Journal of Flood Risk Management

DOI: 10.1111/jfr3.12220

BACK TO THE FUTURE: ASSESSING THE DAMAGE OF THE 2004 DHAKA FLOOD IN THE 2050 URBAN ENVIRONMENT

David M. Khan[1,*], William Veerbeek[2], Albert S. Chen[3], Michael J. Hammond[3], Feroz Islam[1], Ismat Pervin[1], Slobodan Djordjević[3], David Butler[3]

[1] Institute of Water Modelling, Bangladesh; [2]UNESCO-IHE Institute for Water Education, Netherlands; [3] University of Exeter, United Kingdom;

[*] *House # 496, Road # 32, New DOS, Mohakhali, Dhaka – 1206, Bangladesh; Tel: +88 (02)8824590-1; E-mail: dmk@iwmbd.org*

ABSTRACT

Planning to make a city flood resilient needs the proper assessment of future conditions. Urban growth models are being used as a planning tool for city development. Within the CORFU project, flood management strategies suitable for cities with varied geographic and socio-economic conditions have been developed. In the paper, we adopted urban growth model to project the possible future conditions of Dhaka City, the rapidly developing capital of Bangladesh. Bangladesh lies in the delta of the Himalayan Mountain range and experiences frequent flooding. In 2004 an extreme nationwide flood event occurred, which caused major damage to Dhaka City. If the same event were to occur in 2050, it can be expected that the damage would increase significantly. Through the application of the urban growth, hydraulic, and damage assessment models, we were able to determine the damage that can be expected to happen in 2050. The paper also describes the key factors that are important to determine this impact and the associated uncertainties.

KEYWORDS

Damage assessment; Dhaka city; extreme event, flood risk; urban flooding; urbanisation; urban growth.

1. INTRODUCTION

Floods are devastating and create multiple problems for society. Although flooding is partially a natural phenomenon, rapid urbanisation has escalated the flood risk in many countries (Lau *et al.*, 2010). Urbanisation affects both the hydrological (Wiitala, 1961) and hydraulic processes involved in flooding, as well as social factors like increased exposure. Changes in land-use and human activities increase surface runoff that results in greater flood extents and depths. The risk of flood related damage is higher in developing countries where there is typically less protection and inadequate infrastructure. With increased migration from rural areas to towns and cities, the urban landscape is changing rapidly across much of the developing world (Montgomery, 2008). Settlements in urban areas are spreading quickly, and most often in an unplanned manner. Low-lying lands and drainage routes are being encroached upon to build settlements. This results in a rapid loss of natural drainage routes and flood retention areas, and major water logging has become commonplace in many town and cities (Adikari et al., 2010).

There is a need to design and implement sustainable drainage management systems for urban areas. The planning, design, operation and maintenance of such measures need an integrated approach (Brown, 2005). Advanced analytical tools are required to understand and analyse complex urban systems. Methods such as urban growth modelling can be used to project future development by identifying key factors and rules, and extrapolating them (Zevenbergen et al., 2008). This paper therefore focuses on i) estimating the possible increases in flooding as a consequence of extensive urbanisation and ii) the potential increase in flood damages given the rapid urbanisation, through increased runoff and exposure of assets. Dhaka, Bangladesh is a prime example of a megacity that is facing unprecedented urban growth combined with a history of major flood events. The city and especially the peripheral areas experience frequent flooding. Some of these floods are catastrophic, and have caused huge damage in the past, such as in 1988, 1998, and 2004.

One of the major obstacles for comprehensive research into Dhaka's flood problems is the poor understanding of design floods. This especially holds for riverine flooding due to the complexity and volatility of the Bangladesh river system, located in the largest delta of the world (Mikhailov and Dotsenko, 2006). To overcome this issue, a more practical approach has been developed where a historic flood event has been projected into the future. The event in 2004 was a catastrophic flood that arose from a combination of extreme river flows and intense rainfall between June and July 2004. The event was also suitable for the study as better information on damage was found for this flood. Using the 2004 flood as a reference event, this paper investigates what the consequences would be if this flood would take place in 2050 given the rapid urban development that is expected. The paper firstly introduces the case study and the models used to explore the scenario. In addition, the outcomes are presented with a focus on the changes in flood characteristics and associated flood damages as a function of the applied spatially explicit urban development scenario. Finally, the outcomes are interpreted and a discussion is provided focussing on factors that influence the outcomes.

2. DHAKA CASE STUDY

2.1 General characteristics of the city

Dhaka is the capital of Bangladesh and is located in the central southern region of the country, surrounded by several rivers. The city covers more than 400 km^2 and is one of the most densely populated cities in the world, with some areas having more than 80,000 people per km^2. The city has historically attracted many migrant workers. Half the workforce is employed in household and unorganized labour, while about 800,000 work in the textile industry. Even so, unemployment remains high at 19%.

The risks associated with floods are expected to increase in coming years due to high rates of urbanisation. The scale and condition of the drainage system has not kept pace with the rapid urban expansion and development. Dhaka can be divided into two: the western and eastern areas (Figure 1). The western part of the city is protected by embankments and has a storm sewer system. The eastern part is the lowest lying part of Dhaka, and faces the most severe risk of flooding. The area is not protected by embankments and mainly consists of open channels. Due to land scarcity in the city, the population of the Eastern fringe has increased rapidly during the last decades. Thousands of people have encroached upon low-lying areas in search of a place to live, reducing the efficiency of natural drainage, and increasing the flood risk.

