Flood Damage Assessment in Taipei City, Taiwan

Ming-Hsi Hsu[1], Meng-Yuan Tsai[2], Yi-Chieh Lin[3], Albert S. Chen[4], Michael J. Hammond[5], Slobodan Djordjević[6] & David Butler[7]

[1] National Taiwan University, Taiwan, mhhsu@ntu.edu.tw
[2] National Taiwan University, Taiwan, mymytsai@ntu.edu.tw
[3] National Taiwan University, Taiwan, julianababe@hotmail.com
[4] University of Exeter, UK, a.s.chen@exeter.ac.uk
[5] University of Exeter, UK, m.j.hammond@exeter.ac.uk
[6] University of Exeter, UK, s.djordjevic@exeter.ac.uk
[7] University of Exeter, UK, d.butler@exeter.ac.uk

ABSTRACT

In this study, we reviewed the literature on flood damage assessment and collected information for related research in Taiwan to analyze the relationships between direct flood damage, flood frequency, flood depth, and land-use. The procedure for flood damage assessment was then developed that includes the following steps: (a) Scenario simulation of inundation potential. (b) Establishment of the relationship between inundation depth and damage loss for varied land-use. (c) Risk analysis of inundation damage.

Taipei City in north Taiwan was adopted as the case study to demonstrate the proposed algorithm. Flood events with return periods of 5, 10, 25, 50, 100 and 200 years were used for flood hazard analysis to cover possible flooding scenarios. The inundation hazard maps were first generated via hydraulic modelling. The regional flood damage was then estimated using a relationship between inundation depth and damage. The flood damage exceedance probability (EP) curve for Taipei City was constructed following the association of the loss with its probability of occurrence. The flood damage EP curve was further used to integrate the damage assessments for individual flood events for a full probability range presentation of the flood risk. The expected annual damage was calculated by integrating the area under the EP curve.

KEYWORDS

Inundation potential, average annual flood loss, exceedance probability curve

1 INTRODUCTION

Natural hazards, such as earthquake, typhoon, flood and debris flow, cause an enormous loss of properties and human lives around the world every year. Various measures including land-use planning and management, construction of structural measures, and flood monitoring and warning systems, can be applied to mitigate the impact of flooding. Sufficient understanding of the hazard risk can help decision makers to adopt adequate measures for flood damage reduction (James and Hall, 1986). The effectiveness of these alternatives can be evaluated by considering the reduction of risk that proceeds from the implementations of these measures. Flood risk can be considered to be related to the nature of the hazard and its probability of occurrence, the people and assets that are potentially exposed to the hazard, and their vulnerability (Kron, 2003). When a potentially exposed population comes into a contact with a hazard, their vulnerability will determine the impacts of the hazard.

Flood hazard can be assessed by field survey, remote sensing during or after an event (Brivio et al., 2002, Islam and Sado, 2000a, Islam and Sado, 2000b, Islam and Sado, 2002) or by inundation simulation modelling (Chen et al., 2011). Defined the risk as a function of hazard and vulnerability: (UNISDR, 2004)

$$R\ (\text{Risk}) = H\ (\text{Hazard}) \times V\ (\text{Vulnerability}) \tag{1}$$

Flood as a major and frequently occurred natural hazard, its risk can also be assessed using the above equation. Flood hazard maps are the first thing to be done in flood risk assessment. Flood hazard can be assessed by field survey, remote sensing during or after an event or by computer modelling. The concept of using depth-damage curves for flood vulnerability study was firstly proposed by White (1945).

2 METHODOLOGY

Since human activities and flood depths are not homogenously distributed over the space, the spatial variations in social and economic activities, and flood hazard have to be taken into account in the assessment of the flood damage. The data needed for this approach including land parcel maps and socio-economic activities on each parcel. These data are multifarious and difficult to establish and maintain. It is more difficult if the country is developing and it suffers natural disasters. To investigate the consequence of flooding via numerical simulations, most models divide the domain into a set of grid cells. The socio-economic activities are considered to be homogeneous within each cell and are aggregated into a single attribute associated with it. The data needed for this model can be derived from the aggregated census data that is easier to obtain than the individual details. The flood damage is then estimated from the flood depth and the damage attributes for each cell. The regional flood damage is calculated as the sum of the loss estimated in cells. This paper focuses on the development of a grid-based regional flood damage assessment model.

