Flood Impact Assessment using Hydrodynamic Modelling in Bangkok, Thailand

Pengyu Chen
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Flood Impact Assessment using Hydrodynamic Modelling in Bangkok, Thailand

by

Pengyu Chen

Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation Specialisation: Environmental Modelling and Management

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Abstract

Flooding has long been recognized as the most damaging and costly natural hazard in many countries considering the frequency and influencing extent. Due to the global climate change and the rapid urbanization in the floodplains, the frequency of devastating floods tends to be higher and the loss of human lives and property show no sign of decreasing. In order to minimize the impact of floods, an effective flood management is required. Towards this end, hydrodynamic models have a great potential to contribute.

In this study, a 1D2D hydrodynamic model using SOBEK was constructed and applied in Bangkok, Thailand to simulate the flood scenarios for return periods of 5, 10 and 25 years. In the modelling approach, there are two ways to represent the build-ups: solid structure and rough surface. The effects of these two ways were examined in the scenario results. Furthermore, a multi-parameter flood impact assessment was proposed to categorize the flood impact according to different interests, such as human safety and property/estate damage. Another flood impact assessment method which integrates depth and velocity was carried out and compared with the proposed one.

The scenario results indicate that the manner in which buildings are represented in modelling approach has a significant impact on the flooding characteristics. Compared to solid building structure, flood extent for rough surface scenarios increased 90%, 30% and 36% at three return periods respectively. For water depth, the percentages of low categories (from 1 to 3) of rough surface scenarios are higher than that of solid structure scenarios for all the return periods. In terms of flow velocity and warning time, the distinctness between two surface types for the same return period decreased from low category to high category.

According to the different emphasis on flood impact, flood impact maps for three visions were created. There are dramatic changes of the area categorization for visions. In Human Safety vision, Category 2 takes account of 56.3% of the total inundated area. For potential damage to properties and estates, 59.6% of flooded area has Category 3 impact. In Equal vision, Category 2 and 3 share over 80% of total inundated area. Thus, the visions of flood impact maps could serve to indicate the disturbance caused by floods to the diverse aspects of the society. The methodology used in flood impact assessment should be adjusted according to local situation.
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1. Introduction

1.1. Research background

Since the last century, natural disasters have gained more and more concern because of the dramatically increasing trend of human life loss and property damage from natural disasters. Natural disasters associated annual economic losses increased from US$ 75.5 billion in the 1960s to US$ 659.9 billion in the 1990s, not including the indirect losses (Munich Re., 2002). Natural disasters not only hinder development, but also exert an enormous toll on human life. According to the report of UNDP (2004), during last two decades of 20th century, about 75% of the world’s population lived in areas threatened by earthquakes, tropical cyclones, floods or droughts.

![Figure 1-1: Total mortality due to natural disasters, 1980-2006](Source: EM-DAT: The OFDA/CRED International Disaster Database)

Flooding has long been recognized as the most damaging and costly natural hazard in many countries. Due to better accessibility and settlement feasibility, floodplains have been increasingly encroached by urbanization in the last few centuries. However, this aggravates the problem – increasing risk and damage of flooding, which is severer in the less developed countries. Generally, these countries have more population and land-demanding pressure, but less mitigation capability towards the flooding hazards than the more developed countries. Most modern cities in the more developed countries experience small scale and local floods due to insufficient capacity of the sewer systems to transport excessive rainfall or the unexpected
breakdown of water-supply pipes (Mark et al., 2004). Whereas, in the cities of other region, for example, South/South-East Asia, much heavier rainfall and lower drainage standards impose more severe flooding.

1.2. Problem statement

Thailand is not an exception to flood hazard. According to the EM-DAT International Disaster Database, flood is the dominant natural disaster in the last fifty years for Thailand. Between 1995 and 2006, 54 flooding events were reported, accounting for 55% of all natural disasters, resulting in US$ 4.5 billion damage, 2,682 people killed and 30 millions affected (Center for Research on the Epidemiology of Disasters). Thai people suffer flood strikes mainly between June and September, the Monsoon season, every year. The Chao Phraya River not only gives convenience to agriculture and transportation, but also creates great destructions through swelling and overflowing during the rainy seasons (ADPC, 2006).

Bangkok is located near the Gulf of Thailand where Chao Phraya River goes into the sea. As the capital and largest city of Thailand, it has around 7 million people and 12 million people in Bangkok Metropolis, and contributes to 43% GDP (2005) of the whole country (Wikipedia, 2006). Bangkok suffered severe floods in 1983 and 1990, which created great disturbance to the social and economic activities. Although flood defence projects were established and improved after the two devastating flood events (Bangkok Metropolitan Administration, 2004), the mega-city is still under threat of flooding, especially in the condition of increasing flooding risk, partly due to the global warming and partly due to rapid urban development.

1.3. Research objectives

1.3.1. Overall objective:

To develop a procedure for flood impact assessment using a 1D2D hydrodynamic model.

1.3.2. Specific objectives:

- Examine the effect of building structures represented in the terrain for scenario floods at different return periods (5, 10 and 25 years).
• Develop a methodology for multi-parameter flood impact assessment.
• Carry out flood impact assessment applying an alternative method for different scenarios.

1.4. Research questions

• What is the effect of building structure in hydrodynamic modelling for urban and sub-urban area?
• What combination of flood characteristics will effectively represent the flood impact?
• Will the selected method be suitable for the study area?

1.5. Hydrodynamic modelling

As with the development of remote sensing technology, near real-time flood monitoring becomes more and more popular and practical. Nevertheless, for the preventive purpose, hydrodynamic modelling has the advantage in the prediction of flood events which did not occur in the history, for example, 100-year or 200-year return period magnitude floods. From the perspective of prevention and mitigation, hydrodynamic modelling is of more importance in the planning phase.

Quite a number of researches have been carried or carrying out, trying to forecast flooding, giving advices on land-use planning and flood defending projects (Alkema et al., 2001). Zerger and Wealands (2004) pointed out that the importance of spatially explicit hydrodynamic flood models in flood risk reduction and their suitability to provide inundation information, such as time, location and severity of anticipative flooding. Such information can be material for land use planning, mapping evacuation routes and locating suitable emergency shelters. Towards this end, the role of flood modelling is becoming more and more important, because of the increasing computation capacity and understanding of the hydrologic system. The overall flooding study could be divided into three steps:

a. To construct hydrologic models, DEM (or DSM), land cover/use map and hydrometeorological information of the study area are needed as input data.

b. Generation of flooding information, including possible inundation areas, water depth, flow velocity, flood duration.

c. Relevant mitigation measures are proposed according to the results from previous step.
Through a better integration of the technical dimensions of flood hazard modelling and social vulnerability issues, flood hazard management could reach more effective stage (Brown and Damery, 2002).

In the last few decades, 1 Dimensional (1D) hydrodynamic modelling has been well developed. It is mainly used for the modelling of rivers, streams and canals. For example, the HEC series are the well known and widely used “one-dimensional movable boundary open channel flow numerical model” which is initiated by US Army Corps of Engineers (Dodson & Associates Inc., 2005). Though 1D modelling has the advantages, the major limitation of 1D model is that it considers the water flows along the main direction of river (Tennakoon, 2004). This gives 1D model limited capability to represent flooding in the complex urban terrain, due to the artificial constructions change water flow, depth etc. However, Mark et al. (2004) claimed that 1D hydrodynamic modelling could be used to simulate urban flooding, capable to deal with the interaction of sewer system, streets and overland flow.

Thanks to the rocketing development of computer engineering, the 2 Dimensional (2D) hydrodynamic modelling now is on the stage. From the view of urban flooding simulation, the 2D hydrodynamic model becomes increasingly popular since it could generate apart from the flood extent, also the water depth and flow velocity. The 2D shallow water model “Rubar 20” was employed to simulate the floods in dense urban area, providing rather satisfying result (Mignot et al., 2006). Horritt and Bates (2002) evaluated the predictive performance of 2D numerical models TELEMAC-2D for Severn river flood inundation, UK. The 2D component in SOBEK, developed by WL/Delft Hydraulics, was designed to simulate the overland flow through complex topography (Alkema et al., 2004).

