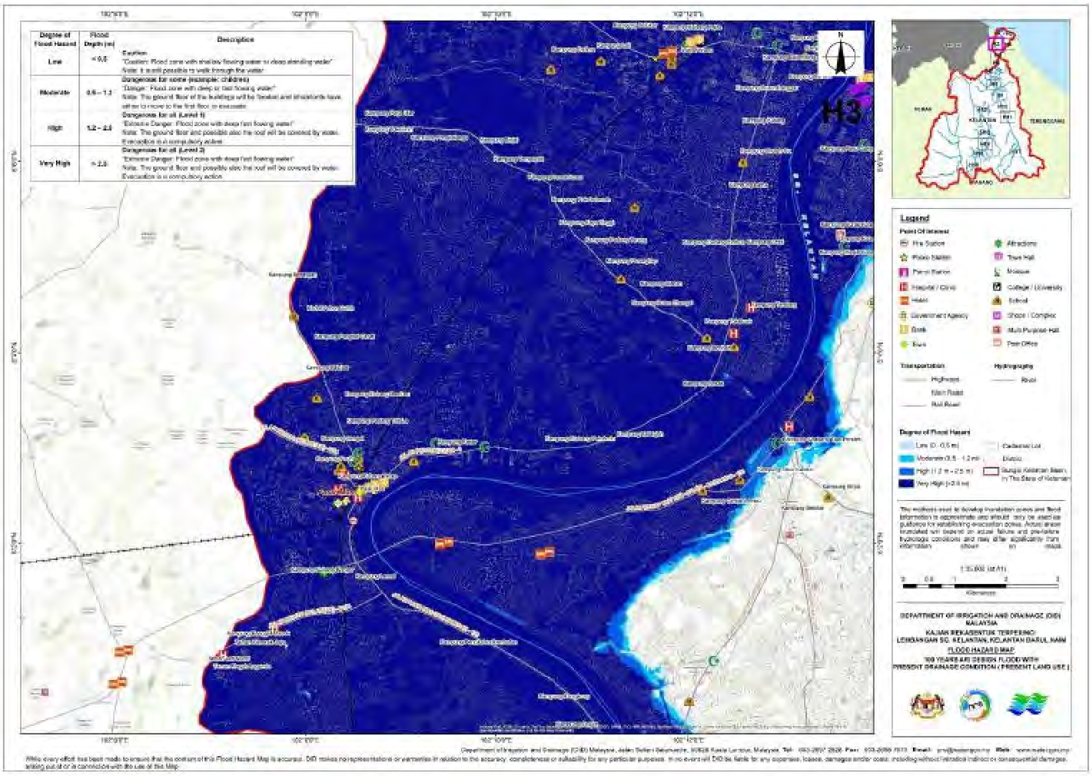
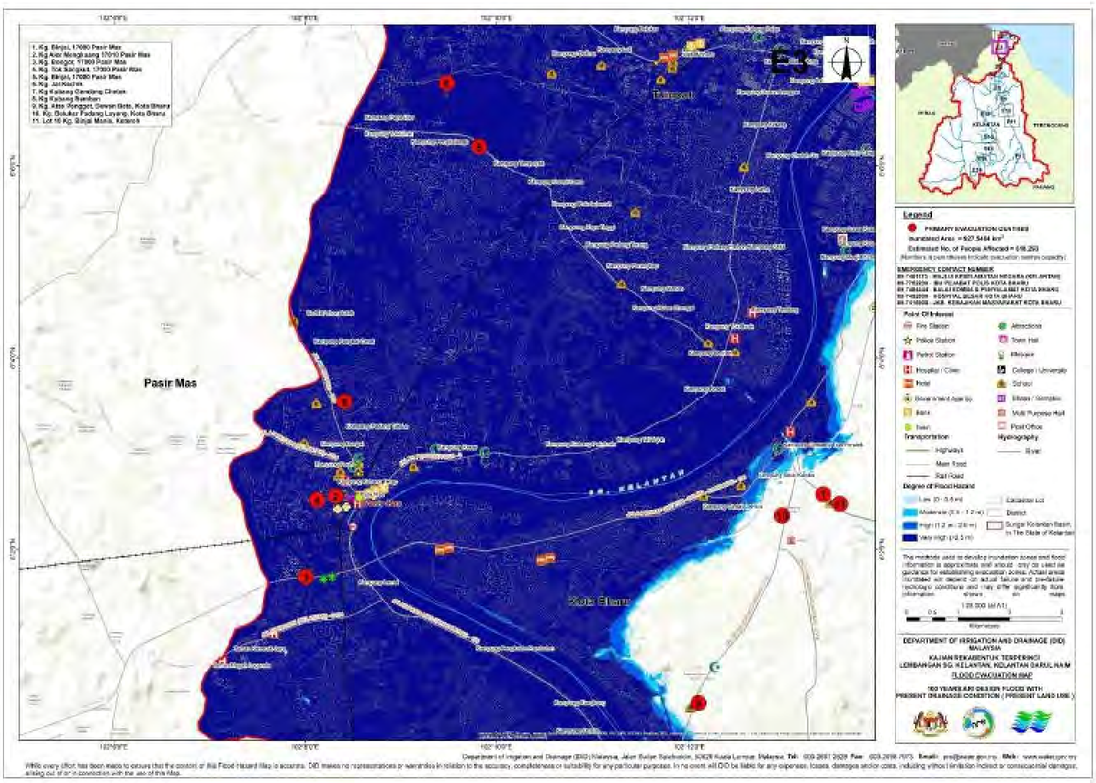


Figure 3.4: Flood Hazard Map for 100 Years ARI Design Flood with Present Drainage Condition (Present Land Use) at H3 Grid Location



(b) Figure 3.5: Flood Evacuation Map for 100 Years ARI Design Flood with Present Drainage Condition (Present Land Use) at E3 Grid Location

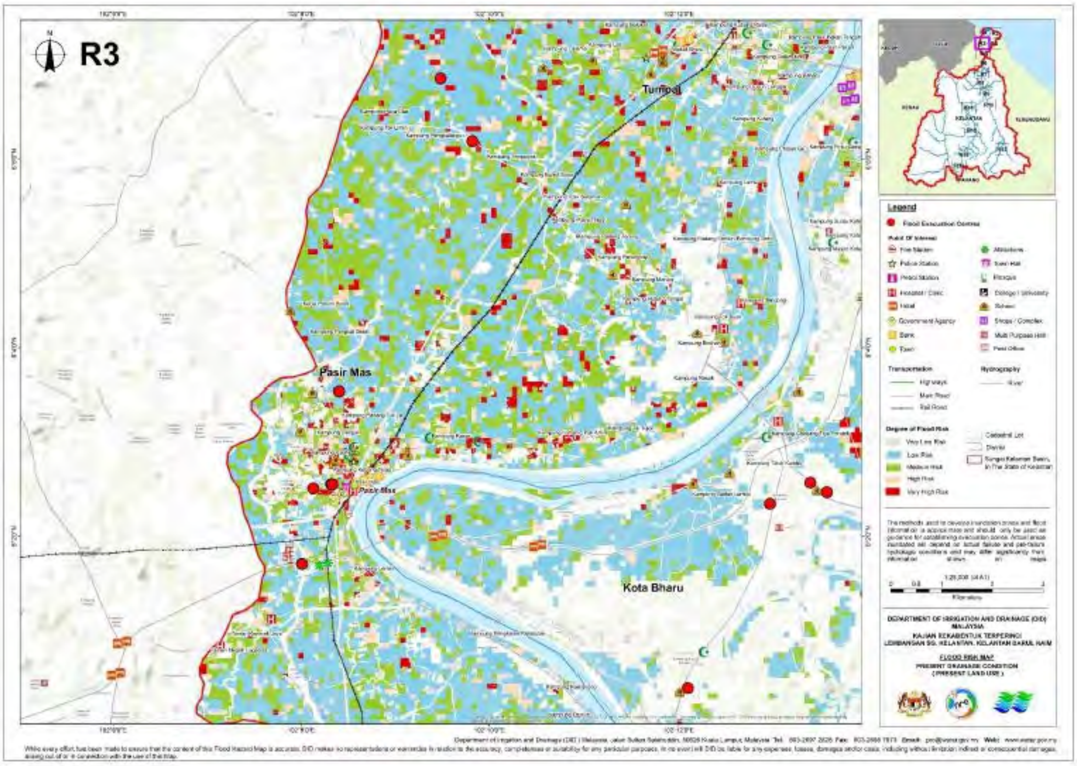


Figure 3.6: Flood Risk Map for 100 Years ARI Design Flood with Present Drainage

4. Challenges and Recommendations

4.1 Lesson Learned and Challenges

It can be deduce that the coverage of the Study is very comprehensive and detailed. Besides the extensive coverage, the challenges confronting this Study are further compounded by (i) time constraints (ii) technical challenges (iii) data availability as further details below;

a. Insufficient data

The availability of historical and real-time meteo-hydrological data is critical to the success of this Study. With insufficient data, the model can only be calibrated and validated for hydrological analysis only. For example, all the hydrographs stations in the Study Area are located in the upstream reach, whereas the critical areas that are being flooded are located in the downstream reaches. The water level and discharge station is located Kuala Krai. Therefore, there is insufficient observed water level and discharges data needed for model calibration in the downstream reach. In this case, the parameter set for the downstream reach was extrapolated from the hydrograph from the upstream reach.

b. Digital Elevation Model Data

One of the major concerns of this Study is related to the accuracy of the DEM data. It should be noted that the DEM forms the backbone of the hydrological model, whereby the level of accuracy of the DEM will have a direct linkage to the accuracy of the flood hazard maps that are produced. Even though IFSAR data available in this Study, the accuracies of 2D simulation particularly for depth of water at inundation area not very accurate. The need to use higher accuracies DEM data such LiDAR will improve the accuracy and reliability of flood maps. The existing LiDAR data coverage is minimal, with coverage limited to only approximately 10 percent of the whole river system. As a result, IFSAR data was used to cover the potential flooded area. This will inadvertently degrade the accuracy of the simulated results.

As the Study area is relatively flat in the downstream floodplain, a slight change in the elevation of the flood level will invoke a substantial change in the area coverage of the flood. However, the differences of flood coverage for different ARIs are not so obvious in the upstream part due to the area being surrounded by hills.

c. River Cross-Section Survey Data

The river survey data made available for this Study was sufficient to complete the modeling setup. However, for the certain river stretch, interpolated dataset from IFSAR data was used to set up the hydraulic model. Smaller interval cross-section data will result more accurate presentation of actual ground elevation to be well match with IFSAR data. The amount of water spill to the flood plain is much depends on the change intervals of the river and the accuracy of the IFSAR data.

d. Data collection

Data collection is therefore needed to enhance existing body of knowledge about previous flood events. The collection pre-existing information, which may seem to be a very simple task, however, actually it was very time-consuming, costly and laborious. Furthermore, this information exists in various forms, standards and data format and also kept by various private and public agencies. Having collated all the existing information, it must also identify if there is any data gap. If there is, then dummy dataset has to be created. This will involve determining the extent of the data required, collection activities, cost estimate and time frame or scheduling of the data collection.

e. Computation time of 2D modeling

A practical computation time is derived by compromising accuracy. Factors affecting computation time include:

- The specification of workstation
- Accuracy of processed Digital Terrain Model
- Mesh Size during development of ground model
- Representation of infrastructure ground model

f. Study case for Flood Risk Index

The categorization of flood risk values into five risk classes requires end values (range) to be determined from a large set of data points (pixels of weighted average damage). In order to ensure that the range for all risk classes is valid, the set of data points must not only represent a variety of return periods, but also derived from river basins that cover all land uses. This is especially pertinent since the end values obtained in this Study will be used as a basis for classification of flood risk for the entire country. The end values (range) must be determined using a rich enough data set that covers all land uses of interest. Unfortunately, the Sg. Kelantan river basin does not cover sufficiently diverse land uses that allows for a determination of end values for national application.

4.2 Recommendation

a. Calculation of Risk Index by Incorporating Shorter Return Period

The initial return period considered for risk index calculation did not include the 2-year return period. In the course of conducting the study, it was considered wise to include 2-year return period in flood risk calculation. This is because relatively small floods (but with relatively high probability of occurrence) do inflict some real damage that must be incorporated in the risk index calculation. Hence, omitting 2-year period flood events would undermine the risk index in a systematic manner.

The risk index is made up of two components i.e. the magnitude of damage and the corresponding probability of occurrence. The second component (probability of occurrence) may be viewed as the „weight" attached to the corresponding flood damage for each return period. In this sense, it is unwise not to include the 2-year return period since it has the highest weight of 0.5, followed by 0.2 for 5-year return period, 0.1 for 10-year return period and so on.

b. Periodic Updating of Flood Risk index

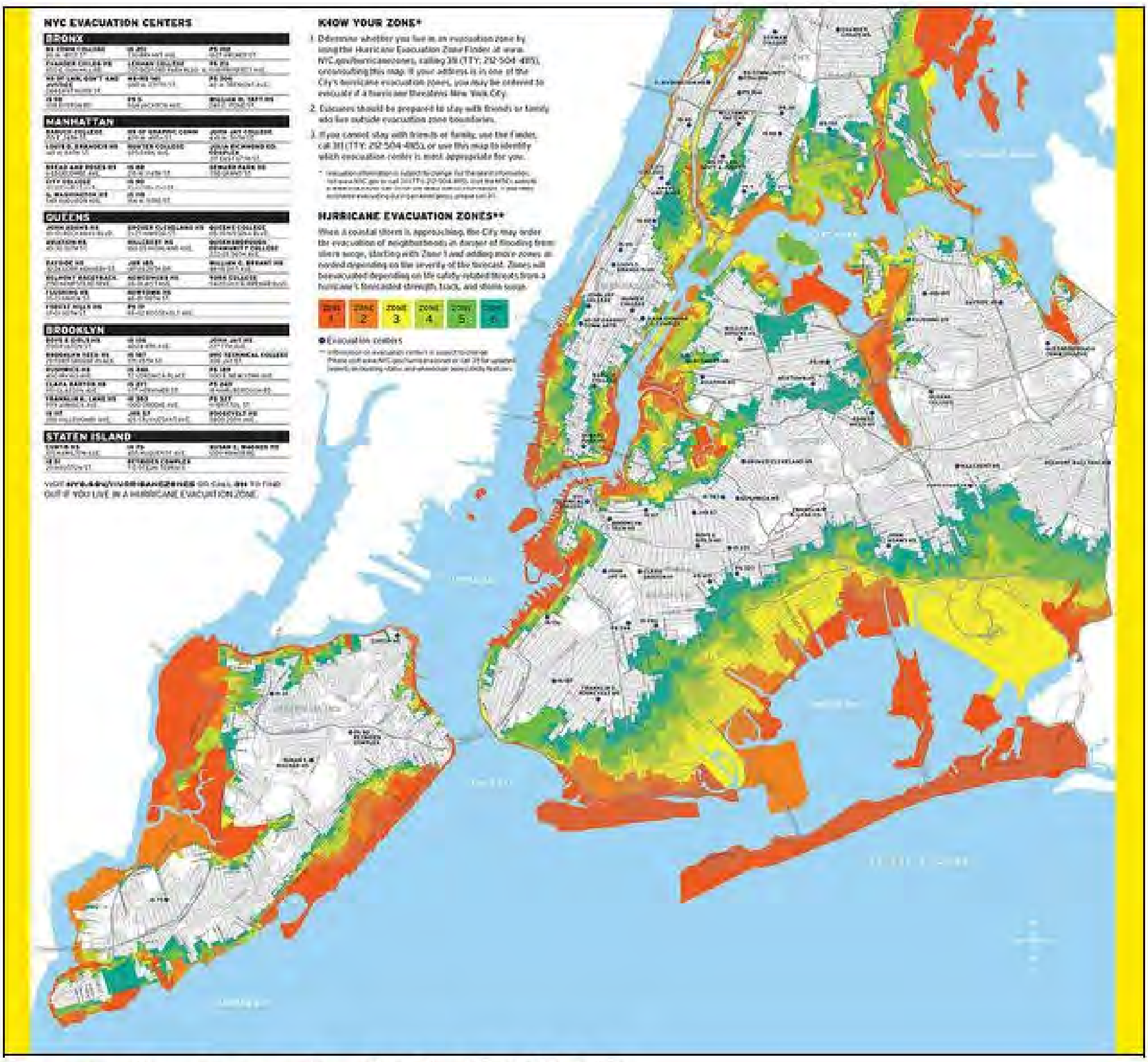
This study recommends that the flood risk index be updated on a periodic basis. Periodic update is necessary to ensure that the flood risk maps reflect the continually changing land uses, economic development status, property values, cost of operations, construction costs and general price levels. Since resources and fund have to allocated for updating purposes, it is recommended that updating interval one every five years is implemented. A shorter between updates maybe costly (or even unnecessary, given that some of the updating factors evolve gradually over time) while too long an interval may render the flood risk map significantly outdated. A five year interval appears to be an optimal balance between the need for the most current flood risk map and the cost (both financial and human resources) of conducting update.