2.1 Hazard analysis

The development of flood potential maps requires a hydraulic model to simulate flooding under various scenarios (Chen et al., 2006). For urban areas, the sewer system plays an important role in the rainfall-runoff process such that an overland flow model that neglects the inertial term in momentum equations, based on the assumption that the acceleration term is small compared with the gravitation and friction terms, is coupled with the SWMM sewer model for hydraulic modelling (Hsu et al., 2002). The depth-averaged shallow water equations on the overland surface are written as:

$$\frac{\partial d}{\partial t} + \frac{\partial[(1-\beta)ud]}{\partial x} + \frac{\partial[(1-\beta)vd]}{\partial y} = q \tag{2}$$

$$-\frac{\partial h}{\partial x} = S_{fx} + \frac{qu}{dg} \tag{3}$$

$$-\frac{\partial h}{\partial x} = S_{fy} + \frac{qv}{dg} \tag{4}$$

where d is depth [m], h is water stage [m], u and v are velocity components in x- and y-direction [m/s], respectively, t is time [s], g is gravitational acceleration [m/s^2], q is source or sink per unit area [m/s], $S_{fx} = n^2 u\sqrt{u^2+v^2} \big/ d^{4/3}$ and $S_{fy} = n^2 v\sqrt{u^2+v^2} \big/ d^{4/3}$ are friction slopes in x and y direction, respectively, n is Manning's roughness, and $\beta = \sqrt{A_b / A}$ is detaining ratio which represents a linear ratio of building area to the total area of interest.

To simulate the flow interactions between the sewer system and the ground surface, the drainage through inlets to the sewer systems and the overflow from the surcharged manholes to the ground surface are used as model linkages between the overland flow and the sewer models. The former are treated as sinks and the latter as sources in the two-dimensional model. Eqs. (2) to (4) are solved by a finite difference numerical scheme, named the Alternating Direction Explicit (ADE) method, which allows an initial condition with zero water depth and velocity (Hsu et al., 2000). A sample flood potential map with a return period of 200 year is shown as in Figure 1.

