Future developments in Bangladesh: urbanization scenarios to assess flood risk

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ABSTRACT

In this research, a national-scale flood risk assessment for four scenarios up to 2100, has been applied to the country of Bangladesh. In order to make this assessment, population projections are made, making use of the four scenarios. Furthermore, an urban driver analysis has been conducted to quantify historical urbanization patterns. Then a land-use model has been altered to model population densities up to 2100 for the four scenarios, using the population projections and the results from the urban driver analysis. The output from the urbanization model is used in a flood impact model in combination with water depth maps, resulting in flood impact maps and tables for each of the four scenarios and for each decade up to 2100 at a resolution of 50x50 meters.

This study suggests that future flood risk, without interventions, may increase with 18 – 65% in 2050, compared to the current situation, attributable to socio-economic change. Moreover, in the same period the population may increase with 13 – 52%, hence, the flood risk may increase disproportionally compared to the population growth. Furthermore, the in this study proposed policy interventions show that the increase in flood risk may better be mitigated by embanking non-protected areas rather than improving already protected areas.

FOREWORD & ACKNOWLEDGEMENTS

This Master Thesis is written as completion of the Master Earth Sciences and Economics, at the VU University Amsterdam. First, I would like to express my gratitude to my on-site supervisor Dr. Ir. Kymo Slager from Deltares for his useful comments and input during this research. I would also like to thank my VU supervisor Dr. Eric Koomen for his support and helpful comments in writing this thesis. Furthermore, I would like to thank Maarten Hilferink for his help with the Land Use Scanner. Finally, I would like to thank CEGIS and IWM in Dhaka, who provided me with data and information about Bangladesh.

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CONTENTS

SECTION I: INTRODUCTION

Bangladesh is one of the poorest countries in the world. In addition, it has the highest population density in the world. It has more than 150 million inhabitants with a prognosis of a 25% increase in the next decades (United Nations, 2014). Bangladesh is located on one of the largest river deltas in the world (Ganges-Brahmaputra-Meghna Basin) (Figure 1), where often disastrous floods occur, and where other climatic events influence the people's livelihood (Brouwers, Akter, Brander, & Haque, 2007; FAO, 2011). Climate change is likely to worsen these environmental events, since "*it is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas on the globe*" (IPCC, 2012). While there is rapid urban growth, flood management is a neglected priority for urban planning in Bangladesh. Moreover, from a hydrological perspective, floods in the 70s were not that different from recent floods. However, the economic loss and vulnerability of the people have greatly increased (Dewan, 2013). These factors emphasize the need for careful spatial planning making cities more resilient, by providing a safer and more sustainable future for the country.

These problems fall within the Bangladesh Delta Plan 2100 (BDP2100), a project for which the Government of Bangladesh requested the Government of the Netherlands for advice and recommendations. The BDP2100 embodies "*a holistic, integrated vision, and the strategy and long term plan for the Bangladesh Delta. It aims to achieve long-term (up to 100 years) sustainable socio-economic development and provide safety in the face of disasters through adaptive water governance for both the monsoon and dry season. The BDP2100 provides vision and criteria to facilitate swifter decision making and implementation of major programs and developments in the country, both in the near future and in the longer term*" (BanDuDeltAS, 2012).

Within the scope of the Bangladesh Deltaplan and for the purpose of this Master Thesis the following research question is formulated:
To what extent may future urban development, change flood risk in Bangladesh?

The following sub-questions will contribute in answering the research question:

- What are future scenarios for demographic, spatial, climatic and economic change in Bangladesh?
- What drove historic urbanization patterns?
- What are possible future urbanization patterns for Bangladesh?
- How do future changes in urban patterns affect flood risk?

In order to get a better view of how Bangladesh feels, looks and works. I traveled to Bangladesh for six weeks, from the start of September 2015, and tried to see different parts of the country. To see what urban and built-up areas look like; to see the sheer size of Bangladesh' rivers and its tremendous rate of change and grasp what flooding means in this country. I went to Dhaka, Barisal, Patuakhali, Chandpur and Noakhali in the south and to Sreemangal in the north-east and everything on the roads in between.

This report is structured as follows; first, a brief introduction on urban development in Bangladesh will be provided (Section I). Next, literature will be discussed to see how the scientific community stands on this thesis' topics (Section II). The following section presents the data with its sources and the methodology of this thesis (Section III). After which the results will be presented and discussed (Section IV). Then there will be a discussion in which assumptions and vulnerabilities of the research will be pointed out (Section V). And finally, there will be a conclusion summarizing the main findings (Section VI).

Figure 1: Satellite map of Bangladesh with relevant cities and the 64 districts (satellite image from ArcGIS basemap)

1.1 Study area

Bangladesh is one of the poorest countries in the world. In addition, it has the highest population density in the world. The largest portion of its population lives in rural areas, where they have adapted their way of life to Bangladesh' floodplain environment. They build their settlements on floodplain ridges, with their houses on earthen mounds or wooden poles raised above normal flood levels. Moreover, most roads and railways are on embankments. The most important agricultural product is rice, which is grown in three seasons, two types of rice (*aus* and *aman*) mainly under rainfed and flooded conditions in the *kharif-I* and *kharif-II* (wet) seasons, and *boro* rice mainly by irrigation in the *rabi* (dry) season (Brammer, 1990).

General figures

Bangladesh's population has grown just over 1.5% a year on average over the last two decades; meanwhile, its GDP has grown by an average of 6% since 1990. Moreover, the annual FDI flow increased from 3.2 million in 1990 to 1.5 billion in 2013. Furthermore, the life expectancy has grown from 60 in 1990 to 70 in 2013 and the child mortality rate has dropped by more than 70% in 2013 compared to 1990 (Figure 2). These figures show how Bangladesh is changing and its potential for better livelihoods for its population.

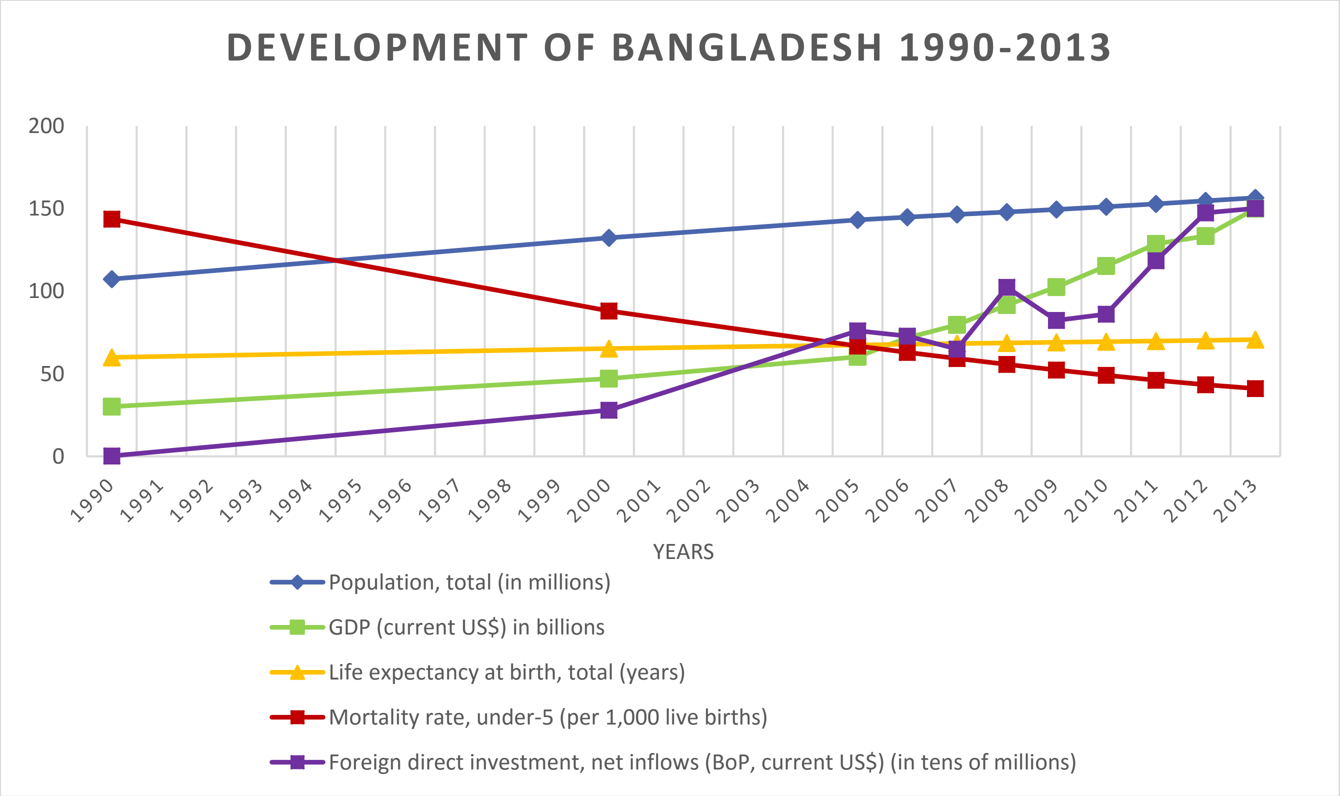

Figure 2: Development of Bangladesh 1990-2013 (Worldbank, 2015)

Urbanization patterns

Every ten years, starting in 1901, there is a census in the region that is now called Bangladesh (except in 1971, due to the independence war, the census was carried out in 1974 instead). Since 1974 people are asked to fill in a questionnaire to obtain, apart from the census, more demographic information from its inhabitants. Urbanization in Bangladesh is mainly the result of rural-urban migration and to a lesser extent population growth (Dewan & Yamaguchi, 2009). As shown in Figure 3, urban population[1] grew from 2.4% of the total population in 1901 to 28% in 2011.

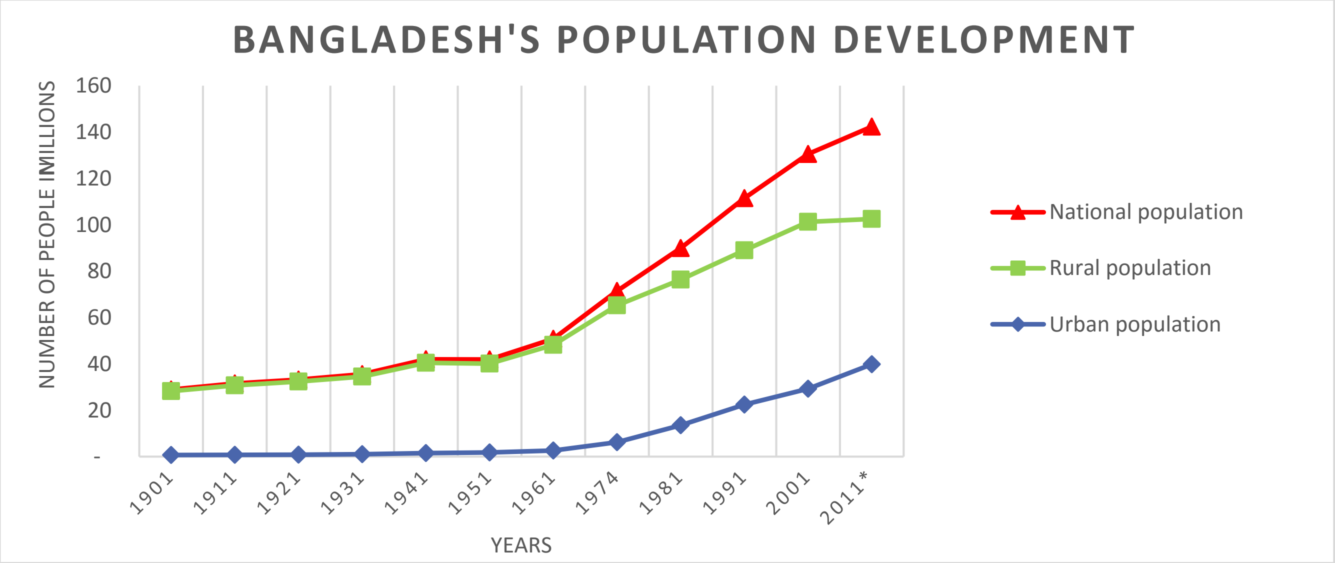

Figure 3: Population development (Bangladesh Bureau of Statistics, 2014)

Bangladesh experienced urbanization since its separation from India in 1947 when Dhaka became the provincial capital of East Pakistan. However, the real substantial urbanization started when Bangladesh became independent in 1971. The urban population grew fivefold in the period 1974-2011.

Figure 4 shows that the Dhaka division (for a map of the divisions, see Appendix A), which holds Dhaka, the nation's capital and largest city, had the fastest increase in the level of urbanization from 1961 to 2001. Meanwhile, the city of Dhaka ranked lowest in prosperity of the Asian countries by the City Prosperity Index (CPI) of the United Nations Habitat (2013). The CPI looks at productivity, quality of life, infrastructure, environment and equity in the cities. The highest-ranking Asian city is the Seoul with a CPI of 0.861, at place 24 of the 72 studied cities. New Delhi has a CPI of 0.635 at rank 55 and Dhaka has a CPI of 0.633 at 58, leaving only African cities behind. The same report gives the proportion of urban population living in slum areas (Figure 5) showing a large decrease for Bangladesh, but the share is still much larger than in China and India.

