Urban Growth Modeling to Predict the Changes in the Urban Microclimate and Urban Water Cycle

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Abstract

The consequences of urban growth on the exposure, sensitivity but also as a driver of flooding are often underexposed. Yet, the rate of current urbanization is unprecedented and might increase future flood risk dramatically. To gain insight in this issue, a study on urban development has been performed using 3 case study areas: the megacities of Beijing, and Mumbai and 1 regular city: Can Tho, Vietnam. Using a physically urban growth model, future growth patterns are obtained that show land cover transformations for the years 2035 and 2060. The growth patterns are based on historical data and a business as usual scenario to gain insight in the impactions of current growth rates. The outcomes have been analyzed in relation to pluvial flooding sensitivities based on the distribution of impervious areas. For the Mumbai case study, the same input is provided used to investigate potential changes in the microclimate by application of a modified mesocale atmospheric model. The outcomes show significant changes in flood risk and precipitation levels, urging for 'smart growth' policies to secure a sustainable future for the investigated megacities.

Introduction

Over the last years, a substantial body of scientific evidence has been presented about the potential effects of climate change (e.g. Milly et al, 2002). The majority of the identified changes will be endured in cities (e.g. UN-Habitat, 2007). Yet, cities act not only as passive receptors but exacerbate the intensity of many natural hazards and their effects. One of the most obvious consequences of urbanization is a decline of the natural drainage capacity caused by extended soil sealing. This upsets the water-balances and has major implications for the drainage systems. Yet, although perceived as important, the dynamics of urbanization are often neglected in assessing future impacts of climate change. Nonetheless it might prove to be the dominant factor in a seemingly ever increasing number of natural disasters.

Currently we are witnessing an unprecedented growth of urban areas (e.g. Angel *et al*, 2005) Furthermore, exceptional urban growth also leads up to city sizes never experienced before. Currently the world hosts 26 megacities with populations exceeding 10 million inhabitants (Brinkhoff, 2011). 17% of the cities in the global south are experiencing very high annual growth rate (more than 4%), which ultimately leads up to a significant amount of land and infrastructure development to cope with the demands of this rapid population growth (UN-Habitat, 2007). In developing countries, only an estimated 5% of the urban growth is planned (ibid). This is alarming since especially poor urban slum dwellers are susceptible to the threats posed by natural hazards (Watson, 20009). For instance in Manila, 35% of the population living in informal settlements is prone to coastal flooding while 60% of informal settlements in Bogota live in areas prone to landslides. Apart from an increasing exposure and sensitivity to flooding, urban growth also intervenes into the water-cycle. An increasing set of evidence suggest that urbanization causes microclimatic changes, resulting in changes in precipitation patterns (Lin, et al., 2008). Often these lead to an increase in the magnitude of rainfall events (Shepherd, 2005). In turn, the subsequent surface runoff can increase peak discharges two to four times, while lag times decrease correspondingly (Chin, 2007).

A potential way to mitigate these threats is to develop more efficient urban growth strategies in which spatial planning is used to limit the sensitivity and exposure to flooding as well as the driving effect on precipitation. ‘Smart urban development’ is often proposed as a vital strategy in greenhouse emissions reduction and energy consumption. Yet, development strategies that include climate adaptation (e.g. flood impact mitigation) are still limited. A possible reason for this might be the absence of future scenarios showing the potential impacts when extrapolating current urban growth trends. This especially holds for emerging megacities in which application of business as usual (BAU) scenarios might lead to sudden shifts in flood vulnerability (threshold effects) that might only be overcome by large structural interventions. Since large urban restructuring projects are often hampered by lack of support and resources, development ‘mistakes’ are difficult to overcome in the future. It is therefore essential to gain insight in potential future threats of current urban growth trends on an explicit, physical level.

