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Tipping points in adaptation to urban flooding under climate change and urban growth: The case of the Dhaka megacity

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ABSTRACT

Envisioning the future city as the outcome of planned development, several master and strategic plans for Dhaka were prepared. However, these plans, do not adequately address the well-known and combined effects of climate change and unplanned urbanization on urban flooding. Additionally, the spatial planning component is missing in adaptation planning, which broadly concentrates on the climate change. Long-term adaptation strategies should consider both the temporal and spatial extent of flooding. Uncertainties in climate change and urbanization will induce planning failure beyond the Adaptation Tipping Point for flooding exceeding the thresholds of the bio-physical system or the acceptable limits of societal preference. In this paper, a shift is proposed from the current planning practice of single-dimensional 'Predict and Act' towards a more resilience-based 'Monitor and Adapt' approach. It is prudent to visualize the effects of urbanization and climate change and translate them into strategies for improved adaptation based spatial planning. Here, Dhaka's exposure to floods under different climate change and urban (planned and unplanned) development scenarios is assessed based on acceptable thresholds obtained from plans (top-down defined) and stakeholders (bottom-up perspectives). The scale of effects of these two drivers on urban flooding is exhibited through the zone differentiated flooding extent. While apparently the effect of climate change on flooding is greater than that of unplanned urban developments, both play an important role in instigating tipping points and intensifying risks.

1. Introduction

Massive urbanization in the last few decades has converted many rural areas into urban areas and cities into mega and meta cities such as Dhaka. The numbers of megacities are growing in the developed as well as developing countries (Nicholls, 1995). This has brought about economic development and often improvement of quality of life. At the same time, urbanization along with climate change has compromised the social welfare of the inhabitants and management of sustainable environment (UNHSP, 2011; Discoli and Martini, 2012). Climate change enhances the frequency and intensity of hazards and then again, cities themselves trigger changes in the climate with increased energy consumption, burning of fossil fuel and economic activity (Roy, 2009).

Cities have grown either in a planned (regular) or in an unplanned (irregular) manner (Alnsour, 2016). Unplanned growth has been experienced in cities of Europe (Costa et al., 1991; Batty et al., 2003; Kaya and Curran, 2006), Africa (Ibrahim Mahmoud et al., 2016; Winsemius et al., 2016; Kithiia and Dowling, 2010) and USA (Graham et al., 2004)

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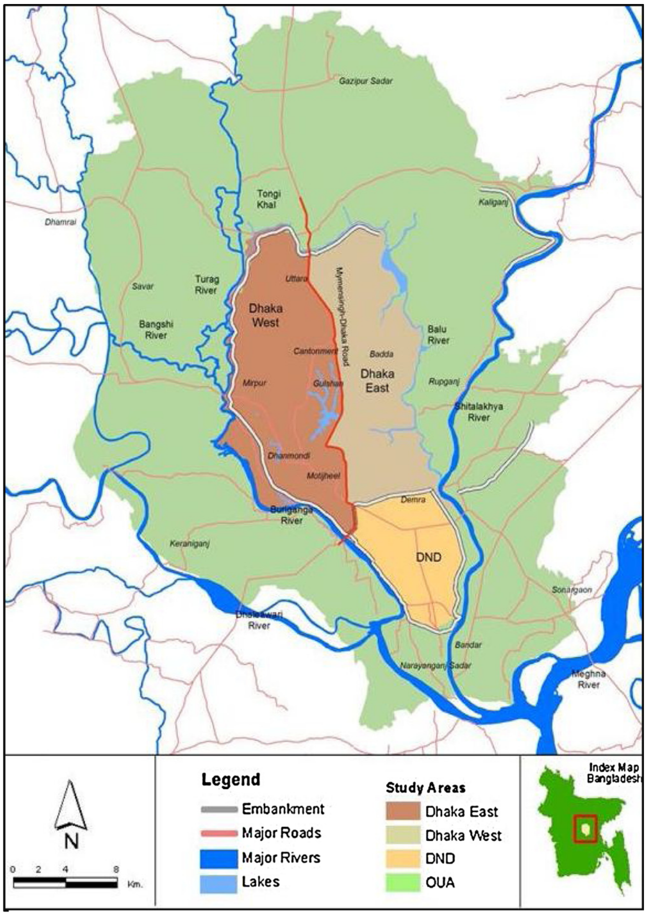

Fig. 1. Map of Greater Dhaka showing the four zones of the study area.

as well as in Asian cities such as Dhaka (Dewan, 2013; Ahmed and Bramley, 2015). In the past, cities in the present developed countries also experienced unplanned growth due to increased housing demand (Costa et al., 1991; Batty et al., 2003). Dense urban growth, inadequate drainage and increased high intensity rainfall events due to climate change have caused urban flooding, damage to life and property, and negative impacts on environment and health (Graham et al., 2004; Dewan, 2013). These impacts of flood vary across social strata, institutional setting, physical conditions and from one region to another (Walters, 2015).

Through many studies the effect of urbanization on flooding has been demonstrated for cities (Young, 2013; Pathirana et al., 2014; Muis et al., 2015; Veerbeek, 2017) in developing countries including Dhaka (Dewan and Yamaguchi, 2008; Gain and Hoque, 2013; Onishi et al., 2013; Dasgupta et al., 2015). In a recent study (Dasgupta et al., 2015), the impacts of climate change and urban growth (planned) were assessed using hydrodynamic models covering the central part and the Dhaka-Narayanaganj-Demra (DND) areas of Greater Dhaka (see Fig. 1). Also, there were studies which by applying land use models specifically looked at the urban growth trend of Dhaka into the future (Corner et al., 2013; Ahmed and Bramley, 2015). Apart from these studies, several plans in the form of master and strategic plans for Dhaka have been prepared. However, these studies and plans, did not adequately address the well-known and cumulative effects of climate change and unplanned growth on urban flooding. Additionaly adaptation plans for Dhaka concentrate broadly on the issues of climate change, in which the spatial planning component is missing.

An important aspect of urban development plans and adaptation plans is to develop short and long term strategies considering the effects of climate change and urban growth on flooding. Since the emergence of climate change as a threat, adaptation and mitigation have become vital parts of policies, plans and programs on urban flood management (Djordjević et al., 2011). This paper shows that stemming from the dynamics of the climatic and non-climatic drivers (i.e. land use change), Adaptation Tipping Points (Kwadijk et al., 2010) will occur in the biophysical system from urban flooding. Adaptation Tipping Points (ATPs) are the thresholds or specific boundary conditions where ecological, technical, economic, spatial or societal acceptable limits are exceeded (Haasnoot et al., 2011). The ATP concept was found useful in the Netherlands, USA, Vietnam and Bangladesh for formulating water management strategies under climate change including the Bangladesh Delta Plan 2100 (BDP2100).