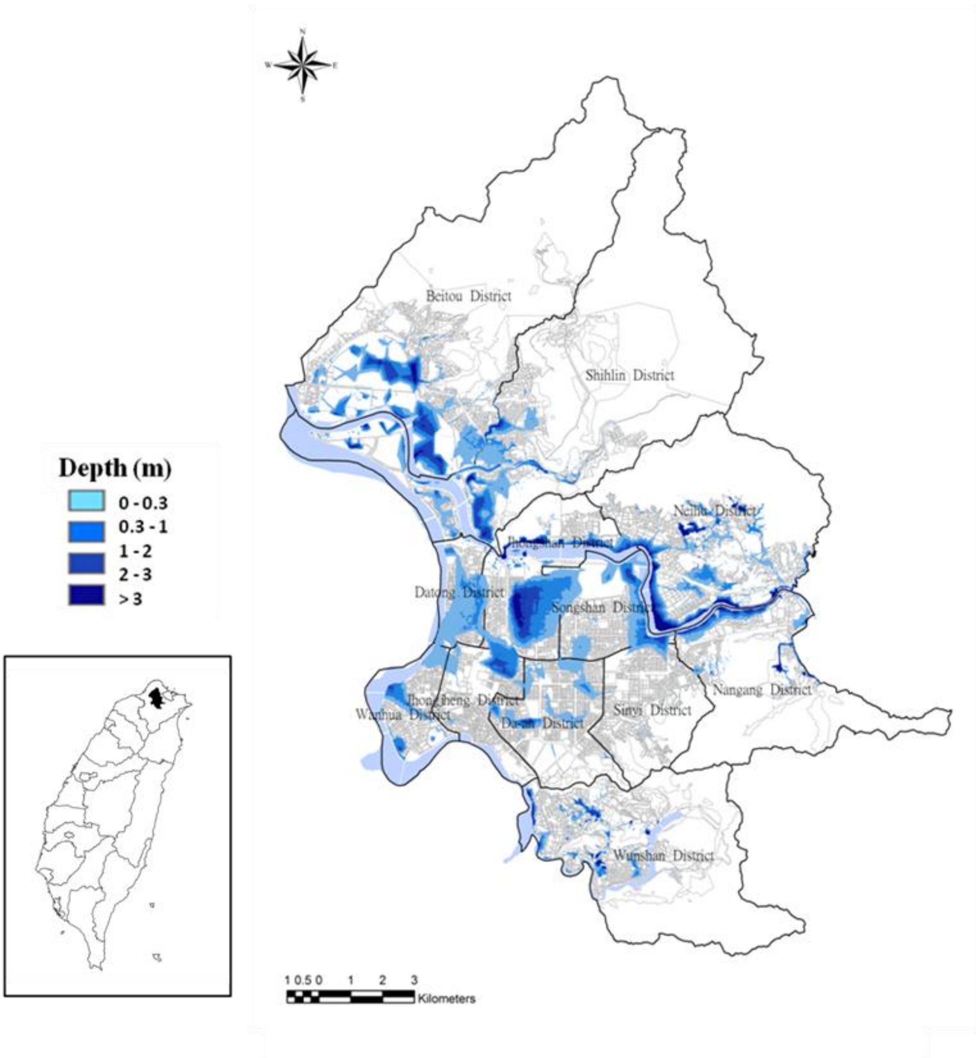

Figure 1. Flood potential map of 200 year return period in Taipei city

2.2 Vulnerability analysis

The flood damage was estimated using the hazard map with the depth-damage curves (Dutta et al., 2003, Smith, 1994, White, 1964). The curve characteristics may be highly affected by the nature of human activities, which relate to the types of land-use. The activities were classified into residential, commercial (retailer, service), industrial (manufacturing, wholesaler) and cultural zone in this study. The flood damage data used to derive the curve were collected from a field survey in the frequently flooded area and the damage claim information filed with the internal revenue service for tax deduction. The data are recorded in a per-household or per-firm bases. The curves for these different activity categories, as shown in Figure 2, were developed in a previous study of the authors (Wang, 2003) based on flood damage data collected after Typhoon Nari that caused a major damage in the Taipei Metropolitan in 2001.