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[1] Urban population is here defined as the population living within urban areas that are defined by the Bangladesh' government

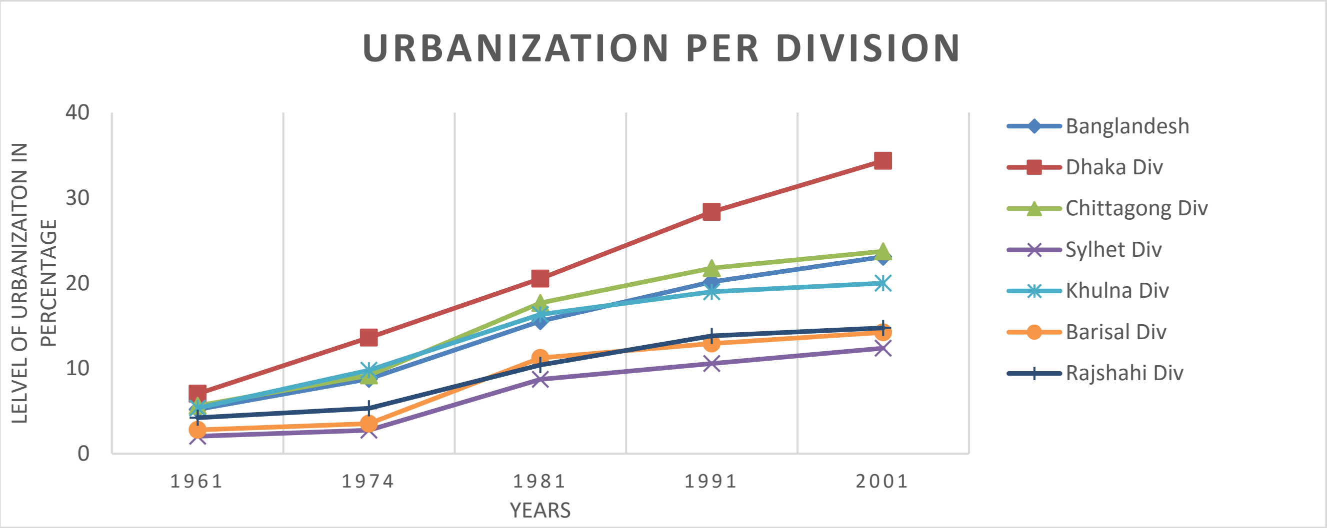

Figure 4: Urbanization per Division (Helas uz Zaman, Tariqul Alam, & Jahirul Islam, 2010)

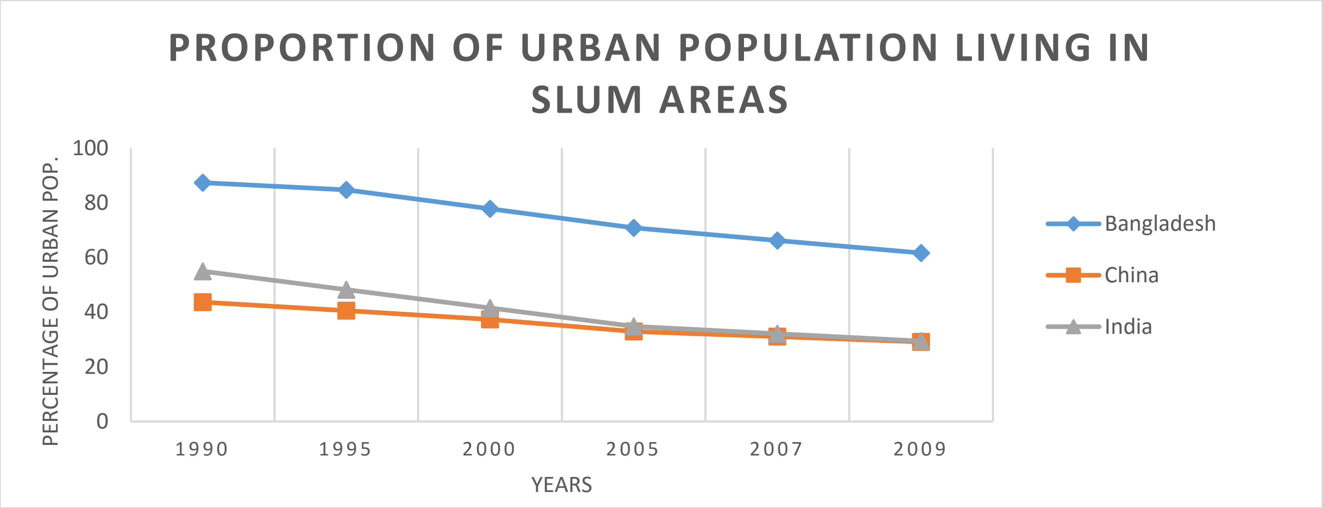

Figure 5: Proportion of urban population living in slum areas (United Nations Habitat, 2013)

In all possible futures, the population of Bangladesh will grow in the future, however to what extent and its spatial distribution will vary. Dhaka will most definitely grow as it is already the country's primary city. However, Dhaka is constrained by rivers and low-lying floodplains to the west, south and east. The floodplains east of Dhaka are increasingly developing into urban areas, while they are much more suitable for agriculture because they are often deeply flooded, making it poorly suited for urban and industrial use (Brammer, 2002; Khan, et al., 2015). There are three ways in which the land-use and land cover of a metropolitan area can change; infill (building on undeveloped spaces in gaps between developed areas), extension (urban growth that expands the contiguous built-up area), and leapfrogging (development of built-up areas that are disconnected from existing urban agglomerations). The urban development in Dhaka between 2000 and 2011 can be classified according to these three categories: infill 1.8%, extension 82%, and leapfrogging 16.2% (Dewan & Corner, 2014).

The best way for Dhaka to grow is towards the north, into the Gazipur District (leapfrogging). This area is moderate to well suited for urban or industrial uses, mostly because of its slightly higher elevation, greatly reducing flood risks (Brammer, 2002). This growth towards the Gazipur District is already happening, having the country's highest annual growth rate (3.78% between 1991 and 2011, and with the District of Dhaka being second at 3.69%), more than doubling its population from 1.6 million in 1991 to 3.4 million in 2011 (Bangladesh Bureau of Statistics, 2012). Therefore, it is expected that a large part of future population growth of Dhaka will be in the Gazipur District (Khan, et al., 2015).

Flooding in Bangladesh

Flooding[2] in Bangladesh is a normal and frequently occurring phenomenon, since 80% of Bangladesh are floodplains of the Ganges, Brahmaputra, Meghna and smaller rivers (Figure 6; Brammer, 1990). On average 21% of Bangladesh is flooded annually, during monsoon season (Dewan, 2015; Khan, et al., 2015). However, in extreme events the affected area can go up to two-thirds of the country and each year's highest flood record gets broken by subsequent years, and simultaneously do the damages (Figure 7 and Table 1). After the disastrous floods of 1987 and 1988, the Bangladesh' government requested funding for a Flood Action Plan from the Asian Development Bank to protect its most important cities. This resulted in the construction of flood protection embankments and flood wall around Dhaka, that were built to withstand a once-in-fifty-year flood (Asian Development Bank, 2002).

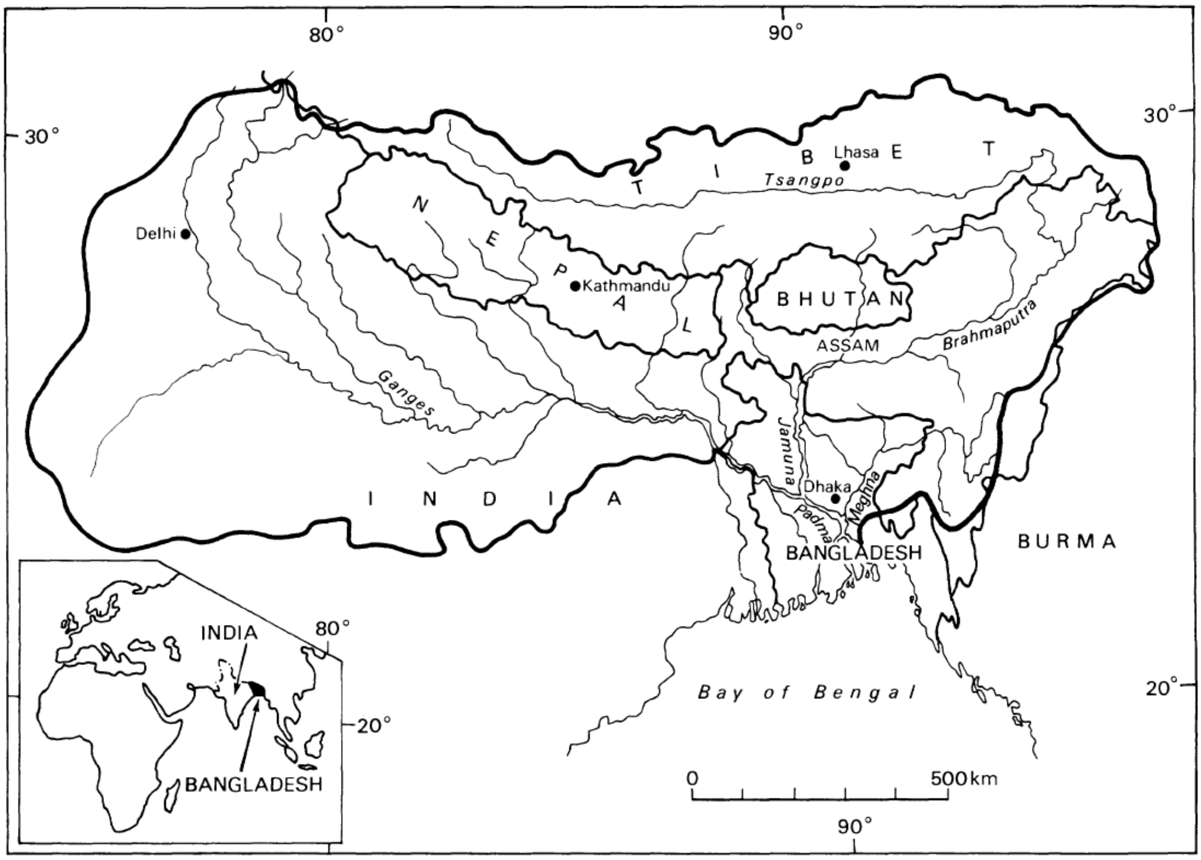

Figure 6: Catchment area of the Ganges, Brahmaputra and Meghna rivers (from Brammer (1990)

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[2] Flooding in this report will be defined as drainage congestion, which are events that occur relatively often with limited damage. While disastrous floods are defined as an extreme event that occurs less often, with much higher damages.

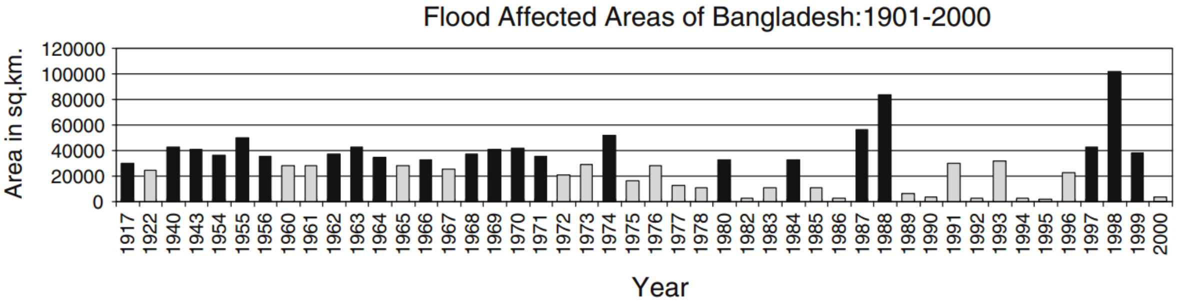

Figure 7: Occurrence of hazardous floods in Bangladesh: 1901–2000 (in black) (from Ali (2007)

Table 1: Historic floods in Bangladesh

Year	Area	Return period	Cause	Duration	Deaths	Affected	Source
1954	36,920 km2 (25%)	-	-	-	112	-	(Dewan, Nishigaki, & Komatsu, 2003)
1955	50,700 km2 (34%)	-	-	-	129	-	(Dewan, Nishigaki, & Komatsu, 2003)
1956	35,620 km2 (24%)	-	-	-	-	-	(Dewan, Nishigaki, & Komatsu, 2003)
1962	37,440 km2 (25%)	-	-	-	117	-	(Dewan, Nishigaki, & Komatsu, 2003)
1963	43,180 km2 (29%)	-	-	-	-	-	(Dewan, Nishigaki, & Komatsu, 2003)
1968	37,300 km2 (25%)	-	-	-	126	-	(Dewan, Nishigaki, & Komatsu, 2003)
1970	42,640 km2 (28%)	-	-	-	87	-	(Dewan, Nishigaki, & Komatsu, 2003)
1971	36,475 km2 (24%)	-	-	-	120	-	(Dewan, Nishigaki, & Komatsu, 2003)
1974	52,720 km2 (35%)	-	-	-	1987	-	(Dewan, Nishigaki, & Komatsu, 2003)
1984	28,314 km2 (19%)	-	-	-	553	-	(Dewan, Nishigaki, & Komatsu, 2003)
1987	57,300 km2 (40%)	30-70 yr	Rain	-	1657	-	(Brammer H. , 1990) (Dewan, Nishigaki, & Komatsu, 2003)
1988	82,000 km2 (60%)	50-100 yr	River	15-20 days	2379	45 mln	(Brammer H. , 1990) (Dewan, Nishigaki, & Komatsu, 2003)
1998	101,000 km2 (69%)	-	Rain + river	65 days	1100	30 mln	(Dewan T. H., 2015) (Dewan, Nishigaki, & Komatsu, 2003) (Ali, 2007)
2004	92,000 km2 (66%)	-	Rain + river	73	500	37 mln	(Harris, et al., 2008) (Ali, 2007) (Mahboob-ul-Kabir, Mahbubur Rahman, & Alam, 2006)
2007	82,000 km2 (60%)	-	-	84	500	20 mln	(Dewan T. H., 2015) (Harris, et al., 2008)

SECTION II: KEY CONCEPTS

In this section, the key concepts of the research will be discussed, based on a short literature review, and in the next section, a more elaborate explanation is given to their implementation in the context of this research. First, population projections methods and the relevance of scenarios are discussed, followed by a brief introduction to the urban driver analysis. These three are inputs for a land-use model (or urbanization model) which will subsequently be discussed and finally some basic flood risk concepts will be defined.

2.1 Population projections

Population projections are basic tools for planners, they can be used to determine how many people there will be in the future and where they are located. Projections are usually mathematical extrapolations of current trends and assumptions about the future (Stoto, 1983). They are often regarded, by users, as predictions; something that is likely to occur. However, that is often not the case, but they can be used to warn policy makers of current trends or illustrate results of different policies (Keyfitz, 1972). Population projections often contain several scenarios, like high, medium or low, as, for example, in recent Dutch scenarios on socio-economic developments (Bruggeman, et al., 2011). For such a mathematical extrapolation one could use the following basic equation:

$$P_{t+\theta} = P_t + f(\theta)$$

Where $P_{t+\theta}$ is population at any year $t+\theta$; P_t is population at base year t; θ is number of years from base year t to the forecast year $t+\theta$. The function f reflects the biological, social, economic, and political determinants of population growth (Isard, 1960).

Another method to obtain population projections is by a statistical analysis of land use demand, that will explain changes using variables that are assumed to be driving forces of the observed change (Hoymann, 2012). However, this method needs much data, for example: population, population density, number of employees, purchasing power parity, gross domestic product, age group, commuters, and attractiveness to tourist (Hoymann, 2012). In a data-scarce country like Bangladesh, such a method might prove to be difficult to implement. Another approach that would need very detailed data is the PEARL-model, developed by the Netherlands Environmental Assessment Agency (PBL) and the Netherlands Bureau of Statistics (CBS). It models population at a regional level by looking at household composition, household transition and migration figures in the Netherlands. This is now the primary model used in the Netherlands (de Jong, 2008).

A potentially useful method for Bangladesh is related to the trend extrapolation technique. The ratio method, wherein it assumes that the population growth in one area has a relationship to the growth in another area. This holds if there are interconnections among the social, economic, political and biological factors governing the growth in both areas (Isard, 1960). In this method, the growth rates can effectively change if the projected total of the larger parent area changes. This method shows improvement over regular extrapolation since it does not assume that the areas will grow in the future precisely as the pattern grew in the past (Isard, 1960). However, this method actually does not project the population, it rather allocates the already projected population totals over different spatial areas.