To solve the constraints in 1D and 2D models, some researchers and commercial modelling software promoted the integration of 1D and 2D modelling, for example, SOBBEK, MIKE-FLOOD and LISFLOOD-FP. The basic scheme is that wherever overland flow happens from river or sewer system, 2D model will be activated. This could dramatically reduce the computation time, simplify the modelling procedure and enrich the results.

The application of Remote Sensing and GIS provides robust support to the flood modelling from the aspects of data acquisition, model calibration, results processing and representation. Remote sensing provides a reliable and cost-effective way for
field data collection, allowing for continuous and large-area coverage of many variables. The current trend is combining optical remotely sensed imagery and synthetic aperture radar imagery to enhance the capability of identifying dry land and water (Levy et al., 2005, Nunes Correia et al., 1998, Tholey et al., 1997) Since flood water will appear darker than adjacent land in a SAR image, Mason et al. (2005) inundation extent measured from SAR imagery to validate the modelled flood extent, with an accuracy of 85-90%. In terms of DEMs (DSMs), the basis of flood modelling, in the developed countries, especially in U.S.A. and Europe, LiDAR (Light Detecting And Ranging) has become very popular for creating DEMs with exceptional accuracy for flood prone areas.

1.6. Flood hazard mapping and impact assessment

The flood hazard maps play an indicative role rather than specific in the flooding prevention and mitigation (Brown and Damery, 2002). The flood delineation and categorization analysis together with an environmental model yields hazard maps, which serve to identify weak points of the flood defence system, or indicate a need for action. In respect of readability and indication of the maps, the appropriate expression of hazard and impact severity is of most importance. For now there is no standard format the flood hazard maps. Nevertheless, the differences among methods are just flood factors considered and number of hazard categories. For example, Islam and Sado (2002) suggested hazard ranking method considering the affected frequency and flood depth. Whereas, CSIRO (2000) refers to the degree of flood hazard should be decided by more factors:

- the size (magnitude) of flooding;
- depth and velocity (speed of flowing water);
- rate of floodwater rise;
- duration of flooding;
- evacuation problems;
- effective flood access;
- size of population at risk;
- land use;
- flood awareness/readiness;
- effective flood warning time.

Governments and insurance companies need flood impact assessment to assist planning national and regional flooding strategies. Governmental usage of the
assessment mainly focuses on social aspects, and insurance companies use it to estimate the potential loss and set different premiums according to the flooding impacts. Many methods varying from simple relationships between water depth and estimated financial damage to complex models requiring data on flood velocity, water depth, building characteristics, cost of restoration, people’s behavior and indirect economic losses were developed to estimate the consequential loss to a certain magnitude flooding (van der Sande et al., 2003). In the flood management guidelines provided by New South Wales Government (Department of Infrastructure Planning and Natural Resources, 2005), flood impact levels were first evaluated from pure hydraulic principles (Figure 1-2), and then refining the hydraulic hazard category considering other relevant factors affecting the safety of individuals and properties (Figure 1-3).

![Figure 1-2: Depth and velocity relationships](image1)

![Figure 1-3: Provisional hydraulic hazard categorization](image2)

Source: (Department of Infrastructure Planning and Natural Resources, 2005)
2. Study Area

2.1. General description

Bangkok is the heart of Thailand, meaning not only the geographical location, but also the cultural, educational, political and economical centre of Thailand (Figure 2.1). Bangkok is one of two special administrative areas in Thailand, under the governance of BMA (Bangkok Metropolitan Administration), differing from other 75 provinces which are administrated by the Thai government (Wikipedia, 2006). Because of the large area occupied by the city and surrounding suburban (amount to 1568.74 km$^2$), Bangkok is divided into 50 districts.

The total population in Bangkok according to household registration is 6.35 million in 2000 (Thai National Statistical Office, 2001), with an average density of 4051 per km$^2$. However, the actual population is believed around 9 million, including seasonal immigrants from rural areas and other surrounding provinces. The total area in this study is 369.8 km$^2$.

Figure 2-1: Study area map
2.2. **Topography**

The geographical coordinates of Bangkok are latitude 13°45', longitude 100°28'. The area of Bangkok located characterizes as flat and low plain, which formed by Chao Phraya River. The mean elevation is just 2.31 m at MSL (Mean Sea Level).

2.2.1. **Land use**

The total area of Bangkok consists of 378.97 km² agricultural land, residential use 366.38 km², commercial/industrial/governmental use 453.50 km² (Bangkok Metropolitan Administration, 2006). Accompanying the rapid development, unorganized land use, especially in the urban fringes, creates severe environmental problems, such as worsening air quality, contaminative water, in particular, serious flooding. The transformation of agricultural land to urban area decreased the capacity of flood water storage, increased the impermeable area, and shortened the time of flood peak formation. For the purpose of improving the environment and more efficient land use management, BMA published the Bangkok Comprehensive Plan 2006, providing guidance for urban development (Figure 2-3).

![Land Use of Bangkok](image)

*Figure 2-2: Proportional land use in 2005*

Source: (Bangkok Metropolitan Administration, 2006)
2.2.2. Land subsidence

Like other cities built on floodplains, for example, Tokyo, Taipei, Shanghai, besides flooding, Bangkok also suffers from land subsidence, resulted from over pumping groundwater and the nature of thick soft clay underneath that area. According to Phien-wej et al. (2006), in the inner Bangkok Metropolis area, the average subsidence rate has reached 5 to 10 mm yr\(^{-1}\), and the maximum subsidence rate now occurs in the outlying southeast and southwest industrial zones, which equals to 30 mm yr\(^{-1}\) (Figure 2-4). Land subsidence not only creates direct damage and threats to human lives and properties, but also intensifies the impacts of flooding. The main flood protections for Bangkok are the dikes and walls along the Chao Phraya River. The efficiency of the flood project is decreased by land subsidence because the crest of dike descends with the subsided ground. Land subsidence imposes dramatically negative effects to the sewer system and underground pipes, which could aggravate the local urban flooding during the monsoon season. Furthermore, it is difficult to drain the low-lying areas that are sinking, which could create “stagnant water” during floods.
2.2.3. Canal network

Named “Venice of the East”, Bangkok is famous for the large and complex canal network, functioning partly as transportation routes and partly as drainage. At normal time, canals transport domestic waste water to the Chao Phraya River. Yet, during the monsoon season, water level in the river could be meters higher than that in the canals. Therefore, some water control gates were built at the places where canals connect the river, to avoid backflow from the river into the city. To some degree, these gates do retard excessive water getting into the canals and propagating in the dense urban area. However, this does not apply during the extreme flooding events, which generate very high hydraulic pressure from the river side.

2.2.4. Flood protection

After the disastrous 1983 flood event, several flood prevention measures emerged to solve the flooding problem in Bangkok, those are (Bangkok Metropolitan Administration, 2004):

- Preventing excessive water from watercourses and outside Bangkok by construction of water barriers, for instance, dikes, embankments and temporarily sand bags.
- Improving the drainage efficiency of the city by pump stations, canals and sewer system.
- “Monkey Cheeks Project”: Construction and improvement of temporary retention basins.

In the last two decades, flood barrier with length of 88 kilometres along the Chao Phraya River was partly completed. Dozens of pumping stations along the Chao Phraya River and canals were established; among them eleven pumping stations had a capacity larger than $20 \text{ m}^3 \text{ s}^{-1}$ each.

2.3. Climate condition

Bangkok has a typical monsoon climate, mainly divided into three seasons: rainy (May - October), cool (November - January) and hot (February - April) (Regional Resource Centre for Asia and the Pacific, 2004). The annual average temperature, wind velocity and humidity are listed in Table 2-1. Rainfall is the second most important contributor to flooding. The annual average precipitation is 1650 mm. Furthermore, the extreme rainfall events during 1993-2002 are shown in Figure 2-6.

| Table 2-1: Annual average temperature, wind velocity and humidity of Bangkok |
|-------------------------|----------|----------|----------|
| Item                    | Average  | Highest  | Lowest   |
| Temperature             | 28.8°C   | 38.8°C   | 13.2°C   |
| Wind velocity           | 4.3 km/hr| N/A      | N/A      |
| Relative Humidity       | 73 %     | N/A      | N/A      |

(Regional Resource Center for Asia and the Pacific, 2004)

Figure 2-5: Daily maximum rainfall in 1993-2002
(Source: Thai Meteorological Department)
3. Material and Methodology

3.1. Data collection

Fieldwork in Bangkok occurred from September 04 to September 23, 2006. The main aim of the fieldwork was visiting the institutes and governmental departments to obtain the essential data for the study. During and after the fieldwork, the following data were obtained from different sources (Table 3-1).