In this paper, we used 3 case studies to identify increased flood risk as a function of urban growth: 2 megacities (Beijing, China and Mumbai, India) and 1 more regular sized city (Can Tho, Vietnam). All 3 cities are experiencing rapid urban growth. Using a spatially explicit urban growth model, historic urban growth patterns for these cities are used to investigate the potential future urban extent. Subsequently, flood sensitivity maps have been developed from these outcomes showing the expected distributions and severity of areas prone to pluvial flooding. Further study is carried out for the city of Mumbai to investigate the impact of urbanization on the urban microclimate.

Urban growth models and flood risk assessment

Urban growth is often assessed statistically, expressed in occupied sq. km of land or inhabitants. The resulting geographic distribution of land cover changes is less well understood, and only sporadically modeled in relation to urban flooding (e.g. Choi and Deal, 2007; Shi et al 2007). Modern geographic urban growth models are often based on cellular automata, in which urban growth is based on local transition rules, derived from geographic time series data (Batty, 2005; Benenson and Torrens, 2004). Future urban patterns for the case study areas have been developed applying the Dinamica-EGO model (Filho et al, 2003; Filho et al, 2009). Training and calibration of the model has been performed by feeding the model with land-cover maps from 2 significantly different years. The land cover distribution has been derived from Landsat ETM and ETM+ images, which have also been used for validation of the model. Furthermore a range of physical characteristics have been used, like morphology (slope), infrastructural development (major road development) and excluded areas (water, protected natural parks, etc.). The estimated growth rules have been applied to horizons up to the year 2060 to forecast the physical propagation of urban landforms. Note that the Dinamica-EGO model 'learns' the urban growth rules for individual cities. The model's growth rules for Beijing might therefore be very different from those for e.g. Mumbai or Can Tho. The growth patterns for the 3 cities have been developed for short and mid-term periods: the years 2035 and 2060. The Dinamica-Ego models have been initialized using land cover maps from the base years 1992 and 2006.

While comprehensive flood hazard and flood risk models exist (e.g. Veerbeek, 2009), these often prove to be data and computationally expensive. Since the current urban extent of e.g. Beijing covers more than 450 sq. km, detailed flood risk mapping for the entire city is infeasible. Yet, the distribution of various levels of impervious surfaces provides an initial indicator of flood prone areas. These have been assessed by applying a set of urban analysis tools able to identify different classes of urban intensities (Angel et al, 2007; Vogt et al, 2007) and their associated levels of imperviousness. Changes in microclimate and precipitation patterns stemming from urban growth have been assessed by using a mesocale atmospheric model (Pathirana, 2010). These are expressed as modified Rainfall-Intensity-Duration curves.

Modeling Results: Beijing, Mumbai and Can Tho

1. Beijing

Since the mid 1980s, China's capital Beijing has transformed into a megacity, currently hosting a population of almost 20 million people and is still growing rapidly. The city is one of China's main economic and cultural centers. The model's outcomes for Beijing revealed a tremendous urban growth during the initial growth phase until 2035. This growth is a continuation from the actual observed growth between 1988 and 2006 which doubled the city in size. Although somewhat less dramatically, this growth continues to the year 2060 in which the urban extent again almost doubles when compared to the base year 2006. The calculated growth patterns confirm the radial setup of the city with the exception of the Western areas which are occupied by relatively steep mountains, unfit for occupation. Existing towns in the proximity of Beijing are expected to be 'swallowed' by the calculated urban growth. A quantitative analysis of the growth rates is shown in table 1.

Table 1. Estimate growth statics for Beijing in the period 1988-2060

Year	Urban Extent		Urban		Suburban	
	area [km2]	Change	area [km2]	Change	area [km2]	Change
1988	947.8		521.0		426.8	
2006	2477.2	161.4%	1663.4	219.3%	813.7	90.7%
2035	4046.2	63.3%	3478.7	109.1%	567.5	-30.3%
2060	4971.6	22.9%	4574.8	31.5%	396.7	-30.1%

Apart from the observed massive urban growth, an important notion from table 1 is the decline of suburbanization in favor of densely occupied urban areas. While the urban growth in many cities is exemplified by endless sprawl, the city of Beijing both expands and densifies. This can be also observed in figure 1, which apart from massive expansions also shows infill of open urban spaces. This might have important consequences for the surface runoff generation since densification generally increases runoff coefficients and subsequent flooding. The physical characteristics of the expected growth are depicted in figure 1. This figure also shows the distribution of impervious areas for the base year 2006 and the long-term horizon of 2060.