c. Flood Evacuation Zones Maps

This study also recommends that flood evacuation zone maps should be adopted in upcoming studies. Flood evacuation zones map is a zonal map that is produced based on combination of flood extent boundaries for various ARIs. The zone are proposed to be six (6) Zone category according to the degree of flood risk (highest to lower risk) based on the flood recurrence interval. Figure 4.1 and Table 4.1 shows a good example practices in the United States of America that can applies in generating flood evacuation zone map for the usage of the response agencies and residents to plan for evacuation.

Table 4.1: Example of Evacuation Guidelines

Evacuation Zones	Probability of Flood Occurrence (ARI)	Description	Evacuation Plan
Zone 1	<2yr ARI	- Up to average 2 years ARI flood extent - Flood at least once in 2 years	Residents in Zone 1 must evacuate
Zone 2	2yr - 5yr ARI	- Up to average 5 years ARI flood extent - Flood at least once in 2 to 5 years	Residents in Zone 1 and Zone 2 must evacuate
Zone 3	5yr – 10yr ARI	- Up to average 10 years ARI flood extent - Flood at least once in 5 to 10 years	Residents in Zone 1, Zone 2 and Zone 3 must evacuate
Zone 4	10yr – 20yr ARI	- Up to average 20 years ARI flood extent - Flood at least once in 10 to 20 years	Residents in Zone 1, Zone 2, Zone 3 and Zone 4 must evacuate
Zone 5	20yr – 50yr ARI	- Up to average 50 years ARI flood extent - Flood at least once in 20 to 50 years	Residents in Zone 1, Zone 2, Zone 3, Zone 4 and Zone 5 must evacuate
Zone 6	50yr – 100yr ARI	- Up to possible maximum flood extent - Flood at least once in 50 to 100 years	Residents in all zones must evacuate



Source: http://www1.nyc.gov (New York City Official Website)

Figure 4.1: Example of New York City Evacaution Zones Map

d. Real-time Flood Hazard Maps

The hydrodynamic model shall further enhance for use of flood forecasting and warning purposes. It can be done through integration with real-time hydrological data such as rainfall and water level. The simulation result will depend on the computation time and the availability of observe hydrological data. Further, output of flood hazard map for the Point of Interest (POI) shall have more accurate classification. The POI can be divided to three groups which are Key Forecast Point, Forecast Point and Target Point. Details for each group show in Table 4.2.

Table 4.2: The classification of Point of Interest

Point of Interest	Description
Key Forecast Point	The main forecast point that means the location that have water level station or streamflow station with the water level threshold
Forecast Point	The location that have the cross sections with the water level threshold.
Target Point	The forecast location in the flood plain with threshold base on flood depth

5. Conclusion

This study was conducted after the extreme flood in December 2014 with the objective to assess the possible impact of risk due to flood. Flood risk with the combination of the probability of a flood event and the potential adverse consequences to human health, the environment economics activities associated with a flood. In line with the Integrated Flood Management (IFM) concept, the structural and non-structural measures are needed to manage flood risk. The technique used in this study is generally acceptable and shall be further enhanced using up-to-date methods and to adopt few recommendation in this paper. In order to expand the similar study for others river basin, involvement from research agencies and university were encourages.

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APPENDIXES

Figures consist of Flood Hazard Maps, Flood Evacuation Maps and Flood Risk Maps for Kelantan river basin for 100 ARI design flood.

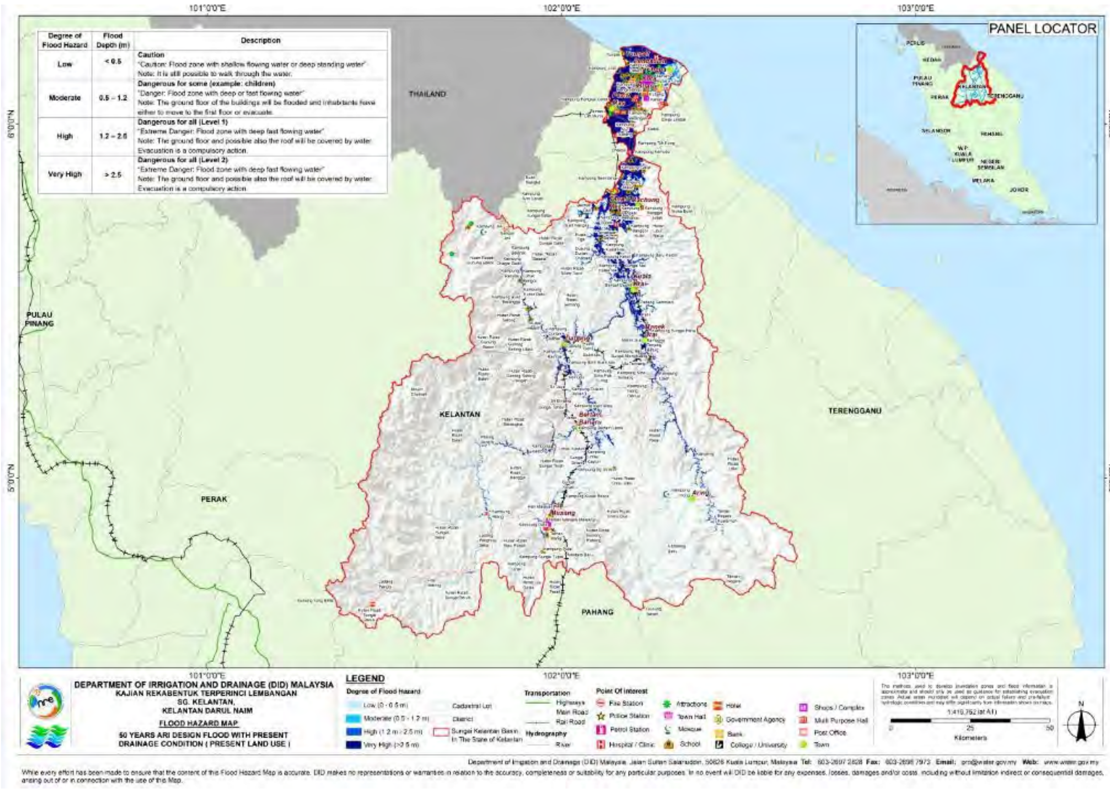

Figure 1: Flood Hazard Map for 100 Years ARI Design Flood with Present Drainage Condition (Present Land Use)

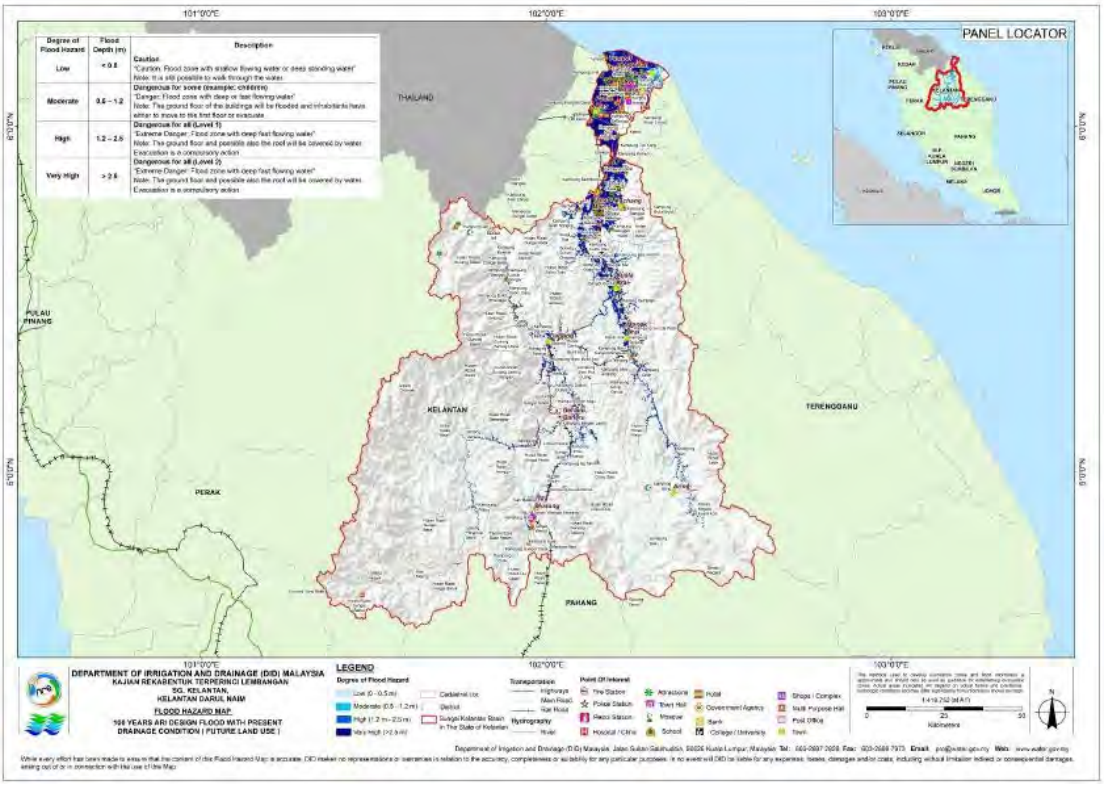

Figure 2: Flood Hazard Map for 100 Years ARI 100 Years ARI Design Flood with Present Drainage Condition (Future Land Use)

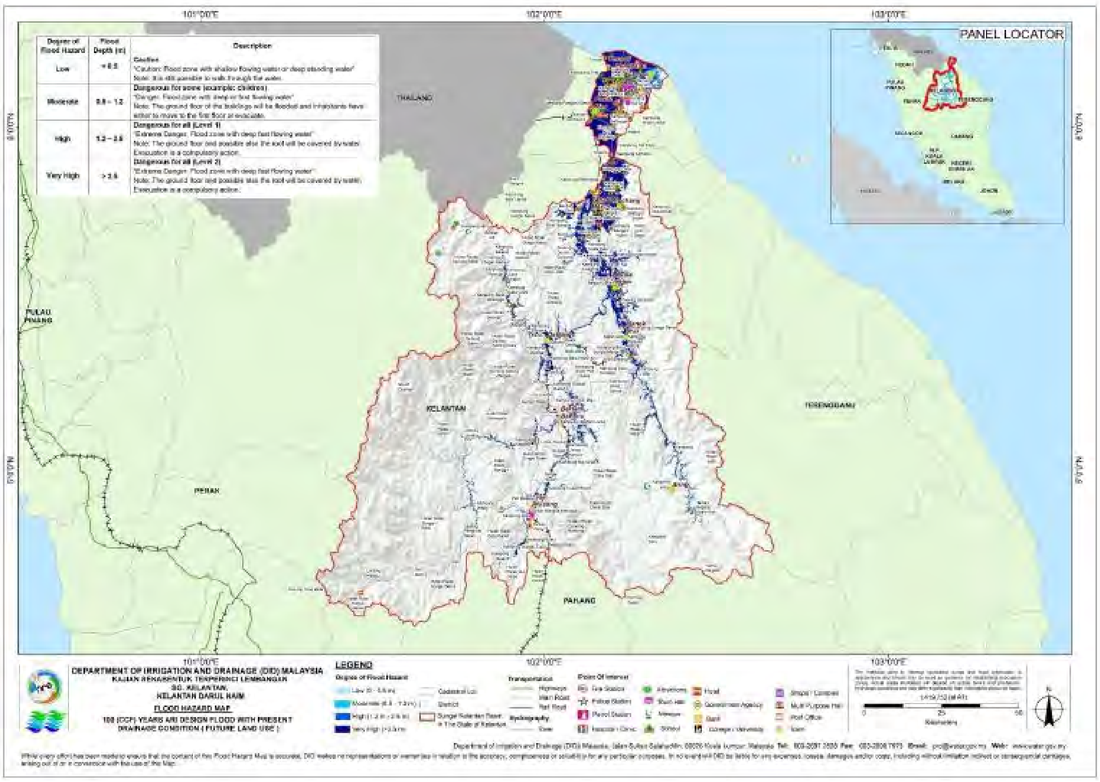

Figure 3: Flood Hazard Map for 100 Years ARI + Climate Change Factor (CCF) Design Flood with Present Drainage Condition (Future Land Use)