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<th>Description</th>
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<td>30m horizontal, 1m vertical resolution</td>
<td>Digital</td>
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<tr>
<td>Discharge</td>
<td>Irrigation Dept.</td>
<td>Daily data for C13 from 1970 to 2004</td>
<td>Digital</td>
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<tr>
<td>ASTER</td>
<td>ITC</td>
<td>L1B (04-06-2005 03:54:57)</td>
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<td>Marine Dept., Ministry of Transp. and Comm.</td>
<td>1:4000, updated in 2002</td>
<td>Topographic sheet</td>
</tr>
<tr>
<td>Road network</td>
<td>MapMagic®</td>
<td>Software</td>
<td>BMP</td>
</tr>
</tbody>
</table>

3.2. Data and preliminary processing

3.2.1. DEM pre-processing

The DEM used in this study was directly acquired from the Royal Thai Survey Department (RTSD). It had 30 m horizontal and 1 m vertical resolution. The primordial data source and the accuracy of this DEM were not available. Because the 1m vertical resolution could not satisfyingly represent the continuous ground surface, the DEM had to be smoothened before using for modelling. The Filter tool in ArcGIS was employed, that had two different filter tools: a low pass and a high pass filter, both based on focal functions with weighted kernel neighbourhoods. The low pass filter calculates the mean for the Focal Statistics function with a 3*3 kernel neighbourhood, within which the high and low values will be averaged, thus reducing the extremes in the data values, whereas the high pass filter accentuates the comparative difference in the values with its neighbours (ESRI, 2005). The different
results from filters are shown in Figure 3-1. Considering the narrow canals and semi-artificial river reaches, the high pass filter tends to sharpen the edges of between watercourses and land by generating unreasonable values, therefore, a low pass filter was adopted to smoothen the DEM.

![Figure 3-1: Comparative results from low pass and high pass filter](image)

To alleviate the flooding threat, BMA started flood prevention projects. The most important ongoing project is building dikes along the Chao Phraya River to protect the urban area. Because of different development levels of east bank region and west bank region, and the limited fiscal budget, the constructed dikes along banks of the river are of different heights. For this reason, elevations of the pixels along the river banks are risen 1 m for west bank, 2 m for east bank, according to estimation and field observation.

3.2.2. Land use map

Determining surface roughness for the study area is a critical step in the modelling approach. According to the land use map, different surface roughness values are assigned to land use classes. Urban land use map further indicates the building locations. In this study, the acquired building map in vector format was not accurate enough as basis for the hydrodynamic modelling, since the dense urban area was
indicated by a big polygon. ASTER imagery has the ability to provide land use information, separating several essential features, such as vegetation, water surface and buildings. Hence, classification of the ASTER image was implemented to derive the land use map of the interest area. For simplification and the actual data requirement of the model, four classes (vegetation, water, buildings includes roads and low vegetated soil) were decided to be separated in the image.

The software and method for image classification were ERDAS IMAGINE 8.7 and supervised classification. The parametric rule used in supervised classification is Maximum Likelihood. The classification procedures are as followings:

- Firstly, import the ASTER .hdf file into ERDAS and remove the Band 3b layer since it is from the backward scanning. Geometric correction is also made by geo-referencing and re-sampling.
- Secondly, carry out atmospheric correction to remove the haze existing in the image.
- Thirdly, determine the spectral signatures for the four classes through visual interpretation with reference to Google Earth (Google™, 2006).
- Fourthly, carry out Maximum Likelihood classification (Appendix A1) and accuracy assessment (Appendix A2).

In respect of the large percentage of vegetation and build-up in the image, stratified random points method was employed to ensure that at least 20 points were assigned for each class. Images from Google Earth (Google™, 2006) were regarded as a true depiction of reality and used as the reference data to do evaluation. Based on the generated error matrix, producers/users accuracy and Kappa statistics of the classification map were calculated (Table 3-2). The calculation procedures of different classification accuracies were described by Congalton (1991). The overall classification accuracy was 75.50%.

**Table 3-2: Accuracies and Kappa coefficient of agreement for ASTER classification**

<table>
<thead>
<tr>
<th>Class</th>
<th>Producer’s Accuracy</th>
<th>Users’ Accuracy</th>
<th>Kappa value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>76.92%</td>
<td>80.65%</td>
<td>0.7133</td>
</tr>
<tr>
<td>Low vegetated</td>
<td>70.83%</td>
<td>40.57%</td>
<td>0.4156</td>
</tr>
<tr>
<td>Vegetation</td>
<td>80.82%</td>
<td>80.82</td>
<td>0.6980</td>
</tr>
<tr>
<td>Water</td>
<td>65.79%</td>
<td>83.33%</td>
<td>0.7942</td>
</tr>
<tr>
<td>Overall</td>
<td>N/A</td>
<td>N/A</td>
<td>0.6581</td>
</tr>
</tbody>
</table>
3.2.3. **Road and canals**

During flood events, roads, streets and sois (Thai name for alleyways) act as important flood propagating ways in the urban area. Therefore, a good road map will help to achieve more accurate simulation. The only available data source with sufficient details were from MapMagic (ThinkNet Co. Ltd, 2006), which provided minute information of Bangkok, such as road network, locations of companies and facilities. For this study, road network was extracted from the user interface of the software only in two levels: main roads and streets. Different road levels will be given different elevations to represent the roadbed in the DSM.

The main canals and distributaries were presented in the DSM, having same initial water level with Chao Phraya River. In view that the constructive and hydraulic information of canals and distributaries, like cross-section and depth, was unreachable for this study, these sorts of information were based on assumptions which were applied in model schematisation.

Due to the low spatial resolution of DSM, sois (width<5m) and narrow streets (width<10m) could not be represented in the urban terrain. Another element omitted in this study was densely spread diminutive canals and open drainages, the width of which ranged from less than one meter to 15 m, too narrow to be shown in 30 m resolution DSM.
3.2.4. DSM

The DSM was generated from the combined basic data: processed DEM, land use map, road network and canal network. Based on assumption, the pixels representing main roads and streets were raised for 0.4 meter and 0.3 meter, respectively. The pixels which represent build-ups were equally elevated by 5 m.

3.2.5. Discharge data

The nearest discharge data available were from upstream gauge stations C13, which was located at the Chao Phraya Division Dam. The daily data covered 35 years from 1970 to 2004. The plot (Figure 3-3) below shows discharges for two severe flood events in Bangkok (1983 and 1995). The log-Pearson Type III distribution method (Robson and Reed, 1999) was adopted to calculate the discharges for different return periods (Table 3-2).
### 3.2.6. Meteorological data

During the monsoon season, precipitation is an important meteorological factor because the excessive rainfall is likely to coincide with the discharge peak in the river from upper basin, which will increase the probability of floods. Moreover, abundant rainfall could result in local flooding in the urban areas far from the river because of the insufficient drainage capacity. Nevertheless, in the 1995 flood event, the amount of rainfall was less than 1% of total water volume input from river into the study domain. Mark et al. (2004) pointed out that comparing to the huge amount of water imposed through the river, the effect of evaporation is insignificant in urban areas. Therefore, for simplification, the assumption that rainfall and evaporation would not significantly affect flood propagation and impacts was used in this study.
3.3. Methodology of the study

3.3.1. Hydrodynamic modelling approach

Although 2D hydraulic modelling is developing very quickly nowadays, the relatively high data requirements would limit the application. Firstly, the pure 2D models require input DTMs containing detailed river bed profiles, as basis of the modelling. However, the river bed profiles are not available in most cases, since this sort of information requires sonar instruments to detect the riverbed rather than normal remote sensing methods. In terms of conventional information of rivers, cross section data are more common and easier to get. The integration of 1 dimensional and 2 dimensional hydraulic modelling became more feasible than pure 2D modelling in the condition of the river profiles are not available recently. Secondly, regarding the data availability of this study, the 30m DEM resolution is not good enough to represent the complex watercourse network in Bangkok region. Therefore the river channel and cannels flow will be separated from 2D floodplain, using the 1D model.