As such the main research question is to see how by taking into account the combined effects of planned and unplanned urban growth along with climate change can support the assessment of ATPs due to urban flooding. In the same line of thinking as the BDP2100 i.e. resilient adaptation based planning, this research additionally explores the differential impacts of unplanned development with climate change on flooding. Resilience based adaptation means such a system which can recover and sustain under the impacts of e.g. climate change and continuous urbanization (Walker et al., 2013). As Dhaka is in its transition of becoming a meta city by 2020 (exceeding 20 million population), unplanned development is taking place beside the planned development. The unplanned growth together with the climate change impacts is likely to enhance urban flooding and compromise urban resilience as it may (over)stretch social adaptive capacity. The uncertainties in climate change and land use development are likely to create a mismatch with the actual changes and cause plans to fail (Walker et al., 2013). Rigid plans based on a single scenario cannot address the existing uncertainties with urban development and climate change. Therefore, adoption of a resilience based approach in the vulnerability assessment and planning process can help to deal with the impacts and improve the planning process.

It is therefore time to rethink the current planning process and shift from a single dimensional 'Predict and Act' approach towards a multidimensional resilience based 'Monitor and Adapt' approach (Walker, 2011) to deal with climate change in an urbanized world. Predict and Act refers to an approach where a fixed plan is prepared based on predicted scenarios (Walker et al., 2013). Resilience based approach is much more dynamic, a flexible plan is prepared so that the system adapts with the continuously monitored change (Walker et al., 2013). The assessment of ATPs gives a platform to consult with the stakeholders and set the standards for acceptable changes. On the basis of community consultations and by reviewing the existing plans, the thresholds were obtained for the assessment of ATPs. Cities growing in an unplanned manner are likely to reach ATPs at a different space if compared to planned growth and will therefore require alternative strategies, as shown in this paper. For this reason, spatially explicit planned and unplanned urban growth scenarios with climate change scenarios were applied in the flood models. Contrary to previous studies, this paper also compares the scale of effects of climate change with the consequences of urbanization on flooding and its implications on spatial planning and flood adaptation in future.

2. Case study area and methodology

2.1. Case study area

Based on the existing setup of the flood management structures and administrative boundaries of Greater Dhaka can be divided into four zones: Dhaka East, Dhaka West, Dhaka-Narayanganj-Demra (DND) and the Outer Urban Area (OUA) (Fig. 1). For example-Dhaka West is fully protected from River floods by the western embankment and the flood proofed Mymensingh-Dhaka road (Fig. 1). Dhaka east is partially protected with the road in one side and wetlands in the other side. The DND is fully protected from the River with circular road cum embankment. The OUA is fully unprotected without any embankment and low drainage system.

2.2. Methodology

The uncertainties in climate change and land use development is likely to create a mismatch with the actual changes and cause plans to fail (Walker et al., 2013) in achieving its future targets. It is therefore prudent to adopt a resilience based approach e.g. ATP that can incorporate multiple urban development scenarios with climate change. However, this study does not follow the ATP approach step by step. Similar to the ATP approach, the thresholds defined in plans are used as the starting point (Kwadijk et al., 2010) for flood vulnerability analysis. The circumstances under which the ATPs might be reached are investigated (Werners et al., 2012) by analysing flood exposure if a proposed plan is fully implemented (Planned Growth) or partially implemented (Unplanned Growth).

Together with the conventional Geographic Information System (GIS) and Remote Sensing (RS) technologies and state of the art urban growth modelling technique, a hydrodynamic model is developed to generate the flood scenarios. Technical tools aside, various social tools like community meetings and stakeholder interviews in relevant agencies were also carried out. The methodology includes the steps shown in Fig. 2.

2.2.1. Step 1. Tracking the past and current trend of urban growth

To determine the spatial changes in urban area, historical data for the year 1600, 1750, 1850, 1950, 1980 available from secondary sources were analysed using GIS. Landsat satellite images of 1993, 2010 and 2015 were classified using remote sensing (RS) image based maximum likelihood classification method. Some of the sub-classes were merged together to derive four major classes namely: developed or built-up area, vegetation, waterbodies and wetland area. Accuracy of the classified images was assessed by generating an error matrix. This error matrix, also known as a confusion matrix, is a specific table layout that allows visualization of the performance of an algorithm, typically a supervised learning one (See Annex C).

2.2.2. Step 2. Review of policies and planning practices in Dhaka

The similarities and dissimilarities between the urban patterns proposed in the urban area development plans and the government approved plans were examined. The divergence between plans and development practices were assessed using GIS and RS tools. The Bangladesh Climate Change Strategy and Action Plan, National Water Management Plan (NWMP) and Bangladesh Delta Plan (BDP 2100) were also reviewed specifically addressing the key issues covered, the approach followed and strategies developed pertaining planning, adaptation and flood or drainage management. Specific policies and Acts related to urban areas were also assessed.

2.2.3. Step 3. Generate the urban growth scenarios by developing an urban growth model

For the urban growth modelling in this particular study, Dinamica EGO (Young, 2013; Veerbeek et. al., 2011) software was used. Dinamica Ego, is a easily available hybrid model that helps predict future growth based on the underlying trend of urbanization patterns using a combination of statistical method (weight of evidence) and Cellular Automata (CA) technique (Ahmed and Bramley, 2015, García et al., 2012). The initial model was setup using a set of geospatial thematic layers (e.g. slope, distance to road) and classified images as base data.

The model was calibrated using the images of 1999 and 2010 and validated using the image of 2014. The similarity map was produced comparing the projected with the existing landuse of 2014 to determine the model accuracy. The similarity map presented good correlation with an overall accuracy of 70%. Kappa index and its variants (Klocation and Kquantity) were calculated for validating the LUCC model result. Factors considered while developing the scenarios are percentage of growth, conversion of one land use to another, land use pattern etc. After several iterations, finally two future scenarios for planned and unplanned urban growth for the year 2035 were developed.

2.2.4. Step 4.Analysis of Climate Change Scenario for Dhaka based on the IPCC-V assessment report

To see the effect of climate change on urban flooding the latest developed RCP (Representative Concentration Pathway) scenario of climate change cited in the IPCC AR5 (IPCC, 2014) is used for this study. The climate induced change in rainfall is estimated using the Bangladesh average rainfall result of an ensemble of GCMs (Global Circulation Models). The monthly average precipitation change for Bangladesh and annual average precipitation for the future time slice with respect to observed time slice has been extracted from Alder et al., (2013). Based on these values, the percentage increase in average precipitation for the future was estimated and applied with the observed rainfall extreme to obtain the climate change induced rainfall event. A 100 year return period rainfall event of one day was the basis of all the flood simulations.