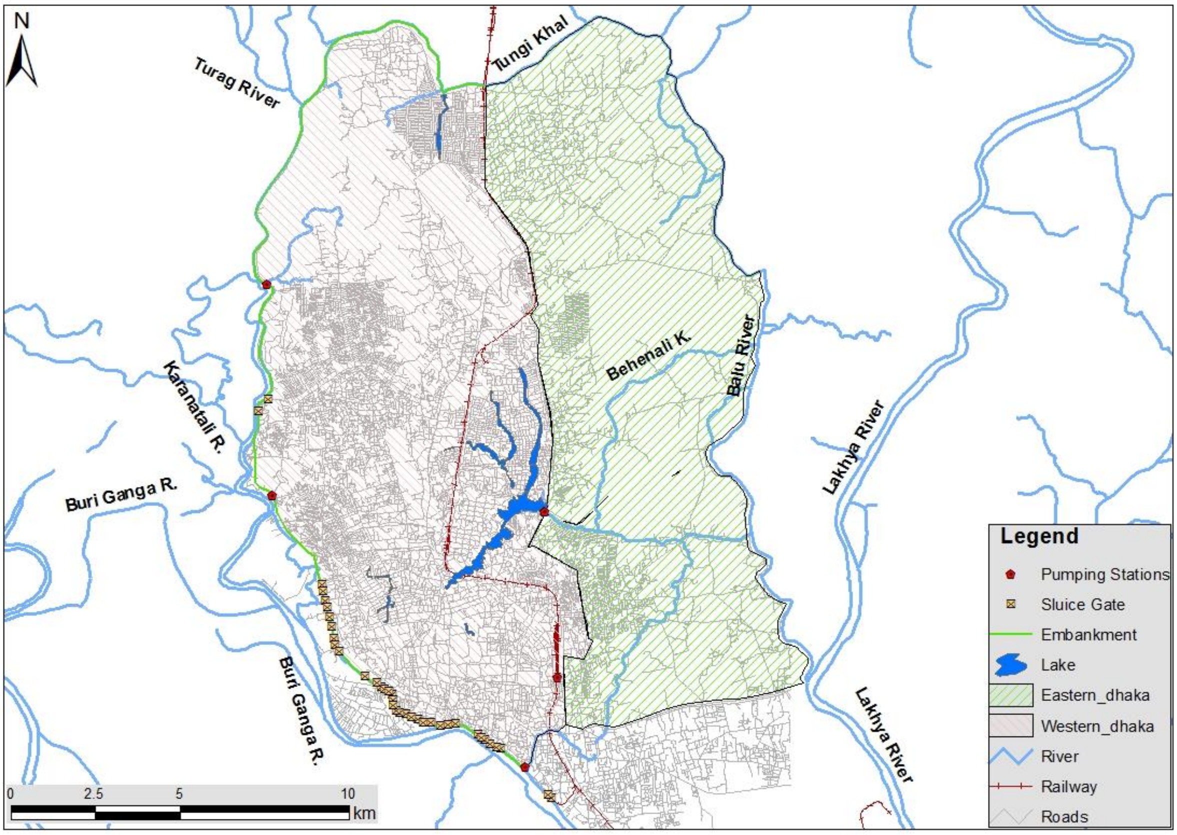

Figure 1: Eastern and Western Dhaka based on drainage separation

2.2 Urban growth

Dhaka has experienced significant urban growth during the last 50 years (Dewan and Yamaguchi, 2009), and urban development and economic growth have sparked a construction boom; high-rise buildings and skyscrapers have changed the city landscape. Currently (in 2014) the population of Dhaka is around 14 million. With annual population growth rates estimated at around 4% (Demographia, 2014), Dhaka is one of the world's fastest growing megacities in the world and is estimated to be the fifth most populated metropolitan area by 2030 (UN, 2014).

The subsequent land use and land cover (LULC) changes in metropolitan can be subdivided into three different categories (e.g. Angel et al.,2007):

- *Infill.* Infill development refers to the practice of building on undeveloped spaces in the gaps between developed areas.
- *Extension.* Urban growth that actually expands the contiguous built-up area as a result of the conversion of rural or peri-urban areas into built-up zones along the fringes of the city. Development and continuous expansion of the city is expected and already happening and accelerated growth is expected in the eastern fringe, the Dhaka-Narayanganj-Demra (DND) triangle, the western fringe and the airport area (Figure 1).
- *Leapfrogging.* This urban growth class covers the development of built-up areas that are disconnected from existing urban agglomerations. In the Dhaka metropolitan regions such areas can be found in Tongi, Gazipur and Savar and may become prominent, as population continues to grow.

Between 2000 and 2011 the ratios of urban development classed as infill, extension and leapfrogging were estimated at 1.8%, 82% and 16.2% respectively (Dewanet al., 2014), which suggests that urban development is mostly occurring along the fringes of Dhaka. Most of this extension took place on the north-eastern part of the city (ibid), since urban development is heavily constrained by the rivers in the south and west. The eastern side of Dhaka is facing a substantial amount of land grabbing, where block by block development is occurring in the lower lying areas. Figure 2 shows the urban development within the low lying areas from 1990 to 2005.

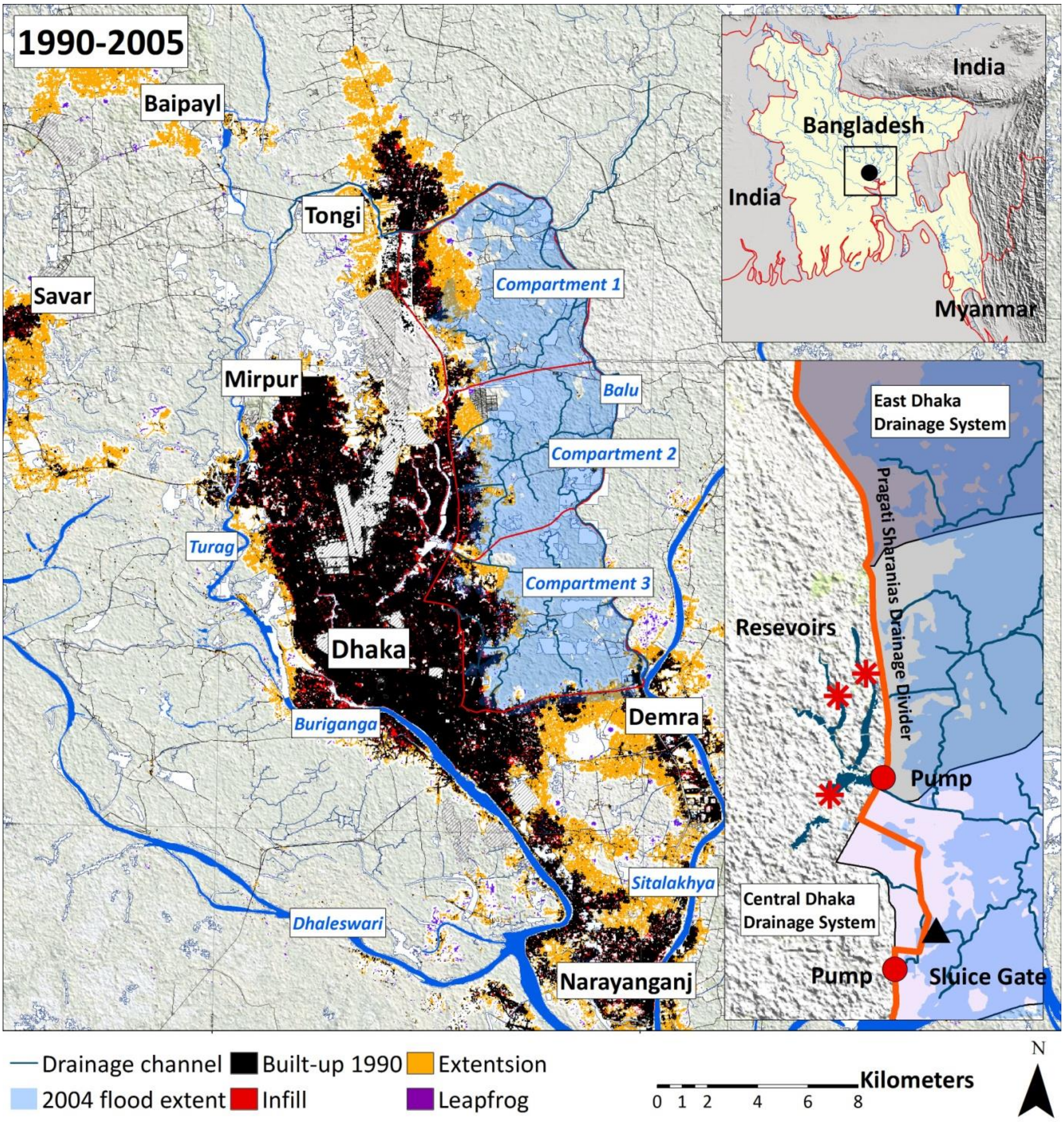

Figure 2: Dhaka urban development between 1990 and 2005 (left) and eastern Dhaka drainage system (right)