This study applied a 1D2D hydrodynamic model to simulate the flooding process on the Lower Chao Phraya floodplain in the Bangkok region, Thailand for different return period of floods. Furthermore, sensitivity analysis of the modelling was also carried out. The overall methodology of the modelling is presented in Figure 3-4.

![Figure 3-4: Framework of Hydrodynamic Modelling](image_url)
The employed modelling tool is SOBEK-Rural, developed by WL | Delft Hydraulics, the Netherlands. This software package has functionality for optimizing flood control, irrigation, canal automation, reservoir operation, and water quality control. For this study, two main components were used: the 1DFlow module and the Overland Flow module (2DFlow), both of which are using the complete de Saint Venant Equations, including transient flow phenomena and backwater profiles (WL | Delft Hydraulics, 2006). The basic Saint Venant equations are listed below:

Continuity:
\[ \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0 \]

Momentum:
\[ \frac{\partial Q}{\partial t} + \frac{\partial (bQ^2 / A)}{\partial t} + gA \frac{\partial y}{\partial x} - S_f + S_y + \beta \nu_x + W_f B = 0 \]

There are already lots of research and publications on the Saint Venant Equations, therefore, the detailed explanation of the equations please refer to Chow et al. (1988), Smith and Ward (1998) and Mujumdar (2001).

In SOBEK-Rural, the concept of 1D2D combination is implemented as follows:
- One dimensional and two dimensional flows are simultaneously simulated.
- The cross-section data are interpolated to define the 1D channel accordingly.
- The 1D and 2D domain are coupled at through 1D calculation points (Figure 3-5(A)).
- Whenever and wherever the discharge exceeds the river reach capacity defined in 1D domain, only then, the 2D calculation will be activated (Figure 3-5(B)) to simulate the overland flow according to the topography represented by the 2D grid.
3.3.2. Flood impact assessment

Flood impact assessment methods which were developed since middle of last century were initiated by governments and insurance companies (van der Sande et al., 2003). In the governmental sectors and insurance industry, flood impact assessment plays a key role for estimating potential danger and loss, helping the decision-making in floodplain management. In general, flood impact assessment should integrate several flood factors such as water depth, flow velocity and duration, to estimate the direct and indirect damage in a given magnitude of flood. However, historically, flood impact assessment is mainly based on two factors, flood depth and duration, sometimes only inundation depth. This is because other important data such as flow velocity during flood event are harder to obtain comparing to the inundation depth which could be estimated according to the remote sensed data.

In this study, the following method was developed to indicate the flood hazard through multi-criteria and user-based impact assessment (Table 3-3, 3-4). This methodology integrates three factors to achieve better representation of flood hazard in urban and sub-urban area, and raises attention to different concerns of the diverse parties potentially affected by floods.

As part of study area is dense urban area, mainly utilized for residential and industrial purposes, the impact of flow velocity is therefore of need to be considered together with inundation depth. Also, in the heavy-populated region, warning time, in another word, time of overland flow happens to flood reaches a particular area, is of importance for the flood mitigation. People could have time to get prepared, including transfer belongings to higher floor and placing sandbags to prevent the water intrusion.
Stakeholders would have different opinions on how the flood could affect their life, according to their different focuses and behalves. In addition, insurance and reinsurance industry have the need to assess and estimate flooding risk from different perspectives, in order to determine insurance premium for insurable subjects. In terms of different concerns, flood hazard mapping and impact assessment should be carried out and published, instead of based on a single evaluation principle. The guiding principle of selection of these weightings was to better represent the interest of different groups and corresponding impact ranks in the composite index. It should be pointed out that the weightings can be modified moderately depending on local conditions.

### Table 3-4: Criteria and weightings for flood parameters

<table>
<thead>
<tr>
<th>Hazard Categories</th>
<th>Max Water Depth (m)</th>
<th>Max Flow Velocity (m/s)</th>
<th>Warning Time (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.25</td>
<td>&gt; 48</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>0.5</td>
<td>≤ 48</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>≤ 24</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>2</td>
<td>≤ 12</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 1.5</td>
<td>&gt; 2</td>
<td>≤ 6</td>
</tr>
</tbody>
</table>

### Table 3-5: Weightings for different interest groups

<table>
<thead>
<tr>
<th>Visions</th>
<th>Max Water Depth</th>
<th>Max Flow Velocity</th>
<th>Warning Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human safety</td>
<td>20%</td>
<td>45%</td>
<td>35%</td>
</tr>
<tr>
<td>Property/estate</td>
<td>50%</td>
<td>35%</td>
<td>15%</td>
</tr>
<tr>
<td>Equal</td>
<td>33.3%</td>
<td>33.3%</td>
<td>33.3%</td>
</tr>
</tbody>
</table>

Furthermore, another method for potential damage assessment (Smith, 2000) was also carried out in this study. According to the formulae listed in the Figure 3-6, critical depths will be calculated from flow velocity. The actual depth value of pixel will compare with the critical values to assign danger degree to this pixel. The resulting maps indicate the different degrees of flood impact, ranging from 0 to 5.
Figure 3-6: Categorization of flood impact based on flood depth and flow velocity

1: \( Y = 1 - 1.55X + 0.595X^2 \)
2: \( Y = 3.25e^{-1.835X} \)
3: \( Y = -0.238 + 1.227/X \)
4: \( Y = 4.7e^{-0.642X} \)
5: \( Y = -0.28 + 5.65/X \)
4. Flood modelling

4.1. Model schematization

The schematization tool in SOBEK is named NETTER, which enables users schematizing hydrodynamic models in GIS-like interface (Figure 4-1). In general, users need to schematize the network first and then define the attributes for the 1D network and 2D surface, such as cross-section data and boundary conditions.

The 1D network is constructed using the vector river channel. The network consists of boundary nodes, connection nodes, calculation points and river cross-sections. The functions of these elements are detailed described in SOBEK online help (WL | Delft Hydraulics, 2003). The flow characteristic in the river channel is determined by reach attributes, mainly cross-sections. The cross-sections determine the shape and
size of the channel profile perpendicular to the flow described, as well as bed level, surface level and friction value (Figure 4-2). The more cross sections on one reach, the better river to be represented. Between two neighbouring cross sections, the profile of channel is interpolated from the existing information. In the condition of only one cross section for one reach, or in the end of one reach, extrapolation will be performed (Figure 4-3). The attributes of 1D network components could further be modified in the Edit mode.

![Cross-section input](image1)

**Figure 4-2: Cross-section input**

![Cross section interpolation and extrapolation](image2)

**Figure 4-3: Cross section interpolation and extrapolation**

Source: (WL | Delft Hydraulics, 2003)

The 2D surface, DSM, is directly imported from ASCII data format. In NETTER, elevation value and surface roughness of every single grid of DSM could be modified manually according to different modelling purposes. For example, the surface roughness of the 2D surface could be accordingly defined as variable with reference to the land use map, or defined as a single value for the whole study area.
4.2. **Boundary conditions**

There are two primary boundaries in the model, upstream and downstream of the Chao Phraya River. For the upstream boundary, a discharge input node was selected and the downstream boundary represented the water levels affected by tidal fluctuation in the Gulf of Thailand. The hourly discharges of upstream boundary for return period 5, 10, 25 and 50 years are interpolated and extrapolated, starting from $500 \text{m}^3\cdot\text{s}^{-1}$ and ended with half of peak discharge (Figure 4-4, details shown in Appendix A3).

The secondary boundary nodes indicate the relatively small water discharges from canals and distributaries into the study domain. Since water from the Chao Phraya River is the main source of flood water and the discharge of it could reach several thousands $\text{m}^3\cdot\text{s}^{-1}$, the contribution of distributaries to flood events is quite limited. Therefore, the discharge of distributaries is assumed as $20 \text{m}^3\cdot\text{s}^{-1}$.