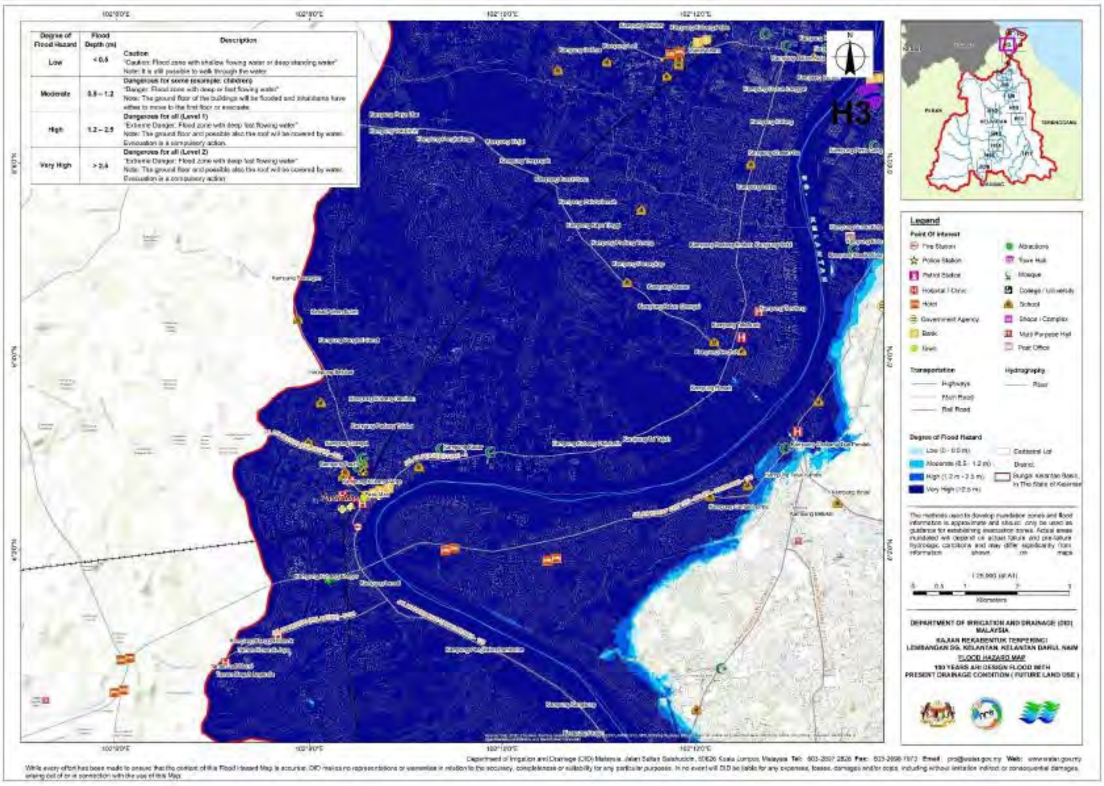

Figure 4: 100 Years ARI Design Flood with Present Drainage Condition (Future Land Use) at H3 Grid location

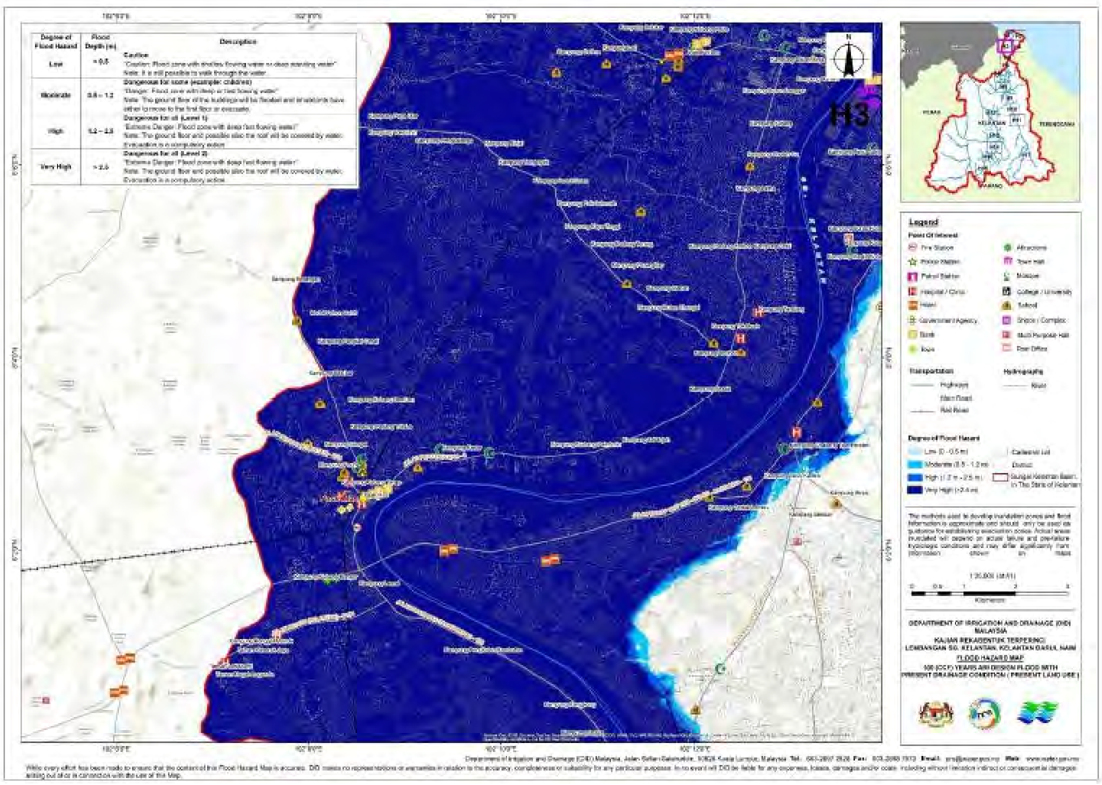

Figure 5: Flood Hazard Map for 100 Years ARI + Climate Change Factor (CCF) Design Flood with Present Drainage Condition (Present Land Use) at H3 Grid Location

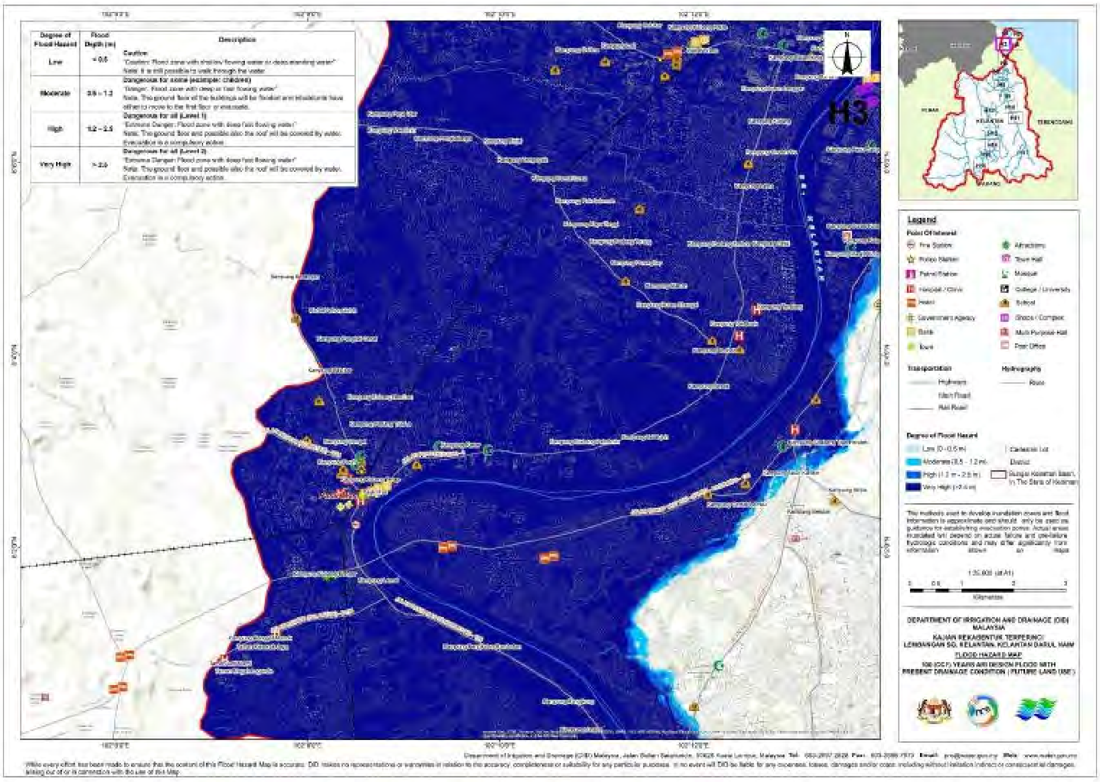

Figure 6: Flood Hazard Map for 100 Years ARI + Climate Change Factor (CCF) Design Flood with Present Drainage Condition (Future Land Use) at H3 Grid Location

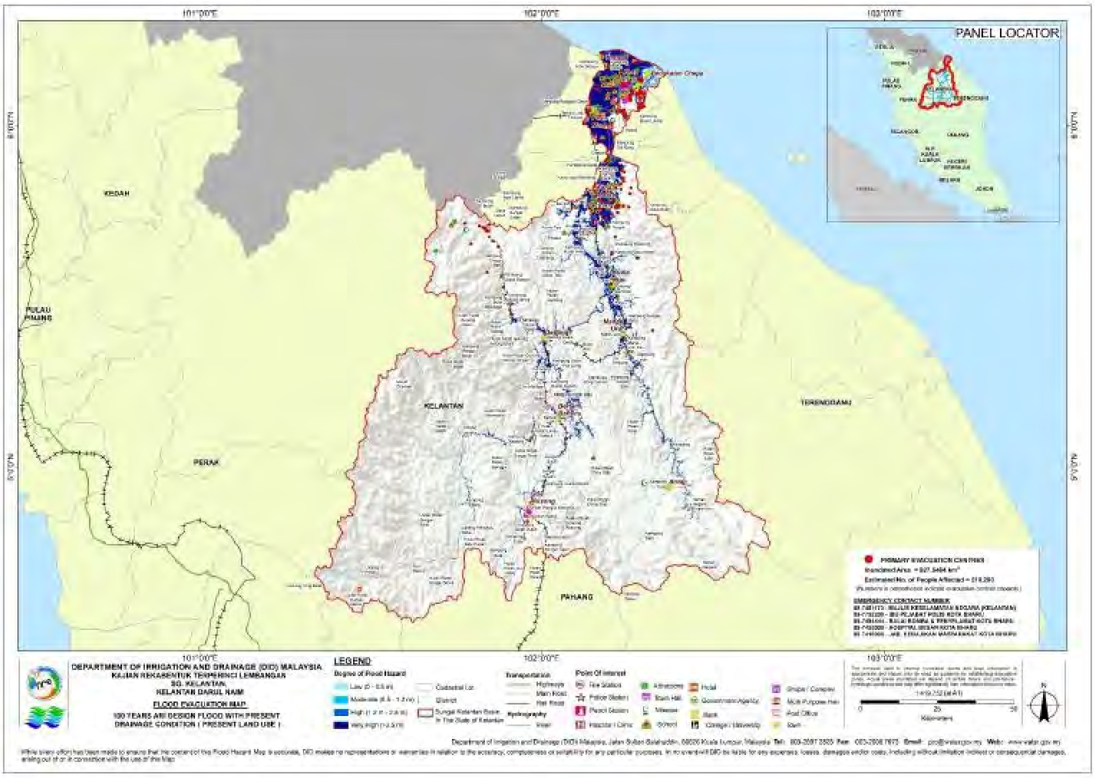

Figure 7: Flood Evacuation Map for 100 Years ARI Design Flood with Present Drainage Condition (Present Land Use)

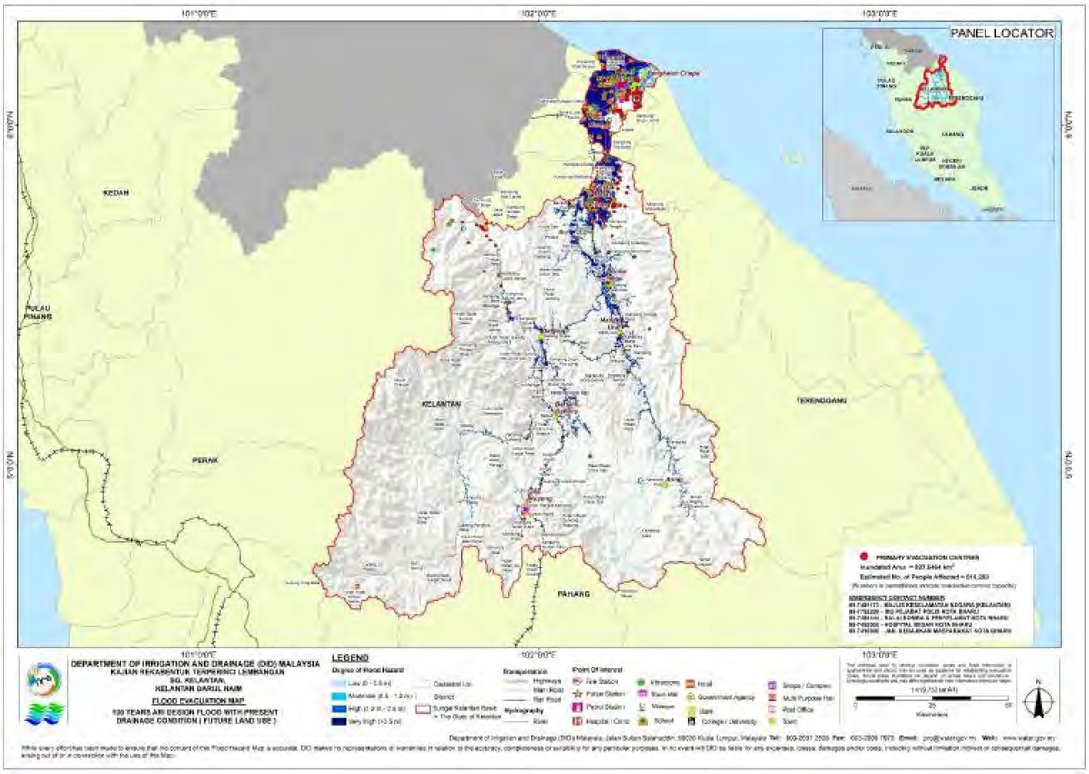

Figure 8: Flood Evacuation Map for 100 Years ARI Design Flood with Present Drainage Condition (Future Land Use)

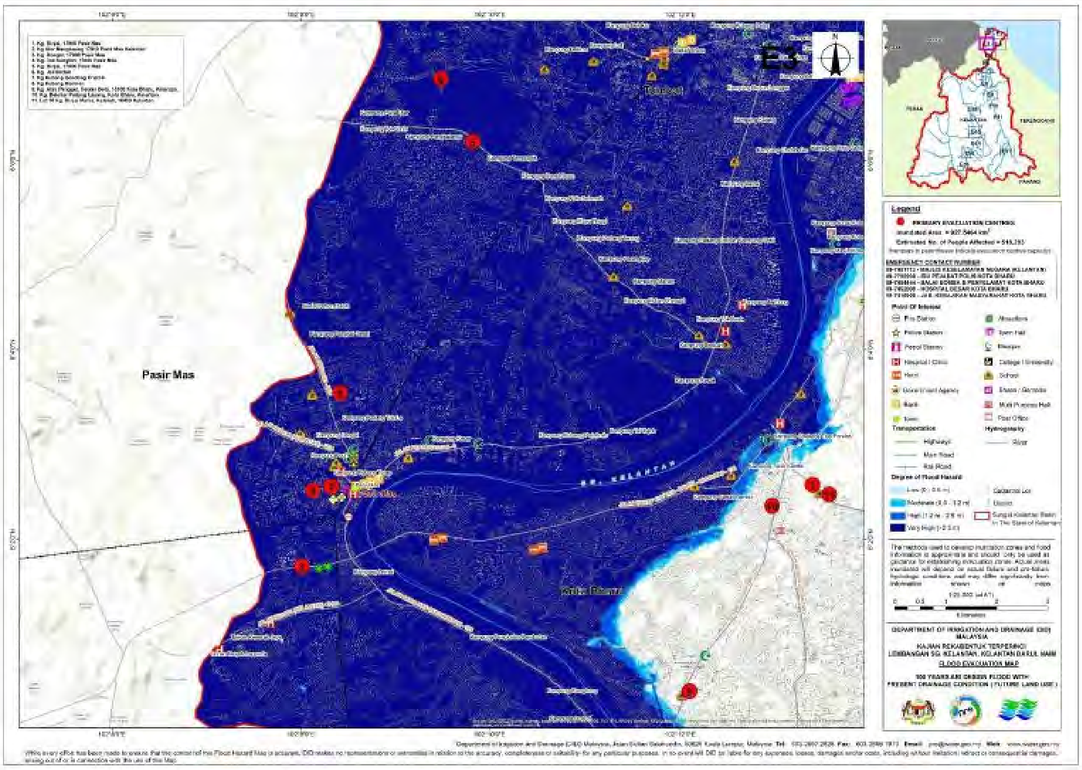

Figure 9: Flood Evacuation Map for 100 Years ARI Design Flood with Present Drainage Condition (Future Land Use) at E3 Grid Location