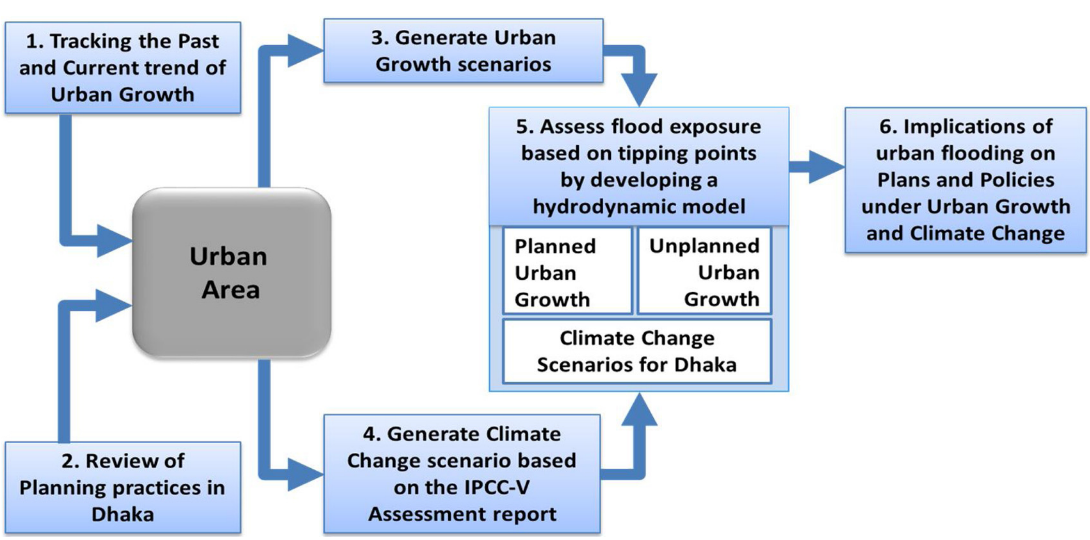

Fig. 2. Schematic overview of the applied methodology depicting the major steps involved.

2.2.5. Step 5. Assess exposure to flood based on tipping points by developing and applying a hydrodynamic model

Exposure to flood is assessed by developing and applying a hydrodynamic model for the Greater Dhaka. The model was developed using SOBEK modelling software which can simultaneously generate both pluvial (rainfall) and fluvial (river) floods for a relatively large areal extent (Abazi, 2005; Bashar, 2005). The 1D-2D modelling suite is used to simulate the flood inundation extent on the surface. The model was calibrated using the extreme flood of 1998 and validated with flood of 2002. The land use scenarios of planned and unplanned growth obtained from the UGM were embedded within the 1D model using the 30 m resolution DEMs for the 2D model runs. For each of the hydrologically different zones, the extent of total flooded area is derived from the 2D model results. Then the exposed area to flood that exceeded the threshold value of allowable and acceptable flood depth, were determined.

2.2.6. Step 6. Implications on policymaking and planning for adaptation to urban flooding

To assess the implications of adaptation planning on future planning and policymaking, stakeholder opinions were obtained through a number of participatory consultation meetings (PCM) with community people as well as experts in the relevant field. The effects of unplanned growth linked with climate change on enhancing flood exposure provide insight on the bottlenecks in achieving complete flood protection. Therefore, the synergies and gaps between spatial plans and adaptation plans and current practices and its implication in future policymaking are addressed.

3. Adaptation Tipping Points to Urban Flooding in Dhaka

3.1. Historical growth of the city to a mega city

Since 1600, Dhaka has grown from a city with population of 0.02 million covering 2.5 km2 area (Tawhid, 2004) to greater Dhaka with a population of 17 million (BBS, 2014) over an area of 1528 km2 (see Figure A-1). Currently Dhaka is the eleventh megacity of the world and expected to reach the sixth position by 2030 (UN, 2014). With a population exceeding the total population of three other major cities (Chittagong, Khulna and Rajshahi) of the country, Dhaka is also termed as the primate city (RAJUK, 2015). As can be seen from the historical images (See Annex) that urban growth has extended beyond the city limits towards the periphery which is also known as the Greater Dhaka or RAJUK area. GIS based analysis showed that the urban area of greater Dhaka has increased from 4% to 33% in the last 43 years between 1972 and 2015 (CEGIS and WARPO, 2012).

3.2. Planning practices in Dhaka city

3.2.1. Development plans at local level

In the last 60 years from 1955 to 2015, a number of spatial and strategic plans were prepared to guide the development of Dhaka City. The first Master Plan was prepared in 1959 which is a 20 year period land use zoning plan. It did not provide any recommendation on how to accommodate the accelerated growth of Dhaka city and also did not include flood control or mitigation strategies. Following the expiration of the Master plan, the Dhaka Metropolitan Area Integrated Urban Development Plan (DMAIUDP, 1981–2000) came into existence jointly prepared and funded by Government of Bangladesh (GoB), ADB and UNDP. The DMAIUDP could not be implemented due to a lack of formal institutional support. Eventually two major consecutive floods occurred in 1987 and 1988 with severe damages to the entire country especially Dhaka city. So, the Flood Action Plan (FAP, 1989–1995) project was initiated by the GoB and the donor agencies for Bangladesh. FAP suggested a complete protection scheme with embankments on the western and eastern part of Dhaka including drainage networks, sluices and pumps (FAP, 1991aa; FAP, 1991bb). Due to their high implementation cost, only the western embankment was completed and the eastern embankment is still pending. The FAP studies were criticised for proposing high cost intensive projects, lacking multi-sectoral issues and people's participation (Brammer, 2010).

Then the Dhaka Metropolitan Development Plan (DMDP) was prepared for the period 1995–2015. This plan followed a hierarchical planning process including 3 components: the long term strategy based Structure Plan (SP) for 20 years, the mid-term Urban Area Plan (UAP) for 10 years and the short term Detail Area Plan (DAP) for 5 years. At that time, only the DAP preparation remained incomplete due to inadequate time and finance. Later in the late 2000, RAJUK initiated the reformulation of DAP, which was gazetted in 2010. The DAP provides detailed planning proposals for specific sub-areas, compliant with the SP and the UP. Recently, the RAJUK has revised the Dhaka Structure Plan for 2016–2035 based on the previous structure plan of 1995–2015 which is still in a draft stage. Review of the DAP has revealed the following shortcomings:

- Provision for retention pond in the DAP is reduced from the originally proposed area;
- In some areas the agricultural land is replaced by the "urban residential use";
- Too much emphasis is given on structural interventions.

3.2.2. Strategic plans at national level

Urban area development plans apart, there are national level strategic plans such as the National Water Management Plan (NWMP, 2001), Bangladesh Climate Change and Strategy Action Plan (BCCSAP 2009), Bangladesh Delta Plan (BDP 2100, draft). The BCCSAP sums up Bangladesh's current thinking on desirable activities to build climate resilience into the economy and society. The NWMP is an integrated water resource development plan prepared with a multi-sectoral approach in the light of National Water Policy 1999 and approved in 2004. NWMP provides regional programmes in three phases from 2010 until 2025, for different hydrological regions including major cities. BDP 2100, provides overall strategic guidelines for the short, medium and long term horizons focusing on the water sector development. With the influx of rapid urbanization, Dhaka is identified as one of the hotspots in the BDP2100 requiring special attention from the policy makers. For flood control and drainage management many strategies are suggested such as restoration and preservation of water bodies, excavation/re-excavation of canals and lakes etc.