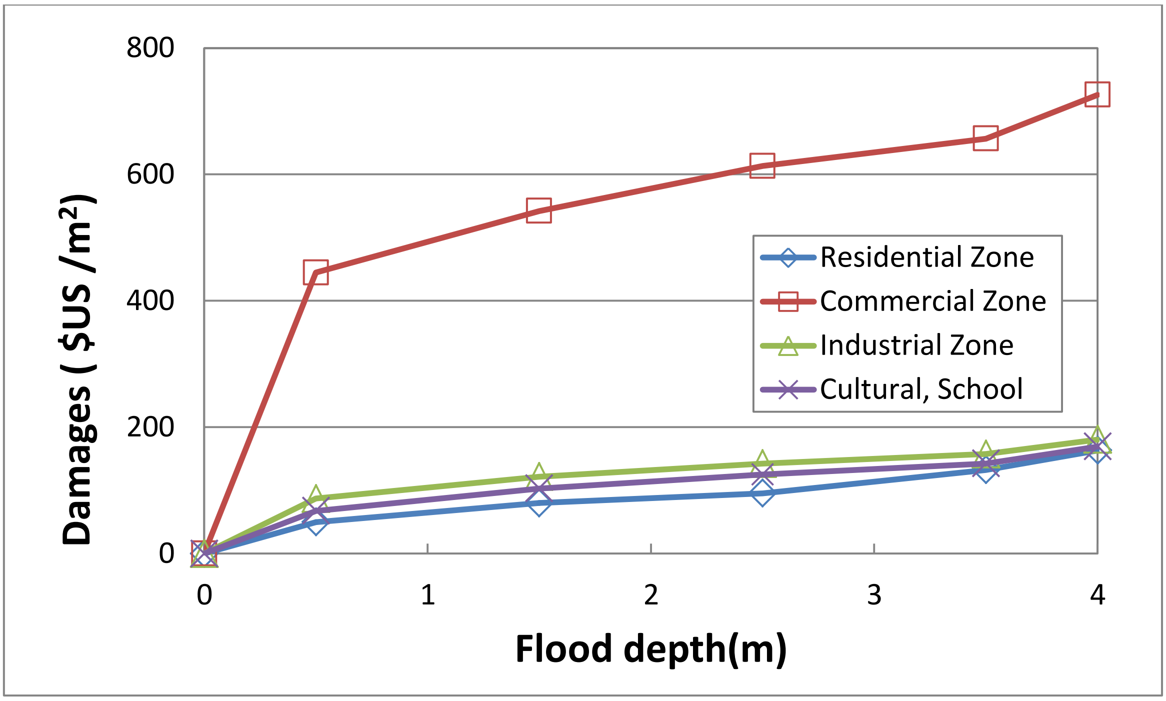

Figure 2. Depth-damage curves for residential, commercial, industrial and cultural zone

2.3 Flood damage assessments

Flood damage can be calculated cell by cell using the flood depths and the respective loss functions. The regional damage caused by a flood event can then be assessed by summing up the damage of all the cells within the region. The risk as shown in Eq. (1) is defined as the damage multiplied by the occurrence probability. A set of flood potential maps (return periods of 5, 10, 25, 50, 100 and 200 years) with different occurrence probability, instead of one for a single event, can be prepared for the region for the full range of knowledge of the risk. The risk of each flood event can first be calculated by multiplying the estimated damage of that event with its occurrence probability. The average annual flood loss (AAFL) caused by flood hazard was used in this study for regional flood risk assessment (Hardison and Jennings, 1972). The exceedance probability (EP) curve for flood damage of a region can be constructed by using the damages of each simulated event and its respective EP. The AAFL can be defined as the area under the EP curve of flood damage and can be calculated by Eq. (5) (Arnell, 1989).

$$AAFL = \int x\, f(x) dx \qquad (5)$$

where, *AAFL* is the average annual flood loss; *x* is the damage of a flood event; *f(x)* is the probability density function of *x*.

3 TAIPEI CASE STUDY

3.1 Study area situation

Taipei City is located at the downstream floodplain of the Danshuei River Basin. The Digital Elevation Model (DEM) of Taipei City that the northeast region is mountainous with elevation above 400m, the southeast and south areas have few hills, and the northwest part is alluvial floodplain with elevation below 5m. The Danshuei River and its tributary, the Sindian River, flow along the west boundary of Taipei City. Another tributary, the Keelung River, passes through Taipei City from east to west and converges into the Danshuei River.

In 1967, Taipei City consisted of ten districts and had a population of 1.20 million. It was upgraded into a municipality administered directly by the Central Government in 1967. Six nearby towns, with a population of 0.4 million, were incorporated into Taipei City in 1968. The land area was extended from 83.6 km^2 to 272 km^2, however, the land zoning area for urban development planning of Taipei City, as listed in Table 1 and Figure 3, show that only 134 km^2 is flat land suitable for urban development. The remaining areais covered by hills, sloped land and low-lying land, which were not appropriate for development. The average precipitation in the central Taipei City is 2,405 mm/year (Central Weather Bureau, 2012) and 68% of the annual rainfall is concentrated in the monsoon and typhoon season between May and October. Typhoons usually carry heavy rainfall in short time periods as intense as 100 mm/hr or 1,000 mm/day.

Table 1. Land zoning of the Taipei City based on urban development plan

Land Zoning		Area (unit: hectare)	
For urban development	Residential zone	3,837	13,394
	Industrial zone	452	
	Commercial zone	919	
	Public facilities zone	7,123	
	Others*	1,063	
Not for urban development	Agricultural and scenic zones	804	13,786
	Conservation zone	11,351	
	Water covering zone	1,631	

* Including Administrative zone, cultural and education zone, zone for specific purposes, airport, recreation zone and others