![Figure 4-4: Hydrograph for different return periods](image)

4.3. **Surface roughness**

The surface roughness (Manning’s coefficient $n$) on four land use types in the study area was derived from previous studies. The spatial distribution of Manning’s $n$ for different land use is indicated in Figure 4-5.
Table 4-1: Manning’s coefficient
(after Rahman (2006))

<table>
<thead>
<tr>
<th>Land use</th>
<th>Manning’s n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads</td>
<td>0.025</td>
</tr>
<tr>
<td>Low vegetated area</td>
<td>0.025</td>
</tr>
<tr>
<td>Water</td>
<td>0.03</td>
</tr>
<tr>
<td>Vegetated area</td>
<td>0.04</td>
</tr>
<tr>
<td>Buildings</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 4-5: Spatial distribution of Manning’s n

4.4. Building structure

In the modelling process, there are two ways to treat building structures: as impermeable solid blocks, or as rough surface which allow water intrusion and detain (Rahman, 2006). These different approaches to represent buildings could give out different results in water depth and inundation area, since the total amount of flood water flowing on land will differ. In this study, the building structures are treated as both solid blocks and rough surfaces to examine the effect to modelling results. Through setting high Manning’s n value to the building-up area in DEM, the effect of allowing flood water to intrude buildings and to be temporally detained was achieved.

4.5. Model calibration and validation

Historically, model application should be carried out sequentially in four stages: **instantiation, calibration, validation and exploitation** (Cunge, 2003). As Werner (2004) stated, there are two challenges faced when calibrating models, firstly, few spatial data on the flood extent are available; secondly, calibration usually requires extrapolation in respect that designed events are most likely of greater magnitude.
than the available observed events. In most calibration approaches researchers globally or locally adjust several parameters in the models, for example, Manning’s $n$, in order to obtain an acceptable model output coinciding with the “training data”. However, Cunge (2003) argued calibration is meaningless and advocated reinforcing validation stage, which focuses on finding out “physically logical reasons for the differences between the simulated and observed results” and exploring the impacts of uncertainties upon the exploitation.

In the modelling approach of this study, the calibration and validation stages are omitted due to the reasons as follows: Firstly, either calibration or validation needs observed data on a series of post-flooding events. This kind of data are not accessible or with low reliability. Secondly, the main focus of this study is on exploring the building structure effect in modelling and proposing a methodology for flood impact assessment, rather than predicting or forecasting flooding hazard.
5. Results of Hydrodynamic Modelling

The results from different flooding scenarios with different return periods and different representation of building structures will be further analyzed in this chapter to determine their effects on floods and, thereafter for flood impact assessment.

5.1. Scenario results

5.1.1. Spatial extent and inundation depth

Generally, the scenarios using rough surface resulted in more flooded area but with less water depth than that of scenarios with solid building structure. In terms of the reoccurrence intervals, both flood extent and maximum flood water depth increased while reoccurrence probability decreasing. In Figure 5-1, rough surface scenario result shows much more inundation in upstream boundary area and middle-right area than solid structure scenario. From Figure 5-2 and 5-3, high water levels were more likely to be observed in solid structure scenarios.

![Maximum Water Depth (5-year return period)](image)

Figure 5-1: Flood extent and Maximum water depth (5-year return period)
Figure 5-2: Flood extent and Maximum water depth (10-year return period)

Figure 5-3: Flood extent and Maximum water depth (25-year return period)
5.1.2. Flow velocity

The following graphs from dynamic simulations indicate the spatial variability of maximum water velocity in the river channel and the floodplain (Figure 5-4, 5-5 and 5-6). For better comparison and visualization, the maximum flow velocity of each scenario result was classified to 10 classes, which had smaller intervals for first five classes and bigger intervals for the rest classes. In general, the high flow velocity in each scenario was observed in the narrow part of the main channel, where the highest value was 15.76 m·s$^{-1}$ in the 25-year return period, solid building structure scenario. For the same 25-year return period, rough surface scenario just had 6.2 m·s$^{-1}$ maximum flow velocity. For the overland flow on the flat plain, maximum water velocity is smaller than flow in the river, mainly under 0.2 m·s$^{-1}$. Some extreme values could reach 2 m·s$^{-1}$ in the places where next to the river channel or canals.

![Maximum Flow Velocity (5-year return period)](image)

Figure 5-4: Maximum flow velocity for 5-year return period
Figure 5-5: Maximum flow velocity for 10-year return period

Figure 5-6: Maximum flow velocity for 25-year return period
5.1.3. Warning time

Here warning time refers to the period from simulation start to when floodwater reaches one particular place. Clearly, people who live near the river channels and canals have less warning time than other places (Figure 5-7, 5-8 and 5-9). Furthermore, it could be observed that the roads are important flooding propagation routes in the solid structure scenarios.

![Warning Time (5-year return period)](image)

*Figure 5-7: Warning time for 5-year return period*
Figure 5-8: Warning time for 10-year return period

Figure 5-9: Warning time for 25-year return period
5.2. Flood impact assessment

For planning flooding prevention or urban development project, the material step is to identify the area most vulnerable to floods, delineate the inundated area under a certain magnitude flood, for example, 25-year return period. Flood impact assessment is just in the position to serve as tool for estimating the overall adverse effects of floods for a particular area.

5.2.1. Impact assessment 1 (three parameters and visions)

To better illustrate the differences among impact results of visions, 25-year return period scenario with solid building structure was selected and displayed. First of all, primary results of three parameters (maximum water depth, maximum flow velocity and warning time) were classified to form thematic maps according to the criteria listed in Table 3-4. Afterwards, the thematic maps were weighted (Table 3-5) and combined to generate flood impact maps for different visions (Figure 5-10).

As shown in the figures below, the dominant impact category varies among the visions. In concern of human safety, most flooded area was assigned to Category 1 and 2. People who focus on property/estate loss during flooding would find most inundated area classified as Category 3. At last, Category 2 and 3 have the leading positions in all five categories while considering three flood parameters have equal impact to the communities.
5.2.2. Impact assessment 2 (two parameters)

Despite the complexity of the methods for impact estimation, the aim is establishing relationship between flooding parameters and potential social or financial impacts. The following plot (Figure 5-11) shows the potential flooding impacts to residents and properties in a series of flooding scenarios. The method applied here was described in Section 3.3.2, Figure 3-6. During this approach, a script was used in ILWIS to implement the method, assigning different values to pixels according to relationship between water depth and flow velocity (Appendix A4).

Figure 5-10: Flood impact maps for different visions (25-year return period)
In all six scenario maps, the river channel has high potential impacts, because of the increased flow velocity and water depth during flood. For rough surface scenarios with different return periods, most inundated area were considered as low impact area, Category 1. In the solid structure scenarios, the first category is still the dominant category. Only some places which near the river channel and canals, or on the roads, are considered more dangerous impact.

Figure 5-11: Flood impact map using velocity and depth
6. Discussion

6.1. Effect of building structure in the modelling

As known, the manner of how to treat building structure in hydrodynamic modelling has effect on the results, especially in urban and sub-urban area. However, the researchers are tending to simply adopt solid building structure, while the calibration of flood extent is mostly based on a single flood event. Mignot et al. (2006) pointed out that few references mentioned the effect of different building structures to model calibration and validation.

In common sense, models adopting solid building structures are thought to have bigger inundated extent while having same peak discharge with models having another building setting, since the area that could be flooded is decreased. Nevertheless, as shown in Figure 6-1, percentages of inundated area in solid structure (SS) scenarios are lower than the corresponding rough surface (RS) scenario of same peak discharge. Hereafter, these abbreviations, RS and SS, will be used to denote Rough Surface and Solid Structure. With comparison to the percentages of flooded area in SS scenarios, the inundated area for 5-year, 10-year and 25-year return period events using RS increased 90%, 30% and 36%, respectively.