3.2.3. Urban Area plans vs the current Urban development

The DMDP, a structure plan drawn up in the 90′s with a 20 yr horizon, gave strategic guidelines with specific indications in which direction Dhaka might grow e.g. by the year 2010 and 2015. These development projections given in the plan (DMDP) are compared with the observed changes in the classified land use map to identify the difference between planning and practices.

Evaluation of urban development patterns predicted for 2010 and 2015 in DMDP with the existing urbanization pattern obtained from the classified land use data indicates huge spatial difference in some areas (Fig. 3). Growth towards the north western side, along the Buriganga river, Shitalakhya or Lakhya river and also in the north-eastern side of the Balu river (see Fig. 3) are prominent from the existing land use. Field verifications revealed that development work is going on in massive scale for residential, commercial, industrial and institutional purposes by both private and public agencies. It means that such huge expansion of urban areas in Dhaka east and outside the city corporation boundary was not anticipated in the DMDP.

Additionally, the retention pond area proposed in the plans has drastically reduced (see Fig. 4) over the last 25 years (1991–2015). Analysis shows that especially in the Dhaka east zone, 20.42 km^2 area originally proposed for retention area decreased to 17.62 km^2 area in

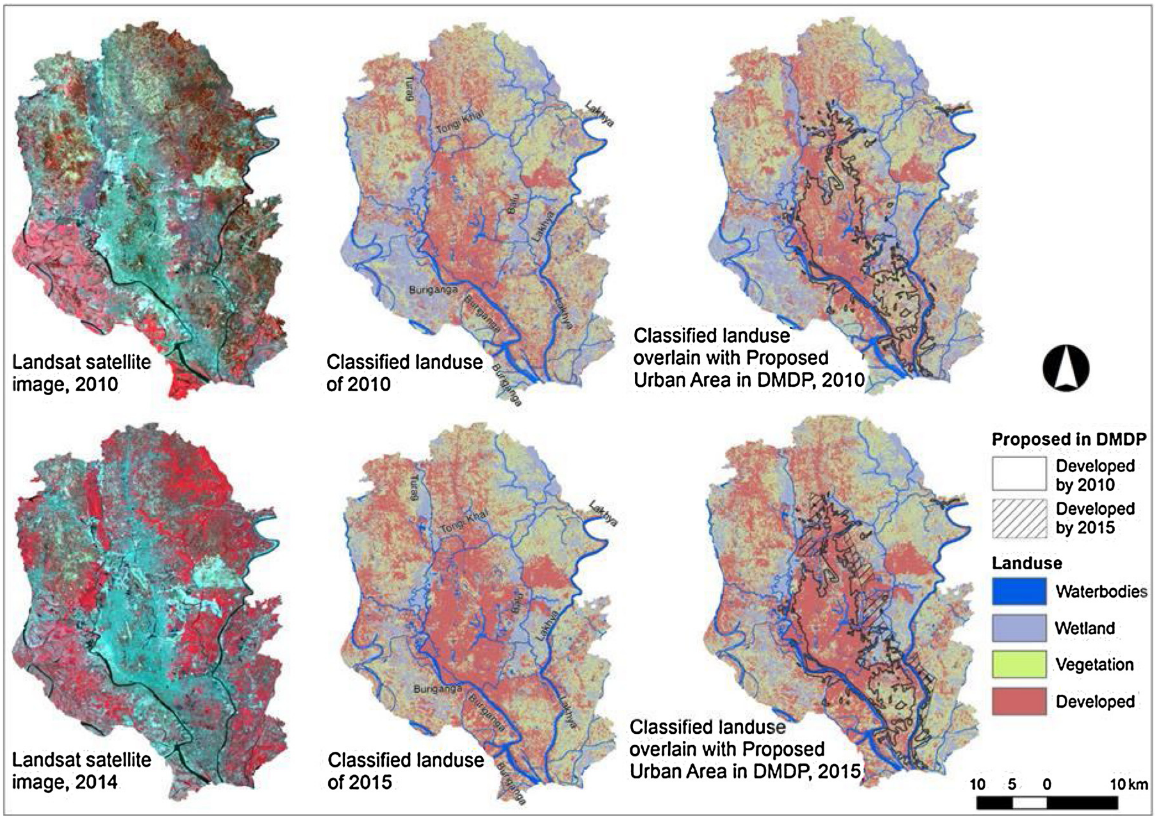

Fig. 3. Comparison between observed urban development, i.e. classified land use based on Landsat images, with the proposed development in the DMDP for the year 2010 and 2015.

the DMDP (1995–2015) and 12.27 km^2 in the DAP and also in the revised DSP (2016–2035). Due to the non-implementation of DAP, the retention ponds are not being preserved and maintained properly. Only a limited number of wetland areas (coloured light blue) are used as retention areas. The current status of retention ponds for Dhaka West is also poor when compared with the planned area in FAP 8B, (see Table 1). In absence of the retention areas excessive rainfall during an extreme event, eventually will end up inundating the settlement areas. The comparative analysis indicates that, Dhaka city has continued to grow at its own pace where the trend of growth has been a mixture of unplanned and planned growth.

3.3. Generate Urban growth scenarios for the planning year

To understand the urban growth pattern and correlate this with future flood risks, a spatially explicit Urban Growth Model (UGM) has

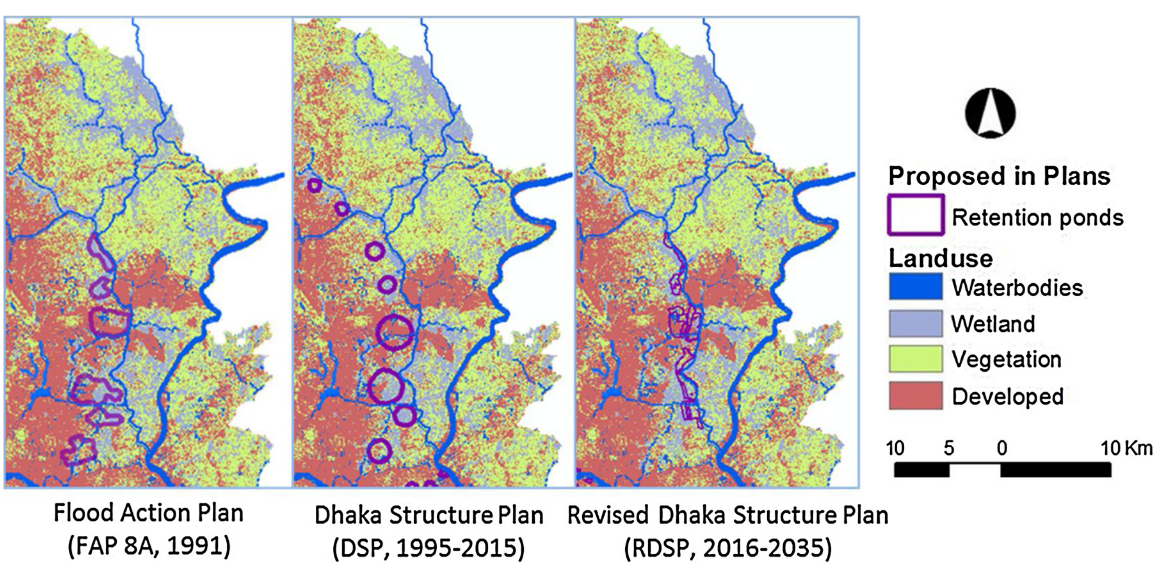

Fig. 4. Comparative view of retention ponds proposed (purple) in the plans (FAP 8 A, DSP and RDSP) overlain with the latest (light blue) land use status of Dhaka East in 2015 shown in the classified image in the background (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Status of retention ponds proposed in FAP 8B for Dhaka West (Source:DWASA, 2014; Islam, 2014).