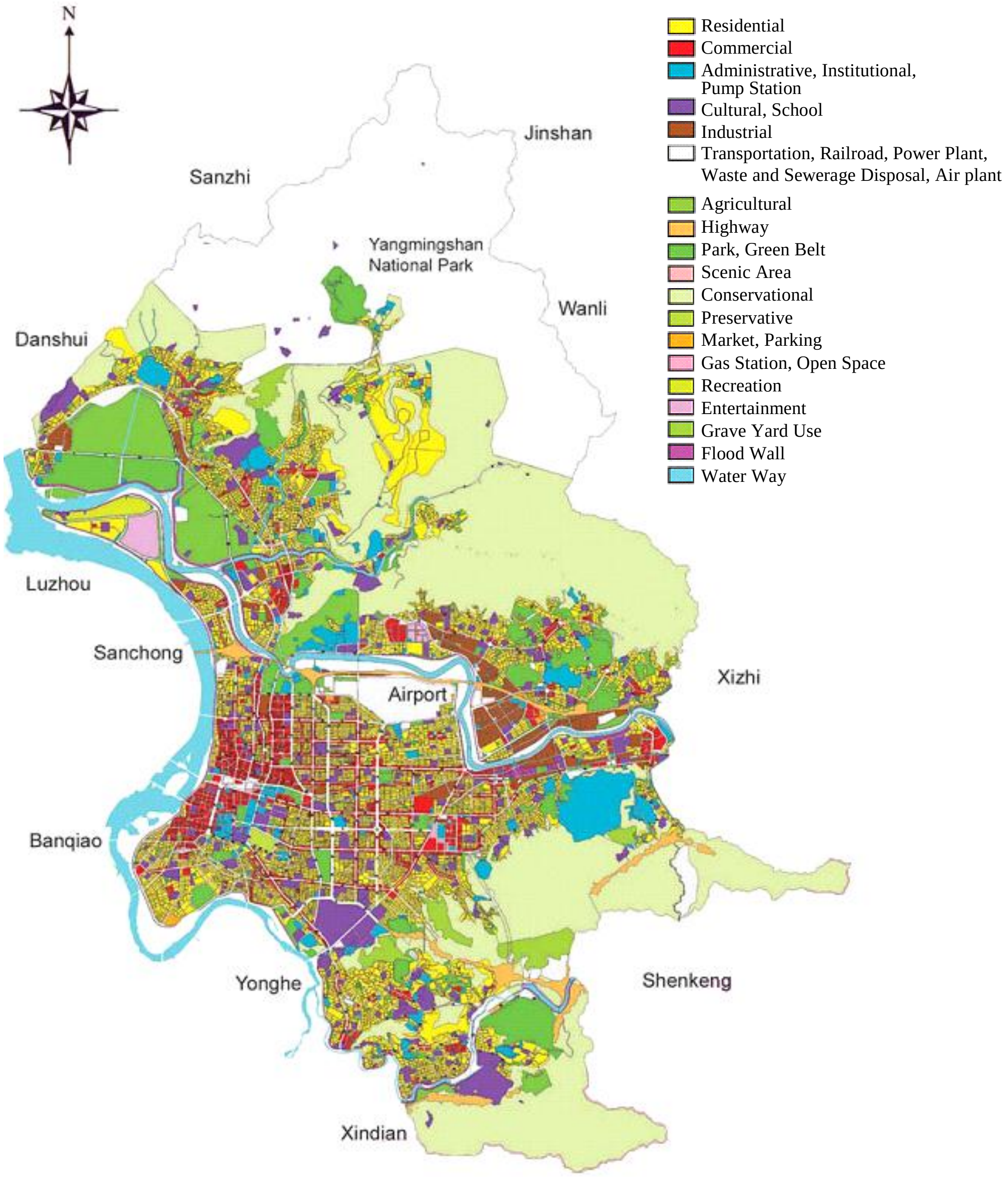

Figure 3. Land zonings in Taipei City

3.2 Urban flood damage assessment

To assess the flood risk for the study area, hazard analysis was first done and flood potential maps under different probabilities of occurrence were generated with a 20 m grid resolution. Flood events with 5, 10, 25, 50, 100 and 200 year return periods were used for this flood hazard analysis to cover the probable situations in a more complete sense. Spatial information was gathered for this area including land-use, zoning, administrative boundary, and digital terrain. The related census data, including data on demography, vehicles, commercial and industrial activities were collected for exposure analysis. These collected census data are in a form aggregated by census tract, the basic unit of city administration. These aggregated data were disaggregated into the 20 m $\times$ 20 m cells to be compatible with the previously generated flood potential maps. Land-use and zoning information was used to assist this disaggregation process.