![Figure 6-1: Percentage of flooded area for scenario](image)

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*FLOOD IMPACT ASSESSMENT USING HYDRODYNAMIC MODELLING IN BANGKOK, THAILAND*

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*39*
If the solid building structure is adopted in the modelling approach, these pixels representing build-ups actually cannot be flooded at all. In fact, if the buildings are already surrounded by water, they are unavoidable to be flooded, at least affected by floodwater outside the building structure. Thus, solid building structure tends to underestimate the flood extent and impact. An algorithm should be used in the result analysis to distinguish whether the buildings are surrounded by water. The build-ups which are surrounded by water should be added into the total inundated area.

Besides the differences in flood extent for two kinds of building structure, there are also differences existing in other flooding parameters for these two structures. The scenario results of three flood parameters were classified accordingly using the criteria listed in Section 3.3.2, Table3-4. Then the percentages of each category comparing with total flooded area in each scenario were plotted in Figure 6-2.

Firstly, in term of water depth, the percentages of low categories (from 1 to 3) of RS scenarios are higher than that of SS scenarios, in despite of the return periods. Nevertheless, this trend cannot be applied in Category 5. In this category, generally speaking, SS scenarios have more area than RS scenarios. The possible explanation should be that floodwater tends to flow along roads and between buildings due to the blocking effect of solid buildings. Thus, water could propagate further from the headwater in the SS scenarios, and accumulate in the dense urban area resulting in deep water depth. On the other hand, rough surface allows water more easily distributing on the floodplain, resulting in more inundated area and relatively shallower water depth.

Secondly, for flow velocity and warning time, the distinctness between two surface types for same reoccurrence interval decreased from low category to high category. In particular, for 25-year return period, percentage of area classified to Category 1 of rough surface is 18% higher than that of solid structure. Whereas, in Category 2 to 5, the situation is adverse, the percentage for solid structure always exceeds that for rough surface. The comparison for warning time is still following the trend.

It could be concluded that the building structure has disparate effect to flooding parameters examined above for different reoccurrence intervals. Most likely, the effect would differ according to the terrain, for instance, urban surrounded by hills and urban located in flat plains. Due to data scarcity, optimal selection could not be decided through this study. Yet, the decision should not be made so easily in future hydrodynamic modelling researches. Complete determinative approach based on a
series of historical flood events is required to choose a more suitable structure which adapts to the particular condition of the study area.

Figure 6-2: Percentages of categories for different building structures and return periods (water depth, flow velocity and warning time)

Note: the percentage values indicate that area classified to each category compare to the whole study area.
6.2. Flood impact assessment

6.2.1. Visions integrating three parameters

Governments use flood impact assessment as a tool to assist macroscopic land use planning and flood management. For the individuals, local societies, and insurance industry, a single flood impact map is not good enough to fully represent the adverse impacts of floods. Households have the need to estimate the flood impact regarding the safety of family members, damages to belongings and properties. Insurers need specific flood impact maps to determine insurance premiums, even to decide to continue or withdraw flood-related insurance service in some areas. Thus, a user-based impact assessing methodology is strongly required.

According to the maps shown previously in Figure 5-10, the percentages of each impact category comparing to the total inundated area were calculated (Figure 6-3). It is easy to see there are dramatic changes among the category percentages for visions. In the Human Safety vision, Category 2 takes account of 56.3% of the total inundated area. For potential damage to properties and estates, 59.6% of flooded area has Category 3 impact. In the Equal vision, Category 2 and 3 share over 80% of total inundated area. These changes reflect the different focuses toward floods, which could be further used to help decision making of either entities or individuals.

![Figure 6-3: Percentages of flood impact categories for visions (25-year return period, solid structure)](image_url)
Not only the flood impacts change in the whole study domain, but also there were notable changes in local scale. In the middle of the study area, an area was selected for closer inspection. As displayed in Figure 6-4, the area located in upper right keeps consistently being classified as Category 3 in each vision. However, impact category for rest of the region varies from 1 to 3 in different visions.

Figure 6-4: Flood impact categorization for visions
(25-year return period, solid structure)
6.2.2. Two parameters: Velocity and Depth

Because of the flat nature of the study area, the velocity of overland flow would not be high enough to damage the structure of buildings, which mainly happens in mountainous regions. Thus, it is predictable that most of flooded area is classified as Category one, meaning dangerous to pedestrians. This had been confirmed through the following histogram showing the percentages of area which were classified into impact categories in each scenario (Figure 6-5). In all six scenarios, the percentages of Category 1 increase from 59.9% to 89.8%. Noticeably, for 10-year and 25-year return periods, high impact categories, from 3 to 5, have smaller percentages than the corresponding percentages for 5-year return period. The reason for this is that the total inundated areas in two 5-year return period scenarios are much smaller than other two return periods scenarios, which are indicated in Table 6-1.

![Figure 6-5: Percentages of flood impact categories (velocity and depth)](image)

Note: 1. RS-rough surface, SS-solid structure
2. The percentages stand for area classified as one category compare with the total inundated area in each scenario.
Table 6-1: Categorized Area for different scenarios

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However, some area with relatively deep floodwater, for example, more than 2 m, but with low flow velocity, just was labelled as Category one. Obviously, the flood impact is underestimated in this condition. Moreover, in terms of “distributed source” floods, say, excessive rainfall, floodwater could be deep but with fairly small flow velocity. Then, the flooding impact maps derived from the empirical correlations between velocity and depth are not proper. Therefore, the relationship between flood impacts and flooding parameters should be developed, at least modified according to local conditions. Neither underestimation nor overestimation of flood impact is good for the society.
7. Conclusion and Recommendations

7.1. Conclusion

This study shows the applicability of hydrodynamic modelling, especially integrated 1D2D modelling in flood impact assessment. The effect of how building structures are represented in the modelling approach was inspected. Furthermore, a user-based flood impact assessing methodology was proposed and examined. The objectives of the study were achieved and several maps were derived to indicate the different characteristics of floods at different return periods and building structures. Thus, the following conclusions could be drawn.

The manner to represent buildings in modelling approach has a significant impact on the flooding characteristics. Compared to solid building structures, flood extent for rough surface scenarios increased 90%, 30% and 36% at 5, 10 and 25 return periods, respectively. For water depth, the percentages of low categories (from 1 to 3) of Rough Surface scenarios are higher than that of Solid Structure scenarios for all the three return periods. Whereas adverse result was observed in Category 5. In terms of flow velocity and warning time, the distinctness between two surface types for the same return period decreased from low category to high category.

Theoretically, the more parameters integrated in the flood impact assessment, the better the tangible and intangible impacts can be assessed. Due to various limitations, flood impact assessment requires simplification of the complex reality, which is achieved through choosing several important parameters. To derive applicable flood impact maps, the characteristics of flood, such as extent, water depth, velocity and warning time, must be given emphasis. Furthermore, flood impact assessment should be carried out according to the different concerns of different parties, instead of indicating by a simple map. The specific flood impact maps which have particular focus can better help the governments, the insurance industry and common people to make their decision towards the flood.

The flood impact assessment methods developed by other researchers and authorities have their own applicable circumstance. It is not advisable to select an assessment method without any change according to local conditions. In this study, the
characteristics of study area restrict the application of the alternative two-parameter method. Unless the formulae used in the method could be modified accordingly, this method cannot be directly applied in the flood impact assessment in this particular study area.

7.2. Limitation of study

Although modelling always requires simplification of reality, the more quality and quantity of data are, the greater the potential reliability of the model. The limitations of this study could be concluded as follows:

- The study was handicapped by the unsatisfying resolution of DEM and image used for building footprint extraction. For urban and sub-urban area, the human-made structures have important influence on the flooding characteristics. Therefore, a better representation of the study area is required in the further study for prediction and forecast. Of course, LiDAR imagery could be the best source to achieve the goal. However, this kind of source is rarely available in the less developed countries due to the financial constraints.

- Lack of information on recent development and ongoing protection programmes is another constraint in this study. Indeed, the protective constructions could safeguard the society. On the other hand, it also decreases the awareness of people and stimulates more development, resulting increased flooding risk.

- Validation data scarcity restricts the application of the model. In the future study, if this problem is solved, the model could be adopted for predictive and indicative purposes.

- Due to long computation time of the model and time limitation for this study, longer simulation duration, for instance, 10 days or one month, was not feasible in this study. Thus, more computation power, time and effort are required to thoroughly examine the impact of building structures in modelling and to perfect the proposed methodology.