Name of Pump Station	FAP 8B Proposed Area (km^2)	Govt. Acquired Land (km^2)	Present Status (km^2)
Goranchatbari	3.044	2.74	2.47
Kallyanpur	3.064	0.03	0.45
Dholaikhal	0.042	0.04	0.04
Total	6.15	2.81	2.96

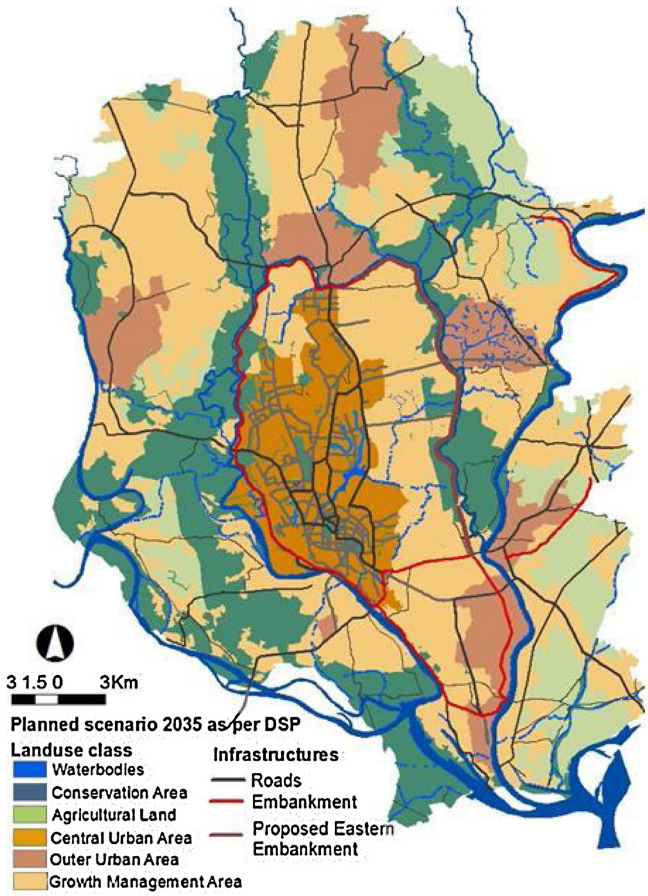

Fig. 5. Urban Growth Scenario 1 (planned) for 2035 based on the revised structure plan (RDSP, 2015–2035).

been developed using Dinamica EGO (Young, 2013), an open access land use based modelling software package. Such an UGM shows the spatial variability of both planned and unplanned growth and can help determine a plausible set of measures to be used in urban development plans. The revised structure plan (DSP, 2016–2035) prepared by RAJUK (Dhaka city's planning agency), shown in Fig. 5, indicates the strategic direction of the urbanization pattern of Dhaka from the year 2016 to the next 20 years until 2035 (RAJUK, 2015). In the revised DSP the long anticipated eastern embankment is proposed to be built along the Balu River. Wetlands are kept as conservation area to maintain the free flow of floodwater.

The Land Use proposed by this structure plan has been used as a reference to generate two urban growth (UG) scenarios: Planned UG scenario and Unplanned UG scenario. To maintain consistency with the structure plan, both scenarios were generated for the same year i.e. 2035 using Dinamica Ego. For the ease of analysis, the central urban area, growth management area and the outer urban area proposed in the RDSP has been re-classed as urban; and the conservation area and

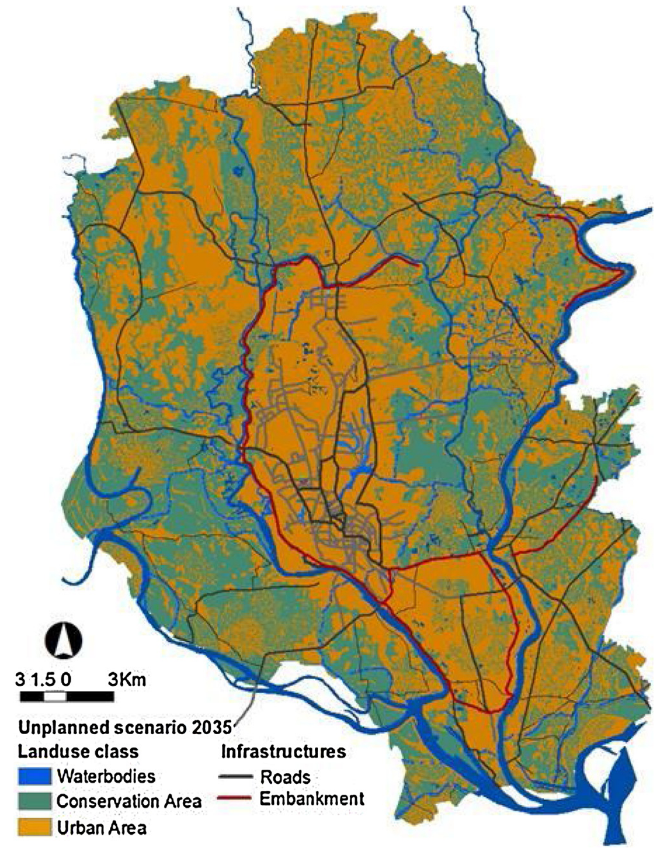

Fig. 6. Urban Growth Scenario 2 (unplanned) for 2035, overlain with infrastructure layer (roads and existing embankments).

the agricultural area has been re-classed as conservation area in the unplanned scenario. The simulated Land Use in the UGM therefore comprised of three Land Use classes namely waterbodies, conservation area and the developed or urban area. The waterbodies and infrastructures e.g. embankments and primary roads have been maintained in accordance to the plan. The first UG scenario was developed assuming that the RDSP is fully implemented. Under the second scenario it was assumed that mainly unplanned growth will take place along with planned development but without the provision for the eastern embankment.