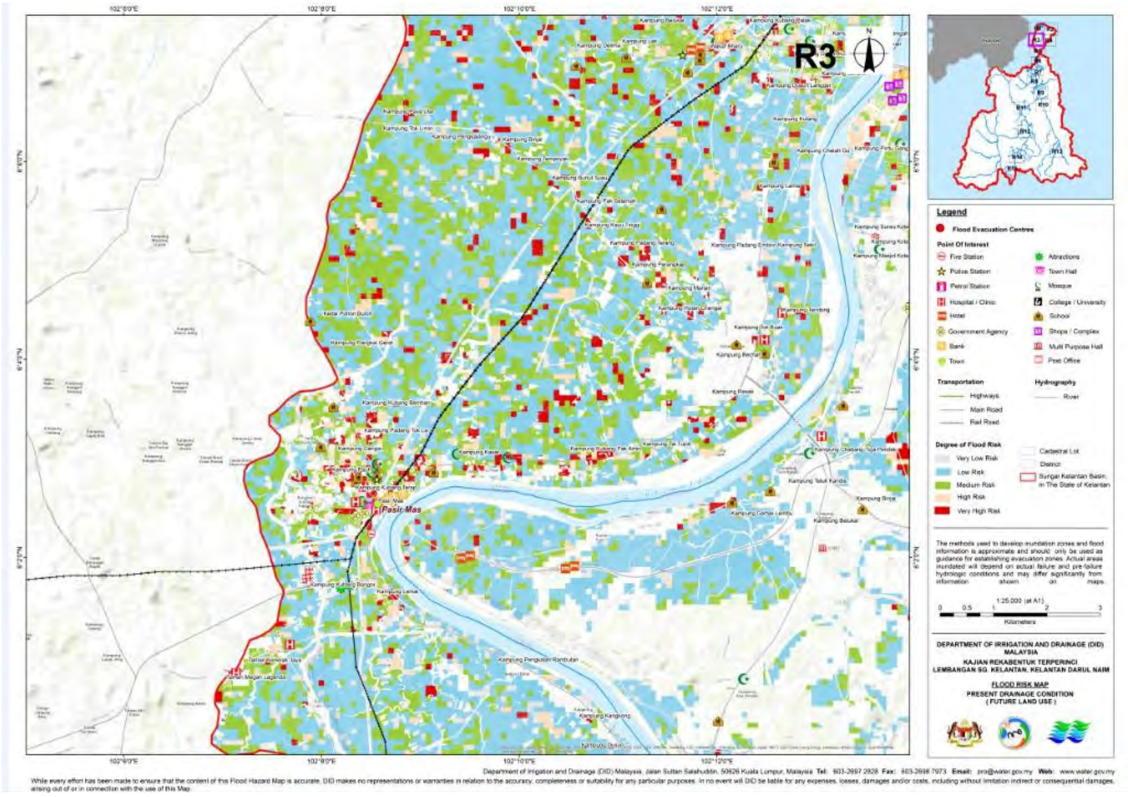

Figure 10: Flood Risk Map for 100 Years ARI Design Flood with Present Drainage Condition (Future Land Use) at R3 Grid Location.

Flood Hazard Mapping at the Bago City in the Bago River Basin

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1. Introduction

1.1 Flood disaster statistics

Flooding is one of the major hazards and the most devastating natural disasters in the world. During the last decades, floods led to loss of lives and properties, damage to critical infrastructures, economic losses and health related problems such as outbreak of water borne diseases when the lakes, ponds and reservoirs got contaminated.

Therefore, many countries try to develop the flood hazard map with different technologies because flood hazard mapping is an important tool for engineers, planners, and government agencies used for municipal and urban growth planning, emergency action plans, flood insurance rates and ecological studies. By understanding the extent of flooding and floodwater inundation, decision makers are able to make choices about how to best allocate resources to prepare for emergencies and to generally improve the quality of life.

Nowadays, floods and inundations are the natural disasters that most frequently hit in Myanmar due to the climate change, land use land cover and river morphology changes. Through the end of June into August 2015, Myanmar had the most disastrous flood that it had worst experienced in 12 States and Regions out of 14 in Myanmar. Due to heavy seasonal rains since end June superimposed by storm winds from Cyclone Komen when it made landfall in Bangladesh on 30 July 2015. Monsoon related heavy rainfall and resultant flash and riverine floods caused devastating disasters in a large part of Myanmar. The series flood killed 117 persons as of 31st August. 1615000 persons and 399.913 households were directly affected based on government sources. And also, the flooding has inundated more than 1.2 million acres of farmland, damaged 485 schools and 16741 homes.

The extent of damage could have been reduced or minimized if an early warning system and systematic evacuation plan have in that place. There is also a need for an effective modeling to understand the problem and mitigate its disastrous effects. There are several factors contributing to the flooding problem ranging from topography, geomorphology, drainage, engineering structures, and climate. In the recent years, remote sensing and Geographic Information Systems have been embedded in the evaluation of the geo-environmental hazards.

1.2 Purpose of flood hazard mapping

The purpose of flood hazard mapping is easy to manage flood disaster response mechanism and evacuate the people who living in the flood plain areas through the flood hazard map information.

2. Flood Hazard Mapping

2.1 Method to develop flood hazard map

The following flood frequency analysis method used to calculate the extreme discharge values of different return periods of 10 years, 20 years, 50 years and 100 years. The Chi-square test has to be used for choosing the best fit distribution of this flood hazard map development.

1. Normal Distribution
2. Log-normal Distribution
3. Pearson Type III Distribution
4. Log-Pearson Type III Distribution
5. Gumbel's Distribution

2.2 Scenario of external force to develop flood hazard map

It is generally accepted that flood has been increasing in Myanmar in the last decades. Accordingly, it becomes a priority to better understand the characteristics of flood and its drivers and mechanisms. And also, a flood characteristic is mainly depended on regional climatic pattern, river morphology, land use and land cover and climate change etc. If one of these factors is change in time, then so does the extreme floods. Consequently, flooding is going to make loss of life and damage their properties. Finally, it makes to reduce the GDP of our country. Nowadays, our country urgently needs to mitigate flood disaster impacts. This is one of scenario of external force to develop flood hazard map in Myanmar.

2.3 Tools and software to develop flood hazard map

The flood hazard map was generated by using HEC-RAS, HEC-GeoRAS, and Arc GIS. The methodology for developing flood hazard map can be explained by the following flow chart of methodology (Figure 1).

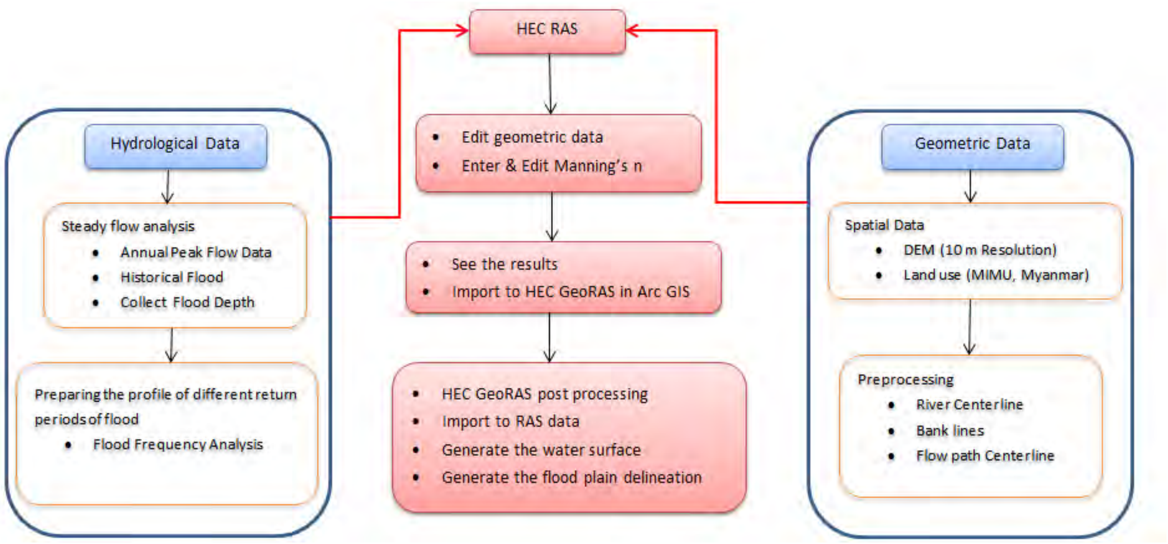

Figure 1 Flow Chart of Methodology

HEC-RAS model has been used to get the surface water profiles of areas Bago city. Frequency analysis of discharge data was carried out different flood frequency analysis methods. Secondly, geometry data were collected from the 10 m resolution of DEM. Digitization of selected stretch of study area on DEM is done using HEC-GeoRAS Tool the results of HEC-GeoRAS are exported to HEC-RAS in .sdf format. HEC-RAS simulates the annual flood peak.

HEC-RAS MODEL SETUP

Various data are required in setting up of the HEC-RAS model. One of the vital information is the geometrical information of a specific river stretch.

The geometrical data of a river is prepared using a tool called HEC-GeoRAS which assists in preparing input file as well as post processing of the HEC-RAS results in GIS environment. Using 10 m resolution of DEM on the study area, HEC-GeoRAS help to prepare the geometric data which is required for HEC-RAS. The important layers that are created are the stream centerline, Flow path centerlines, main channel banks and cross section cut lines as RAS layers. These parameters are used to establish series of cross-sections along the stream. HEC-RAS is a one dimensional flow model, intended for computation of water surface profiles for steady flow case.

The present case, steady flow simulation option of HEC-RAS is performed. The boundary condition at the downstream end of the river system was assumed as normal depth condition as it was the only available data for the study area. Before simulating the flows, certain certain data have to be defined viz- normal depth slope, discharge at the inlet, Manning's "n" value, expansion and contraction coefficients, etc., The model simulations were conducted for various return periods to estimate the water surface profiles for subcritical condition as the Froude's number was found to be less than 1 for the stream. The input data for the steady state is the peak discharge data for the particular return period. The model yields the water surface profiles for each of the flood magnitudes and the results are then again exported to HEC GeoRAS. Eventually, flood hazard map have to be generated with different return periods.

3. Dissemination of Flood inundation Map Information

Flood hazard map is one of the critical tools for informing communities about the flood disaster risk and flood disaster management discussions. In this regard, the Department of Meteorology and Hydrology (DMH) developed flood hazard maps and flood inundation maps for different cities along Myanmar Rivers. After generating the flood hazard maps, the DMH hold a meeting with water related organizations and departments, local authorities and communities at the respective cities in Myanmar. The DMH welcome any advises and suggestions from this meeting about this flood hazard map regarding its reliability and usefulness. Then, the DMH improve and/or redevelop if needed the flood hazard maps at the respective cities based on the advised and suggestions in the meetings. Finally, DMH disseminate the flood hazard maps and related information to the communities through the local authorities, water related organizations and departments and at its DMH's website.

4. Application of Flood Hazard Map

4.1 Flood hazard map for Bago river basin

4.1.1 Location of Bago River Basin

Bago river basin is a flood prone area in Myanmar. The Bago city is one of flood prone area in the Bago river basin. It is located between 96°26´ E – 96°31´ E longitudes and 17°15´N – 17°22´ N latitudes in the southern central Myanmar (Figure 2). The Bago River flows from the Pegu Yoma mountain range at an elevation of 800 m.a.s.l. in the north, running south through meandering sections of over 331 km before it reaches the Yangon River near Yangon City.

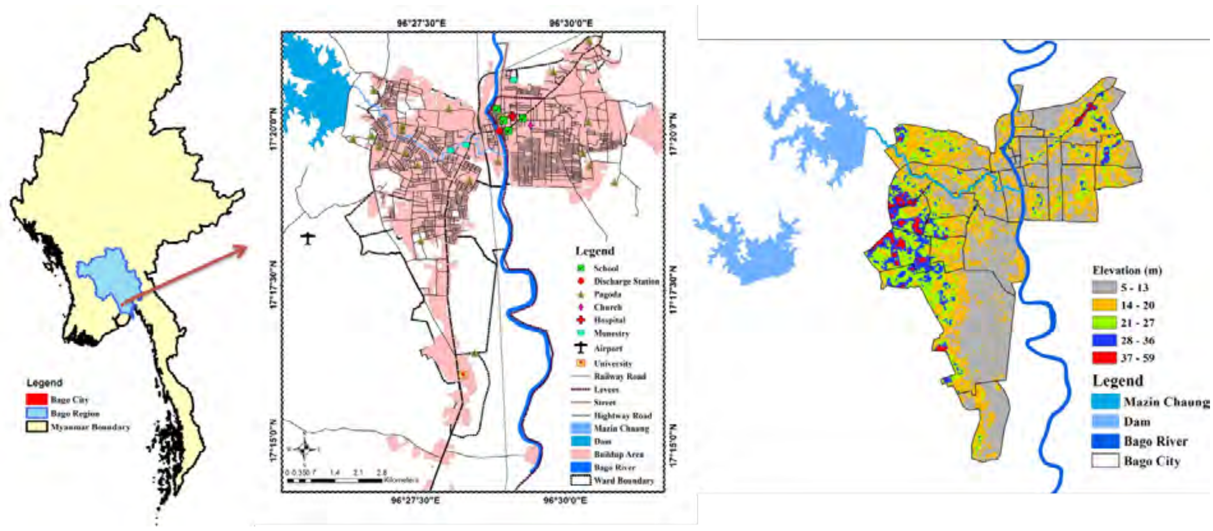

Figure 2 Location map of Study area

4.1.2 Hydrological Characteristics of Bago River Basin

The climate in the Bago river basin is characterized by tropical monsoon with distinct wet and dry seasons. The monthly normal rainfall at Bago gauging station is shown in Figure 3. And also, the yearly maximum water level of Bago gauging station is shown in Figure 4. According to floods at Bago city, it is generally occurred in monsoon season, especially in month of July and August.