The continuing unplanned and unmanaged urban development has a severe impact on the LULC, which consequently impacts the physical characteristics of the flood regime. While severely limiting the infiltration capacity which gives rise to seasonal drainage congestion, the ever increasing concentration of people and assets in flood prone areas significantly increases the potential consequences of floods.

2.3 Historical flood impacts

By virtue of being located adjacent to the Buriganga, Turag and Balu rivers, the city has been subject to periodic flooding since its early days. The inundation pattern of the city has undergone many changes as the city continued to grow and new flood control structures were put in place. In 1988, the worst ever flood in living memory occurred, and almost all of the eastern part and about 70% of the western part of the capital were inundated. The flood affected more than 4.55 million people. About 30% (860,000) residential buildings were damaged as well as more than 384km of paved roads (Alam and Rabbani, 2007).

After the 1988 flood a country wide study was conducted called the Flood Action Plan (FAP). For Dhaka, one of the major recommendations was to construct an embankment to protect the western part of the city. It also included regulators at the outfall of drainage channels, raised road and flood wall. Construction of these flood control and drainage works has brought major changes in the flood regime in the Dhaka West (Nishat et al., 2000). During the nationwide floods in 1998, caused by extreme river levels, 23% area of the western city was inundated. Even then the western side was less affected compared to the eastern side due to the flood protection measures (Siddiqui and Hossain, 2006).

Another catastrophic flood hit Dhaka in 2004 (see Figure 2), causing major health impacts and economic losses (Siddiqui and Hossain, 2006). First, high river discharges caused by prolonged monsoon rainfall affected much of eastern Dhaka. In September 2004, extreme rainfall over four days overwhelmed the capacity of the urban drainage system causing extensive flooding in the protected area of western Dhaka (Alam and Rabbani, 2007). A major flood also occurred in 2007 which affected the eastern part significantly. Untreated waste water mixing with flood water caused a large number of patients getting admitted for water borne diseases (Islam et al., 2008).

The 2004 flood was considered to have a return period of one hundred years (Rahman et al 2005). The flooding occurred due to a combination high water level in the river which affects in the eastern side and also high intensity rainfall which affects the western and central side. The extent and depth of flooding and the consequence of it for the city was evident from several studies done later one, which was valuable for the comparative assessment under the current study. Damage estimations have been made for Bangladesh which ranged between 2.2 billion USD (Islam, 2006) and 6.6 billion USD (Hossain, 2006). Hasnat (2006) urged for future assessments and provided recommendations and a procedure for the task.

3. URBAN GROWTH MODEL, FLOOD MODEL AND DAMAGE MODEL

3.1 Urban growth model

Up till now, applications of urban growth models (UGM) in flood risk management are limited. Studies are often based on retrospective analysis (e.g. Weng, 2001; Xian & Crane, 2005) or are limited to estimating future changes in the impervious surface ratio (ISR) distribution which increases surface runoff and subsequent flooding (e.g. Weng, 2001). Other applications in the field of environmental studies include relating explicit urban growth scenarios to changes in the urban heat island (Pathirana et al., 2014) and pollutant loads due to extensive slum formation (Veerbeek et al., 2012).

For this study, a stochastic LULC change model by Veerbeek et al. (2014) has been used to project urban development scenarios. By using historic LULC cover data in combination with a range of thematic maps (e.g. road network, elevations) the model attempts to derive a set of transition rules that describe LULC changes based on the occurrence of local conditions (e.g. the influence of the proximity to a public transport hub on the development of built-up areas from agricultural land). Together, these rules define the suitability of individual patches of land for LULC transitions, which are subsequently executed based on the amount of observed LULC changes (i.e. the growth rates) identified in the LULC base maps used for training (e.g. between 1990 and 2010). Calibration of the model is performed by a machine learning algorithm, in which the transition rules are iteratively optimised to mimic observed LULC change trends. Once a satisfactory goodness-of-fit is reached between the predicted and observed LULC patterns used for validation of the model outputs, the obtained transition rules are used iteratively to create a set of future LULC maps for a given interval and horizon. These projections can be regarded as a business-as-usual (BAU) scenario for urban growth.

3.2 Flood model

The hydraulic modelling for Dhaka comprised two separate models to reflect the unprotected eastern side with mostly open channels and protected western side with mostly piped drainage. The eastern side was delineated into three compartments or hydrological units that were used to calculate the surface runoff resulting from the changes in LULC. The modelling relies upon hydrological inflows at certain points as well as precipitation inputs. An urban rainfall-runoff model, based on the Time-Area method was used to estimate the runoff from the rainfall. The central part was again divided hydraulically into 22 catchments, having single primary drainage system. Primary line is divided into secondary, tertiary and catchpit connection system. To prevent backflow towards the city in monsoon period when water level of Balu River is higher, there are 3 drainage control structures which were included in the model. The cross sections of the open channels in the eastern model were updated based on 2004 conditions.

The hydraulic model of drainage network was then coupled with the DEM (Digital Elevation Model) with cell size of 25m to simulate 2D surface runoff propagations. Mike Flood was used to perform the modelling exercise for both the 1D drainage and 2D surface models. In the 2D model the retention ponds were replaced by the pond bathymetry and surrounding connectivity were established accordingly. In central Dhaka, most of the urbanized areas are at elevation of 6 to 8 meters above the msl. While more than 70% area of Eastern Dhaka is below 6 meters.