Such a ratio method that is well-known and widely used in the field of regional economics is the Shift-share analysis (Arcelus, 1984; Esteban-Marquillas, 1972; Knudsen, 2000; Stevens & Moore, 1980). This method is mostly used because little statistical information is needed while it offers many analytical possibilities (Esteban-Marquillas, 1972). The Shift-share analysis that was first proposed by Daniel Creamer in the 1940s and later formalized by Edgar Dunn in 1960, was extended by Esteban-Marquillas. The method is often used to express factors that influence growth among regions. Often for employment growth, the factors that are influential are three components: national growth, industry-mix and competitive effect:

$$d_{ij} = g_{ij} + k_{ij} + c_{ij}$$

d_{ij} is the employment growth in sector *i* of region *j*, g_{ij} is the national growth effect in sector *i* in region *j*, k_{ij} the industry-mix effect in sector *i* and of region *j* and c_{ij} competitive effect in sector *i* of region *j* (Esteban-Marquillas, 1972).

2.2 Scenarios

An often used definition for a scenario is that it usually provides a more qualitative and contextual description of how the present will evolve into the future, rather than one that seeks numerical precision. Based on that it tries to identify a set of possible futures, which occurrence is plausible, but not assured (Bunn & Salo, 1993; Schnaars, 1987). Important is that those scenarios provide multiple forecasts since a forecast is only as accurate as its underlying assumptions. Therefore, it is better to consider a number of plausible assumptions rather than one (Schnaars, 1987). These scenarios are cornerstones in between which it is likely that the actual future will develop. Scenario analysis has two primary goals, first to forecast the environment in which decisions have to be made, and second to evaluate strategic options against chosen scenarios (Bunn & Salo, 1993).

2.3 Urban driver analysis

Empirical estimation models describe the relationships between land-use changes and their drivers, using statistical techniques based on historical data (Hu & Lo, 2007). Logistical regression has often been used as an empirical estimation method for urban growth modeling (Allen & Lu, 2003; Hu & Lo, 2007; Landis & Zhang, 1998; Wu & Yeh, 1997). These statistical approaches can identify the influence of independent variables and provide a degree of confidence in the described relationships. These models fit spatial processes and land-use change reasonably well (Irwin & Geoghegan, 2001). The results from the logistical regression are urban growth probabilities, which is a convenient outcome to be used in a land-use model. The land-use change is dichotomous: presence or absence of urban growth (1 or 0). The probability of a land-use cell to change to urban follows the logistic curve, described by the logistic function (Kleinbaum, 1994):

$$f(z) = \frac{1}{1 + e^{-z}}$$

Wherein *e* is a mathematical constant, and *z* a value that represents the growth rate. The probability of a cell being urbanized can then be modeled by the following logistic regression model:

$$P(Y = 1|X_1, X_2, \ldots, X_k) = \frac{1}{1 + e^{-(\alpha + \sum_{i=1}^{k} \beta_i X_i)}}$$

$P(Y = 1|X_1, X_2, \ldots, X_k)$ is the probability of Y being 1 given the sum of all X's, meaning the probability of a cell being urbanized (Y=1) given its driving forces (the X's) (Hilferink & Rietveld, 1999; Hu & Lo, 2007; Koomen, Diogo, Dekkers, & Rietveld, 2015).

The drivers in the analysis can be categorized into two categories: static and dynamic. The static components are drivers that will, or are assumed to, not change in different time periods. Like distance to roads or elevation. The dynamic components are assumed to change over time, e.g. the number of urban cells within a 7x7 raster of a certain cell.

Logistic regression modeling allows for an inductive (data-driven) rather than a deductive (theory-based) approach to the choice of predictor variables (Hu & Lo, 2007; Kleinbaum, 1994; Koomen et al., 2015). Inductive approaches are rather popular since they seem to perform better in reproducing existing spatial patterns. However, the theory-based approach is better at understanding causal relations and ongoing processes. The use of either method is more dependent on the background of the researcher since geographers rather want to explain and describe spatial patterns (inductive), whereas economists rather focus on processes which they deduce from theoretical principles (deductive) (Koomen et al., 2015).

This thesis will use the inductive approach, even though the choice of predictor variables can arise from the data itself, the variables should still be chosen with care. A widely used set of determining factors for econometric and biophysical variables is 'SLEUTH' (Slope, Land use, Exclusion, Urban extent, Transportation, and Hill shade) as in Clarke's SLEUTH model (Ahmed & Bramley, 2015; Clarke, Hoppen, & Gaydos, 1997; Dietzel & Clarke, 2006; Yang & Lo, 2003). However, slope and hill shade are probably irrelevant for nearly all of Bangladesh, since most of the country is relatively flat (Ahmed & Bramley, 2015). Nevertheless, elevation might be a factor for flooding and the corresponding inundation depths (Dewan & Yamaguchi, 2008). A variable in order to consider spatial interaction effects is calculated by looking at the number of urban cells within a neighborhood of a cell (Hu & Lo, 2007). Population density is a variable that can be included because it is established to be a determinant to indicate labor availability, accessibility, or presence of local markets (Agarwal, Green, Grove, Evans, & Schweik, 2001; Allen & Lu, 2003; Hu & Lo, 2007). Several binary design variables should be constructed to distinguish between different land-use types (Hu & Lo, 2007).

2.4 Urban development models

Urban land-use systems are a result of human activities with complex spatiotemporal dynamics. Spatial dynamics, temporal dynamics, human drivers of land-use change and scale dynamics are important in land-use modeling (Veldkamp & Lambin, 2001). Rule-based simulation models and Cellular Automata models can incorporate the spatial and temporal dynamics, but these models focus on spatial patterns rather than understanding spatiotemporal processes of urban growth (Hu & Lo, 2007; Koomen, Stillwell, Bakema, & Scholten, 2007). Empirical estimation models simulate the relationship between land-use changes and the drivers, using statistical techniques based on historical data (Hu & Lo, 2007). The results from the logistical regression are urban growth probabilities, which is a convenient outcome to be used in a land-use model. To combine these two models, they are both incorporated in a hybrid dynamic land-use modeling framework in combination with population projections (Ahmed & Bramley, 2015). Most urban growth models do not differentiate between low- and high-density urban areas (Hu & Lo, 2007) while this might be an important aspect to consider.

Such a hybrid dynamic land-use model is the Land Use Scanner. Development of the model started back in 1997 by Hilferink and Rietveld (1999) and has since been used in a large number of policy-related research projects in the Netherlands and abroad (Koomen et al., 2015; Loonen & Koomen, 2009). The Land Use Scanner is a discrete choice model, which allows modeling the choices made by actors between mutually exclusive alternatives. For land-use modeling, this explains the probability that a certain use is chosen for a particular location, based on the utility or suitability[3] of that location for that land-use type (Koomen et al., 2015).

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[3] In land-use modeling, the concept utility is replaced by the term suitability.

The basic model used in the Land Use Scanner is a doubly-constrained logit model, which entails that a cell gets not just the land-use type allocated for which it has the highest suitability, but it also depends on the demand[4] for that land-use type and on the amount of land that is available. This relation is described by the following formula:

$$M_{cj} = a_j * b_c * e^{(\beta * S_{cj})}$$

Wherein, M_{cj} is the amount of land in cell c expected to be used for land-use type j. a_j is the demand balancing factor that ensures that the total amount of allocated land for land-use type j equals the sector-specific claim. b_c is the supply balancing factor that ensures that the total amount of allocated land in cell c does not exceed the amount of land that is available for that particular cell. S_{cj} is the suitability of cell c for land-use type j. β is a scaling parameter that specifies the importance of the suitability value that is usually left at a value of one (Koomen et al., 2015).

The allocation results from an iterative process in which it finds appropriate values for a_j to meet the demand (for more in detail information see Hilferink & Rietveld (1999).

This process of allocation can also be altered to allocate population instead of land-use types. Such an extension to the Land Use Scanner is being developed by the Netherlands Environmental Assessment Agency (PBL). They allocate population using the dynamic allocation procedure, which an iterative process that models urbanization for a number of future time steps (van Huijstee, et al., 2017).

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[4] The demand or claims, are external regional projections of land-use change.

2.5 Flood Impacts

Making cities more flood resilient can imply different strategies. Looking at impacts this could mean in the short term; loss of life, property damage, and failure of infrastructure. While in short to medium term; contaminated water and stagnant water can be the largest problems, due to the risk of spreading diseases. In the long term, economic consequences have proven to be a major problem (Hammond, Chen, Djordjevic, Butler, & Mark, 2013). For example, Thailand's GDP growth was 0.8% in 2011, compared to 7.5% and 7.3% in 2010 and 2012, because of the severe flood disaster in the fourth quarter of 2011 (Office of the National Economic and Social Development Board, 2015).

Flooding can occur through pluvial, fluvial, groundwater and coastal flooding. Pluvial flooding is the combination of heavy rainfall and poor urban drainage. The fluvial flooding comes from overtopping or bypassing of flood defenses adjacent to rivers. Groundwater flooding results from high groundwater levels and coastal flooding from tidal surges and waves (Hammond et al., 2013).

In countries like Bangladesh, floods are very common, yearly flooding is said to be preferable since it brings water and nutrients to agricultural areas, this has however never been proven (Brammer, 2004). The country has been dealing with this flooding since they first cultivated the area; the inhabitants have adapted their way of life to it. Hence, problems do not arise with this yearly flooding, but with more extreme floods that occur less frequently. Once every 10 years, there are severe floods that affect roughly one-third of the country. In the disaster years 1988, 1998 and 2005 more than 60% of the country was inundated for nearly three months (Brouwers, Akter, Brander, & Haque, 2007). Floods in Bangladesh are mostly caused by a large inflow from upstream catchments, low floodplain gradients, cyclonic storm surges, drainage congestion in older floodplain areas, effects of the confluence of the major rivers, siltation in dry seasons, and the overtopping and/or breaching of embankments (Tingsanchali & Karim, 2005).

The intensity of a flood corresponds with the chance of a certain event happening. A flood with a return period of once every 10 years is less extreme than a flood that occurs once every 50 years (Tingsanchali & Karim, 2005). As might be expected, floods have a different impact on different types of land-uses. Yearly flooding has a more or less positive impact on the agricultural areas while having a somewhat neutral effect on urban areas[5]. The more extreme floods have a negative impact on both agricultural areas and urban areas, albeit much more on urban areas since there are more people, property and economic activity vulnerable to floods (Hammond et al., 2013).

Flood risk is defined as the product of the probability of flooding and the consequential damage (exposure and its vulnerability), summed over all possible flood events (Figure 8; Hall, Sayers, & Dawson, 2005; Klijn, Samuels, & van Os, 2008). The probability is the chance that a certain flood occurs, exposure is, for example, the land-use of an area, and vulnerability is the amount of damage a flood can do. Scenarios have impacts on these components. Climate change mainly has an impact on the probability of a flood and the exposure. Moreover, socio-economic change will mainly have an effect on the vulnerability. There are numerous strategies that can diminish the component that comprises risk. Embankments can lower the probability that an area will flood, compartmentalization can mitigate the exposure by decreasing the affected area in case of a dike breach, and flood proofing houses can limit the vulnerability for floods (Figure 8; Klijn, Samuels, & van Os, 2008).

Flood risk or flood impact can be modeled, and several models are available for this purpose. These models combine four components: flood hazard (mostly inundation depth), the exposure (e.g. land use), the value of elements at risk, and the susceptibility of the elements at risk to hydrologic

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[5] Except for pluvial floods that inundate many cities multiple times a year.

conditions (e.g. depth-damage curves) (de Moel & Aerts, 2011). Such models can range greatly in complexity, they can simply intersect an assumed water level with a Digital Elevation Model (DEM) to define the flooded area, or they can incorporate three-dimensional topography, in which an inundation model is combined with hydrodynamic models and probabilistic dike breach models, such as the 3Di model by the 3Di Foundation (2014), and IHAM by Vorogushyn, et al. (2010) (Bates & de Roo, 2000).

One of the three-dimensional models is the Flood Impact Assessment Tool (Delft-FIAT) developed by Deltares. It is a model that links flood parameters to exposure characteristics of flood-prone areas (Wagenaar, Bouwer, Slager, & de Bruijn, in preparation). It uses water depth maps created, for example, by combining elevation from a Digital Elevation Model (DEM) and water heights for different frequencies from a 1D hydrological model for rivers and the Delft3D model for the coasts. Forthwith, it uses these water depth maps in combination with land-use maps to determine the impacts of floods. Different damage functions can be used; a 2 cm inundation depth will have a different impact than a 3-meter inundation depth. It can look at monetary damages, but also at affected people based on the population density. A damage function gives for each inundation depth a damage factor which can later be translated to monetary values or the number of affected people. Then the model calculates for each scenario, decade, and water depth the number of affected people and generates maps and statistics.

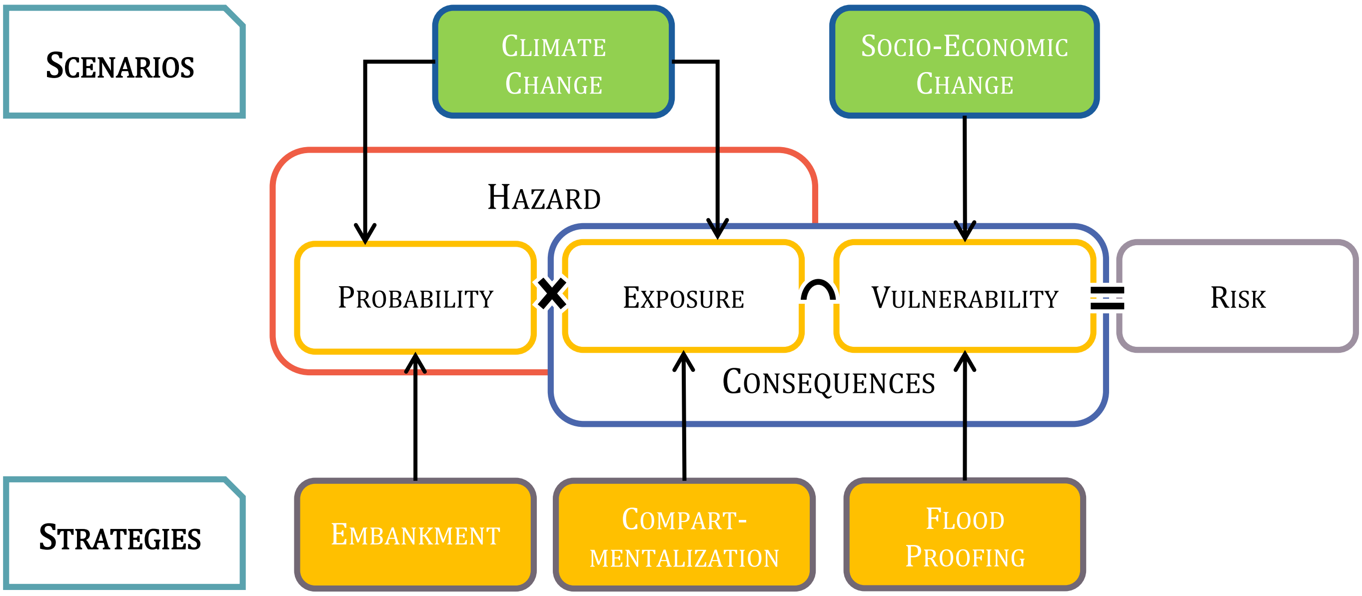

Figure 8: Flood Risk and its components (Klijn, Samuels, & van Os, 2008)

SECTION III: METHODOLOGY AND DATA

There are several steps in the process of trying to answer the research question (Figure 9). First, past changes are analyzed using a GIS transition analysis. Hereafter, the urbanization patterns are explained in the urban driver analysis using logistic regression. By applying this method, the different drivers will be assessed for their importance. Next, a land-use model is developed and adapted to simulate future population densities. To attach weights to urban drivers, the results from the Urban Driver Analysis are used. Population projections are used to allocate population in the urbanization model. The output of the model, population density maps for each scenario for each decade, are then used as input in the flood impact assessment. As an extension to the model, possible future policy interventions are added to the model to evaluate its implications on urbanization patterns and the corresponding land-uses.