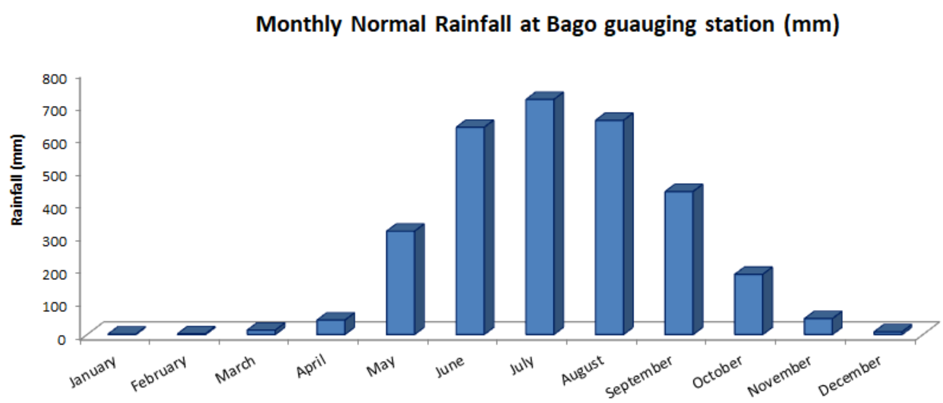

Figure 3 Monthly Normal Rainfall at Bago gauging station (mm)

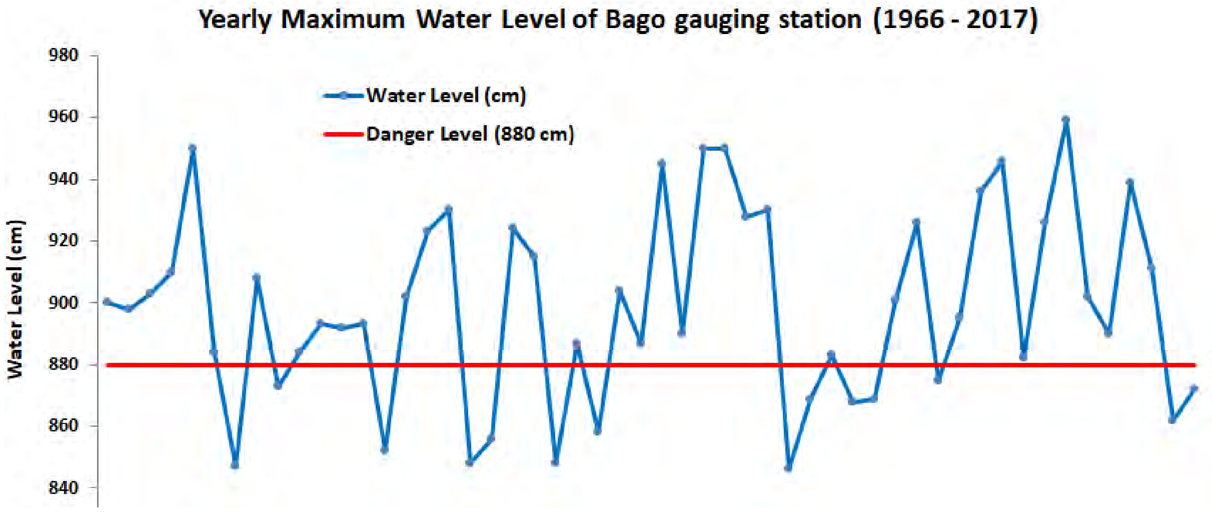

Figure 4 Yearly maximum water level of Bago gauging station

4.1.3 Flood Hazard map for Bago River Basin

Flood hazard maps are used for various ways especially in flood disaster management activities and city development planning. The following Figure 5 and 6 show the flood hazard maps of Bago city with 10, 20, 50 and 100 year return periods.

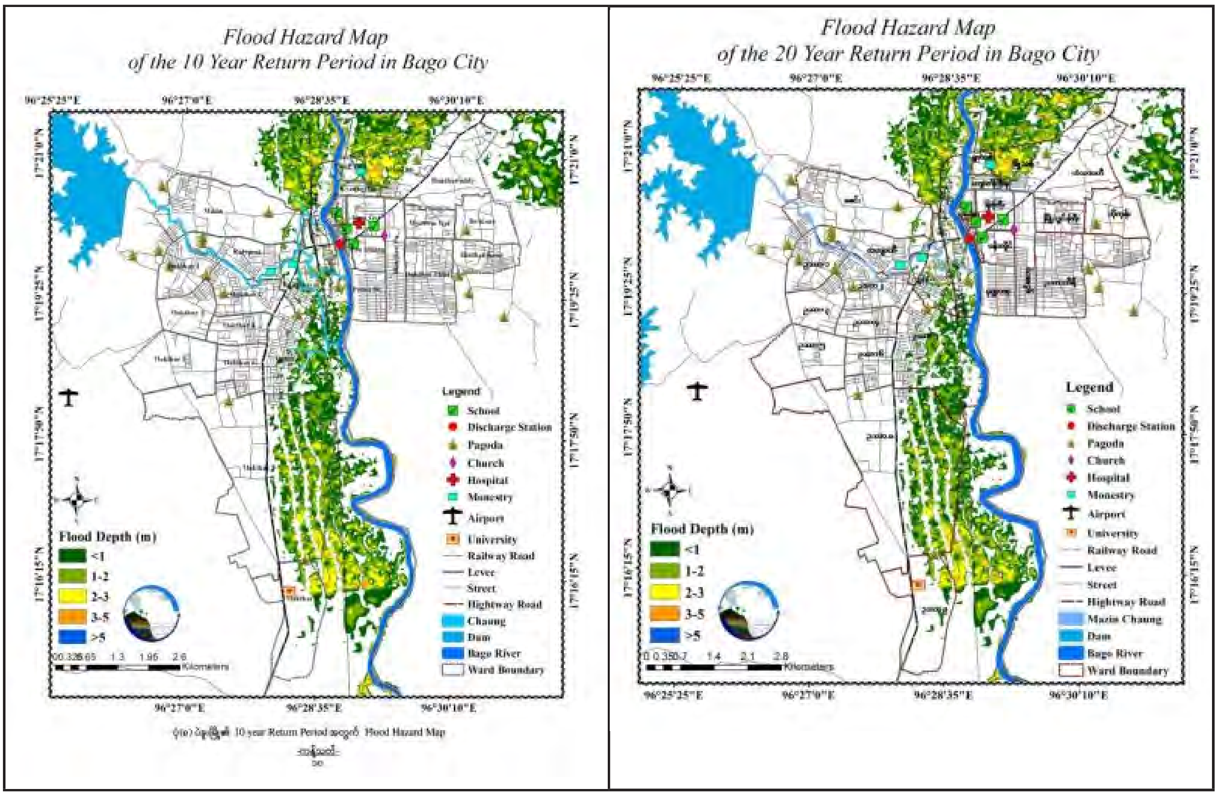

Figure 5 10 and 20 year return periods Flood hazard maps of Bago City

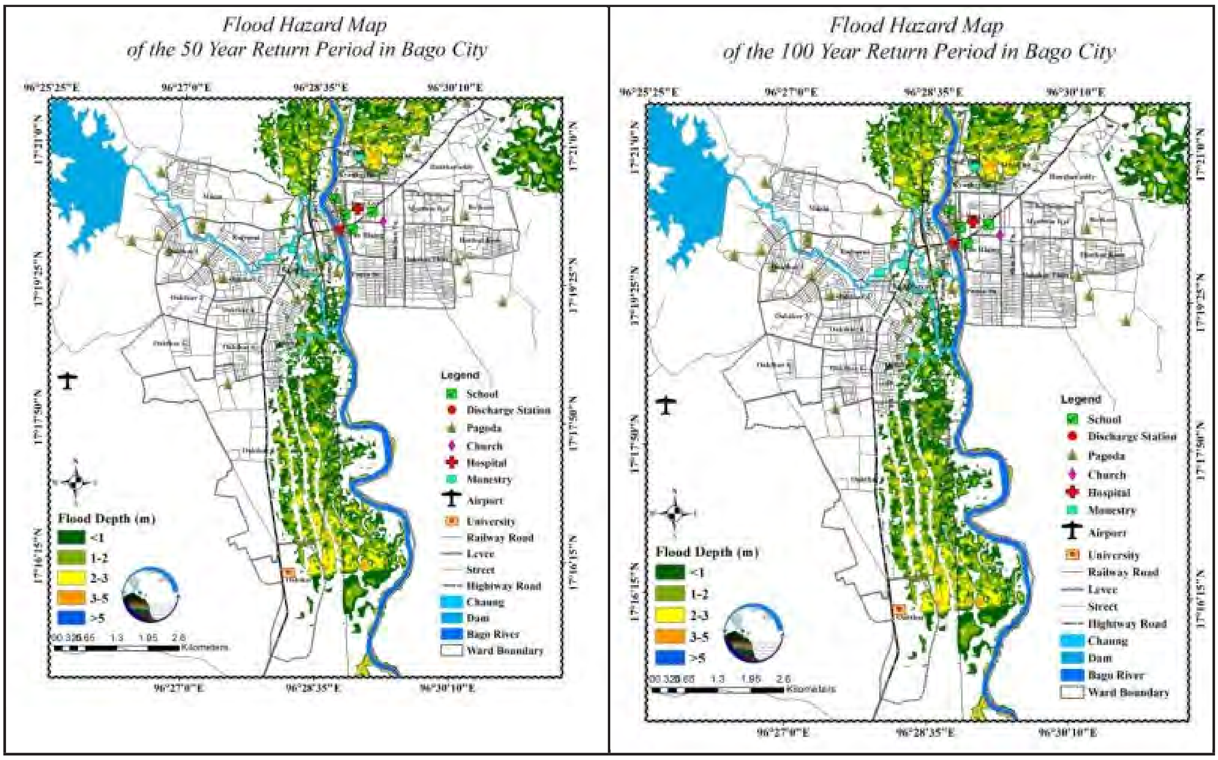

Figure 6 50 and 100 year return periods Flood hazard maps of Bago City

This flood hazard map is also includeinformation about the flood inundation areas and flood depth that related to flood with different return periods. This flood hazard maps are also typically provided the location of school, hospital, airport, monastery, pagoda, church, university, railway, and highway road etc.

5. Good Practice and Lesson Learned from the Recent Floods

5.1 Lesson Learnt from 2015 Nation-wide flooding

Myanmar's people faced nation-wide flooding during the month of July and August 2015. This is the Cyclone Komen that made landfall in Bangladesh on 30 July, has brought strong winds and additional heavy rain in Myanmar. That's why, 12 out of 14 states and regions are flooded. At that time, our president U Thein Sein issued a statement proclaiming (1) Chin State, (2) Sagaing Region, (3) Magway Region and (4) Rakhine State, as natural disaster zones. During the flood, Government, NGOs, INGO, Civil Society Organization (CSO) and Community-Based Organization (CBO) are closely collaborated with each other to find out the best way flood response mechanism and drawn out the flood disaster management activities in Myanmar. And also they evaluate and help the people who living in flood prone areas. This is good practice and lesson learnt from the recent nation-wide flooding in 2015.

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Flood Mitigation Planning and Hazard Mapping for Cagayan de Oro River in Mindanao, Philippines

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1. Introduction

This flood mitigation planning and associated flood hazard mapping is motivated in response to the devastation of Cagayan de Oro City brought by Typhoon Sendong that occurred in Cagayan de Oro River (CDOR) Basin in Mindanao, Philippines in mid-December, 2011. Originally, JICA funded a Master Plan and Feasibility Study for Flood Risk Management Project for Cagayan de Oro City (FRIMP-CDOR) in June 2011. Since it was overtaken right away with Typhoon Sendong occurring in that December 2011, JICA funded another study in March 2014 (JICA, 2014) to review and update the previous flood masterplan for CDOR Basin. However, the March 2014 updated flood mitigation plan has encountered some resistance by concerned parties that include Paseo Del Rio (PDR) and Torre de Oro (TDO), both being major land developers of the city and the former with an ongoing commercial/residential project complex along the Cagayan de Oro River. In response to this, the Department of Public Works and Highways (DPWH) commissioned the National Hydraulic Research Center of the University of the Philippines (UP-NHRC) to serve as third party to conduct a review and value engineering study of the flood risk management project for Cagayan de Oro City. An important task of UP-NHRC is to engage the stakeholders such as DPWH's Flood Control Management Office, the City Mayor's Office, Mindanao Development Authority, PDR, TDO, among others to meetings and consultations so that these stakeholders are informed and their inputs properly solicited in the course of this study. Specifically, this study evaluated the hydraulic performance and level of protection that can be provided by the alternative flood mitigation plans for FRIMP-CDOR. The resulting flood hazard maps produced in this study and particularly the recommended flood mitigation plan can be utilized for flood management. This study highlights the importance of stakeholder participation throughout the course of the flood study resulting in proper consideration, formulation and eventual selection and recommendation of best flood mitigation plan. A two-dimensional (2d) flood inundation model is utilized in the hydraulic simulation studies.

2. Flood Inundation Modeling and Alternative Flood Mitigation Plans

2.1 Flood Inundation Model with Watershed Model

A 2-d flood hydraulic model (Tabios, 2008) based on the finite volume method (FVM) formulation of the mass conservation equation and the momentum conservation equations in the x- and y-directions is utilized in this study. This 2d model is described in the Appendix A.

As shown in Figure 1, the portion with the finite element mesh is modeled. The inflows to the 2-d model were computed from a continuous-time, distributed model where the soil-moisture accounting model is the Sacramento model (Tabios et al, 1986) with watershed modeled area shown in Figure 2 with a drainage area of 1,370 km2. Note that the area modeled by the 2-d hydraulic is also shown in Figure 2 located at the top of the figure. Flood inundation simulation studies were conducted to evaluate the alternative flood mitigation plans.