3.3 Flood Damage model

While the requirements and methods to perform a comprehensive flood damage assessment that includes direct and indirect damages are well established (e.g. Merz et al., 2010; Messner*et al.*, 2007; Penning-Rowsellet al., 2005), operationalizing such a task in the context of a megacity in the developing world is virtually impossible due to the extensive data requirements across many economic sectors and assets. Within the context of EU-funded CORFU project (Djordjević et al., 2011), the development of a flood damage model and associated depth-damage curves (DDCs) that relate expected damages to inundation depths have therefore been limited to residential and commercial properties only (Hammond et al., 2012). DDCs for Bangladesh have been developed previously by Islam (2005) but were updated for the CORFU project by using data acquired by a survey among 215 households and 215 businesses that suffered flood damages in recent years (Haque et al. 2014). In order to be used in combination with the urban growth scenarios, the property-based (i.e. building type) DDCs were aggregated and converted to fit with the corresponding 10 LULC-density classes. Although some information from the DDCs is lost during aggregation, this step is essential when integrating the future LULC scenarios in the damage modelling. The resulting DDCs are depicted in Figure 3. Note that for inundation levels beyond 5.6m, the damage levels are kept at the depicted maximum level for the respective LULC-density class.

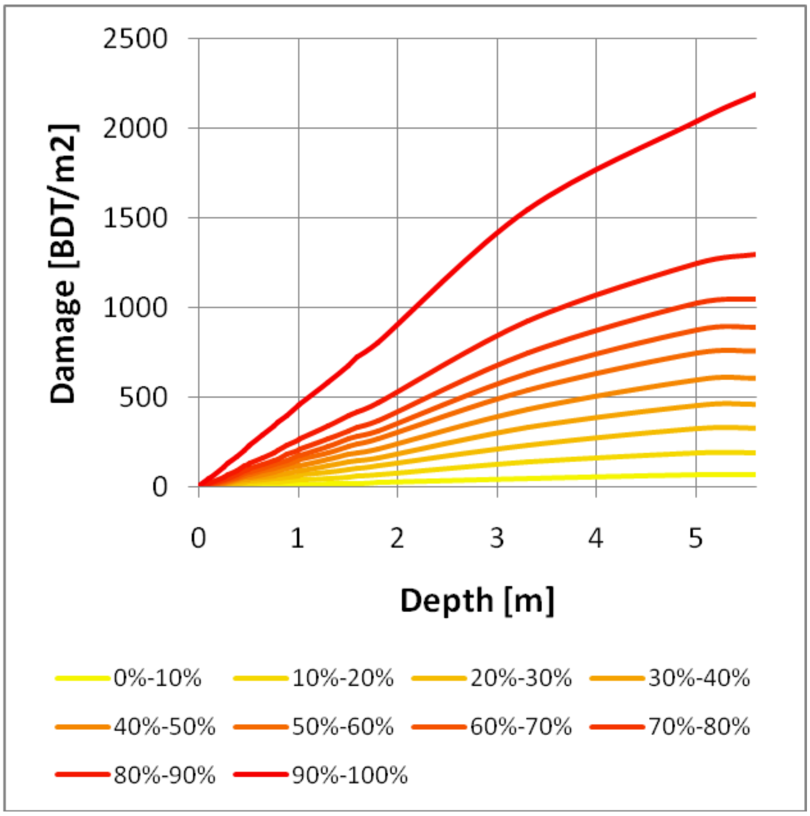

Figure 3: Aggregate damage curves for different densities

The actual damage calculations are performed by i) determining the inundation depth for each individual built-up LULC patch from a given flood depth map, ii) identifying the associated damage level using the lookup table from the appropriate DDC and iii) aggregating the damage of patches with the same LULC. These steps are combined in a single model developed by Chen et al. (2015) that also compensates for potential misalignment of the spatial characteristics of the required flood maps (e.g. regular grids, irregular meshes) and feature maps (e.g. LULC grids, polygons).

4. SCENARIOS

The three scenarios considered for this paper are:

- Scenario 1: Baseline condition, flood damage in study area in 2004
- Scenario 2: Flood damage in 2050 BAU high growth scenario due to 2004 event (without considering the impact of urban growth on hydraulic condition)
- Scenario 3: Flood damage in 2050 BAU high growth scenario due to 2004 event (with the impact of urban growth on hydraulic condition)

The CORFU project considered 9 urban development scenarios for Dhaka, which were combinations of three population growth and economic development conditions, developed by Schlitte (2013), and three spatial development situations that include a BAU case. Apart from the BAU scenario for urban growth, the spatial scenarios for urban development incorporated constraints and development zones based on Detailed Area Plan (DAP) of the city. Out of the 9 scenarios, BAU with the high growth rate scenario resulted in the most dramatic LULC changes in flood prone areas. Consequently, this scenario was regarded as the upper bound for the potential flood damages as a function from the changing in built-up area distribution. This LULC scenario was therefore used in the hydraulic model (Scenario 3) as well as damage model to compare the estimated flood damages for the long term horizon of 2050 (Scenario 2 and 3). The growth characterisation as well as the LULC distribution are shown in Figure 4.

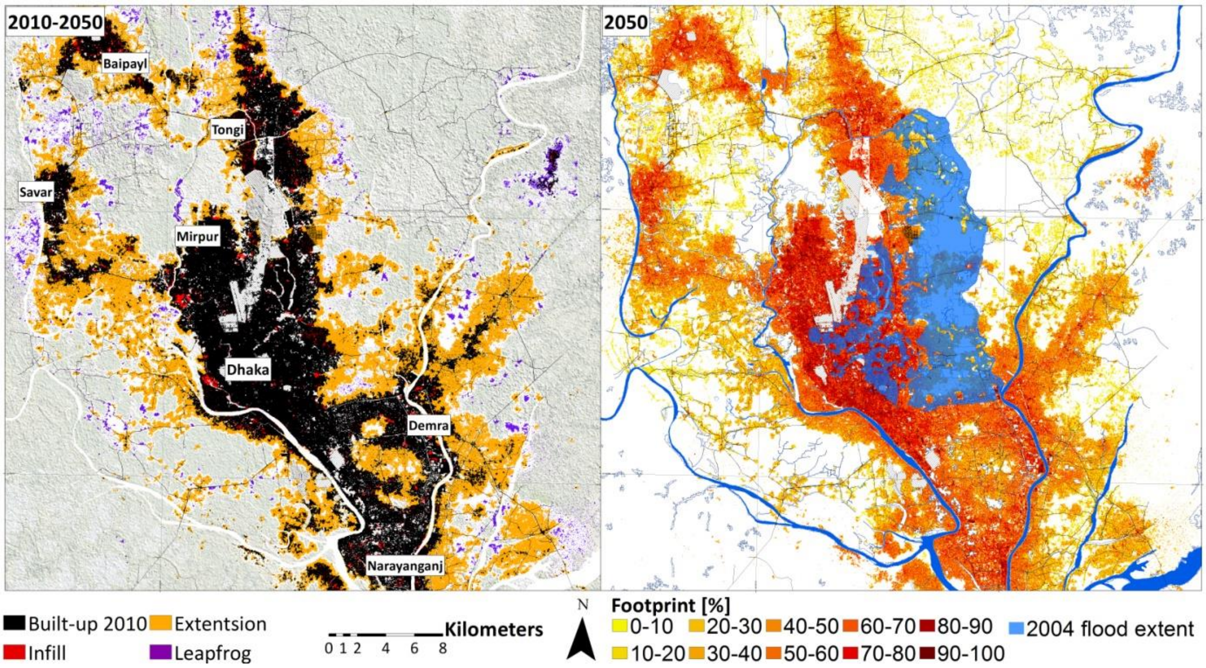

Figure 4: Growth characterisation (left) and resulting distribution of built-up areas including flood extent (right)