Under the second UG scenario of 2035, urban area expansion has followed a linear pattern of growth along the roads and major rivers channels. New settlements have formed as clusters in the marked wetland areas and agricultural lands. The diminishing patterns of floodplain areas, waterbodies and agricultural land are quite visible while comparing the two scenarios. So, the agricultural land and conservation area for wetlands proposed under the plan (Fig. 5) will be reduced more in near future (Fig. 6) if the unplanned development is allowed to continue.

3.4. Analysis of climate change scenarios based on IPCC 5th assessment report

Due to climate change, more extreme rainfall induced floods are predicted in Dhaka as experienced in the past (Dasgupta, 2015, Thiele-Eich et al., 2015). For instance, a maximum rainfall of 340 mm and 333 mm were recorded in a day in 2004 and in 2009 respectively. These events are well above the estimated 100-year return period (RP) storm event of 262 mm based on the frequency analysis of the rainfall data of Bangladesh Meteorological Department from 1972-2014. Therefore, the basis of all the flood simulations was the flood of 2004 with a maximum of 341 mm rainfall, which was an event more extreme than a 100 year

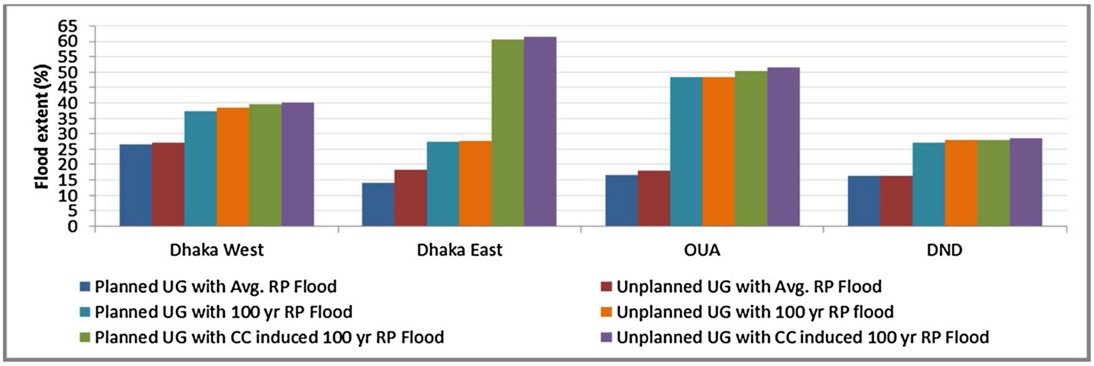

Fig. 7. Zone-wise Total Extent of Flood based on the acceptable thresholds.

return period rainfall event of one day.

From the analysis of climate change data derived for Bangladesh based on the IPCC 5th Assessment report, it was found that the annual maximum rainfall of 1 day event would increase by 20 mm and 40 mm under the moderate and high emission scenarios-RCP 4.5 and RCP 8.5 respectively by the year 2035. This result corresponds with the climate change projections cited in the Bangladesh Delta Plan report (GoB, 2014). Flood simulations of Dhaka for the two scenarios of RCP 4.5 and RCP 8.5 for the year 2035 show negligible difference between the inundation extent and depth. So, the flood simulation result of only the moderate emission scenario RCP 4.5 has been used for the analysis of flood exposure. However, since the basis of the simulations are a 100 yr return period event, therefore under both scenarios extreme flood events are generated.

3.5. Assess flood exposure based on tipping points under urban growth and climate change

For the assessment of flood exposure, two land use change scenarios (planned and unplanned growth) and events representing average flooding, an extreme flooding (i.e. 100 yr RP) and climate change induced extreme flooding (i.e. 100 yr RP of flood with climate change) were used in the hydrodynamic model. Classification of the model results using GIS revealed the areas exposed to flooding (Fig. 10a–d). Flood hazard maps were produced using a classification index different from the established flood classification index of Bangladesh (MPO, 1986; Mirza, 2002). The new classification index is derived in this study from people's perception of hazards risks. Six flood depth categories are assigned (Ahmed et al., 2018) to interpret the flood depths which are: ankle deep (0-0.15 m); lower than knee deep (0.16–0.29 m); knee deep (0.30–0.49 m); waist deep (0.50-0.91 m); chest deep (0.92–1.07 m) and higher than chest deep (1.08–2.5 m).

Coverage of areas that might experience low to high level (0.16–2.5 m) of flooding in each of the four zones of Dhaka are shown in Figure 10 (a to d) and zone-wise total flood extent is shown in 7. In the flood management plan (DWASA, 2014), 0.5 m is defined as the allowable flood depth for the built-up areas. In this study people's opinion is also considered significant in determining the critical value of flood depth. From the consultations with community people or people's perception 0.3 m is identified as the acceptable threshold. So, using these threshold values, the areas that exceeded the threshold of 0.5 m and 0.3 m and hence where an ATP has been reached, are shown in Fig. 8 and 9 respectively.

Analysis shows that more areas will be vulnerable if the unplanned growth prevails (Fig. 7, 10c and 10d). The floodwater spreads into the surrounding builtup areas (Figure 10c and 10d) when owing to unplanned growth, the wetlands and flood plains are occupied by new housing projects and industries (Fig. 5). An obvious increase of total flood extent from the effects of climate change induced extreme flooding than the average RP of flooding scenario can be seen in each zone.

Zonal characteristics play a vital role in influencing the flood regime (Fig. 8, 9, 10a, 10b, 10c and 10d). Over the years canals inside and around Dhaka city have diminished in the name of urbanization and industrialization. Inadequate drainage associated with reduced wetlands, silted up and shrunk canals and lack of storm water drainage system, causes inundation into the low-lying areas in the eastern part, western part, DND and the outer periphery of Dhaka (Figure 10c and 10d). These activities have reduced the flood flow passage causing internal drainage congestion within the confinement of fully embanked areas e.g. Dhaka West and DND. A sharp rise in the total flood extent due to the effect of climate change compared to a slight increase due to the impact of unplanned urban growth is visible in all the zones except Dhaka East. In Dhaka East the impact of unplanned growth is distinguishable as under the unplanned scenario it was assumed that the eastern embankment will not be constructed. Therefore, during an event of extreme flooding, the high level of water will overflow the banks of the River Balu and thus inundate the unprotected (un-embanked) part of Dhaka East (Fig. 8 and 9). The embanked areas of Dhaka west can also face internal flooding and drainage problems from

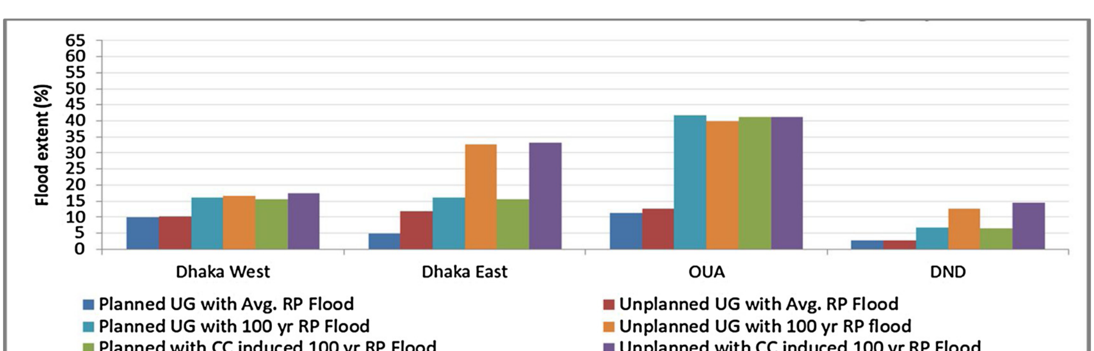

Fig. 8. Zone-wise Extent of Flood based on ATP of 0.5 m from Planning Perspective.