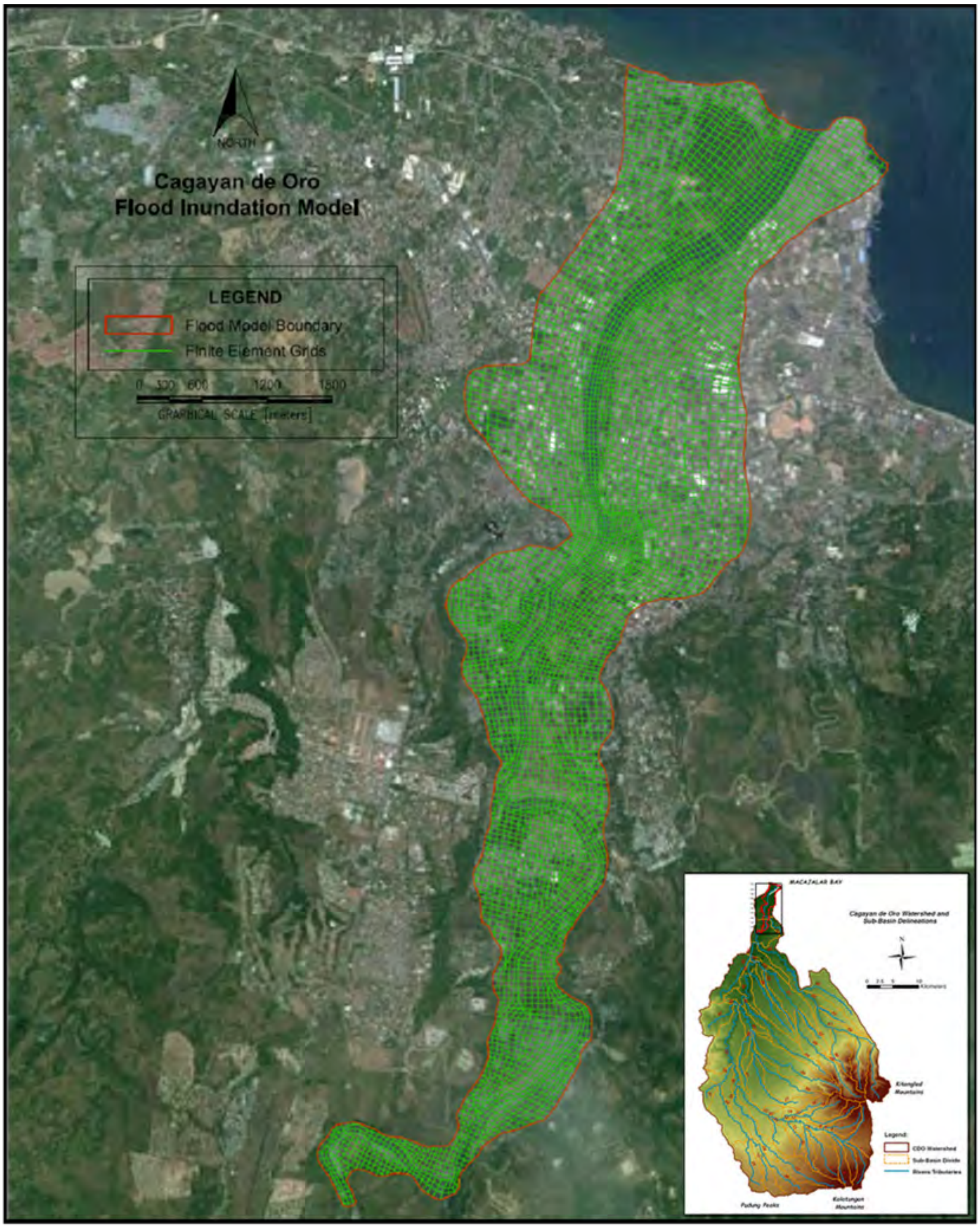

Figure 1 Cagayan de Oro River (2-d finite volume mesh) covered in the 2-d flood inundation model. The inset figure shows the location of the mesh area relative to the entire Cagayan de Oro River Basin.

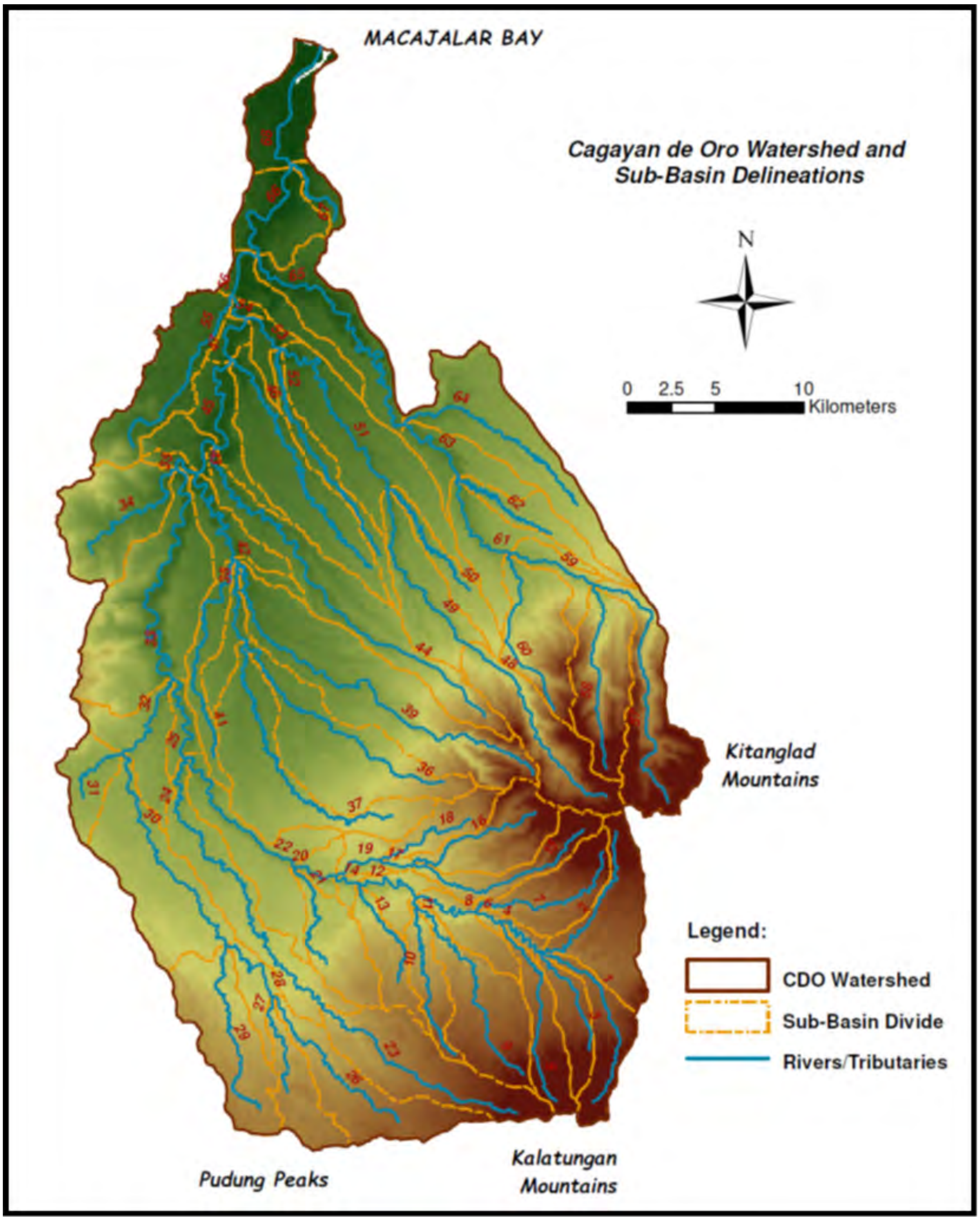

Figure 2 Cagayan de Oro River Basin watershed area with drainage area of 1,370 km2.

2.2 Alternative Flood Mitigation Plans

Based on meetings with DPWH engineers, JICA experts and a series of public consultations held in Cagayan de Oro City, 7 alternative flood mitigation schemes were developed namely: 1) existing condition (present flood control structures); 2) existing and urgent-ongoing flood control projects; 3) DPWH-JICA proposed long-term flood mitigation project; 4) same as Case 3 but with realigned dike at Paseo del Rio-Torre de Oro area; 5) same as Case 4 but with one additional retarding basin upstream of the realigned dike; 6) same as Case 4 but with two additional retarding basins; and, 7) same as Case 6 with river flood storage using a notched, overflow weir downstream of Pelaez Bridge. Note that Case 3 above is the original flood mitigation plan developed in the March 2014 JICA study. Figure 3 shows the resulting alternative flood mitigation plans.

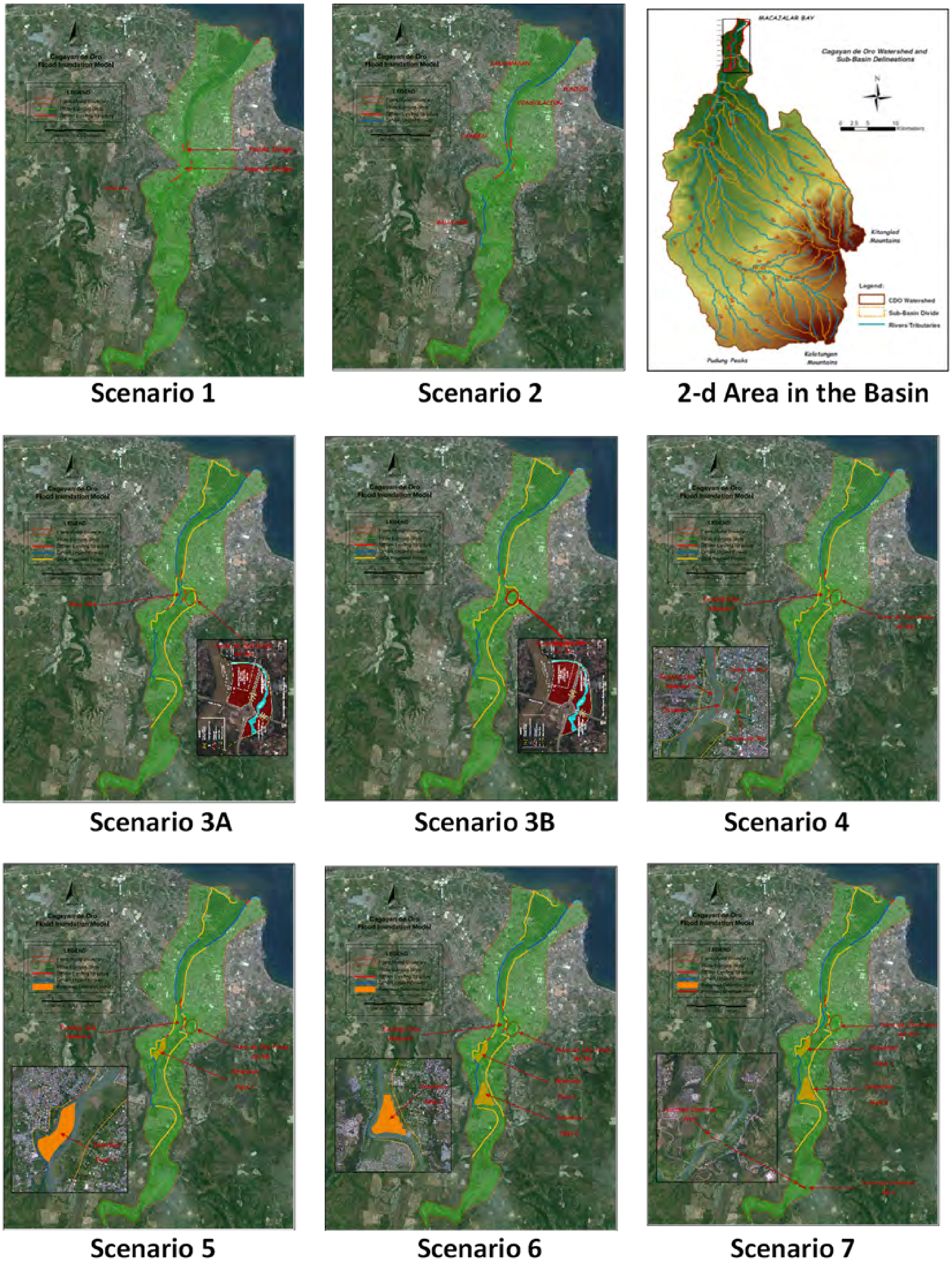

Figure 3 Eight (8) flood mitigations plans or scenarios for Cagayan de Oro River Basin.

3. Results of Flood Inundation Model Simulations

3.1 Inflow Flood Hydrograph Computations with Watershed Model

The watershed model developed in this study is used to generate river flood discharge of selected historical and/or hypothetical storms as input to the two-dimensional (2-d) flood hydraulic model to evaluate the performance of possible or identified flood mitigation measures in the City proper area.

To compute the flood hydrograph associated to Typhoon Sendong, the rainfall hyetograph developed in the 2014 JICA study (Preparatory Survey for FRIMP-CDOR) was adopted in this study. Using the time pattern or distribution of this Typhoon Sendong rainfall hyetograph, the rainfall hyetographs of the 10-yr and 50-yr return period, 24-hr total rainfall were derived. With this rainfall hyetographs, the corresponding flood hydrographs at the location slightly upstream of Pelaez Bridge as well as those at the outlet of sub-basin 67 were calculated using the watershed model.

Table 1 below shows the rainfall hyetographs for Typhoon Sendong of December 17-18, 2011 and 10-yr return period rainfalls and their corresponding flood hydrographs calculated from the watershed model. Note that the total 24-hr rainfall associated to Typhoon Sendong from 2014 JICA study is only 130.9 mm compared to the 24-hr rainfall totals of 156 mm and 215 mm corresponding to the 10-yr and 50-yr Lumbia Airport storm rainfalls, respectively. Also, it may be noted that the peak flow of Cagayan de Oro River at Pelaez Bridge from the 2014 JICA study is 4,924 m3/s in contrast to the peak flow of 5,715 m3/s of Typhoon Sendong computed from the watershed model using the same Typhoon Sendong rainfall hyetograph from the 2014 JICA study.

Time (hr)	JICA Sendong Rainfall (24-hr total = 130.9 mm)	10-Yr Rainfall from Lumbia RIDF (24-hr total = 156 mm)	JICA Sendong Flood Hydrograph at Pelaez Bridge	Inflow Flood Hydrograph from Watershed Model	
				JICA Sendong Rainfall	10-yr Lumbia Rainfall
1	0.39	0.46	131.73	106.97	107.15
2	0.39	0.46	131.73	115.97	116.21
3	0.39	0.46	131.73	140.03	140.46
4	0.39	0.46	131.73	182.76	183.67
5	0.39	0.46	131.74	232.70	234.47
6	0.39	0.46	131.75	273.19	276.21
7	0.82	0.98	131.82	298.71	303.32
8	0.82	0.98	132.04	311.81	318.50
9	1.18	1.41	134.03	317.21	326.60
10	1.18	1.41	155.71	320.35	333.59
11	1.44	1.72	194.28	325.39	343.86
12	2.08	2.48	301.58	335.17	360.41
13	3.02	3.60	599.73	353.03	387.40

14	5.73	6.83	1060.63	385.77	434.11
15	12.58	14.99	1881.88	459.38	537.70
16	52.00	61.95	3121.92	699.91	879.56
17	22.36	26.64	4326.58	2804.74	3803.41
18	8.01	9.54	4924.51	5715.15	7209.49
19	4.19	4.99	4556.73	5522.53	6605.18
20	2.85	3.40	3787.47	4004.80	4615.24
21	1.76	2.10	3063.28	2756.88	3094.04
22	1.45	1.73	2473.08	1960.43	2163.13
23	1.21	1.44	2010.56	1472.05	1612.75
24	0.90	1.07	1653.61	1164.26	1274.24
25	0.90	1.07	1378.36	959.51	1051.54
26	0.90	1.07	1164.82	815.86	896.21
27	0.46	0.55	997.60	711.36	783.56
28	0.46	0.55	865.23	631.27	696.90
29	0.46	0.55	759.27	566.85	626.63
30	0.46	0.55	673.53	513.33	567.86
31	0.46	0.55	603.43	468.30	518.33
32	0.46	0.55	545.54	430.39	476.74
33	0.46	0.55	497.30	398.58	442.02

Table 1 Rainfall hyetographs and flood hydrographs as 2-d model inputs.
(Highlighted below are peak rainfall and peak runoff.)