The 2050 BAU scenario urban growth is characterised (see Figure 4) by 7.3% infill, 84.6% urban expansion and 8.1% of leapfrogging. Compared to the recent development of Dhaka (i.e. 1995-2005) the projections suggest an increase of urban infill and a reduction of leapfrogging development. This observation is supported by measuring the fractal dimension (FD) of the built-up areas, which provides a measure of the complexity of the observed perimeter in relation to its footprint (e.g., Turner, 1990; Herold et al., 2005). The FD dropped from 1.51 in 2005 to 1.47 in 2050 indicating a more compact urban form with less open areas or complex perimeters.

The hydraulic modelling focused on the particular conditions of the 2004 event. Nearly 600mm of rainfall occurred in 5 days of September 2004. This rainfall was included in the model. Water level in the Balu River during 2004 was used as the boundary condition for the hydraulic model. The average ISR in the Dhaka metropolitan area as a result of the changing urbanisation almost doubles from 0.26 in 2004 to an estimated 0.43 in 2050, compared to 0.36 to 0.54 respectively in the eastern part of the city which is not protected by embankment. The change in impervious area affects runoff process, which was incorporated in the hydrologic process of the flood model for Scenario 3. For damage estimation 2050 LULC was used with 2004 flood depth for Scenario 2 and 2050 LULC was used with 2050 BAU flood depth for Scenario 3. DCCs were estimated based on present value and no adjustment was made for 2050 scenarios. Table 1 shows the combination of models used for each scenario.

Table 1: Model combinations for scenarios

Scenario	UGM	Flood Model	Damage model
1	2004 condition	2004 hydrology	2004 LULC
2	2050 BAU	2004 hydrology	2050 LULC
3	2050 BAU	2050 BAU hydrology	2050 LULC

5. OUTCOMES

The produced flood map and damage map are presented in Figure 5.**Error! Reference source not found.** For reference, the DEM clearly shows the relatively low laying area of eastern Dhaka which almost coincides with the flood extent. The estimated inundation depths are considerable; flood levels reach over 6 meters in some of the uninhabited areas. Yet, even in medium density built-up areas, flood level often reach several meters.

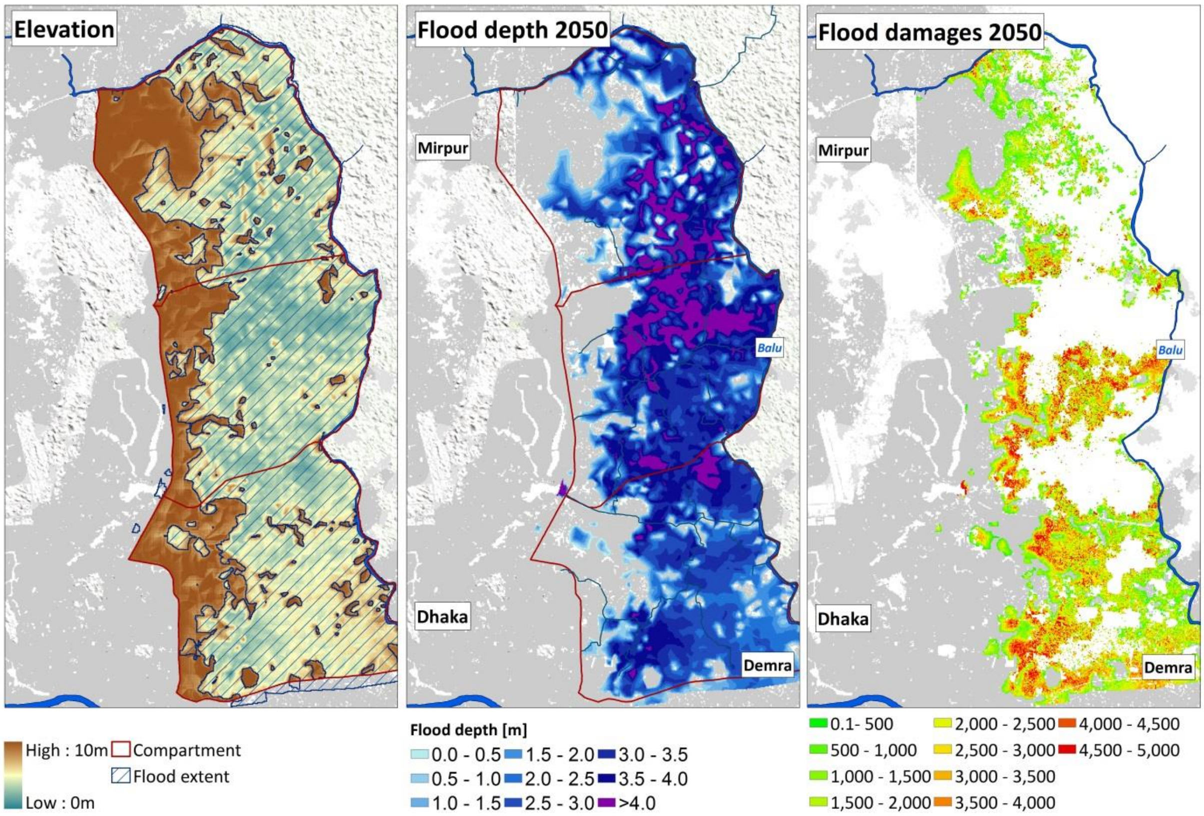

Figure 5: Terrainmap (left), Estimated flood depth (centre) and flood damages (right) for the 2050 scenario

5.1 Comparison of flooding

In the 2004 flood event about 80 sq km of the study area was inundated (almost 65% of the case study area). It has to be mentioned that most of these areas were on the eastern part. In the 2050 condition the increasing ISRs have a substantial effect on the estimated runoff volumes and peak levels in the 3 compartments of eastern Dhaka. These are shown in Figure 6. For all 3 compartments, the model outcomes clearly show a dramatic increase of peak flow rates 6.3, 6.1 and 4.5 times higher than those in 2004 for compartment 1, 2 and 3 respectively.