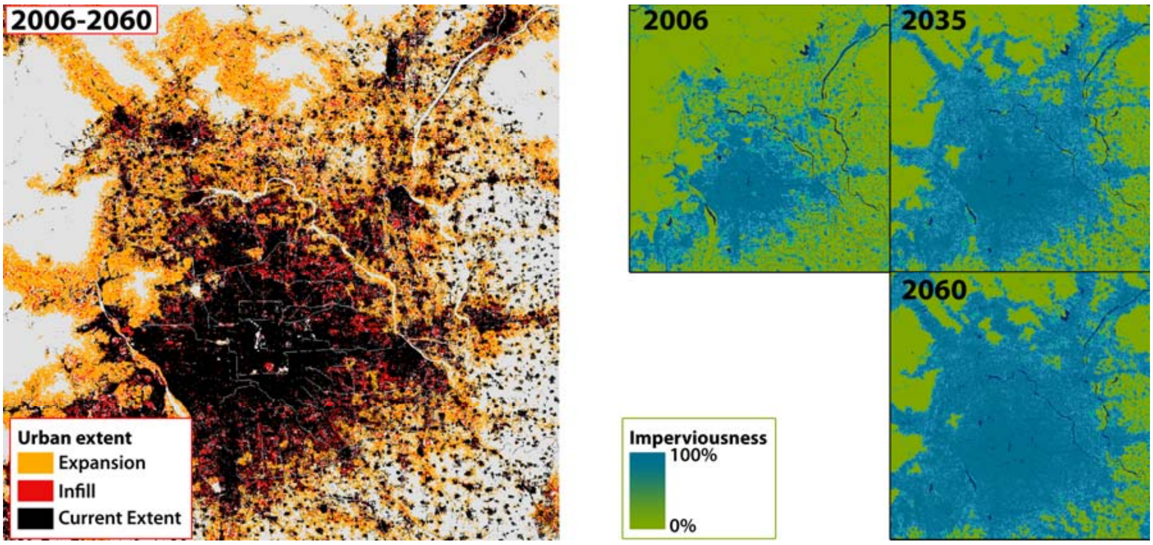

Figure 1. Expected urban development of Beijing (left) and the resulting distribution of impervious land cover (right). Also online: http://assela.pathirana.net/ICUD_2011_UG

2. Mumbai

As one of the densest urban megacities, Mumbai (current population over 20 million) has witnessed urban growth mostly as urban expansion. Because located on a peninsula, there is little room for infill in the southern areas (the central business district), which is exemplified by the decline of growth in dense urban areas after 2006 (see table 2). Most growth takes place in the eastern areas around the twin city Navi Mumbai, which is currently relatively dislocated from Mumbai's main urban core. Nevertheless, a substantial amount of infill can be observed (see figure 2); remaining open urban areas are rapidly densified which results in an increasing contiguous area of impervious land cover.

Table 2. Estimate growth statics for Mumbai in the period 1988-2060

Year	Urban Extent		Urban		Suburban	
	area [km2]	Change	area [km2]	Change	area [km2]	Change
1988	398.4		216.2		182.1	
2006	485.7	21.9%	281.4	30.1%	204.3	12.2%
2035	547.3	12.7%	325.8	15.8%	221.5	8.4%
2060	509.5	-6.9%	362.0	11.1%	147.5	-33.4%