3.2 Discussion of Flood Inundation Model Simulations

In the flood simulations upstream boundary is the inflow at Pelaez Bridge including the inflow hydrograph at Sub-basin 67 peak flows of 37.59 and 45.46 m3/s for JICA and 10-yr Lumbia rainfall respectively. Also, the downstream boundary condition is tidal water level at Macajalar Bay (mouth of Cagayan de Oro River) during the typhoon. The flood simulations were carried out for a period of 33 hours on an hourly basis. The results of the flood simulations are too long to show here but one useful output is to compare the different plans or scenarios is to examine the plots of the profiles of maximum water surface elevations. Figure 4 shows the maximum water surface profiles which was averaged from 2 to 3 elements or grids (transverse-wise) at that location. Generally, there are practically no differences between the water surface elevations using watershed model-based and JICA-based flood hydrographs. It is seen here that Scenario 1 resulted in lowest water surface elevations compared to the other scenarios at around Ysalina Bridge (at distance 4.2 km from Macajalar Bay) because the floodwaters spread into the floodplain in these areas since there were no dikes, compared to the other cases where the floodwaters were confined by the diking system. On the other hand, comparison of the water surface elevations among Scenarios 3A, 3B and 4 through 7, show that Scenario 4 followed by Scenarios 5, 6 & 7 result in lower water surface elevations compared to the other cases and in particular Scenario 3C. The reason for this is that in Scenario 3A, the existing (ongoing project) baby dike segment constructed around the Ysalina (Carmen) Bridge where the Commission of Audit Building is located (also across the City Hall Building) was retained (although it was opened at the upper and lower end of the dike segment) in contrast to Scenarios 3B and 4 through 7 in which that particular segment of the dike was removed. In any case, overall, it can be concluded that the differences in water surface profiles among Scenarios 3A, 3B and 4 through 7 are not that significant.

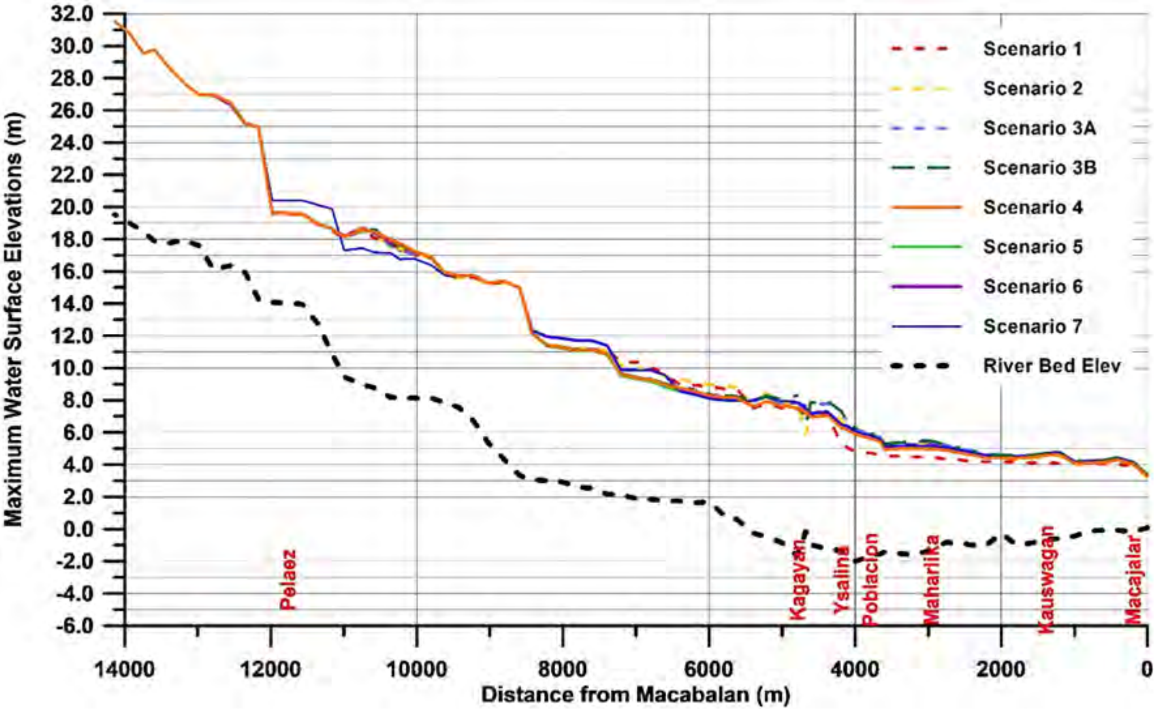

Figure 4 Resulting water surface profile of the alternative flood mitigation plans.

Generally, the flood analyses and model simulations show that there are only slight differences among the different flood plans/configurations. In particular, however, Cases 4 and 5 and especially Case 7 result in smaller flood inundation levels compared to case 3A/B especially at higher rainfall amounts. A cost analysis was also conducted but too long to show here, and it can be concluded that Cases 3A/B and 4 are equally competitive based on flood level reductions and project costs. However, Case 7 results in the best flood level reduction but it costs higher and in the long term due to maintenance dredging costs.

4. Application of Flood Hazard Mapping

For purposes of flood hazard mapping which may be used for flood management purposes, the maximum water depths (in meters) over the simulation period of 33 hours are illustrated for two cases as shown in Figures 5 and 6 for Scenarios 1 and Scenario 3B. In these figures, the maximum water depths are plotted by class posting at every grid cell whereby different colors represent the different ranges of depths as indicated in the legend. These maps may be used to determine areas that should be zoned as no-build zones as well as to identify staging and evacuation areas.

Another useful information for flood management is based on determining the areas flooded (in hectares or ha) and average depths (in meters) of flood inundations in the built-up areas at the different barangays as shown in Table 2 for the 50-yr return period flood for the different flood plans (cases 1 through 7). Figure 7 is the accompanying map of the locations of the barangays referred to in Table 2. Generally, the results show that Scenarios 1 and 2 result in more areas flooded and higher average depths of flooding compared to the other cases. It may be noted that the areas flooded and even depths of flooding for Scenarios 3A, 3B and 4 through 7 are almost the same with some few exceptions which may be due to the relatively coarse grid cells of the model geometry thus the areas flooded maybe the same while the average depths can be different.

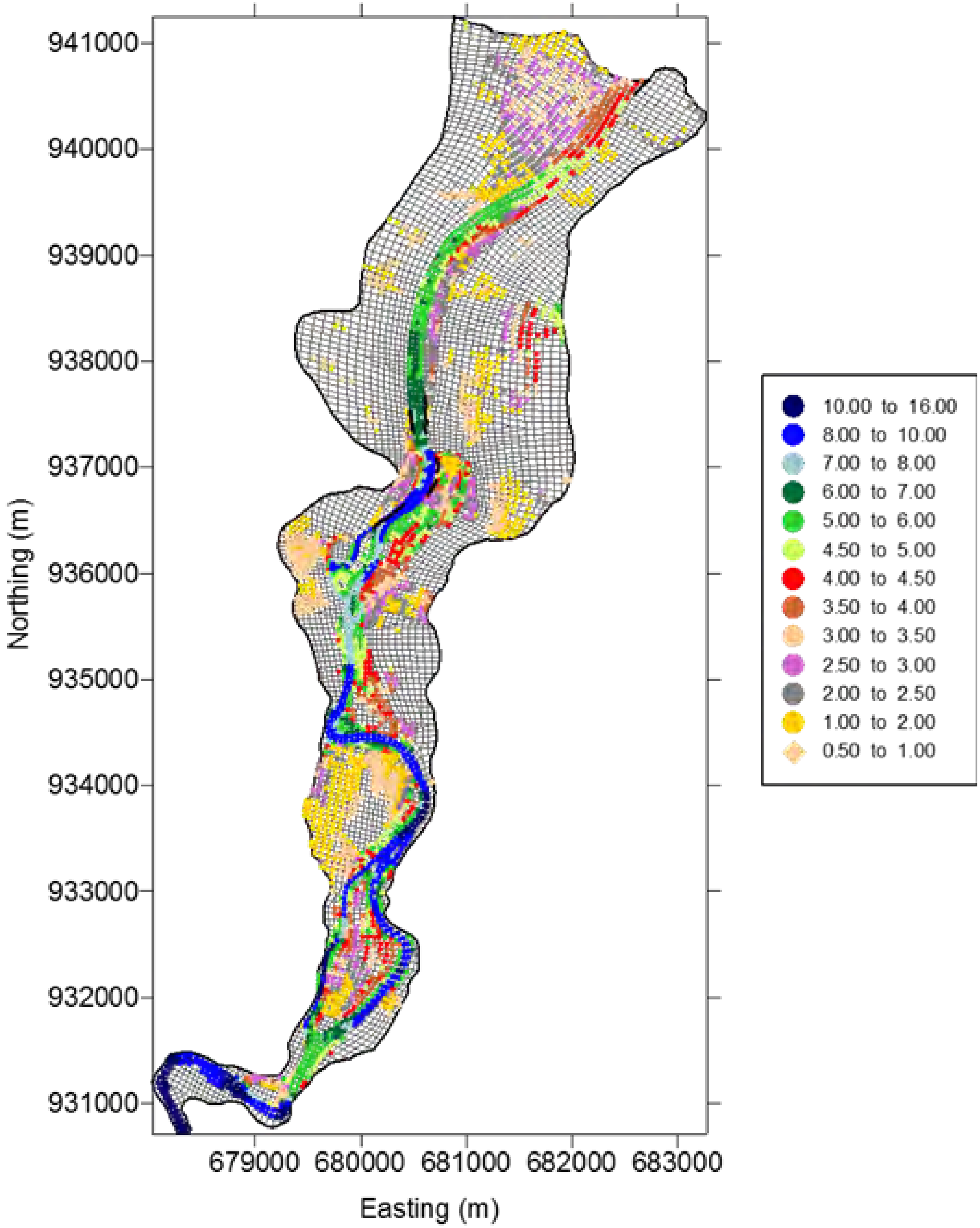

Figure 5 Scenario 1 (base case) simulation results for Typhoon Sendong with watershed model-based hydrographs (peak flow of 5715 m^3/s).

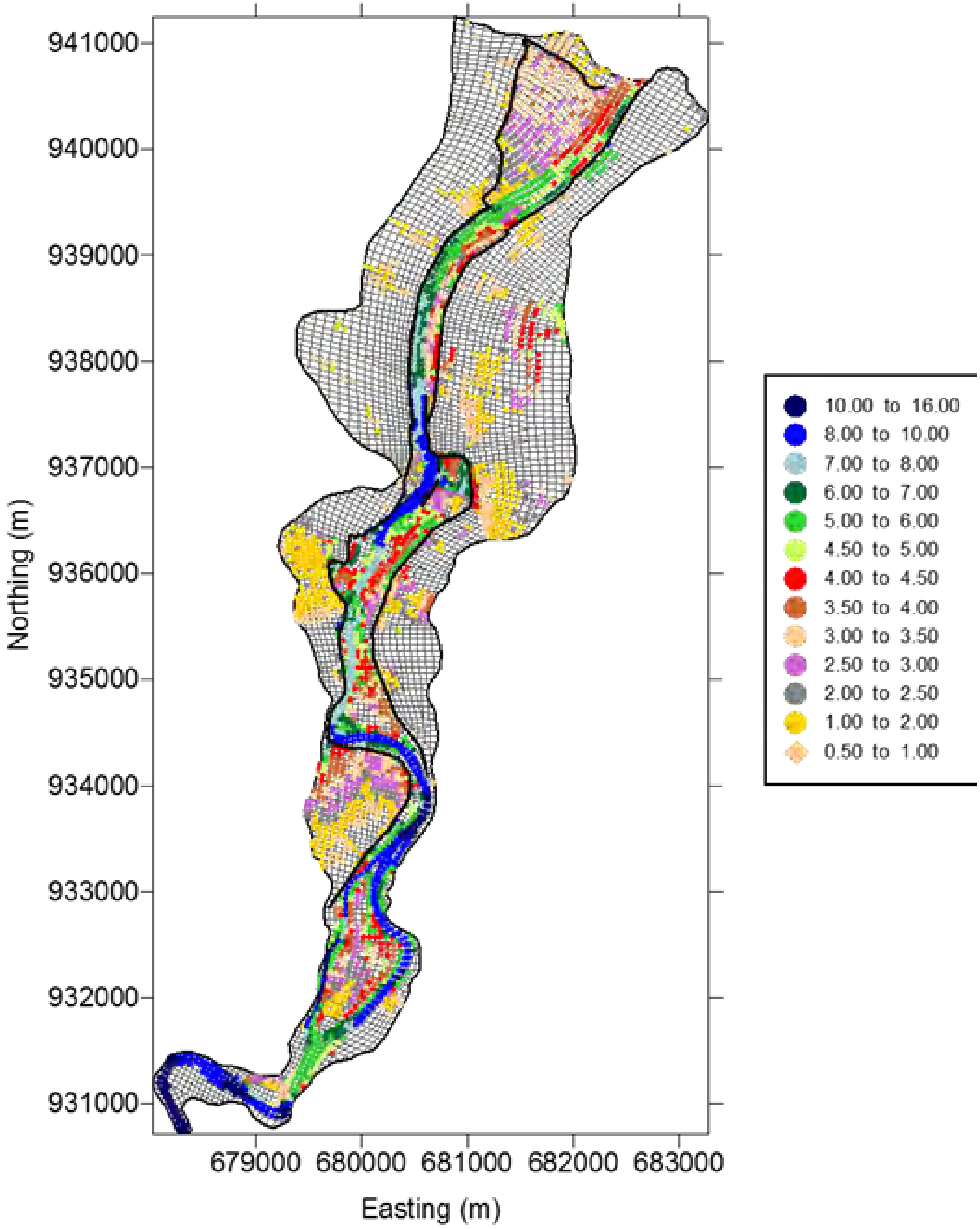

Figure 6 Scenario 4 (Recommended Plan) simulation results for Typhoon Sendong with watershed model-based hydrographs (peak flow of 5715 m^3/s).

Table 2 Total area flooded (ha), percent area flooded and average flooding depth (m) per barangay area for 50-yr return period rainfall for the seven (7) flood mitigation plans or scenarios. See Figure 7 for locations of the barangay areas.