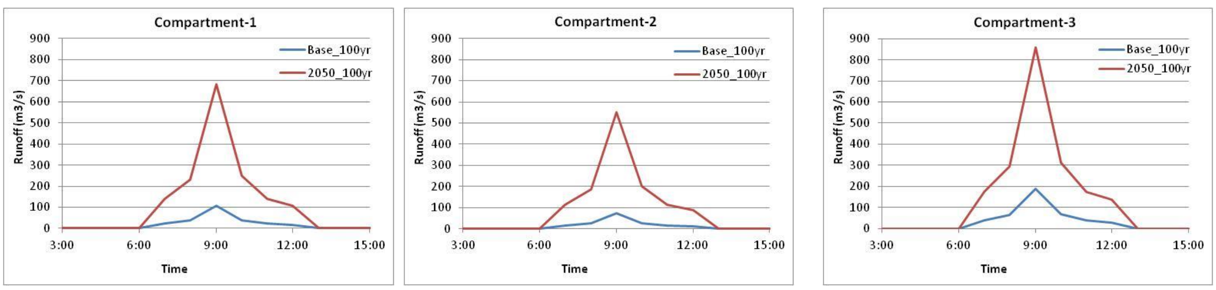

Figure 6: Comparison of overland flow at different scenario

Despite the substantial increases in peak and total runoff volumes, the estimated impacts on the actual flood are expected to be minimal. This is because flooding in eastern Dhaka is mainly caused by overtopping of the Balu river banks. The resulting flood volume caused by overtrumping therefore far exceeds the impact of any changes in runoff volume. Consequently, the model outcomes produce only limited changes in flood extent and depths. In the baseline condition (2004), the total flooded area in eastern Dhaka is 70.7%, whereas in 2050 the flooded area is estimated at 71.5%.The changes in expected flood depths are somewhat more significant. The trend can be observed towards higher inundation depths for the 2050 scenario. The total area with expected inundation depths of 3 meters or more increases at the expense of areas previously flooded with inundation depths between 1 and 3 meters.

Likewise, little changes in inundation were also observed in Central protected part of the city. This is because the flooding occurs due to drainage blockage at the outfall. In most areas the network has adequate capacity. In Central Dhaka about 87% of the model area is inundated up to 0.5m in the baseline condition whereas in 2050, 92% of the area is expected to be inundated up to the same depth.

5.2 Comparison of flood damages

The aggregate damage for the 2004 event was estimated at 22.8M USD for the case study area. For the 2050 BAU high growth scenario the damages are expected to increase almost 7-fold to 154.8M USD. If the impact of urban growth on hydrologic condition is also considered in flood modelling, the damage will further increase to 178.1M USD for the same event. The comparison of the damage estimated from the different scenarios is shown in Table 2.

Table 2: Total damage in Study area for different scenarios

No.	Scenarios	Damage (million USD)
1	Baseline scenario: The flood damage of 2004 event using LULC base map	22.8
2	The flood damage of 2004 event (without considering the impact of urban growth on hydraulic condition) for the 2050 BAU high growth scenario	154.8
3	The flood damage of 2004 event (with the impact of urban growth on hydrologic condition) for the 2050 BAU high growth scenario	178.1

In Figure 7 the estimated flood damages are related to the 10 LULC-density classes. To provide a qualitative classification, the densities have been designated as Open, Low, Medium and High intensity developed areas using a standardised classification scheme by Homer (2004). In the baseline scenario, the majority (70.4%) of the area was occupied by either open or low intensity developed areas that together suffered about half of the total flood damages (55.6%). In the development scenario for 2050, this proportion shrunk to almost half the original size (38.3%) while the estimated share of damages lowered to 36.4%. While high intensity developed areas increase more than 3-fold in size, the share of damages almost remains the same (7.4% to 8.3% respectively). Subsequently, the most dramatic shift occurs in the medium intensity developed areas that double in size and suffering more than half (55.3%) of all flood damages.

These figures show flood damages that were formerly suffered in mainly rural and peri-urban areas, characterised by detached farmhouses in small villages, shift to medium to high intensity urban areas with urban footprints of up to 80% of ground cover. This also means that the spatial distribution of flood damages is changing, from more dispersed small pockets to more homogenous residential areas.

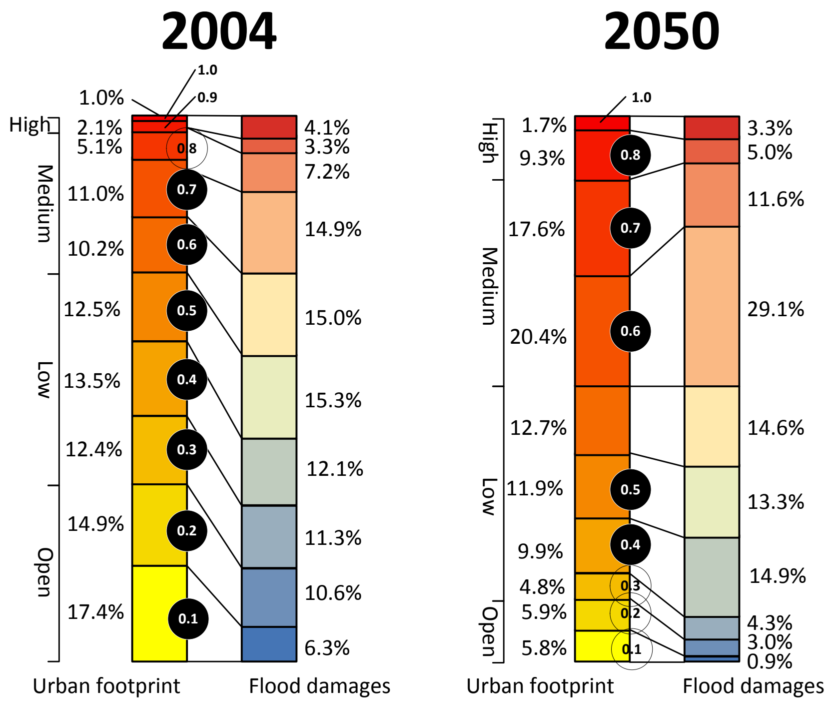

Figure 7: Proportionality of urban footprint and damages for 2004(left) and 2050(right)

5.3 Interpretation

The first and foremost outcome of this study is the disproportional increase of expected flood damages as a function of extensive urban growth in eastern Dhaka. While the growth scenario projects a 49.5% increase of built-up areas in eastern Dhaka (compared to 70% in the Dhaka metropolitan area), the flood damages increase almost 8-fold. Thus, both in absolute and relative terms future flood damages increase considerably. Even if the hydrological characteristics of the projected flood remain relatively stable, the increased exposure of urbanised areas to the flood could cause massive impacts that might take a substantial recovery period.

This outcome should definitely serve as a signpost for the representative authorities to take action since even with a moderate flood hazard, the growing population and assets in flood prone areas surge the flood risk level. Investment in both flood mitigation and 'smart urban planning' are therefore essential to maintain Bangladesh' ambition to become a middle income country by 2021 (BOI, 2014).