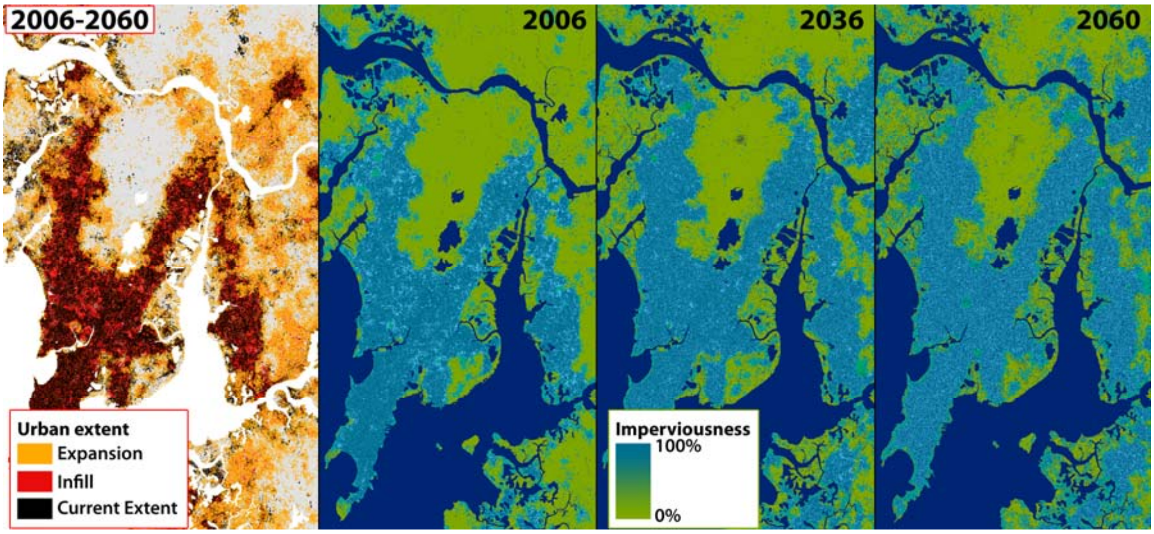

Figure 2. Expected urban development of Mumbai (left) and the resulting distribution of impervious land cover (right). Also online: http://assela.pathirana.net/ICUD_2011_UG

3. Can Tho

As the largest city in the Mekong river Delta (current population about 1.2 million), Can Tho experienced strong growth in the past decades. The modeling results suggest that this trend continues until 2035. After this period, the growth slows down significantly. Yet, over the complete period 2006 to 2060, the city almost doubles in size. The characteristics of this expansion are different from those for Beijing or Mumbai. The majority of growth from 2006 on is caused by urban sprawl. While the densely occupied urban centers only increase marginally, the suburban areas show a rapid expansion (see table 3.)

Table 3. Estimate growth statics for Can Tho in the period 1988-2060

Year	Urban Extent		Urban		Suburban	
	area [km2]	Change	area [km2]	Change	area [km2]	Change
1988	44.5		19.4		25.0	
2006	68.1	53.2%	29.2	50.0%	38.9	55.7%
2035	95.7	40.5%	32.0	9.7%	63.7	63.6%
2060	106.5	11.3%	34.8	8.7%	71.7	12.6%