The steps to be made are displayed schematically in the following flow diagram (Figure 9) and will be discussed on the following pages.

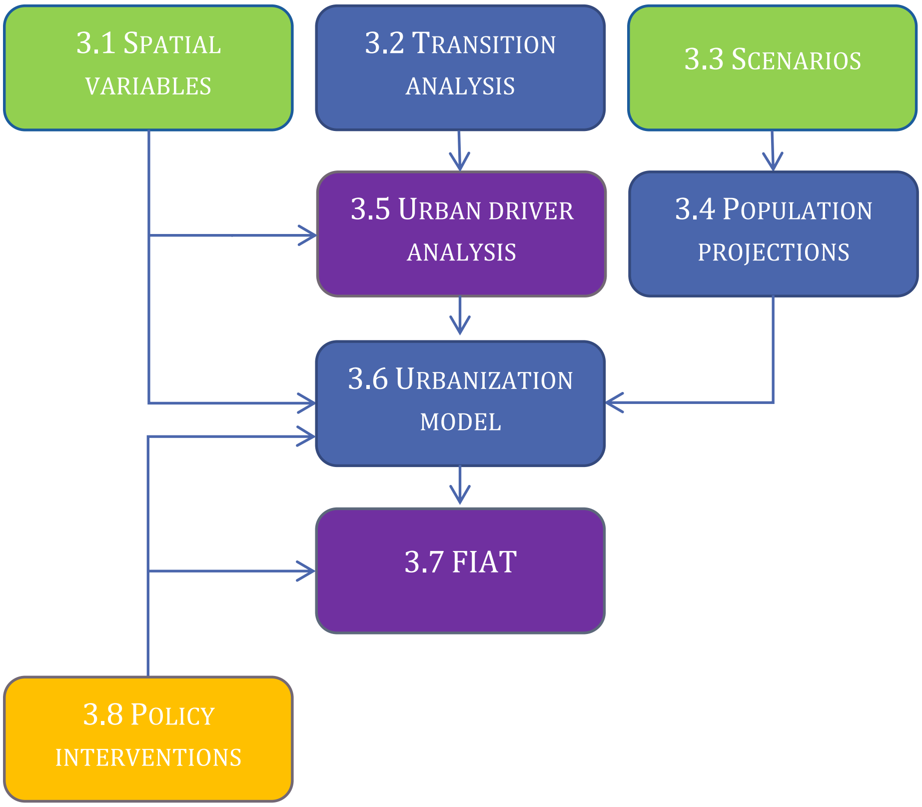

Figure 9: Schematic research set up

3.1 Spatial variables

Multiple spatial variables were created and incorporated in several steps of this research (Table 2). One of the most important variables is current land-use (2014) (Figure 10) and a historic land-use map from 1989 (Figure 11). These are classified land-use maps from a LANDSAT source obtained from CEGIS and NWRD in Bangladesh and made available in the database of the BDP2100 project. The maps miss a small part of the country at its very edges that are complemented with another land-use map (2010) obtained from CEGIS, to create a complete land-use map. These complemented maps are only used in the Urbanization model, not in the Urban Driver Analysis. Also, from CEGIS several infrastructural datasets are obtained: National, Regional, District, Upazila, Union and village roads, railroads and navigational rivers (see Appendix B). From the same source an elevation map (DEM), administrative boundaries (national, division, district, Upazila and Union level) and outlines of urban zones (City Corporations, District Paurashavas, and other Paurashavas) are obtained. Important to note is that in the remainder of this thesis there won't be a distinction between rural settlements and urban areas, due to data and time constraints. The terms settlement and urban areas will be used interchangeably in this report.

Table 2: Used data sets

Dataset	Type	Description
Historic land-use	Raster	Historic (1989) land-use divided into the land-use types mentioned in Table 3
Current land-use	Raster	Current (2014) land-use divided into the land-use types mentioned in Table 3
Infrastructure	Polyline	National, Regional, District, Upazila, Union and Village roads, railways and navigational rivers
Elevation	Raster	Digital Elevation Model and derived slopes
Population	Table	Population census 1991, 2001, 2011 at National, District, Upazila and Union level
Population projections	Table	Projected population for different scenarios per decade per District and Upazila
Zones	Polygon	Outlines of City Corporations, District municipalities, and Paurashavas
Annual floods	Raster	Areas that flood annually
Administrative boundaries	Polygon	Administrative boundaries: National, Divisions, Districts, Upazila's, Unions

Table 3: Land-use types in 2014 LANDSAT map

Endogenous						*Exogenous*	
Settlement	**%**	**Forest**	**%**	**Agriculture**	**%**	**Other**	**%**
Settlement	19.06	Forest	11.27	Current crop	26.71	Water	11.56
				Current fallow	29.41	Salt farm	0.16
				Sand	0.84		
				Shrimp farm	0.93		

The two land-use maps from 1989 and 2014 were readily available; both LANDSAT maps were already classified by CEGIS making it convenient to use. Moreover, LANDSAT gives a relatively good resolution. For example, a MODIS satellite image has typically a 300 to 1000-meter resolution, compared to the 50-meter LANDSAT resolution, making it less preferable to use.

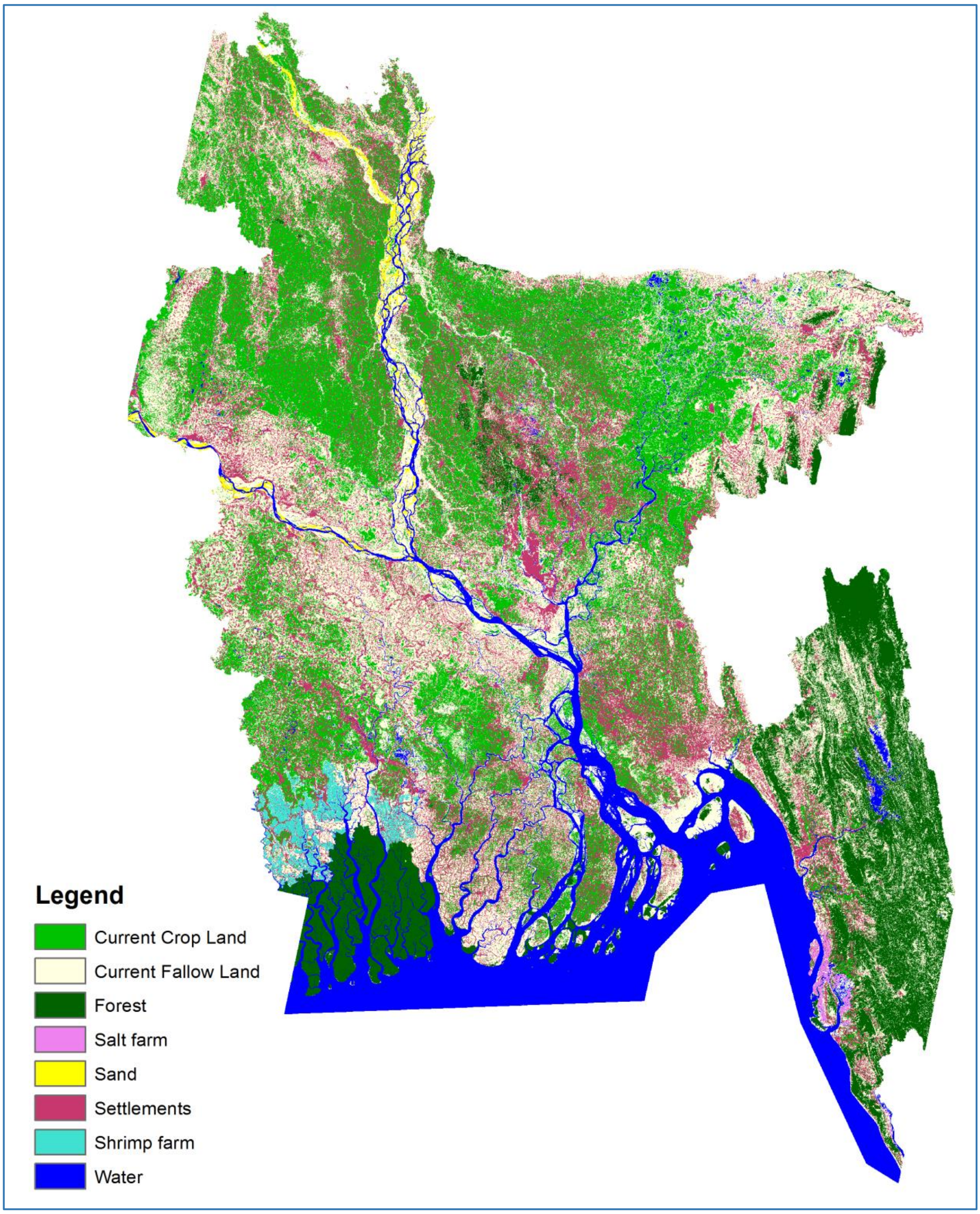

Figure 10: Land-use in 2014 (source: CEGIS)

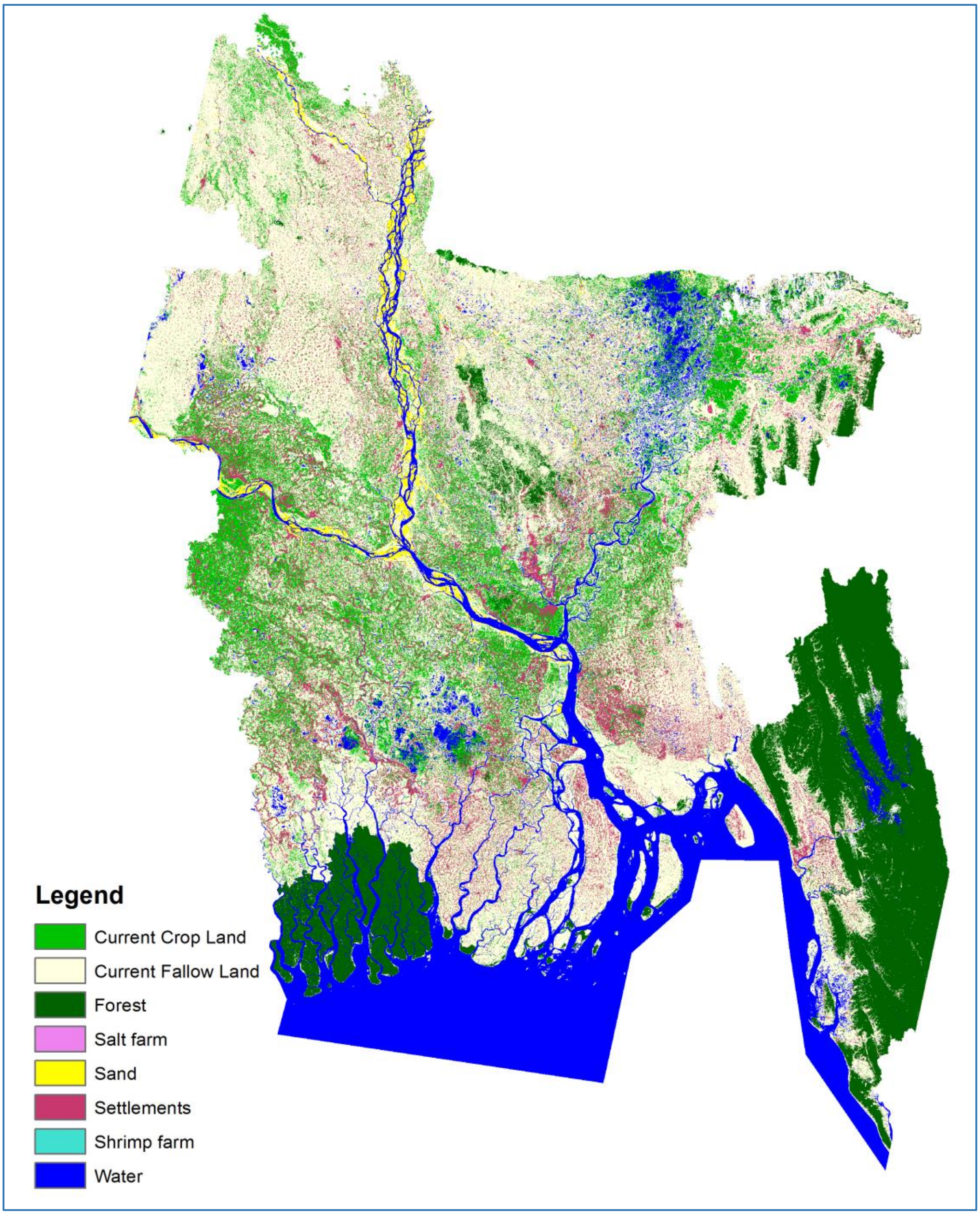

Figure 11: Land-use in 1989 (source: CEGIS)

3.2 Transition analysis

The two land-use maps from 1989 and 2014 are compared using ArcGIS 10.2. By comparing these two time steps, a transition matrix can be constructed. This matrix shows how much of each land-use type changed into another land-use type, between the two time periods. In the land-use map of 1989, there are no categories for shrimp farms and salt farms, which are present in the 2014 map.

3.3 Scenarios

In this thesis, four different scenarios will be used. These scenarios are developed in the Bangladesh Delta Plan 2100 and formulated in the Bangladesh Delta Scenario report. The four scenarios are the ‘Production’, ‘Resilient’, ‘Congestion’ and the ‘Stagnation’ scenarios (BanDuDeltAS, 2015).