The related loss functions were applied to these disaggregated data with the flood depths for damage assessment for each cell and each category. As a comparison, the flood damage was also estimated at the basic city administrative unit level using the aggregated census data and the results are displayed as shown in Figure 4 and Table 2.

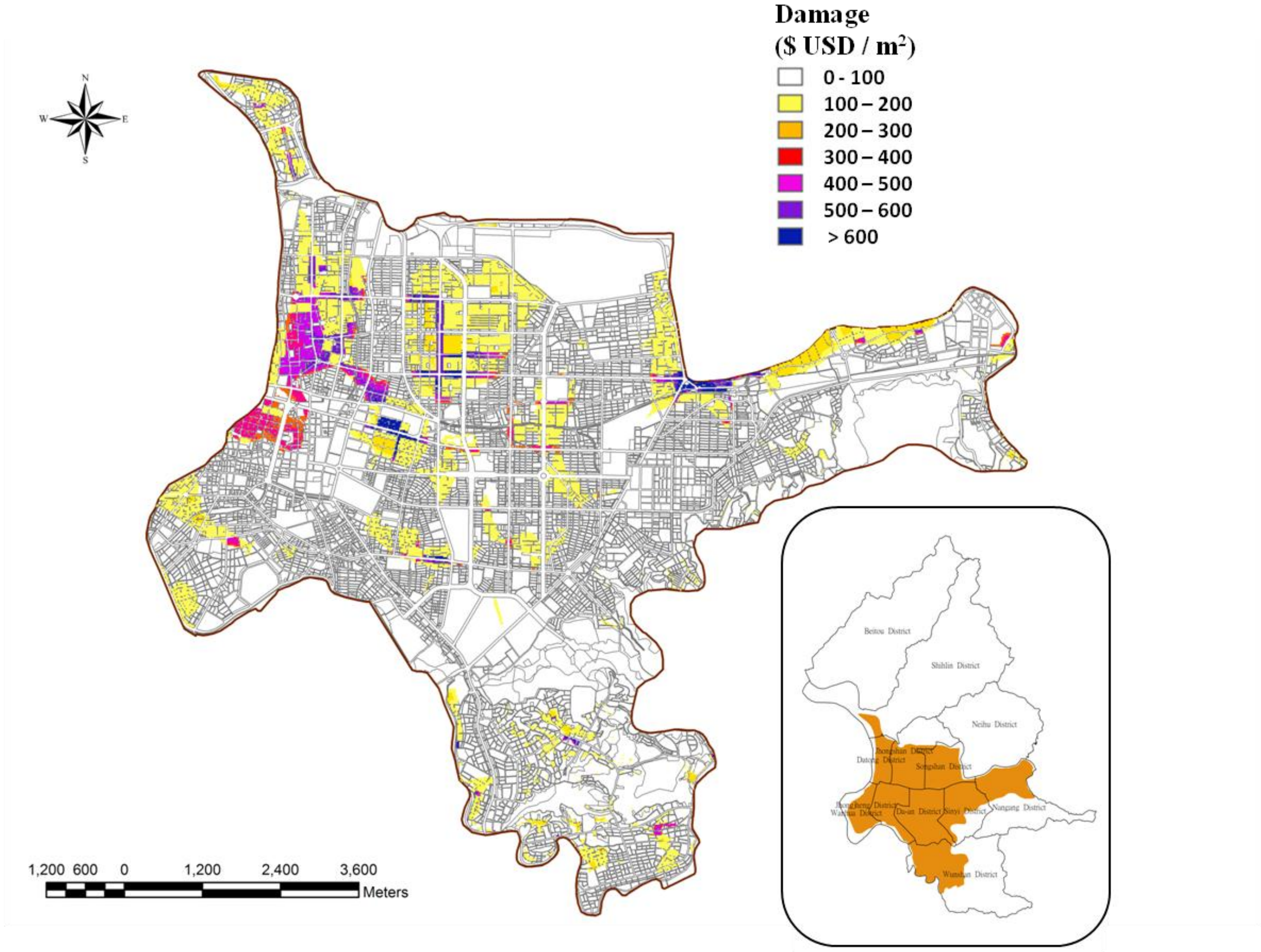

Figure 4. Grid-based flood risk map with 200 year return period in Taipei central area