While many studies focus on the potential impacts of future climate change in developing countries, the potential consequences of unplanned urban development receive relatively little attention. Hopefully this study can contribute to put this issue high on the policy agenda especially since the problem is widespread. UN Habitat (2007) estimated that only 5% of total urban growth is planned in developing countries, which apart from flood impacts could increase exposure and sensitivity to all kinds of natural hazards.

6. DISCUSSION

One of the basic assumptions for this study is that the projected urban development will not be protected from future flooding by any new measures. After the 2004 floods a plan was developed to construct a 100 year standard embankment along the Balu River. Implementation of the structure is still unsure due to the financial and legal requirements involved to expropriate landowners and relocate inhabitants. There are also the negative impacts of constructing these kinds of structures measures (Tobin, 1995) which needs to be adequately studied. Flood protection is also established by application of local practises: often the ground floor level for new structures is raised by landfills.

Thus, 'local knowledge' is used and propagated to establish an event driven flood standard. Adoption of measures like these can also minimize the risk of flooding in case of failure of embankment (Montz et al, 2008).

Various additional factors can be identified that either over- or underestimate the estimated damages. A major factor for underestimation of flood damages is the exclusive focus on direct damages to residential and commercial properties. Flood damages to the transportation network, utility lifelines as well as to other facilities were not incorporated into the calculations. Furthermore, indirect damages due to business interruption or ripple effects in supply chains were omitted. Especially since many major floods in Bangladesh last for a considerable amount of time, the resulting economic disruptions are often large and therefore represent a significant share of the total flood damages. On the other hand, various behavioural aspects might limit the expected damage levels. Dhaka has a long flood history and most residents have experienced a number of flood events first hand. The subsequent coping and recovery capacity should therefore be considerable, thus limiting the extent and severity of suffered flood damages.

Beyond the potential shortcomings of the damage assessment, many uncertainties can be identified in relation to the developed urban growth scenario. Both the growth rates as well as subsequent LULC changes are likely to differ from actual developments. The volatility of the urban development in Dhaka only adds that uncertainty. Long term projections might therefore be better presented accompanied by a "probability map" in which the likelihood of urbanisation is presented across the area. Yet, such an approach would also imply a different approach for the use of the LULC maps in the hydraulic model and the subsequent flood damage model. A solid framework and methodology that facilitates such an approach needs further study.

7. CONCLUSIONS

This paper describes the models developed in the CORFU project for Dhaka Case study and their application for flood management strategy development. A set of hypothetical scenarios was considered and the models were applied to analyse that scenarios. The key features in the analysis were identified. These also depict the limitations of the models as well as the analysis. It was found that the model set-up, calibration and input are important considerations. For Dhaka, much of the data required for model set-up and future scenario development were collected and then processed to meet the requirements of the model inputs. The results showed due to urban growth flood damage can increase significantly. So it is important to depict a proper picture of future urban condition for flood management. In the study, we focused on the central part Dhaka, the analysis for the remote parts that could also be urbanised in the future can be replicated with the similar setup and the results can aid the development of an effective flood management strategy.

The results provided a better understanding of the potential flood impact, especially the direct damage, due to urban growth for Dhaka Case study area. This will aid decision making during planning for future city development. Many uncertainties still exist in the analysis. It does however provide an indication of the importance of UGM in relation to flood risk. A contemporary issue is climate impact assessment and this paper shows that urban growth is also a very important factor for future flood damage. In this paper we have deliberately neglected the effects of climate change, which will exacerbate the increase in flood risk due to urbanisation. In developing countries like Bangladesh where huge urban growth is taking place with much uncertainty, UGMs can be a very useful tool for decision making. Combining urban growth modelling, hydraulic modelling and damage assessment can provide details of the flood impact for various conditions, as shown in this paper. Many more factors can be added to these tools to determine the measures that need to be taken to make a city flood resilient.

ACKNOWLEDGEMENTS

Research on the CORFU (Collaborative research on flood resilience in urban areas) project was funded by the European Commission through Framework Programme 7, Grant Number 244047. We would also like to thank the valuable comments by reviewers whose comments helped to improve the manuscript.

REFERENCES

Adikari, Y., Osti, R., Noro, T., 2010. Flood-related disaster vulnerability: an impending crisis of megacities in Asia. Journal of Flood Risk Management 3, 185–191.

Alam, M., Rabbani, M.D.G., 2007. Vulnerabilities and responses to climate change for Dhaka. Environment and Urbanization 19, 81–97. doi:10.1177/0956247807076911

Angel S., Parent J. &Civco DL (2007) Urban sprawl metrics: an analysis of global urban expansion using GIS. ASPRS annual conference, Florida, 7–11 May 2007

Apel, H., Thieken, A. H., Merz, B. &Blöschl, G. (2004). Flood risk assessment and associated uncertainty. Nat. Hazards Earth Syst. Sci., 4 (2), p.295–308.

BOI, Board of Investment Bangladesh Prime Minister's Office (2014) URL (accessed December 2014) http://www.boi.gov.bd/index.php/about-bangladesh1/government-and-policies/government-vision-2021

Brown, R.R., 2005. Impediments to integrated urban stormwater management: the need for institutional reform. Environmental management 36, 455–468.

Chen, A. S., Hammond, M. J., Djordjević, S., Butler, D., Khan, D. M. & Veerbeek, W. (2015). From hazard to impact: the CORFU flood damage assessment tools. Environmental Modelling & Software, in review.

Demographia (2014) Demographia World Urban Areas: 10th Edition (201405 Revision) URL[htp://www.demographia.com/db-worldua.pdf] Accessed December 2014

Dewan, A.M., & Yamaguchi, Y., 2009. Using remote sensing and GIS to detect and monitor land use and land cover change in Dhaka Metropolitan of Bangladesh during 1960–2005. Environmental Monitoring and Assessment 150, 237–249.

Dewan, A. M., & Corner, R. J. (2014).Spatiotemporal Analysis of Urban Growth, Sprawl and Structure.In Dhaka Megacity (pp. 99-121).Springer Netherlands.

Djordjević, S., Butler, D., Gourbesville, P., Mark, O., Pasche, E., 2011. New policies to deal with climate change and other drivers impacting on resilience to flooding in urban areas: the CORFU approach. Environ. Sci. Policy 14, 864–873. doi:10.1016/j.envsci.2011.05.008

Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., Khan, D. M., Rahman, S. M. M. &Haque, A. K. E. (2012).The development of a flood damage assessment tool for urban areas.In: Int. Conf. on Urban Drainage Modelling UDM 2012, Belgrade, Serbia.

Hasnat, M. A. (2006) Flood disaster management in Dhaka city in (eds) Siddiqui, K., &Hossain, A. A. (2006). Options for flood risk and damage reduction in Bangladesh. University Press of America, Incorporated.

Haque, A. K. E., Chakroborty, S., Zaman, A. M. (2014). Developmentof Damage Functions for Dhaka City, Collaborative Research on Flood Resilience in Urban Areas (CORFU), Deliverable 3.4, Sec 4.4.2 , (47-51).