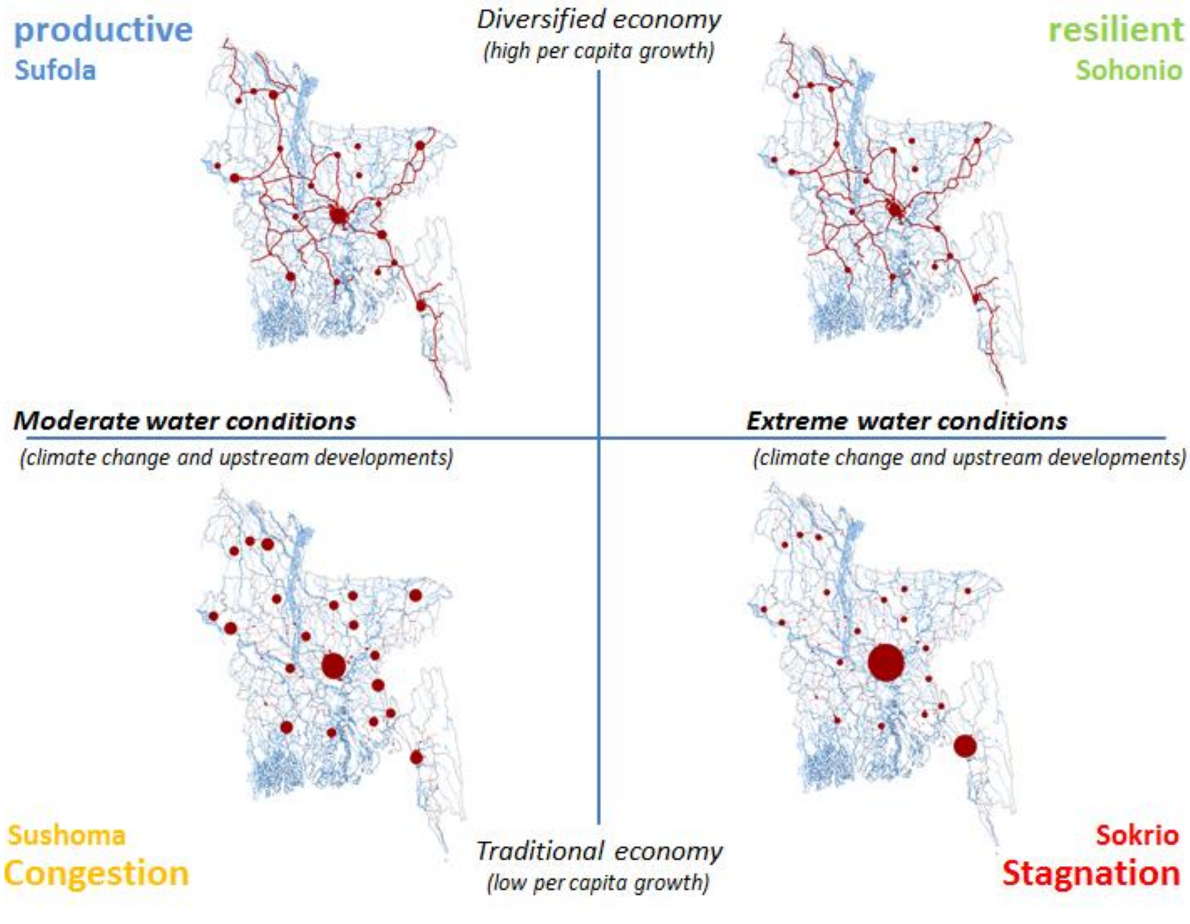

Figure 12: Overview of the four Delta scenarios (BanDuDeltAS, 2015)

These four scenarios follow a comparable scenario approach as in the IPCC reports. There are two main drivers that correspond to the two axes in Figure 12: future water conditions based on trans-boundary developments and climate change, and economic development and related land-use changes (BanDuDeltAS, 2015). The two top scenarios consider high economic growth while the bottom two, use low economic growth. Similarly, the left two scenarios are characterized by moderate water conditions and the right ones by extreme water conditions. From these scenarios the main driving forces for land-use change will be extracted and within this, the focus will lie on urban areas and infrastructure. There is deliberately chosen to not consider climate change because the focus in this thesis is more on the effects of urbanization and, it is also not incorporated due to time restrictions. And on top of that, it is argued that climate change has a smaller impact on flood risk than economic growth and population growth (Ward, et al., 2013; Winsemius, van Beek, Jongman, Ward, & Bouwman, 2013). A short summary of each scenario will be given in the next subsections.

3.3.1 Production scenario

The production scenario is characterized by increased GDP per capita, stabilizing population growth and large investments in infrastructure (see Table 4 below). The population will peak at 200 million in 2050. In this scenario, there is very high global economic growth in which Bangladesh actively participates. Bangladesh will become a middle-class country which results in a stabilizing population growth. The country will urbanize into some major hubs. Existing larger cities will grow fast due to foreign investments. It will result in more high-rise buildings and less informal housing. Agriculture will modernize and become more productive and produce high return agricultural products. As a result, the prospects for many of the rural population worsen and they migrate to cities. Consequently, second-tier cities start to emerge, relieving the largest cities. However, the growth is hampered by high transport costs, which results in large investments in infrastructure (BanDuDeltAS, 2015).

3.3.2 Resilient scenario

In this scenario, there is high global economic growth, which benefits Bangladesh and results in a high GDP growth. Many people will seek opportunities outside Bangladesh. This high out-migration combined with a decreasing fertility rate will result in the lowest population of the four scenarios, 175 million in 2030 and down to 125 million in 2100. The agriculture is modernizing and the economy is diversifying. The country will urbanize to 60% in 2050 and agri-business hubs will emerge, with an increased urban-rural connectivity. In this scenario, the country will develop into a resilient country with a stable economic growth per capita that is equally distributed (BanDuDeltAS, 2015).

3.3.3 Congestion scenario

The congestion scenario is characterized by a low GDP growth and a moderate global growth. Bangladesh will have to compete with other developing countries over low-value production and protectionism grows. The population will grow to 212 million in 2060 and down to 190 million in 2100 due to high fertility rates and low out-migration. Dhaka and Chittagong will grow unsustainably due to a lack of good connectivity and urban infrastructure. There will be a lot of urban sprawl and 52% of the population will live in cities by 2050 and 70% in 2100 (BanDuDeltAS, 2015).

3.3.4 Stagnation scenario

The stagnation scenario depicts a stagnation of GDP per capita growth due to unfavorable economic growth conditions and an exponential population growth (see Table 4). The population will continue to grow to 260 million in 2100. Due to the stagnation of global economic growth, there is a decrease in global demand for low-value products, resulting in a growing pool of unemployed low-skilled laborers. Many people move to Dhaka, which is growing exponentially. At the same time, due to a lack of urban opportunities and investments, a large part of the population is forced to remain in rural areas, dependent on self-sufficient rice farming. This results in a rapid growth of the largest cities combined with high urban sprawl while the rural population also remains large and highly scattered. There are no investments in infrastructure (BanDuDeltAS, 2015).

Table 4: Key characteristics of the Delta scenarios

Scenario	Economic Growth	Infrastructure	Population (in mln)		Urban population	
			2050	2100	2050	2100
Production	++	++	200	165	70%	85%
Resilient	+	++	170	125	60%	75%
Congestion	+-	-	210	190	52%	70%
Stagnation	-	--	230	260	48%	60%

The results from these scenarios in the land-use model will give four cornerstones to create a range wherein possible futures will lie. It can be used for a what-if approach, as a way to evaluate proposed strategies (policy interventions).

3.4 Population projections

To allocate the future population in the urban development model, population projections will be created. In order to do this, the Shift-share method is applied to historical population census data per District level (64 districts) and Upazila level (544 Upazilas, an administrative boundary, from big to small: National, Division, District/Zila, Upazila/Thana, Union). In the BDP2100 project, there was already a population projection provided by Leo Beumer from ECORYS within the Bangladesh Delta Plan at a District/Zila level, albeit for different scenarios. Initially, a more detailed projection seemed preferable for this research and was thus created. But due to allocation restrictions, the district level projections were chosen. Because if the regions to allocate in are too small, while the projected growth is very large, they reach quickly their maximum population density, all the while this excess population should have been spilled over to adjacent regions.

To create the population projections, the Shift-share method, as mentioned in the literature section, is applied to census data from 1991, 2001 and 2011 (obtained from the Bangladesh Bureau of Statistics (BBS). However, unlike the Shift-share method, as mentioned earlier, the interests in this research lie not in employment growth or different sectors, but in population growth in different regions based on historical trends. Therefore, the Shift-share function is adapted for these goals into an approach proposed by Smith & Sincich (1988):

$$P_{tj} = P_{tn}\left[\frac{P_{lj}}{P_{ln}} + \frac{x}{y}\left(\frac{P_{lj}}{P_{ln}} - \frac{P_{bj}}{P_{bn}}\right)\right]$$

Wherein P_{tj} is the population in the target period t of region j, P_{tn} is the national population in target period t, P_{lj} is the population in the launch[6] period for region j, P_{ln} is the national population in the launch period, P_{bj} is the population in the base[7] period for region j, P_{bn} is the national population in the base period, x is the number of periods in the projection horizon, and y is the number of periods from the base period till the target period (Smith & Sincich, 1988; Smith, Tayman, & Swanson, 2013). The population in the base and launch periods are easy to obtain from the census data. However, the national population in the target period is not. These are projections itself and were discussed in the previous section about the scenarios.

Historical growth rates may not always be accurate to extrapolate into the future. If a certain region has an exceptionally high growth rate, that growth rate will probably not stay constant, and is likely to decrease over time (Smith, Tayman, & Swanson, 2013). Some alterations must be made to correct for this. This is relevant for the Dhaka, Chittagong and Gazipur Zila's (Districts). According to the projections (production scenario) without an alteration, Dhaka will grow from 12 million in 2010 to 69 million in 2100 and Gazipur from 3 to almost 42 million in 2100. If the growth rate diminishes with 10% each period, these projections will decrease to 32 million and 20 million respectively. Moreover, some other Districts will be adjusted to give a more realistic projection. It is expected that most of the Division capitals will grow more than their historical trend projects. Therefore, their growth rate is set at 20%[8] in the first period and diminishes over time at a rate different for each scenario. Additionally, several other Districts manually got a higher growth rate (20%), these are Bogra, Naogaon, and Patuakhali. They got these higher growth rates because of the planned Bangladesh-China-India-Myanmar (BCIM) Corridor (a major infrastructural plan to connect India and China) and the plans to build the seaports; Payra Port, Mongla Port, and Sonadia Port (see Figure 1).

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[6] The launch period is the year from which the projection is started, in this case 2010.

[7] The base period is the year from which the historical time series begins, in this case 1991.

[8] This percentage is highly subjective, however, it is based on expert judgement.

The projections will use the national population per decade from the different Delta scenarios; Productive, Resilient, Congestion, and Stagnation. These population projections are then spread over the 64 Districts or 544 Upazila's.

3.5 Urban Driver Analysis

To determine weights for the urbanization factors that are used in the land-use model, a statistical analysis of historical urbanization is performed. First historical land-use changes between 1989 and 2014 are analyzed. Then from each cell with new urban areas, the distance to relevant factors will be calculated. Distance from new urban areas to already existing urban areas, infrastructure, economic centers, etc. Furthermore, population growth or density per administrative region will be incorporated into the analysis. Then a logistic regression analysis is performed to obtain possible relationships. This can later be used as weights in the land-use model.

The two land-use maps that will be compared are from 1989 and 2014, both from March in the dry season. By subtracting the urban-cells, the results are new urban areas developed between 1989 and 2014. However, in this comparison, some cells that had urban areas in 1989 now are not urban in 2014. It is unlikely that urban area disappeared; it is more likely that this results from a classification difference in the two datasets and is therefore discarded in further analysis. This process results in a variable 'newurb', in which a cell is of a dichotomous nature, it is 1 if it is urban in 2014 and 0 if it is not (Figure 16).

The infrastructure datasets mentioned in Section 3.1 are used to create distance raster maps by calculating for each cell the Euclidean distance to the nearest feature for which the map is made, e.g. railroads. The existing urban areas are treated similarly, these are cells that were already urban in 1989, 'eucdist_oldurb'. The existing urban areas dataset is also used to create a layer in which each cell gets a value corresponding to the number of urban cells in a 7x7 cell perimeter around itself, called 'urbprox'.

The administrative boundaries of City Corporations, District municipalities, and Paurashavas are used to represent some form of urban centers. These boundaries are at three different hierarchical levels, of which City corporations can represent the Division capitals, the District municipalities the District capitals and the Paurashavas Municipal capitals. However, not at each level, all capitals are included because they are deemed too small by the Bangladesh' government. The population density per Union in 2011 is rasterized, just as the upper poverty rate dataset.

Not all cells are included in the analysis for computational reasons; alternatively, a random sample has been created to obtain 122.938 points, which are derived from a grid with points at one-kilometer intervals. The coordinates are then allowed to randomly deviate up to 1 km in all directions from the origin. Next, the sample tool is used in ArcGIS to extract the variable values from a set of raster datasets. After that, the values are exported to a table format to be loaded into the statistical software package STATA.

The following table shows the descriptives of all variables that can be used, all the distance variables are also log transformed[9] to be normally distributed.