The estimated regional flood damage for each flood event was then associated with its occurrence probability to construct the EP curve for flood risk of the city (as shown in Figure 5). This AAFL can be used as a basis for evaluation of the flood management measures through with-and-without analysis. The difference of the AAFL with and without the implementation of a flood mitigation project could be evaluated as the annual benefit of the measure. Together with the annual cost estimated for implementing the project, the planner can better determine whether the project would be economically viable.

Table 2. Flood damage assessment in Taipei city

Return period (year)	24 hr rainfall accumulation (mm)	Inundated area (Km^2)	Inundated area / Total area (%)	Flood damage (US $ million)		
				Household	Industry & Commerce	Total
10	374	2.4	0.97	93.6	34.3	154.8
25	426	3.22	1.30	114.2	40.6	209.4
50	463	4.01	1.62	157.9	51.5	263.4
100	505	5.34	2.15	202.0	61.5	344.9
200	550	6.77	2.73	267.7	77.2	388.7

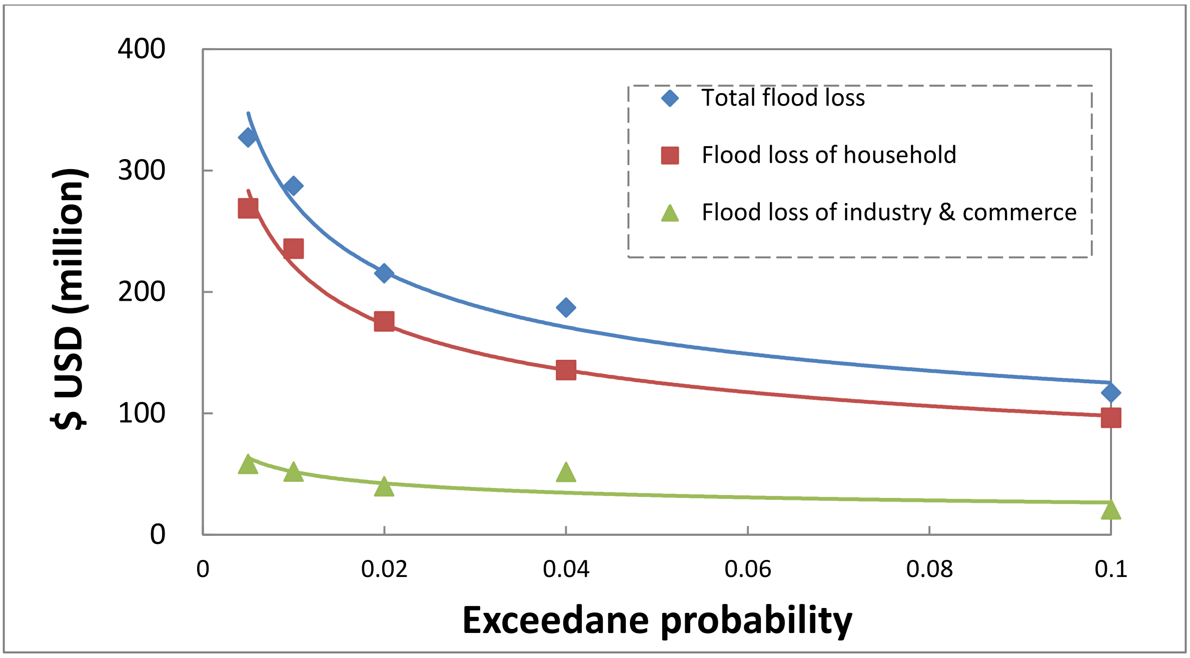

Figure 5. The flood damage exceedance probability curve for Taipei City

4 DISCUSSIONS AND CONCLUSIONS

1. The proposed approach uses only aggregated census data that are comparatively easier to collect. A disaggregation algorithm was proposed to decompose the aggregated census data down to a smaller grid cell data model for matching with the flood hazard maps generated from flood simulation models. Spatial information such as land-use, zoning, and terrain were used as background support for a more realistic decomposition.
2. The concept of EP curve was used to establish a regional risk assessment at full probability range. The AAFL combined with the with-and-without analysis was also proposed for better economic evaluation among flood mitigation measures.
3. The AAFL can be calculated for each grid cell instead of the region as a whole. The resulting map can be taken as risk map showing the spatial variation of average flood risk in the region. A sample risk map is shown in Figure 4 for the study area. With the information of risk spatial variation, current land-use can be reviewed and a more reasonable land-use pattern can be proposed for effective flood risk mitigation.