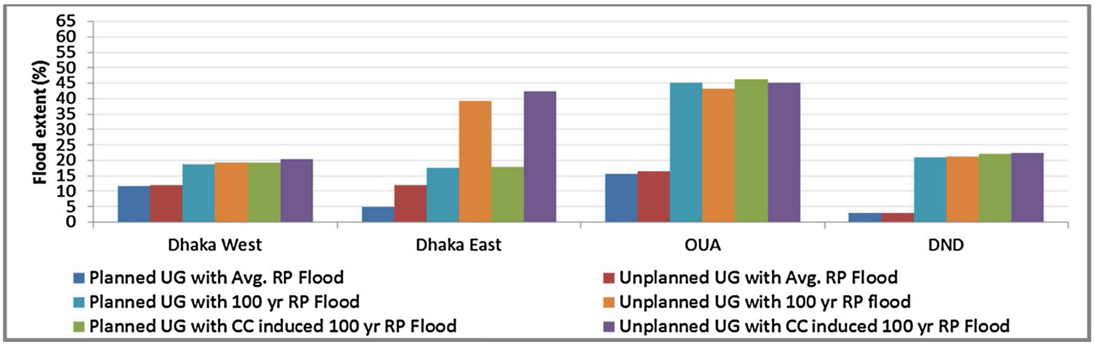

Fig. 9. Zone-wise Extent of Flood based on ATP of 0.3 m from People's Perspective. (Here, UG refers to urban growth).

intense rainfall of few hours as a result of climate change (Fig. 7).

The areas that are built following the planning guidelines with required drainage facilities e.g. located in the Dhaka West, Dhaka East and OUA zone are less vulnerable to flooding both in planned (Figure 10a and 10b) and even under the unplanned condition. Also, due to the raised ground above the flood height, some areas will be less exposed to high level of flood as can be seen in Fig. 8 and 9. Climate change (e.g. sea level rise) and land use change, both are slow moving variables or drivers which alters gradually over the years (Kwadijk et al., 2010). However, an increasing trend in the frequency of high-intensity rainfall events would have more severe impact on peak runoff and urban flooding. These changes in climatic pattern can induce extreme rainfall events within a short duration lasting from few hours to one day resulting into floods. Although it is true that in other places and under certain conditions the effect of urbanization can be greater than climate change (Veerbeek, 2017). This research revealed that even the planned areas can be flooded when the design capacity of drainage network is exceeded due to climate change induced rainfall. The impacts of urban growth in reaching tipping points due to flooding are site specific meaning limited to unplanned areas only, while the vast effects of climate change are visible in both planned and unplanned areas. So, the effect of climate change on flooding is apparently larger than that of unplanned urbanization. However, both are responsible in instigating tipping points in the socio-physical system and increasing the risks of flooding in urban areas.

4. Implications on policymaking and planning for adaptation to urban flooding

To ensure efficient flood control and adaptation, often plans are prepared which are idealistic by nature, but in reality difficult to maintain or implement due to unplanned urbanization. Land use proposed in the plans is supposed to be developed under the guidelines of the Land Use Policy (2001), Water Policy (2010), National Urban Sector Policy (2011, draft). The Land Use Policy (2001) reiterates the optimized use of land in harmony with the environment. Land zoning for integrated planning and management is emphasized in this policy to apply development control. The National Urban Sector Policy (2011, draft) on the other hand aims for decentralized and sustainable urbanization involving stakeholder participation to deal with the multifaceted challenges of urban development. However, unplanned development continues to have detrimental environmental impacts through encroachments (Alam, 2014) of mainly waterbodies, wetlands and agricultural land etc.

The government agencies with the aid of legislation e.g. the Bangladesh Environment Conservation Act 1995 (Amendment in 2010), Water Body Conservation Act 2000, Open Place, Park & Wetland conservation Act, 2000, Water Act 2015, sometimes evict illegal encroachers from rivers and other wetland areas. The Urban and Regional Planning Act (Draft, 2014) suggested punitive measures against the land grabbers. The RAMSAR Convention (of which Bangladesh became a signatory in 1992), also promotes wise use of wetland, i.e. sustainable management of wetlands maintaining the ecosystem.

Apart from the local level plans the overall direction for managing floods and tackling climate change is provided by the national level plans e.g. National Water Management Plan 2004, Bangladesh Climate Change and Strategy Action Plan (BCCSAP) 2009 and the Bangladesh Delta Plan 2100 etc. Similar to (Araos et al., 2016), it was found that although a number of policies and strategic plans exist, the policy directives are not trickled down into municipal or city level plans and projects. Climate change for instance is not mainstreamed within urban spatial planning processes as suggested in the BCCSAP (2009). Another critical issue is that the Urban Sector Policy and the Urban and Regional Planning Act, are not finalized yet. This Policy and Act, both are two important components required to control unplanned development.

Introducing flexibility in the urban area plans by incorporating the opportunities that the unplanned construction may offer could be a good way forward for cities with similar conditions as Dhaka. Strategic plans can provide flexible options to accommodate the growth of urban areas and tackle the extreme changes in climate. The recently revised structure plan (RDSP, 2016–2035) is such a strategic plan which seemingly has the provision to encompass unplanned urban growth under the land use option of 'Growth management area'. However, the combined effects of planned and unplanned development with climate change (Shahid et al., 2016) e.g. intensity and volume of rainfall events, are far greater than expected. These combined effects were not considered in the planning process which can have dangerous consequences for the future.

This research, combining model results with the community perspective emerging from consultations, proved that critical thresholds or tipping points will be reached in the socio-physical system due to unplanned development and extreme changes in climate (Ahmed et al., 2018). The paper demonstrates that this will trigger changes in policymaking or planning process known as Adaptation Tipping. Zone-wise analysis of flood exposure of Dhaka further revealed that the impacts of river and rainfall flooding differ on the scale of effects of climate change and urban growth. However the urban development plan neither recommends zone specific strategies nor is the criteria for strategy selection and prioritization defined. Prior to the finalization of the policies and plans, climate change mainstreaming together with the consideration of unplanned development are suggested. Implementation and monitoring through the operationalization of the proposed policies/plans with the legal aid of Acts and Rules are to be ensured. This indicates the need for a shift from the current planning practice of 'Predict and Act' towards a more resilience-based 'Monitor and Adapt' approach which requires a continuous monitoring plan and fit for the purpose governance arrangements.