Table 5: Urban driver analysis descriptives

Variable STATA	Description	Obs	Mean	Std. Dev.	Min	Max
newurb	New urban area (dichotomous)	122937	0.11	0.31	0	1.00
eucdist_oldurb	Dist to existing urban cell in 1989 (m)	122937	2279.44	6267.29	1	60417.72
eucdist_ndr	Dist to Nat, District, Regional roads (m)	122937	4893.31	6853.27	1	66295.47
eucdist_upar	Dist to Upazila road (m)	122937	2833.13	5396.50	1	61807.86
eucdist_natr	Dist to National road (m)	122937	20806.14	18826.83	1	100855.60
eucdist_rail	Dist to Railroad (m)	122937	24162.18	24567.60	1	174745.30
eucdist_unir	Dist to Union road (m)	122937	2450.80	5034.70	1	63333.61
eucdist_regr	Dist to Regional road (m)	122937	15337.82	14424.24	1	105318.90
eucdist_navr	Dist to Navigational rivers (m)	122937	20368.02	26002.94	1	160689.50
eucdist_disr	Dist to District road (m)	122937	6306.88	7363.94	1	66295.47
eucdist_vilr	Dist to Village road (m)	122937	11062.49	10819.25	1	76405.77
eucdist_cc	Dist to City Corporation (m)	122937	54094.11	27059.79	1	186975.60
eucdist_gazicc	Dist to Gazipur CC (m)	122937	151207.70	76082.90	1	411102.10
eucdist_distm	Dist to District municipality (m)	122937	21709.38	14740.45	1	105112.10
eucdist_paura	Dist to Paurashava (m)	122937	11808.99	11055.80	1	94198.78
dem	Elevation (cm)	122937	2661.49	6322.99	-39	94006.00
popdens	Population density (pers/km^2)	122937	914.88	1444.45	0	107234.00
poppov	Population below upper poverty rate (%)	122937	33.19	12.99	0	68.80
annexpo	Annual flooded area (dichotomous)	122937	0.20	0.40	0	1.00
urbprox	No. of urban cells within 7x7 window	122937	1.93	4.99	0	47.00
lnoldurb	Ln Dist to existing urban cells in 1989	122937	6.02	1.72	0	11.01
lnupar	Ln Dist to Upazila road	122937	7.09	1.44	0	11.03
lnnatr	Ln Dist to National road	122937	9.40	1.29	0	11.52
lnrail	Ln Dist to Railroad	122937	9.50	1.30	0	12.07
lnunir	Ln Dist to Union road	122937	6.93	1.44	0	11.06
lnregr	Ln Dist to Regional road	122937	9.13	1.21	0	11.56
lnnavr	Ln Dist to Navigational rivers	122937	9.13	1.49	0	11.99
lndisr	Ln Dist to District road	122937	8.15	1.28	0	11.10
lnvilr	Ln Dist to Village road	122937	8.84	1.12	0	11.24
lncc	Ln Dist to City Corporation	122937	10.65	1.13	0	12.14
lngazicc	Ln Dist to Gazipur CC	122937	11.71	0.98	0	12.93
lndistm	Ln Dist to District Municipality	122937	9.67	1.15	0	11.56
lnpaura	Ln Dist to Paurashava	122937	8.83	1.59	0	11.45
lu89sand	Sand land-use in 1989	122937	0.02	0.13	0	1.00
lu89crop	Crop land-use in 1989	122937	0.70	0.46	0	1.00
lu89forest	Forest land-use in 1989	122937	0.00	0.00	0	0.00

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[9] When using the term log transformed, it will always refer to the natural logarithm.

3.5.1 Logistic regression

Then the logistic regression will be performed, but first, the right specification must be determined, and additional tests can be carried out to test the robustness of the regression. Moreover, the regression will be carried out using robust standard errors which improve the regression in such a way that it corrects for heteroscedasticity, the variance, in the error terms.

Variable selection

There are several methods available to determine which specification of the model should be used. A widely used tool is the Likelihood-ratio test. In this test, you compare a specification to a reduced version of it. The output tells you if the null-hypothesis, that the coefficients of the variables left out in the reduced version, is equal to zero. So it tests if removing the variables has no effect so that it does not lead to a poorer-fitting model (Chen, Ender, Mitchell, & Wells, 2016). The full model is then a specification that holds all the variables that are thought to be important, which is discussed in the literature section. This method will be used to determine the best specification.

Influential observations

There might be influential observations present in the dataset, these single observations may have a significant impact on the model. It is, therefore, possible that they might skew the regression estimation. To check for influential observations, one can plot the predicted probabilities against the standardized Pearson residuals. The Pearson residuals measure the relative deviations between the observed and fitted values. In a logistic regression the sum of the deviance residuals is minimized, so if there is one observation with exceptional high relative deviation, it will impact the estimation. The resulting graph of the predicted probabilities against the standardized Pearson residuals will show whether there are large outliers (see Figure 27 in Appendix C). In this case, one observation was such an outlier with a residual of -56 compared to the next lowest residual of -8. Inspecting this observation showed that it had the third highest population density, while not being urban. This is clearly a data error resulting from combining different data sources. Consequently, this observation is omitted.

3.6 Urbanization model

The basic layout of the Land Use Scanner is displayed in Figure 13. The four scenarios are used for the region demand/claims.

The suitability in the land-use model is a combination of positive and negative factors. The land-use type with the highest value or suitability will be allocated to that cell. To achieve this, a suitability map for each land-use type was created. The suitability of a cell depends mostly on its surrounding cells. For example, urban land-use: if the population grows in an administrative area, there will be a higher demand for urban land-use in this area (urban is, for lack of detail, a combination of residential areas and industrial areas). Where this additional urban area will be located depends on the proximity to existing urban area and to the proximity to infrastructure, since urban areas tend to develop near major infrastructure. The proximity is valued by a logarithmic function, cells closer to this process will get the highest value and cells further away a lower value. This method gives for urban areas an expansion around current urban areas and around current infrastructure. Each cell gets a positive value added for its proximity. However, in this expanded area there are already other land-use types. Current land-use might be protected by policy (e.g. nature areas). To take this into account, a high negative value for that land-use type will be given to that cell, decreasing the value in that cell for urban, making it less suitable for urban. Many other factors can be included that can influence the suitability for a land-use type. The transition costs might play an important role for certain land-use types. Areas that have a high flood risk are less favorable for urban areas while flooding might be beneficial for certain agricultural land-use types. On the other hand, flash floods and cyclones will be negative for all land-use types. The risk for those factors varies spatially and thus, can be incorporated into the suitability maps, but will not be done in this research.

So in each suitability map for a certain land-use type, each cell gets a value. First, a positive value if the cell has already the land-use type for which the suitability map is created. Next, it gets positive values for proximity to beneficial land-use types. Negative values are obtained when there are detrimental factors in that cell. On top of that, it will get a negative value if the cell has a protected status. If all the factors for each cell in the suitability map are accounted for, they will be summed to give a value for each cell. Thereafter all the suitability maps for the different land-use types will be overlaid.

The magnitude of the values that are given for each factor, are derived from the statistical analysis of historical urbanization to obtain the urbanization drivers (discussed in section 3.5 Urban Driver Analysis) and are shown in a table in Appendix D.

From this point the urbanization model will be different from the basic Land Use Scanner, instead of allocating land-uses, it will allocate population according to the external claims at a district level, taking the calculated suitabilities into account. This results in future spatially distributed population densities for each decade and for each scenario.

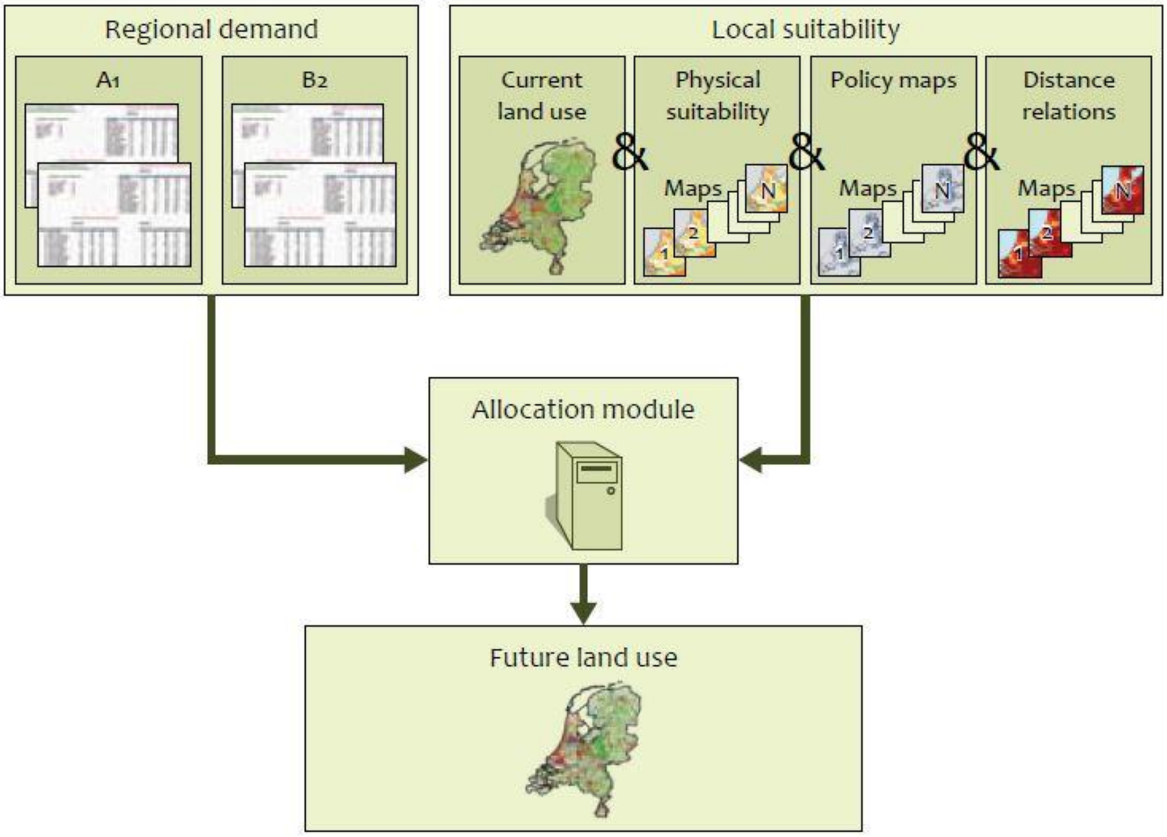

Figure 13: Basic layout of the Land Use Scanner (from Loonen & Koomen, 2009)

3.7 Flood Impact Assessment

The Flood Impact Assessment Tool (Delft-FIAT) developed by Deltares is a model that links flood parameters to exposure characteristics of flood-prone areas (Wagenaar, Bouwer, Slager, & de Bruijn, in preparation). The output maps of the Urbanization model will be used as an input in Delft-FIAT. These population density maps per scenario at different time steps can be loaded into the model.

In the model, a depth-damage function can be chosen or constructed and four water depth maps are included. These correspond to flood intensities that happen once every 10, 25, 50 and 100 years[10] (IWM, 2015 for the BDP2100 Project; see Appendix E). Then the model calculates for each scenario, decade, and water depth the number of affected people and generates maps and statistics. This results in 160 maps and tables of results, because of ten time steps, four scenarios, and four water depths give 160 different combinations. In Figure 14 an example of the number of affected people per return period is shown. If one would want the total affected people if all events would occur, you would take the integral of the line to get the area beneath the line to get the total amount of affected people for all return periods (both axes are not properly scaled). Delft-FIAT will give an output in terms of annual expected affected people, this means that each return period is included, but is scaled for each year. A flood with a return period of 100 years is much more severe but does only happen once every 100 years. But each year there is a chance of this event happening, hence, these values are incorporated in the number of annual expected affected people. In the end, this is a risk parameter; e.g. in the case of damage, one would call this damage risk or annual expected damage.

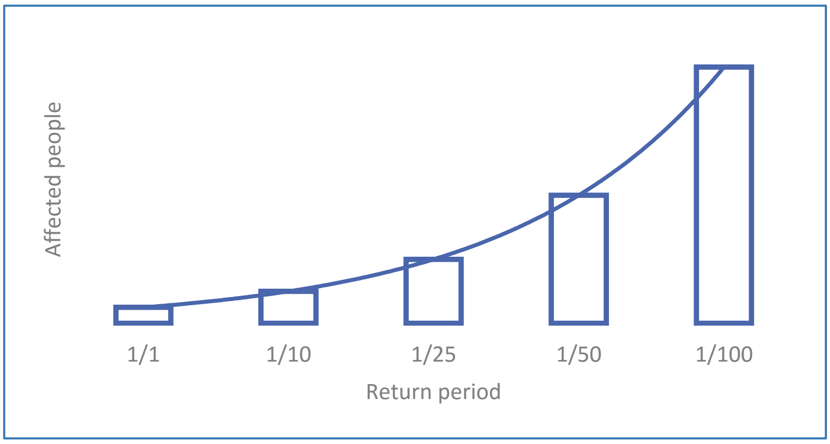

Figure 14: Amount of affected people per return period

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[10] The 1:1 flood event, is subtracted from each other map, because these floods are assumed to not be damaging or may even be beneficial to agricultural areas.

3.8 Policy interventions

As an extension to the flood impact assessment, discussed in the previous subsection, several policy interventions can be modeled and evaluated. Two types of interventions are chosen; 'embankment improvement', in which existing dikes are heightened or more dikes are built; and 'flood proofing', wherein the building's height above ground level are varied. Additionally, these two types are also combined (see Table 6). These interventions are chosen to represent the extremes of the full range of interventions possible. As such, one gets an idea about the effectiveness of an intervention or combination. However, the costs are not involved, as some interventions will be much costlier than others. Costs should be involved to be able to really compare interventions.

The embankment improvement (EI) variant has two versions, a and b, EI-a is where all the existing dikes are heightened to withstand a flood with a return period of 1:50 years and EI-b is if the entire country is embanked to withstand a flood with a return period of 1:50 years (this will give just an indicative result since this not a very realistic option).

The flood proofing (FP) variant has five versions, which represent five different building heights; 0 cm, 30 cm, 60 cm, 90 cm and 120 cm above ground level. The 30 cm version is equal to the regular flood impact assessment from the previous subsection.

Table 6: The different variants used in the FIAT

Variants	Description
Base	This is regular case that is described in subsection 3.7
EI-a	Existing dikes heightened to withstand a flood of 1:50 years.
EI-b	Entire country embanked to withstand a flood of 1:50 years.
Flood Proofing	Change the height at which houses are built above ground (0, 30, 60, 90 and 120 cm).

The two embankment improvement versions are calculated for each of the four scenarios and for different time steps. The five flood proofing versions are calculated for the four scenarios and only in the year 2050. This is not only calculated for the base variant, which is the one calculated in the previous subsection, but also for EI-a and EI-b for comparison.

The embankment improvement variants are created by altering the water depth maps. The current dikes in Bangladesh, in a dataset obtained for CEGIS, are built to withstand a flood with a return period of 1:25 (WARPO, 2001). For the EI-a variant, in the water depth map of 1:50 the currently diked areas[11] are clipped out so that only the areas that will still be flooded by a 1:50 flood remain. For the EI-b variant, only the water depth map for 1:100 is considered in the calculation since the entire country would be protected against a 1:50 flood.

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[11] Protected areas within the BWDB project categorized as having flood control or town protection

To calculate the flood proofing variants, five different depth-damage functions (Figure 15) are used corresponding to the building heights, and the water depth maps for the base, EI-a, and EI-b variants are used. The depth-damage functions indicate at what water depth people are affected, the 30 cm line indicates that if an area gets flooded by 10 cm, no one is affected, but if it is flooded by 40 cm, everyone in that area with that inundation depth is affected.