7.3. Recommendations

The 1D2D hydrodynamic modelling widens the possibility for effective flood management. In addition, the effective flood impact assessment proposed could offer more help in information delivery and indicating risk. For future studies in this research area, the following recommendations should be considered:
- The selection of how to deal with the building structure in hydrodynamic modelling for urban and sub-urban area should be given more attention. The decision should be based on thorough examination, comparing simulation results using different structures with series historical flooding data.

- Higher resolution DEM/DSM is suggested in the future study. The finer resolution not only gives better visualisation for results, but also improves the reliability.

- It is strongly recommended that warning time should be considered in the flood hazard and impact assessment. People who get the flood warning in time would be better prepared, at least mentally prepared, to deal with the water. Lack of information and preparedness is more dangerous than a rare flood event.

- Besides the selection of flood characteristics to be used in impact assessment, the way in which these factors are integrated to generate a useful and readable indicative map should also be considered carefully. Some methods could be suitable in some particular regions, but overestimate or underestimate the flood impact while applied to other places.
REFERENCES

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Bangkok Metropolitan Administration (2006) *Geography of Bangkok*  


APPENDIX

A1 Classified ASTER image
### A2 Error matrix for accuracy assessment

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A4 Script for two-parameter impact assessment using

Description:

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<th>Value</th>
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<td>1</td>
<td>[ Y = 1 - 1.55X + 0.595X^2 ]</td>
</tr>
<tr>
<td>2</td>
<td>[ Y = 3.25e^{-1.835X} ]</td>
</tr>
<tr>
<td>3</td>
<td>[ Y = -0.238 + 1.227/X ]</td>
</tr>
<tr>
<td>4</td>
<td>[ Y = 4.7e^{-0.642X} ]</td>
</tr>
<tr>
<td>5</td>
<td>[ Y = -0.28 + 5.65/X ]</td>
</tr>
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</table>

\[
\text{risk01} := \text{iff} (\text{depth01} > (-0.28 + 5.65/(\text{vel01} + 0.0000001)), 5, \text{iff} (\text{depth01} > (4.7 \times e^{-1.835 \times \text{vel01}}), 4, \text{iff} (\text{depth01} > (-0.238 + 1.227/\text{vel01}), 3, \text{iff} (\text{depth01} > (3.25 \times e^{-1.835 \times \text{vel01}}), 2, \text{iff} (\text{depth01} > (1 - 1.55 \times \text{vel01} + 0.595 \times \text{vel01}^2), 1, 0))))
\]

\[
\text{risk02} := \text{iff} (\text{depth02} > (-0.28 + 5.65/(\text{vel02} + 0.0000001)), 5, \text{iff} (\text{depth02} > (4.7 \times e^{-1.835 \times \text{vel02}}), 4, \text{iff} (\text{depth02} > (-0.238 + 1.227/\text{vel02}), 3, \text{iff} (\text{depth02} > (3.25 \times e^{-1.835 \times \text{vel02}}), 2, \text{iff} (\text{depth02} > (1 - 1.55 \times \text{vel02} + 0.595 \times \text{vel02}^2), 1, 0))))
\]

\[
\text{risk03} := \text{iff} (\text{depth03} > (-0.28 + 5.65/(\text{vel03} + 0.0000001)), 5, \text{iff} (\text{depth03} > (4.7 \times e^{-1.835 \times \text{vel03}}), 4, \text{iff} (\text{depth03} > (-0.238 + 1.227/\text{vel03}), 3, \text{iff} (\text{depth03} > (3.25 \times e^{-1.835 \times \text{vel03}}), 2, \text{iff} (\text{depth03} > (1 - 1.55 \times \text{vel03} + 0.595 \times \text{vel03}^2), 1, 0))))
\]

\[
\text{risk04} := \text{iff} (\text{depth04} > (-0.28 + 5.65/(\text{vel04} + 0.0000001)), 5, \text{iff} (\text{depth04} > (4.7 \times e^{-1.835 \times \text{vel04}}), 4, \text{iff} (\text{depth04} > (-0.238 + 1.227/\text{vel04}), 3, \text{iff} (\text{depth04} > (3.25 \times e^{-1.835 \times \text{vel04}}), 2, \text{iff} (\text{depth04} > (1 - 1.55 \times \text{vel04} + 0.595 \times \text{vel04}^2), 1, 0))))
\]

\[
\text{risk05} := \text{iff} (\text{depth05} > (-0.28 + 5.65/(\text{vel05} + 0.0000001)), 5, \text{iff} (\text{depth05} > (4.7 \times e^{-1.835 \times \text{vel05}}), 4, \text{iff} (\text{depth05} > (-0.238 + 1.227/\text{vel05}), 3, \text{iff} (\text{depth05} > (3.25 \times e^{-1.835 \times \text{vel05}}), 2, \text{iff} (\text{depth05} > (1 - 1.55 \times \text{vel05} + 0.595 \times \text{vel05}^2), 1, 0))))
\]

\[
\text{risk06} := \text{iff} (\text{depth06} > (-0.28 + 5.65/(\text{vel06} + 0.0000001)), 5, \text{iff} (\text{depth06} > (4.7 \times e^{-1.835 \times \text{vel06}}), 4, \text{iff} (\text{depth06} > (-0.238 + 1.227/\text{vel06}), 3, \text{iff} (\text{depth06} > (3.25 \times e^{-1.835 \times \text{vel06}}), 2, \text{iff} (\text{depth06} > (1 - 1.55 \times \text{vel06} + 0.595 \times \text{vel06}^2), 1, 0))))
\]

\[
\text{risk07} := \text{iff} (\text{depth07} > (-0.28 + 5.65/(\text{vel07} + 0.0000001)), 5, \text{iff} (\text{depth07} > (4.7 \times e^{-1.835 \times \text{vel07}}), 4, \text{iff} (\text{depth07} > (-0.238 + 1.227/\text{vel07}), 3, \text{iff} (\text{depth07} > (3.25 \times e^{-1.835 \times \text{vel07}}), 2, \text{iff} (\text{depth07} > (1 - 1.55 \times \text{vel07} + 0.595 \times \text{vel07}^2), 1, 0))))
\]

\[
\text{risk08} := \text{iff} (\text{depth08} > (-0.28 + 5.65/(\text{vel08} + 0.0000001)), 5, \text{iff} (\text{depth08} > (4.7 \times e^{-1.835 \times \text{vel08}}), 4, \text{iff} (\text{depth08} > (-0.238 + 1.227/\text{vel08}), 3, \text{iff} (\text{depth08} > (3.25 \times e^{-1.835 \times \text{vel08}}), 2, \text{iff} (\text{depth08} > (1 - 1.55 \times \text{vel08} + 0.595 \times \text{vel08}^2), 1, 0))))
\]

\[
\text{risk09} := \text{iff} (\text{depth09} > (-0.28 + 5.65/(\text{vel09} + 0.0000001)), 5, \text{iff} (\text{depth09} > (4.7 \times e^{-1.835 \times \text{vel09}}), 4, \text{iff} (\text{depth09} > (-0.238 + 1.227/\text{vel09}), 3, \text{iff} (\text{depth09} > (3.25 \times e^{-1.835 \times \text{vel09}}), 2, \text{iff} (\text{depth09} > (1 - 1.55 \times \text{vel09} + 0.595 \times \text{vel09}^2), 1, 0))))
\]

\[
\text{risk10} := \text{iff} (\text{depth10} > (-0.28 + 5.65/(\text{vel10} + 0.0000001)), 5, \text{iff} (\text{depth10} > (4.7 \times e^{-1.835 \times \text{vel10}}), 4, \text{iff} (\text{depth10} > (-0.238 + 1.227/\text{vel10}), 3, \text{iff} (\text{depth10} > (3.25 \times e^{-1.835 \times \text{vel10}}), 2, \text{iff} (\text{depth10} > (1 - 1.55 \times \text{vel10} + 0.595 \times \text{vel10}^2), 1, 0))))
\]
risk12:=iff(depth12>(-0.28+5.65/(vel12+0.000001)),5,iff(depth12>(4.7*exp(-
0.642*vel12)),4,iff(depth12>(-0.238+1.227/(vel12+0.000001)),3,iff(depth12>(3.25*exp(-
1.835*vel12)),2,iff(depth12>(1-1.55*vel12+0.595*vel12^2),1,0))))