5 ACKNOWLEDGEMENT

The work is supported by the National Science Council, Taiwan (NSC 99-2915-I-002-120) and the CORFU project, funded by the European Commission through Framework Programme 7, Grant Number 244047.

6 REFERENCES

Arnell, N. W. 1989. Expected Annual Damage and Uncertainties in Flood Frequency Estimation. *J. Water Res. Pl. Management*, 115**,** 94-107.

Brivio, P. A., Colombo, R., Maggi, M. & Tomasoni, R. 2002. Integration of remote sensing data and GIS for accurate mapping of flooded areas. *International Journal of Remote Sensing*, 23**,** 429-441.

Central Weather Bureau. 2012. *Climate Statictics - Monthly mean of precipitation 1981-2011* [Online]. Taipei, Taiwan: Central Weather Bureau, Taiwan. Available: http://www.cwb.gov.tw/V7e/climate/monthlyMean/Precipitation.htm.

Chen, A. S., Hsu, M. H., Huang, C. J. & Lien, W. Y. 2011. Analysis of the Sanchung inundation during Typhoon Aere, 2004. *Natural Hazards*, 56**,** 59-79.

Chen, A. S., Hsu, M. H., Teng, W. H., Huang, C. J., Yeh, S. H. & Lien, W. Y. 2006. Establishing the database of

inundation potential in Taiwan. *Natural Hazards,* 37**,** 107-132.
Dutta, D., Herath, S. & Musiakec, K. 2003. A mathematical model for flood loss estimation. *Journal of Hydrology,* 277**,** 24-49.
Hardison, C. H. & Jennings, M. E. 1972. Bias in Computed Flood Risk. *J. Hydr. Div-ASCE,* 98**,** 415-427.
Hsu, M. H., Chen, S. H. & Chang, T. J. 2000. Inundation simulation for urban drainage basin with storm sewer system. *Journal of Hydrology,* 234**,** 21-37.
Hsu, M. H., Chen, S. H. & Chang, T. J. 2002. Dynamic inundation simulation of storm water interaction between sewer system and overland flows. *Journal of the Chinese Institute of Engineers,* 25**,** 171-177.
Islam, M. D. M. & Sado, K. 2000a. Development of flood hazard maps of Bangladesh using NOAA-AVHRR images with GIS. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 45**,** 337-355.
Islam, M. M. & Sado, K. 2000b. Flood hazard assessment in Bangladesh using NOAA AVHRR data with geographical information system. *Hydrological Processes,* 14**,** 605-620.
Islam, M. M. & Sado, K. 2002. Development priority map remote sensing data with for flood countermeasures by geographic information system. *Journal of Hydrologic Engineering,* 7**,** 346-355.
James, L. D. & Hall, B. 1986. Risk Information for Floodplain Management. *Journal of Water Resources Planning and Management-Asce,* 112**,** 485-499.
Smith, D. I. 1994. Flood Damage Estimation - a Review of Urban Stage-Damage Curves and Loss Functions. *Water Sa,* 20**,** 231-238.
Wang, R. Y. 2003. Establishment of Systematic Models for Flood Damage Evaluation. Taipei, Taiwan: Water Resource Agency, Ministry of Economics Affairs, Taiwan.
White, G. F. 1945. Human Adjustment to Floods (Research Paper No. 29). Chicago, IL: Department of Geography, University of Chicago.
White, G. F. 1964. Choice of Adjustments to Floods (Research Paper No. 93) Chicago, IL: Department of Geography, University of Chicago.
UNISDR, 2004. Living with Risk: A Global Review of Disaster Reduction Initiatives, United Nations Publications.