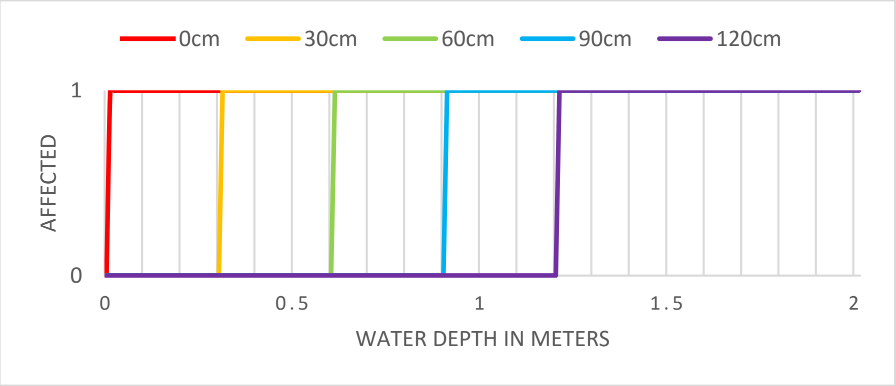

Figure 15: Depth-damage functions corresponding to water depth and building height

SECTION IV: RESULTS

4.1 Transition analysis

Table 7 shows the transition matrix and can be interpreted as follows: 68% of the water in 1989 is still water in 2014, and 15% of the water in 1989 is converted into fallow agricultural land[12]. These values can also be flipped to look at the changes from 2014 to 1989 (Table 8), this shows that 83% of the water in 2014 was already water in 1989. But more interesting is the value for settlement, it shows that only 51% of the settlements in 2014 were there in 1989, which means that the amount of settlement has doubled in those 25 years. This can also be seen when looking at the totals, Table 7 shows that in 1989 10% was settlement, compared to 19% in 2014. This change in settlement is shown in Figure 16, the change between 1989 and 2014 is red and the existing settlements are in gray. The 1989 value of 10% compares very well to the 9% figure from the 1991 official census (WARPO, 2001, p. 16). Moreover, the Bangladesh Bureau of Statistics (2014) did release figures about the extent of urban areas, which are 6% of the country in 2011. These urban areas contain only larger cities and thus no rural built-up areas. Moreover, a report from Hasan et al. (2013) found that 6.3% was settlement in 1976, 10.36% in 2000 and 12.72% in 2010. Considering these facts, the used land-use maps may prove to be quite accurate.

Table 7: Transition matrix of land-use change, 1989-2014

		Land-use map 2014								
		Water	Fallow	Crop	Settlement	Forest	Sand	Cloud	Shrimp	Salt
Land-use map 1989	Water	68%	15%	11%	0%	3%	2%	0%	0%	0%
	Fallow	3%	37%	41%	14%	2%	1%	0%	2%	0%
	Crop	1%	46%	36%	15%	0%	0%	0%	0%	0%
	Settlement	1%	1%	4%	94%	0%	0%	0%	0%	0%
	Forest	1%	20%	3%	3%	73%	0%	0%	0%	0%
	Sand	17%	53%	7%	2%	0%	20%	0%	0%	0%
	Cloud	3%	54%	13%	9%	20%	0%	1%	0%	0%
	Shrimp	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Salt	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Total	12%	29%	27%	19%	11%	1%	0%	1%	0%

Table 8: Transition matrix of land-use change, 1989-2014, flipped

		Land-use map 2014									
		Water	Fallow	Crop	Settlement	Forest	Sand	Cloud	Shrimp	Salt	Total
Land-use map 1989	Water	83%	7%	6%	0%	3%	27%	6%	7%	28%	14%
	Fallow	11%	58%	72%	35%	7%	33%	42%	86%	72%	46%
	Crop	2%	22%	18%	11%	1%	6%	33%	7%	0%	14%
	Settlement	1%	0%	2%	51%	0%	0%	1%	0%	0%	10%
	Forest	1%	9%	2%	2%	88%	0%	6%	0%	0%	14%
	Sand	2%	3%	0%	0%	0%	33%	0%	0%	0%	1%
	Cloud	0%	1%	0%	0%	1%	0%	12%	0%	0%	1%
	Shrimp	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Salt	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

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[12] This can have many reasons, it might be a classification error, or it might be newly accreted river lands.

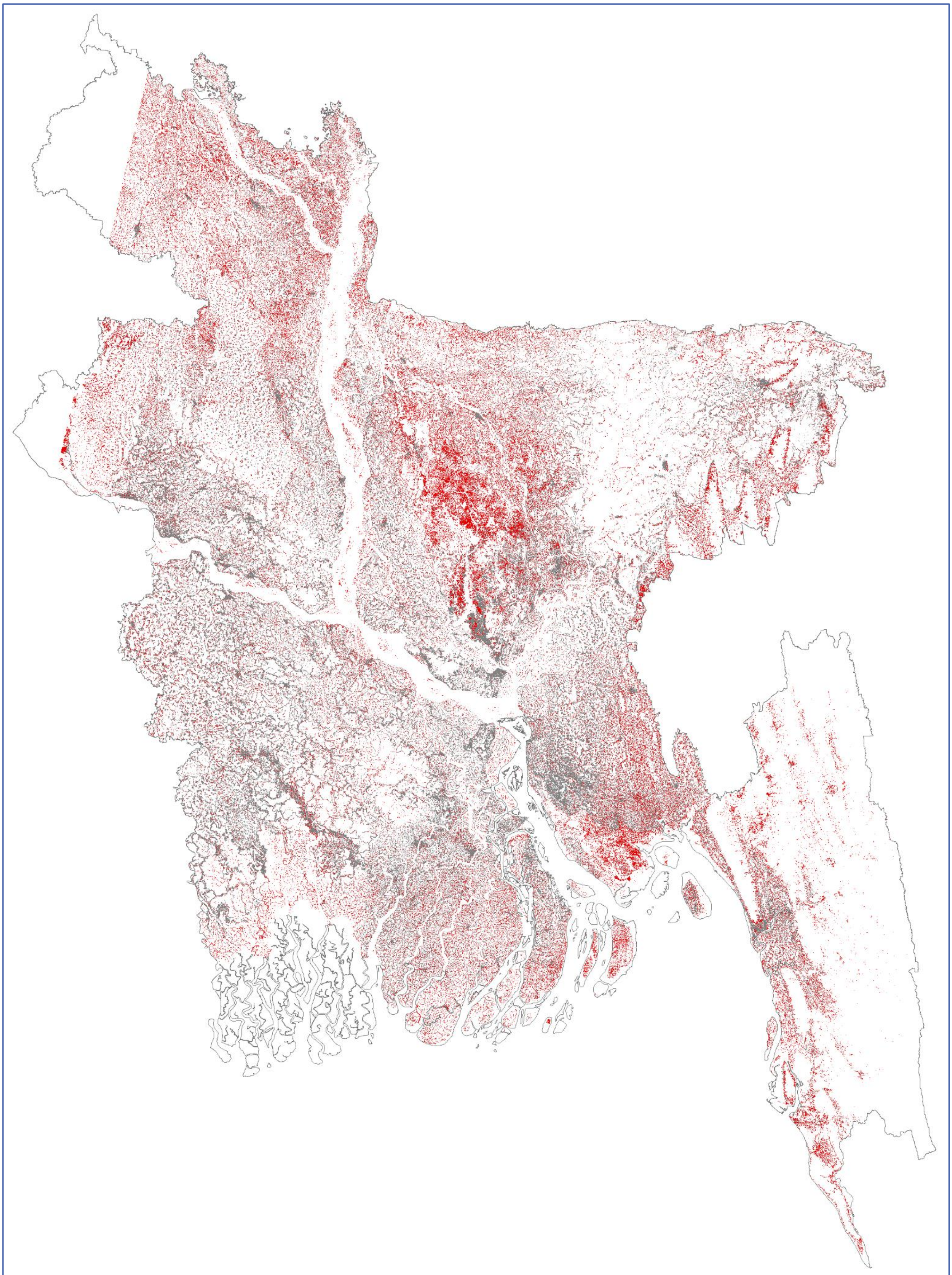

Figure 16: Change in built-up areas 1989-2014 in red and built-up area in 1989 in gray.

4.2 Urban Driver Analysis

The results of the Urban Driver analysis are listed in Table 9, wherein the variable ‘new urban area’ is the dependent variable:

Table 9: Logistic regression results

Variables	(1)	(2)	(3)	(4)
	newurb	newurb	newurb	newurb
Population density (pers/km^2)	6.38e-05***	6.38e-05***	6.33e-05***	6.26e-05***
	(8.95e-06)	(8.84e-06)	(8.63e-06)	(8.68e-06)
Population below upper poverty rate (%)	-0.00410***	-0.00297***	-0.00282***	-0.00367***
	(0.000835)	(0.000807)	(0.000807)	(0.000833)
Annual flooded area (dichotomous)	-0.513***	-0.515***	-0.510***	-0.516***
	(0.0329)	(0.0329)	(0.0329)	(0.0329)
Ln Dist to City Corporation	0.00915	0.0124	0.0279**	0.0224**
	(0.0111)	(0.0111)	(0.0110)	(0.0108)
Ln Dist to District Municipality	0.0948***	0.106***	0.117***	0.102***
	(0.0116)	(0.0112)	(0.0113)	(0.0114)
Ln Dist to Paurashava	0.0356***	0.0366***	0.0430***	0.0366***
	(0.00691)	(0.00674)	(0.00689)	(0.00674)
Ln Dist to Gazipur CC	-0.107***	-0.101***	-0.0919***	-0.0964***
	(0.0106)	(0.0106)	(0.0106)	(0.0105)
Ln Dist to National road	0.0495***	0.0432***		
	(0.00921)	(0.00907)		
Ln Dist to District road	-0.0192**		-0.0221**	
	(0.00887)		(0.00887)	
Ln Dist to Regional road	0.0515***			0.0454***
	(0.0102)			(0.0101)
Ln Dist to existing urban cells in 1989	-0.993***	-0.990***	-0.981***	-0.989***
	(0.0206)	(0.0205)	(0.0205)	(0.0204)
Ln Dist to Navigational rivers	0.187***	0.192***	0.187***	0.181***
	(0.00995)	(0.00997)	(0.00992)	(0.00988)
Elevation (cm)	3.21e-05***	3.28e-05***	3.35e-05***	3.26e-05***
	(2.93e-06)	(2.90e-06)	(2.90e-06)	(2.90e-06)
Crop land-use in 1989 (dichotomous)	0.613***	0.618***	0.619***	0.616***
	(0.0589)	(0.0589)	(0.0588)	(0.0588)
Sand land-use in 1989 (dichotomous)	0.879***	0.896***	0.893***	0.870***
	(0.157)	(0.156)	(0.156)	(0.156)
No. of urban cells within 7x7 window	0.0551***	0.0552***	0.0556***	0.0553***
	(0.00232)	(0.00231)	(0.00232)	(0.00231)
Constant	-0.170	-0.130	0.00691	-0.136
	(0.186)	(0.187)	(0.191)	(0.186)
Observations	122,937	122,937	122,937	122,937
Pseudo R^2	0.2973	0.2969	0.2967	0.2969

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

These coefficients give probabilities of a cell being urbanized. So in specification (1), the coefficient of -0.513 for Annual flooded area would mean that we would expect a 0.513 decrease in the log odds of the dependent variable, new urban area, for areas that are annually flooded, ceteris paribus. However, the signs are more important than the absolute values of the coefficients. Hence, the positive sign for the coefficient of population density means, that if the population density increases, the chance of a cell being urbanized increases too. Conversely, if the percentage of people under the poverty threshold increases, the chance of urbanization decreases. The distance variables can be interpreted as follows; if the distance to a District Municipality increases, the chance of urbanization also increases. This effect looks counterintuitive since one would expect areas closer to urban centers to be more likely to be urbanized. An explanation could be that the administrative boundaries of urban areas continuously change, new urban areas are included. So areas that were being built-up between 1989 and 2014, are already included in those urban areas, hence, this would distort the coefficient for other built-up areas nearby, giving it a negative sign. However, the expected sign does appear for the distance to the Gazipur City Corporation.

A similar counterintuitive result can be seen for the distance to National roads and Regional roads, if farther away from the road, the chance of urbanization increases. To test if these results are robust, three specifications in which each time only one road type is included (specification 2-4). For each road type it gives nearly the same values, hence their value seems to be appropriate. This would mean that living near the highway might be less attractive than expected while living along a district road is more preferred looking at its negative coefficient.

Moreover, if the distance to navigational rivers increases, the urbanization chance also increases. A higher elevation also has a positive effect on the urbanization chance. Just as if the 1989 land-use was cropland or sand, in these cases those areas are frequently converted to urban areas. As one would expect, if there are other urban areas in the proximity, the chance of being urbanized increases. Just as if the distance to existing urban areas increases the urbanization chance decreases. This is in contrast to the variables distance to District Municipalities and Paurashavas, as one would expect those to be urban centers.

In a logistic regression a normal R^2 cannot be calculated, therefore, alternatives are used such as the pseudo R^2. These values of the pseudo R^2 are considerably lower than the more familiar R^2 index from OLS and a value between 0.2 and 0.4 represents an excellent fit (McFadden, 1977, p. 35). In these results, the Pseudo R^2 is almost 0.3 meaning an excellent fit of the model.

4.3 Urbanization Model

In this section, the results of the urbanization model will be presented. First, in Figure 17 the simulated population densities for 2010 are shown on the right, and on the left, the observed population densities at Union level are shown. The left figure considers homogeneous areas while the simulated densities are modeled per cell (50x50 meter). These figures validate the model's results, however, their representation in a map might give a distorted result since they use different units and it is, therefore, difficult to create comparable categories.