risk13:=iff(depth13>(-0.28+5.65/(vel13+0.000001)),5,iff(depth13>(4.7*exp(-
0.642*vel13)),4,iff(depth13>(-0.238+1.227/(vel13+0.000001)),3,iff(depth13>(3.25*exp(-
1.835*vel13)),2,iff(depth13>(1-1.55*vel13+0.595*vel13^2),1,0))))

risk14:=iff(depth14>(-0.28+5.65/(vel14+0.000001)),5,iff(depth14>(4.7*exp(-
0.642*vel14)),4,iff(depth14>(-0.238+1.227/(vel14+0.000001)),3,iff(depth14>(3.25*exp(-
1.835*vel14)),2,iff(depth14>(1-1.55*vel14+0.595*vel14^2),1,0))))

risk15:=iff(depth15>(-0.28+5.65/(vel15+0.000001)),5,iff(depth15>(4.7*exp(-
0.642*vel15)),4,iff(depth15>(-0.238+1.227/(vel15+0.000001)),3,iff(depth15>(3.25*exp(-
1.835*vel15)),2,iff(depth15>(1-1.55*vel15+0.595*vel15^2),1,0))))

risk16:=iff(depth16>(-0.28+5.65/(vel16+0.000001)),5,iff(depth16>(4.7*exp(-
0.642*vel16)),4,iff(depth16>(-0.238+1.227/(vel16+0.000001)),3,iff(depth16>(3.25*exp(-
1.835*vel16)),2,iff(depth16>(1-1.55*vel16+0.595*vel16^2),1,0))))

risk17:=iff(depth17>(-0.28+5.65/(vel17+0.000001)),5,iff(depth17>(4.7*exp(-
0.642*vel17)),4,iff(depth17>(-0.238+1.227/(vel17+0.000001)),3,iff(depth17>(3.25*exp(-
1.835*vel17)),2,iff(depth17>(1-1.55*vel17+0.595*vel17^2),1,0))))

risk18:=iff(depth18>(-0.28+5.65/(vel18+0.000001)),5,iff(depth18>(4.7*exp(-
0.642*vel18)),4,iff(depth18>(-0.238+1.227/(vel18+0.000001)),3,iff(depth18>(3.25*exp(-
1.835*vel18)),2,iff(depth18>(1-1.55*vel18+0.595*vel18^2),1,0))))

risk19:=iff(depth19>(-0.28+5.65/(vel19+0.000001)),5,iff(depth19>(4.7*exp(-
0.642*vel19)),4,iff(depth19>(-0.238+1.227/(vel19+0.000001)),3,iff(depth19>(3.25*exp(-
1.835*vel19)),2,iff(depth19>(1-1.55*vel19+0.595*vel19^2),1,0))))

risk20:=iff(depth20>(-0.28+5.65/(vel20+0.000001)),5,iff(depth20>(4.7*exp(-
0.642*vel20)),4,iff(depth20>(-0.238+1.227/(vel20+0.000001)),3,iff(depth20>(3.25*exp(-
1.835*vel20)),2,iff(depth20>(1-1.55*vel20+0.595*vel20^2),1,0))))

risk21:=iff(depth21>(-0.28+5.65/(vel21+0.000001)),5,iff(depth21>(4.7*exp(-
0.642*vel21)),4,iff(depth21>(-0.238+1.227/(vel21+0.000001)),3,iff(depth21>(3.25*exp(-
1.835*vel21)),2,iff(depth21>(1-1.55*vel21+0.595*vel21^2),1,0))))

risk22:=iff(depth22>(-0.28+5.65/(vel22+0.000001)),5,iff(depth22>(4.7*exp(-
0.642*vel22)),4,iff(depth22>(-0.238+1.227/(vel22+0.000001)),3,iff(depth22>(3.25*exp(-
1.835*vel22)),2,iff(depth22>(1-1.55*vel22+0.595*vel22^2),1,0))))

risk23:=iff(depth23>(-0.28+5.65/(vel23+0.000001)),5,iff(depth23>(4.7*exp(-
0.642*vel23)),4,iff(depth23>(-0.238+1.227/(vel23+0.000001)),3,iff(depth23>(3.25*exp(-
1.835*vel23)),2,iff(depth23>(1-1.55*vel23+0.595*vel23^2),1,0))))

risk24:=iff(depth24>(-0.28+5.65/(vel24+0.000001)),5,iff(depth24>(4.7*exp(-
0.642*vel24)),4,iff(depth24>(-0.238+1.227/(vel24+0.000001)),3,iff(depth24>(3.25*exp(-
1.835*vel24)),2,iff(depth24>(1-1.55*vel24+0.595*vel24^2),1,0))))

risk25:=iff(depth25>(-0.28+5.65/(vel25+0.000001)),5,iff(depth25>(4.7*exp(-
0.642*vel25)),4,iff(depth25>(-0.238+1.227/(vel25+0.000001)),3,iff(depth25>(3.25*exp(-
1.835*vel25)),2,iff(depth25>(1-1.55*vel25+0.595*vel25^2),1,0))))

risk26:=iff(depth26>(-0.28+5.65/(vel26+0.000001)),5,iff(depth26>(4.7*exp(-
0.642*vel26)),4,iff(depth26>(-0.238+1.227/(vel26+0.000001)),3,iff(depth26>(3.25*exp(-
1.835*vel26)),2,iff(depth26>(1-1.55*vel26+0.595*vel26^2),1,0))))
risk27 := if (depth27 > (-0.28 + 5.65/(vel27+0.0000001)), 5, if (depth27 > (4.7*exp(-0.642*vel27)), 4, if (depth27 > (-0.238+1.227/(vel27+0.0000001)), 3, if (depth27 > (3.25*exp(-1.835*vel27)), 2, if (depth27 > (1-1.55*vel27+0.595*vel27^2), 1, 0)))))
risk28 := if (depth28 > (-0.28 + 5.65/(vel28+0.0000001)), 5, if (depth28 > (4.7*exp(-0.642*vel28)), 4, if (depth28 > (-0.238+1.228/(vel28+0.0000001)), 3, if (depth28 > (3.25*exp(-1.835*vel28)), 2, if (depth28 > (1-1.55*vel28+0.595*vel28^2), 1, 0)))))
risk29 := if (depth29 > (-0.28 + 5.65/(vel29+0.0000001)), 5, if (depth29 > (4.7*exp(-0.642*vel29)), 4, if (depth29 > (-0.238+1.229/(vel29+0.0000001)), 3, if (depth29 > (3.25*exp(-1.835*vel29)), 2, if (depth29 > (1-1.55*vel29+0.595*vel29^2), 1, 0)))))
risk30 := if (depth30 > (-0.30 + 5.65/(vel30+0.0000001)), 5, if (depth30 > (4.7*exp(-0.642*vel30)), 4, if (depth30 > (-0.238+1.230/(vel30+0.0000001)), 3, if (depth30 > (3.25*exp(-1.835*vel30)), 2, if (depth30 > (1-1.55*vel30+0.595*vel30^2), 1, 0)))))
max_risk_1 := max(risk01, risk02, risk03)
max_risk_2 := max(risk04, risk05, risk06)
max_risk_3 := max(risk07, risk08, risk09)
max_risk_4 := max(risk10, risk11, risk12)
max_risk_5 := max(risk14, risk15, risk13)
max_risk_6 := max(risk16, risk17, risk18)
max_risk_7 := max(risk19, risk20, risk21)
max_risk_8 := max(risk22, risk23, risk24)
max_risk_9 := max(risk25, risk26, risk27)
max_risk_10 := max(risk28, risk29, risk30)
max_risk_11 := max(max_risk_1, max_risk_2, max_risk_3)
max_risk_12 := max(max_risk_4, max_risk_5, max_risk_6)
max_risk_13 := max(max_risk_7, max_risk_8, max_risk_9)
max_risk_14 := max(max_risk_10, max_risk_11, max_risk_12)
max_risk := max(max_risk_13, max_risk_14)