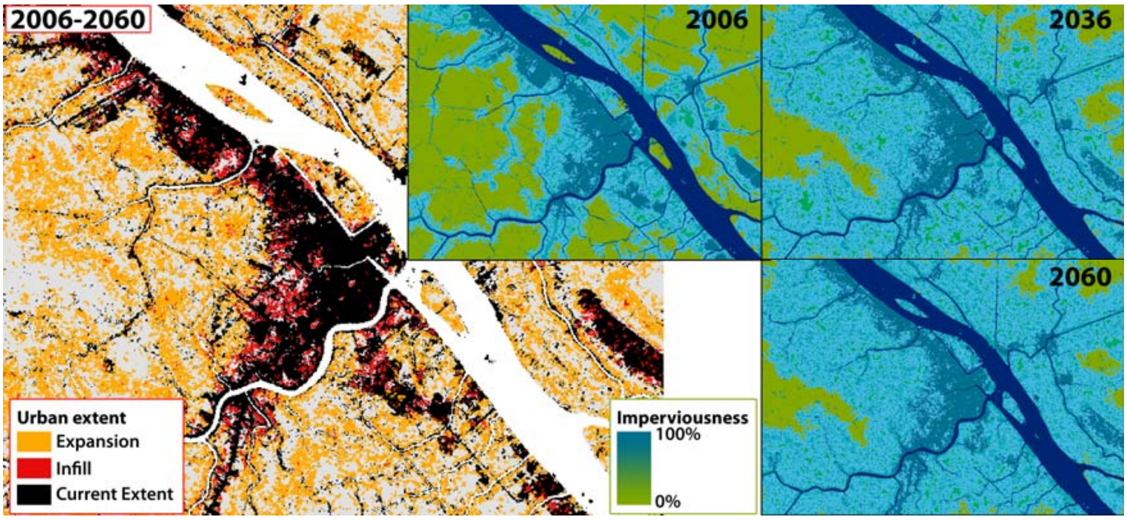

Figure 3. Expected urban development of Can Tho (left) and the resulting distribution of impervious land cover (right). Also online: http://assela.pathirana.net/ICUD_2011_UG

These growth characteristics can also be perceived in figure 3; suburbanization covers large areas of unoccupied land but is distributed relatively sparse. Extensive contiguous urban areas can only be found in the existing urban center along the Hâu River and its tributaries.

Consequences for urban flooding

Both Mumbai and Can Tho suffer from river flooding as well as monsoon driven urban flooding. Wile Beijing’s main problem appears to be water scarcity, the city is also vulnerable to flooding: In 2004 the city experienced substantial flooding causing the collapse of 6 buildings and almost a complete stop of traffic in the downtown areas. There are two classes of reasons for increase of urban floods with urbanization: Hydrological, owing to increase of imperviousness resistance to flow and hydro-meteorological, by the changes in the microclimate above cities. Figure 4 shows the expected current and future distribution of imperviousness levels for the 3 case study cities.

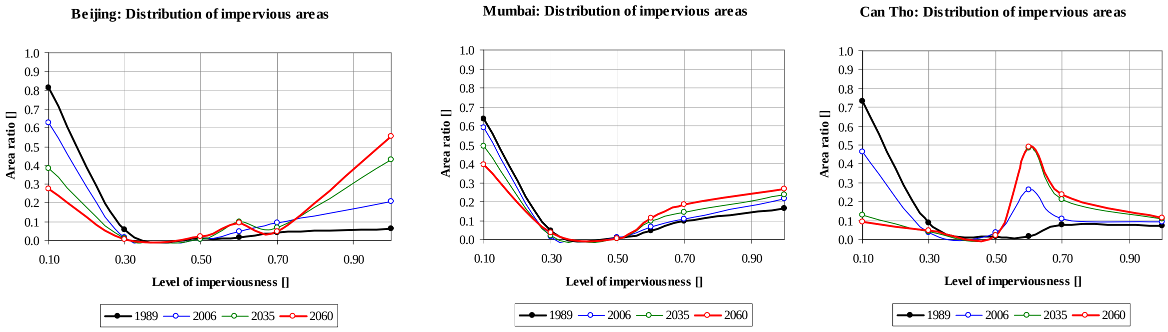

Figure 4. Expected distribution of impervious land cover for Beijing (left), Mumbai (middle) and Can Tho (right) for the years 1989, 2006, 2035 and 2060.

While in all cities trends towards higher levels of impervious areas can be identified, the extreme urbanization of Beijing shifts the values towards higher levels substantially. Furthermore, the suburbanization in Can Tho can be perceived by a peak in medium imperviousness levels, increasing flood prone areas to only a limited extent. The distributions for Mumbai suggest only a minor trend change towards higher levels of imperviousness.

Although the observed shifts suggest an increase in flood prone areas, this conclusion might not be drawn directly. This depends to a large extent on the actual building and neighborhood layout. Especially in Beijing, much of the urban development takes on the form of high-rise buildings surrounded by green areas, which effectively increase the overall drainage capacity of the city. In Mumbai on the other hand, the substantial slum development (currently 60% of the inhabitants live in urban slums) covers any leftover space. Hence the natural drainage capacity is practically eliminated. This holds especially for the densely populated tip of the peninsula which hosts the cities central business district. Although substantial, the expected suburbanization of Can Tho might not increase urban flooding dramatically. Yet, suburbanization might provide a seed for further future densification, which in turn might lead to a sudden shift in the occurrence of urban flooding events.