Herold, M., Couclelis, H. & Clarke, K. C. (2005) The role of spatial metrics in the analysis and modeling of urban land use change. Computers, Environment and Urban Systems, 29:4 (369-399)

Homer, C. C. Huang, L. Yang, B. Wylie and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. Photogrammetric Engineering and Remote Sensing, Vol. 70, No. 7, July 2004, pp. 829-840)

Hossain, A. N. H. (2006) The impact of floods on Bangladesh and options for mitigation, an overview in (eds) Siddiqui, K., &Hossain, A. A. (2006). Options for flood risk and damage reduction in Bangladesh. University Press of America, Incorporated.

Islam, K. M. N. (2005). Flood loss potentials in non-agricultural sectors: assessment methods and standard loss database for Bangladesh. Dhaka, Bangladesh: Palok Publishers.

Islam, K. N. (2006). Impacts of flood in urban Bangladesh: micro and macro level analysis. AH Development Publishing House.

Islam, A. K. M. S., Haque, A. & Bala, S. K., (2008). Hydrological Aspects of Flood 2007. Final Report, Institute of Water and Flood Managment.

Lau, C. L., Smythe, L. D., Craig, S. B. &Weinstein, P. (2010). Climate change, flooding, urbanisation and leptospirosis: fuelling the fire? Transactions of the Royal Society of Tropical Medicine and Hygiene, 104, p.631–638.[Online]. Available at: doi:10.1016/j.trstmh.2010.07.002.

Liu, H., Zhou, J. G. & Burrows, R. (2009). Multi-block lattice Boltzmann simulations of subcritical flow in open channel junctions. Computers & Fluids, 38 (6), p.1108–1117.[Online]. Available at: doi:10.1016/j.compfluid.2008.11.005.

Merz, B., Kreibich, H., Schwarze, R., &Thieken, A. (2010).Review article" Assessment of economic flood damage". Natural Hazards and Earth System Science, 10(8), 1697-1724.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S. & van der Veen, A. (2007). Evaluating flood damages: guidance and recommendations on principles and methods.

Mikhailov, V.N., Dotsenko, M.A., 2006. Peculiarities of the hydrological regime of the Ganges and Brahmaputra river mouth area. Water Resour 33, 353–373. doi:10.1134/S0097807806040014

Montgomery, M.R., 2008. The urban transformation of the developing world.Science 319, 761–764.

Montz, B.E. and Tobin, G.A. (2008) Livin' Large with Levees: Lessons Learned and Lost. Natural Hazards Review, Vol. 9, No. 3, pp. 150-157.

Nishat, A., Reazuddin, M., Amin, R. and Khan, A. R. (eds.) (2000). The 1998 Flood: Impact on Environment of Dhaka City. Dept. Of Environment in Cooperation with IUCN Bangladesh, Dhaka, Bangladesh

Oliveri, E. & Santoro, M. (2000). Estimation of urban structural flood damages: the case study of Palermo. Urban Water, 2, p.223–234. [Online]. Available at: doi:10.1016/s1462-0758(00)00062-5.

Pathirana, A., Denekew, H. B., Veerbeek, W., Zevenbergen, C.,& Banda, A. T. (2014). Impact of urban growth-driven landuse change on microclimate and extreme precipitation—A sensitivity study. Atmospheric Research, 138, 59-72.

Penning-Rowsell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J. & Green C.(2005). The Benefits of Flood and Coastal Risk Management: A manual of Assessment Techniques (The Multi-coloured Manual). Flood Hazard Research Centre, Middlesex University.

Rahman, R., Haque, A., Khan, S. A., Salehin, M., &Bala, S. K. (2005).Investigation of hydrological aspects of flood-2004 with special emphasis on Dhaka city. Bangladesh. Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET), Dhaka.

Schlitte, F. (2013). Scenarios for long term economic city growth - models and results for selected CORFU case studies. In: Chen, A. S., DJordjević, S. and Hammond, M. J. (eds.), Urban flood resilience, 5 September 2013, Exeter, United Kingdom: University of Exeter. [Online]. Available at: http://corfu7.eu/media/universityofexeter/research/microsites/corfu/1publicdocs/conferencepapers/A2_145_Russo.pdf.

Siddiqui, K. & Hossain, A. A. (2006).Options for flood risk and damage reduction in Bangladesh. University Press of America, Incorporated.

Soares-Filho, B. S., Rodrigues, H. O. & Costa, W. (2009).Modeling environmental dynamics with Dinamica EGO.Centro de SensoriamentoRemoto.Universidade Federal de Minas Gerais. Belo Horizonte, Minas Gerais, 115.

Tang, J. S., Vongvisessomjai, S. &Sahasakmontri, K. (1992). Estimation of flood damage cost for Bangkok. Water Resources Management, 6 (1), p.47–56.[Online]. Available at: doi:10.1007/BF00872187.

Tobin, G.A. (1995) The Levee Love Affair: A Stormy Relationship. Water Resources Bulletin, Vol. 31, No.3, pp. 359-367.

Turner, M. G. (990) Spatial and Temporal Analysis of Landscape Patterns, Landscape Ecoolygy 4(1):21-30

UN (2014) United Nations, Department of Economic and Social Affairs, Population Division World Urbanization Prospects: The 2014 Revision, CD-ROM Edition.

UN Habitat (2007). Sustainable urbanization: Local actions for urban poverty reduction, emphasis on finance and planning. 21st session of the Governance Council, 16-20 April, Nairobi, Kenya, 2007

Veerbeek, W., Pathirana, A., Ashley, R. &Zevenbergen, C. (2014) Enhancing the calibration of an urban growth model using a memetic algorithm, Computers, Environment and Urban Systems, In Press

Veerbeek, W., Pathirana, A., Mudenda, S. H., &Brdjanovic, D. (2012). Application of urban growth model to project slum development and its implications on water supply and sanitation planning.In Proceedings 9th International Conference on Urban Drainage Modelling (pp. 3-7).

Weng, Q. (2001). Modeling urban growth effects on surface runoff with the integration of remote sensing and GIS.Environmental management, 28(6), 737-748.

Wiitala, S. W. (1961). Some aspects of the effect of urban and suburban development upon runoff.U.S. Geological Survey open-file report, U. S. Geological Survey.

Xian, G., & Crane, M. (2005).Assessments of urban growth in the Tampa Bay watershed using remote sensing data.Remote Sensing of Environment, 97(2), 203-215.

Zevenbergen, C., Veerbeek, W., Gersonius, B. & Van Herk, S. (2008). Challenges in urban flood management: travelling across spatial and temporal scales. Journal of Flood Risk Management, 1 (2), p.81–88.[Online]. Available at: doi:10.1111/j.1753-318X.2008.00010.x.