This research paves the way for the use of the resilient based approach e.g. Adaptation Policy Pathways (APP), but does not actually apply this approach. Adaptation policy pathways typically rely on or

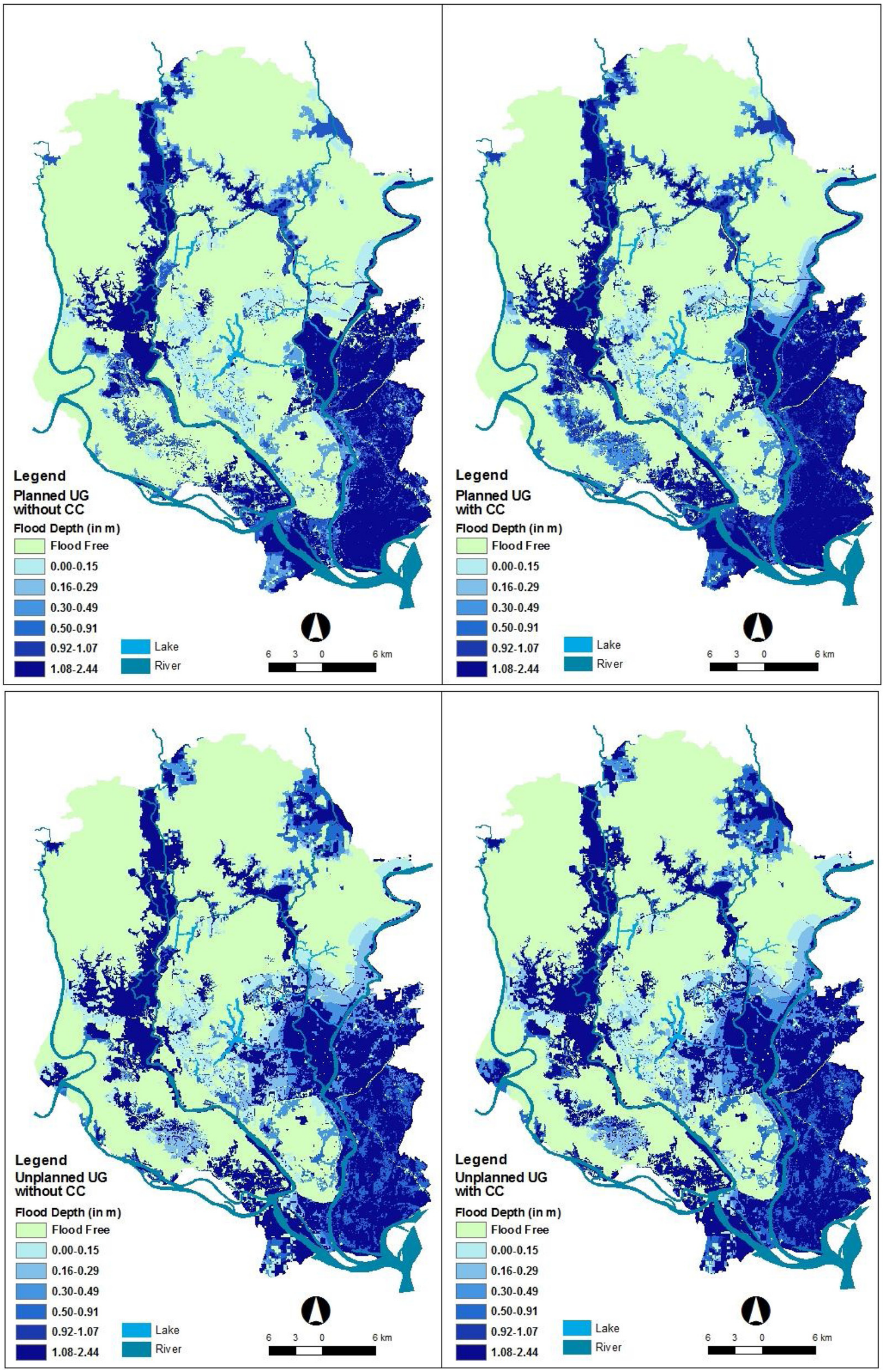

Fig. 10. Zone-wise extent of flooded area in 2035 under scenarios of a) planned urban growth without climate change, b) planned urban growth with climate change, c) unplanned urban growth without climate change, d) unplanned urban growth with climate change.

are dependent on ATP analysis. Built upon the current assessment of flood exposure adaptation policy, pathways including adaptation strategies can be formulated. The policy pathways then can be translated into adaptive (land use) policy guidelines. APP formulation for flexible resilience and adaptation based planning can be explored in future studies which could not be conducted within the limited scope of this study.

In this paper, only two scenarios of planned and unplanned growth were incorporated into the hydrodynamic model which helped assess the flood risks under varying levels of urbanization. More urban growth scenarios may help to further detail the planning options, however, it is difficult to identify the pattern of unplanned development which requires expert judgement to assess where and when unplanned growth is likely to happen, along with the historical landuse change data to derive model results.

5. Conclusion

This research shows that tipping points from planning or people's perspective due to urban flooding are bound to occur in a city having a complex socio-physical system and where the policy process is not linearly correlated with development such as Dhaka, meaning unplanned development continues through non-compliance to the existing planning guidelines and acts. Additionally two missing links in the policymaking process are the proposed Urban Sector Policy and the Urban and Regional Planning Act. It is seen that the urban development plans are not entirely synced with the existing national level policies and plans. For instance the multitudinal effects of climate change and unplanned urbanization is not adequately addressed in the planning process.

The failure to apprehend the impacts of possible future urbanization patterns in especially unplanned development along with climate change can result into ineffective plans and Adaptation Tipping Points being reached sooner. Immediate attention from the policymakers is required without any further delay to finalize and operationalize the Policy and the Act. The paper stressed the need for synchronization across the tiers of policy making, planning and implementation to deal with urbanization and climate change. The plans and policies also need to be updated with zone differentiated strategies to delay the occurrence of tipping points in the bio-physical system and prevent planning failure or ATP occurrence.

Apart from the conventional practices, the planners should also think out of the box and introduce resilient options that are adaptive to the city's exponential growth and changes in climatic conditions. This research revealed that the impacts of urban growth in reaching tipping points due to flooding are site specific: limited to unplanned areas only, while the vast effects of climate change are visible in both planned and unplanned areas. Even the planned areas can be flooded when the drainage capacity is exceeded due to climate change induced rainfall. Climate and urban growth both play an important role in instigating tipping points and intensifying the risks. In light of the analysis particularly for the case study of Dhaka mega city, the effects of climate change on urban flooding appears to be greater than compared to unplanned growth. The policies and plans are to be strictly applied using the existing Acts. In this way spatial planning complemented with climate change adaptation planning can ensure resilient built environment for city dwellers.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2018.05.051.

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