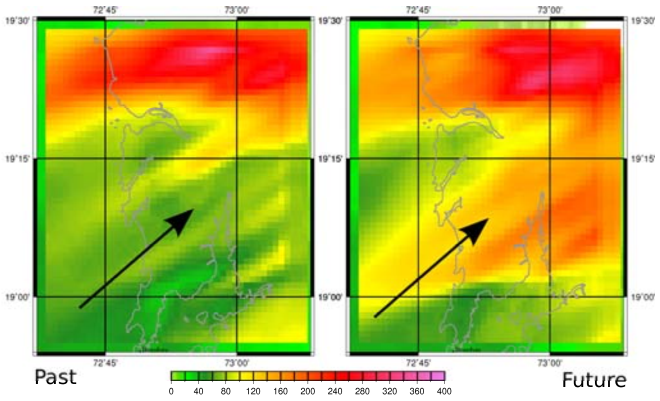

Figure 5. Total rainfall simulated during the 2007/07/01-06 rainfall event. Left: Past, Right: Future.

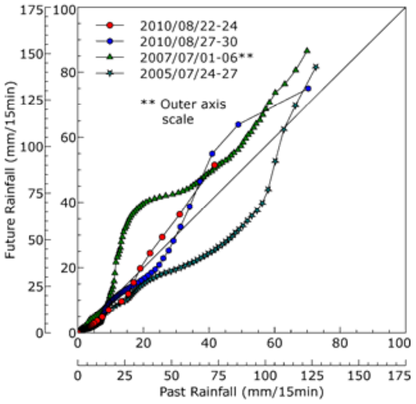

Figure 6. Quintile-quintile plots of rainfall intensities (100 equal quintiles)

In order to ascertain the hydro-meteorological impacts of the estimated urban growth, a meso-scale atmospheric model (WRF) coupled with a land-use model with vegetation parameterization (Noah LSM) was applied. The process of obtaining these results were as follows: Several historical storms over Mubai city and setup WRF/Noah using NCEP-FNL global data as initial/boundary conditions and land-use data from our models (2006 as `Past' and 2060 as `Future') were selected. The models were validated to closely reproduce the historical results with the `Past' scenario. Then the same model parameters were used with `Future' scenario to answer the question. `What would be the extreme rainfall outcome should these events take place under the post-growth (2060) situation`. Figure 5 shows the total simulated rainfall amounts for an extreme event recorded in July 2007. Figure 6 shows the distribution of rainfall intensity quintiles at 15min resolution, for four historical events. There is a clear impact of urban growth to increase the extreme rainfall quantities. If similar results can be obtained for the other case studies is yet still unclear.

Discussion

This study reflects only a proof of concept for a larger comparative study on the effects of urban growth on flood risk. Although the initial results are promising, there are still many issues to be solved. First of all, the level of expression of the model should be extended by including a range of urban typologies and their associated imperviousness levels. Furthermore, training of the model should be performed using a larger set of time-series data. This might increase precision, but also provides better insight in the temporal dimension of urban growth (e.g. the occurrence of sudden growth spurts). Finally, actual population and economic predictions could feed the model and limit or stimulate growth rates.

Conclusion

As shown in this study, rapid urbanization causes major increase in contiguous impervious urban areas which in turn result in rising surface runoff levels and subsequent urban flooding. It also cause extreme rainfall events to increase in magnitude, compounding the problem. For the investigated cities, this threat seems substantial, and might be bigger than that of the expected increased precipitation rates caused by climate change. Yet, since the horizon of the experiments is about 50 years, there are many possible scenarios that can alter the calculated outcomes; global and local changes in policy, economy or culture can significantly affect the actual growth patterns and progression. However, the presented outcomes show what might happen if current trends remain unchanged. They could provide an incentive for 'smart growth'-policies or even growth caps which might be a vital instrument in the future sustainability of the world's metropolitan areas.

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