	50-Yr Rainfall	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Bonbon								
84.767 ha	*Total Area Flooded (ha)*	7.549	7.549	5.680	5.680	5.680	5.680	5.680
	% Area Flooded	8.905	8.905	6.701	6.701	6.701	6.701	6.701
	Average Depth (m)	0.970	0.904	0.722	0.722	0.722	0.722	0.722
Macabalan								
60.031 ha	*Total Area Flooded (ha)*	2.525	2.126	2.126	2.126	2.126	2.126	2.126
	% Area Flooded	4.207	3.542	3.542	3.542	3.542	3.542	3.542
	Average Depth (m)	1.084	1.081	1.081	1.081	1.081	1.081	1.081
Kauswagan								
105.592 ha	*Total Area Flooded (ha)*	6.018	6.018	4.037	4.037	4.037	4.037	4.037
	% Area Flooded	5.700	5.700	3.823	3.823	3.823	3.823	3.823
	Average Depth (m)	0.815	0.815	0.760	0.760	0.760	0.760	0.760
Puntod								
33.178 ha	*Total Area Flooded (ha)*	0.000	0.480	0.480	0.480	0.480	0.480	0.480
	% Area Flooded	0.000	1.448	1.448	1.448	1.448	1.448	1.448
	Average Depth (m)	0.000	0.603	0.603	0.603	0.603	0.603	0.603
Consolacion								
48.173 ha	*Total Area Flooded (ha)*	0.572	0.903	0.653	0.653	0.653	0.653	0.653
	% Area Flooded	1.187	1.875	1.356	1.356	1.356	1.356	1.356
	Average Depth (m)	0.859	0.897	0.706	0.706	0.706	0.706	0.706
Carmen								
127.498 ha	*Total Area Flooded (ha)*	3.103	3.103	3.341	3.341	3.341	3.341	3.341
	% Area Flooded	2.434	2.434	2.620	2.620	2.620	2.620	2.620
	Average Depth (m)	0.794	0.794	0.804	0.804	0.804	0.804	0.804
Nazareth								
98.365 ha	*Total Area Flooded (ha)*	6.983	7.801	8.081	4.165	4.165	4.165	4.165
	% Area Flooded	7.099	7.930	8.215	4.234	4.234	4.234	4.234
	Average Depth (m)	2.261	2.326	4.215	1.558	1.558	1.558	1.558
Macasandig								
265.702 ha	*Total Area Flooded (ha)*	71.359	72.026	56.705	57.718	58.465	56.032	49.757
	% Area Flooded	26.857	27.108	21.342	21.723	22.004	21.088	18.727
	Average Depth (m)	5.633	5.705	6.585	6.457	6.477	6.451	5.999
Balulang								
151.032 ha	*Total Area Flooded (ha)*	40.430	29.859	12.435	12.435	12.435	12.435	12.435
	% Area Flooded	26.769	19.770	8.233	8.233	8.233	8.233	8.233
	Average Depth (m)	1.633	1.529	1.570	1.564	1.563	1.559	1.719
Pualas								
42.053 ha	*Total Area Flooded (ha)*	1.143	1.143	1.143	1.143	1.143	1.143	0.581
	% Area Flooded	2.717	2.717	2.717	2.717	2.717	2.717	1.382
	Average Depth (m)	9.258	9.287	9.392	9.380	9.377	9.353	9.419

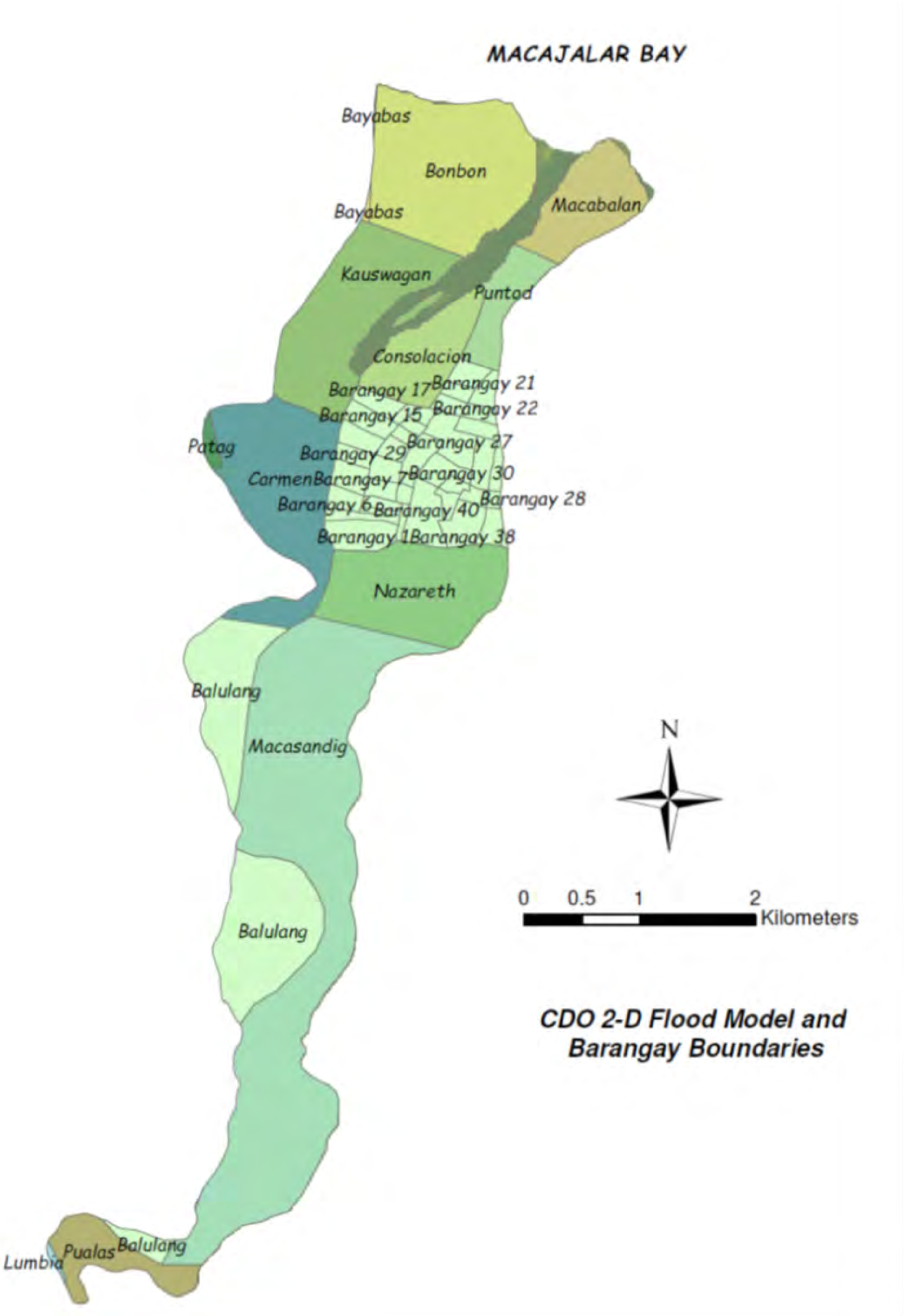

Figure 7 Reference of barangay areas covered in the 2-d flood inundation model accompanying Table 2.

5. Summary and Conclusions

This flood mitigation planning and associated flood hazard mapping is motivated in response to the devastation of Cagayan de Oro City brought by Typhoon Sendong that occurred in Cagayan de Oro River Basin in Mindanao, Philippines in mid-December, 2011. In the process of reassessing the revised flood mitigation plan, the government encountered some resistance by concerned parties in the city thus the need to conduct a review and value engineering study of the flood mitigation plan. This required engaging the stakeholders through meetings and consultations so that they are informed and their inputs properly solicited in the course of this study. A total of eight (8) alternative flood mitigation plans were formulated and their performance were evaluated based on two-dimensional flood inundation model simulation studies. The associated flood hazard maps produced in this study and particularly the recommended flood mitigation plan can be utilized for flood management. For instance, areas that maybe zoned as no-build zones as well as flood staging and evacuation sites can be identified using the flood hazard maps. To reiterate, this study highlights the importance of stakeholder participation throughout the course of the flood study resulting in proper consideration, formulation and eventual selection and recommendation of best flood mitigation plan.

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Appendix A: Shallow Water Equations

The two-dimensional shallow water equations are composed of the mass continuity equation and the two components (in the x- and y- directions) of the momentum equations. These equations river flow hydraulics in terms of the changes of water stages and velocities in time and space.

Continuity equation

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=q_L \qquad \text{(A.1)}$$

Momentum equation in the x-direction:

$$\frac{\partial hu}{\partial t}+\frac{\partial (hu^2+gh^2)}{\partial x}+\frac{\partial huv}{\partial y}=gh(s_{ox}-s_{fx})+\frac{1}{\rho}\left[\tau_x^s+\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right] \qquad \text{(A.2)}$$

Momentum equation in the y-direction:

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial (hv^2+gh^2/2)}{\partial y}=gh(s_{oy}-s_{fy})+\frac{1}{\rho}\left[\tau_y^s+\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right] \qquad \text{(A.3)}$$

In the above equations, the variable denotes the water depth; and denote the depth-averaged velocity components in the - and -directions, respectively; is the lateral inflow; and are the bed slope and friction slope in the -direction, respectively; and are bed slope and friction slope in the -direction, respectively; is the gravitational acceleration; and are surface stresses such as wind stresses; , , and are the turbulent shear stresses in which for instance is the shear stress in the -direction on a plane perpendicular to the -direction; and, is the density of water.

Appendix B: Watershed Model with Sacramento Soil-Moisture Accounting Model

The SAC-SMA model developed by Burnash et al (1973) when it was incorporated in the National Weather Service River Forecasting System (NWSRFS) sometime mid-1980's for real-time river forecasting over 4,000 river systems in the United States (Burnash, 1985), it was too large a computer program and can only be implemented in mainframe computers. During that period, the IBM personal computer (IBM-PC) also came out so that in order to use the SAC-SMA model, Tabios et al (1986) developed a small version of the NWRFS model for IBM-PC application, hence the name NWSRFS-PC Version. Also, instead of using the flow routing models in the original NWSRFS model, the kinematic wave routing model adapted from HEC-1 computer model of the U.S. Army Corps of Engineers (USACE, 1985) for overland flow and channel routing, including the unit hydrograph method for overland flow planes and Muskingum method for channel routing was utilized as optional methods. For model calibration, the constrained Rosenbrock optimization routine given by Kuester and Mize (1973) was used as an option to automatically calibrate selected model parameters in the SAC-SMA model.

Referring to the model structure of SAC-SMA as shown in Figure B.1 below, the model utilizes conceptual storages to represent the watershed hydrology starting with precipitation, the subsequent vertical and horizontal movement of water through and over the soil, and finally the production of runoff.

In the model, the subsurface layer or soil moisture storage is divided into the upper zone and lower zone. The upper zone represents the upper soil layer and interception storage, while the lower zone represents the bulk of the soil moisture and groundwater storage. Each zone stores water in the form of tension water and free water. Tension water is that which is closely bound to the soil particles by tension or electrostatic forces in contrast to the water that is free to move by gravitational forces. In these conceptual storages, tension water storage must be filled before free water storage is supplied. Tension water can only be removed by evaporation and free water can be depleted by evapotranspiration as vertical percolation. In the lower zone storage, there are two types of free water storages: primary which is slow draining and provides baseflow over long periods of time; and, supplementary which is fast draining and provides baseflow after relatively short period from recent rainfall. Movement of water from the upper zone to lower zone is by percolation process which is a nonlinear function of the available free water in the upper zone and the soil moisture deficiency in the lower zone.

Finally, the model generates five (5) flow components, namely: 1) direct runoff from impervious areas; 2) surface runoff which occurs when the upper zone free water storage is full and the rainfall intensity exceeds the rate of percolation and interflow rates; 3) interflow resulting from lateral drainage of the upper zone free water storage; 4) supplemental baseflow; and, 5) primary baseflow. The first three flow components represent the total inflow while the latter two is the total baseflow. The total channel inflow constitutes the entire surface runoff contribution to the stream flow hydrograph routed via kinematic wave or combined unit hydrograph-Muskingum routing and a portion of total baseflow is the subsurface runoff contribution to streamflow. This subsurface flow contribution is added to the routed streamflow at the basin or sub-basin outlet using a linear, decay weighting function similar to unit hydrograph routing.

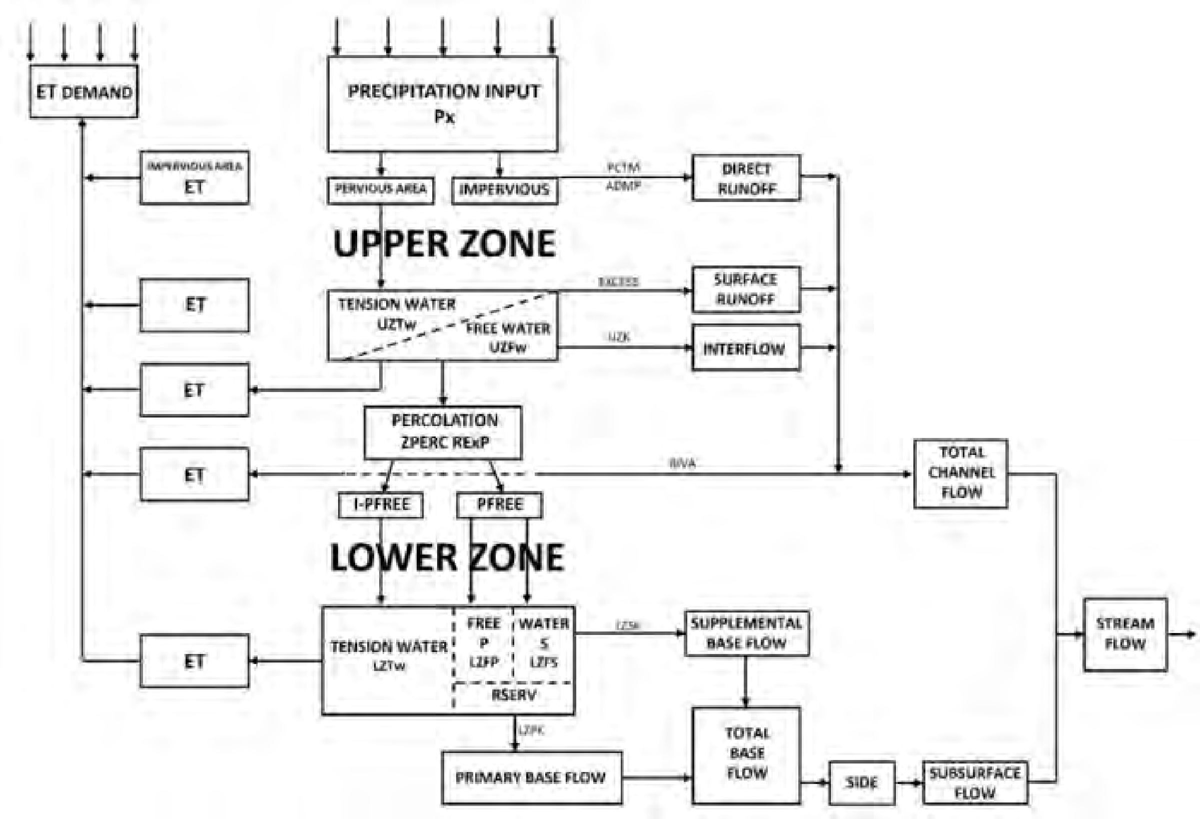

Figure B.1 Model structure of Sacramento soil-moisture accounting model. Also indicated in some boxes are key model parameters described in Burnash et al (1973).

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