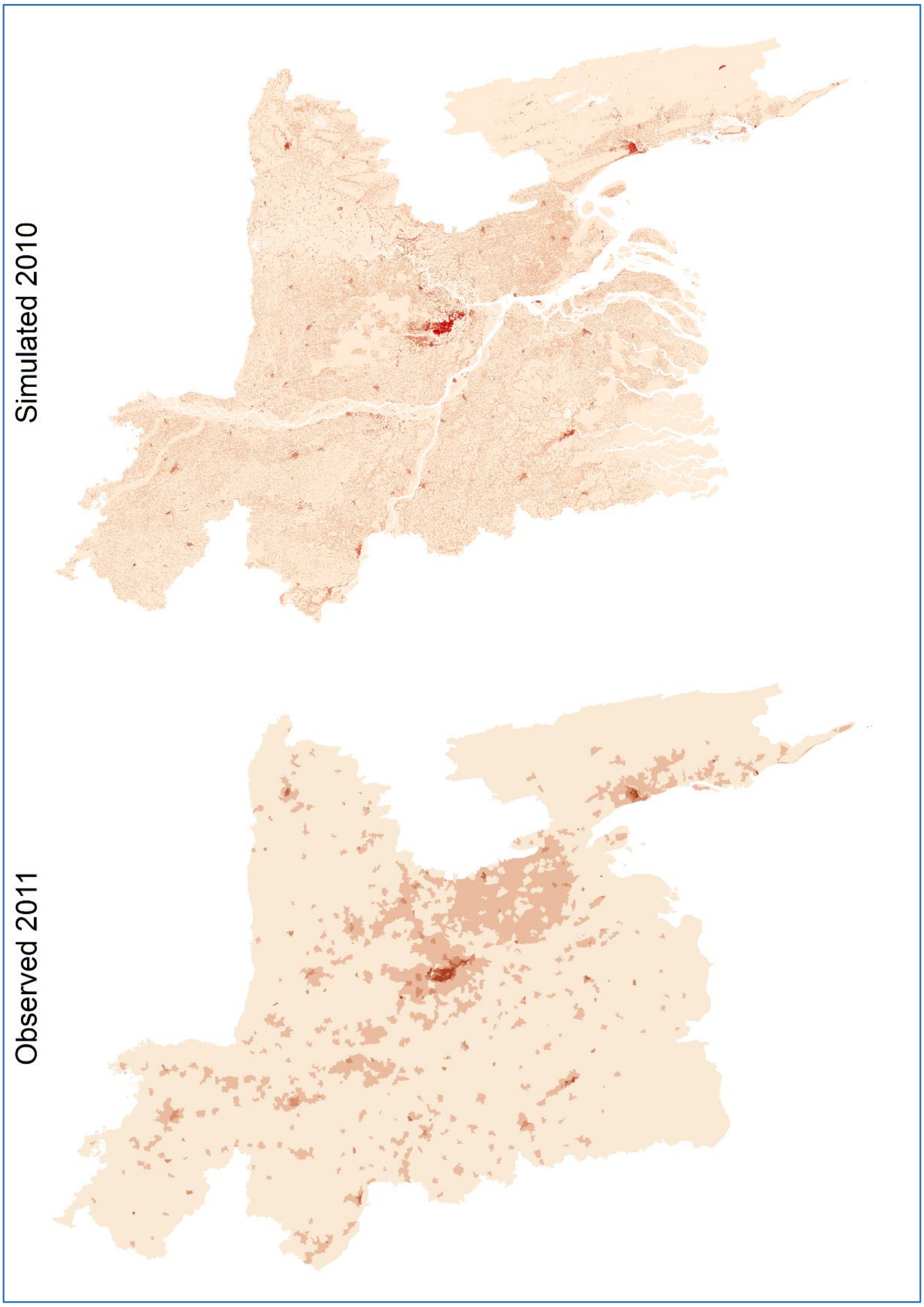

Figure 17: Observed population densities at Union level and simulated population densities.

In Figure 18 the results for the Congestion scenario are shown. In this scenario, the population grows according to its scenario parameters to 212 million in 2060 and then decreases to 190 in 2100 with 70% of the population living in cities. In this scenario mostly Dhaka and Chittagong grow, which can clearly be seen in the figures.

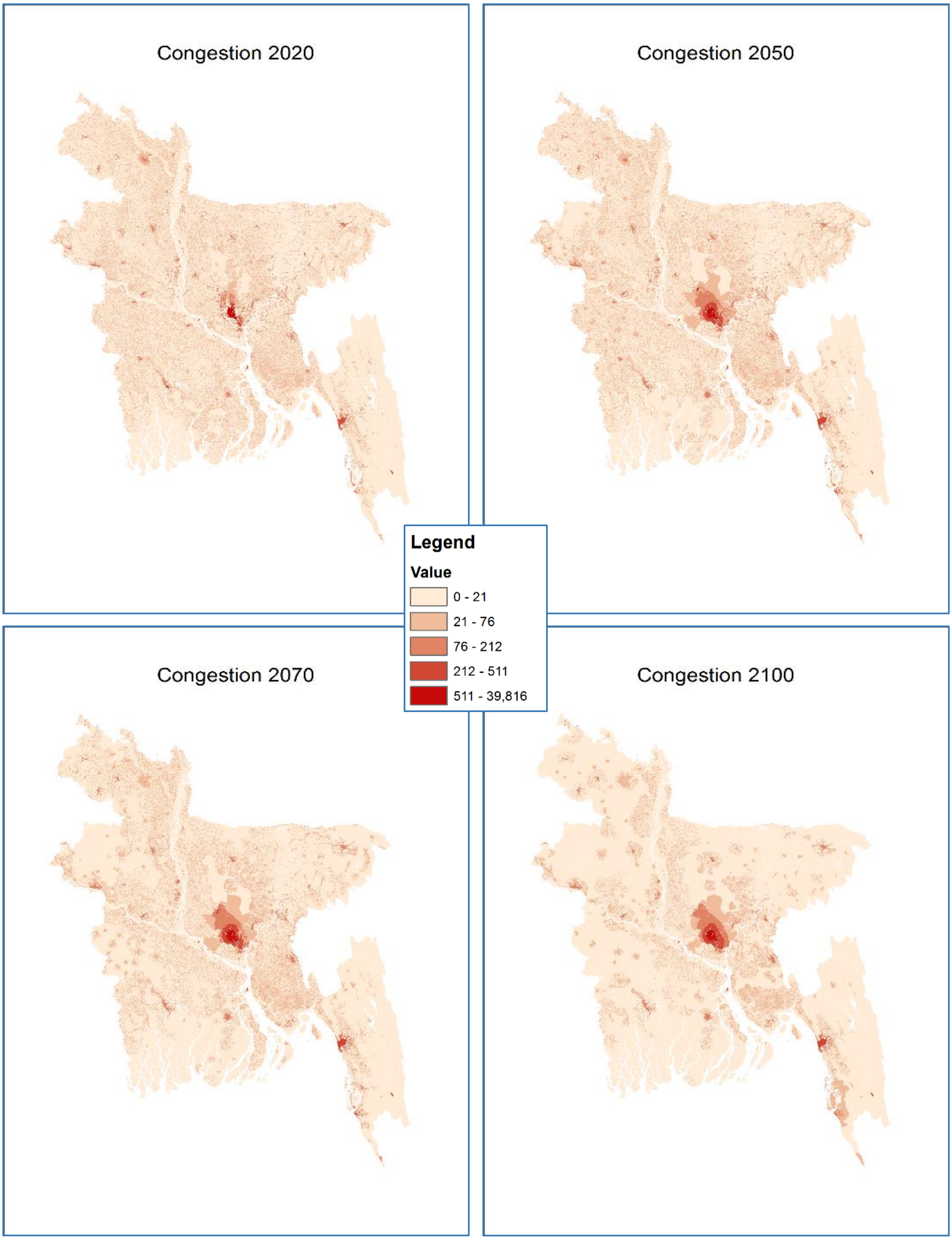

Figure 18: Urbanization models results - Congestion scenario for 4 time periods.

Figure 19 shows the maps for all four scenarios in the year 2050. In each scenario, Dhaka is obviously the largest and most densely populated city, followed by Chittagong with slightly varying sizes. Furthermore, it shows only small differences in population densities in the rest of the country.

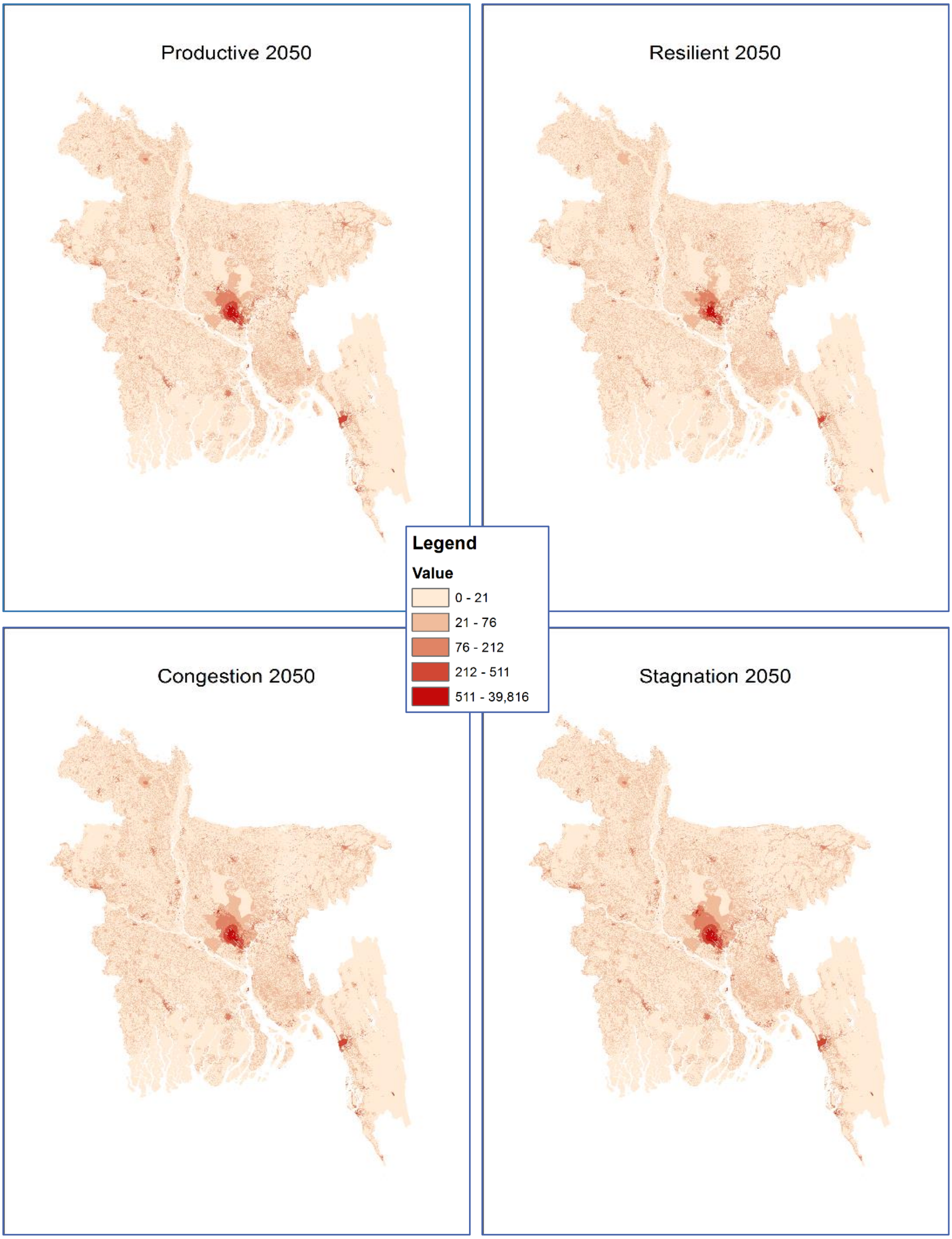

Figure 19: Urbanization result - Scenarios 2050

Similar to the previous figures, in Figure 20 are the results for all scenarios in the year 2100. In these maps, the differences between the scenarios are more noticeable compared to the maps of 2050, because in this time step, the national population figures differ more between the scenarios, especially for the Resilient scenario.

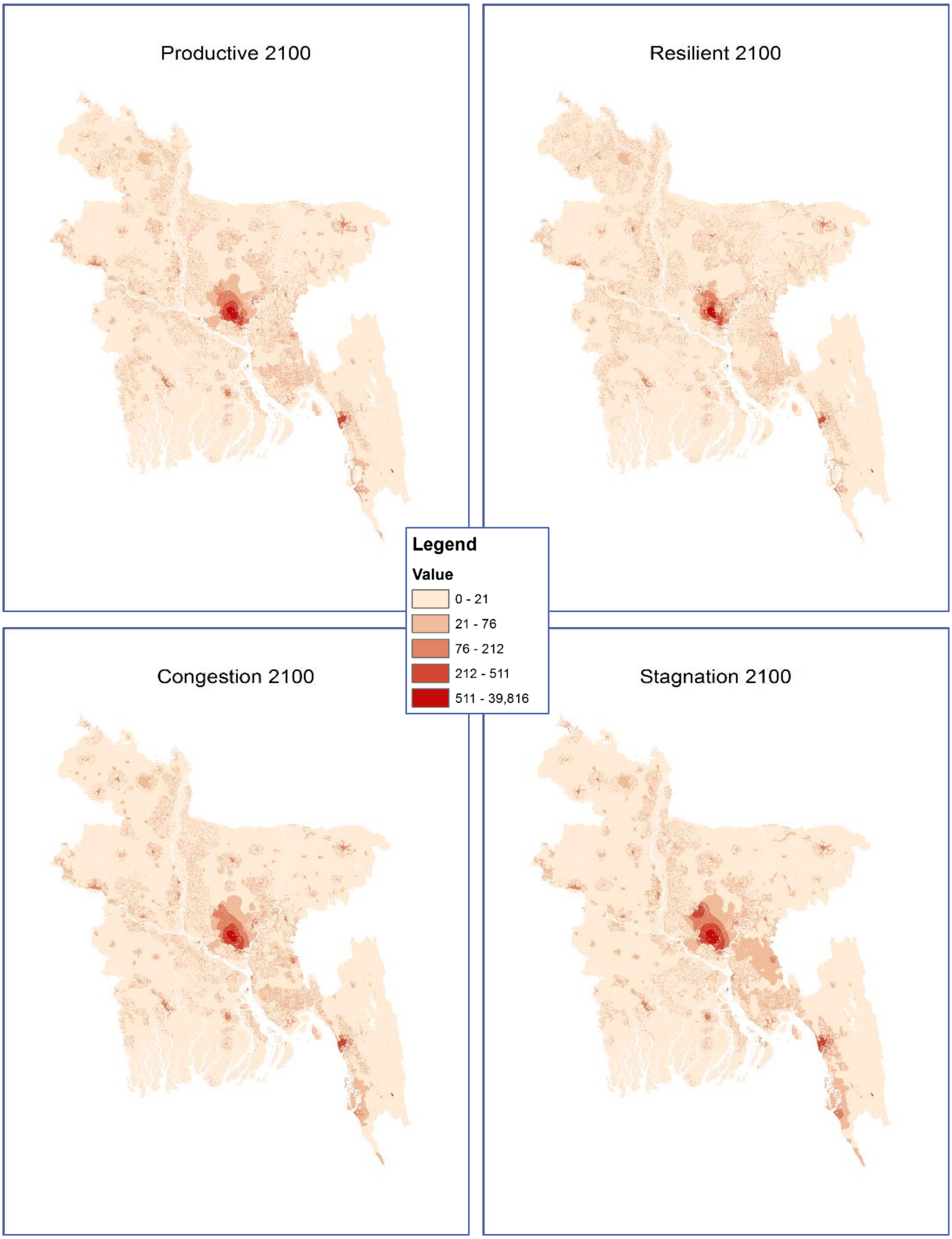

Figure 20: Urbanization result - Scenarios 2100

4.4 Flood Impact Assessment

Figure 21 shows the flood risk in the stagnation scenario in 2050, for flood events with a return period of 10, 25, 50 and 100 years. The values represent the amount of annually expected affected people per hectare. It clearly shows that the most people at risk are in the district of Dhaka and the adjacent districts, but not in the city Dhaka itself, because of its protection measures. The area north of Dhaka has no people at risk, since this area has little higher elevation, and therefore no major rivers crossing the area.

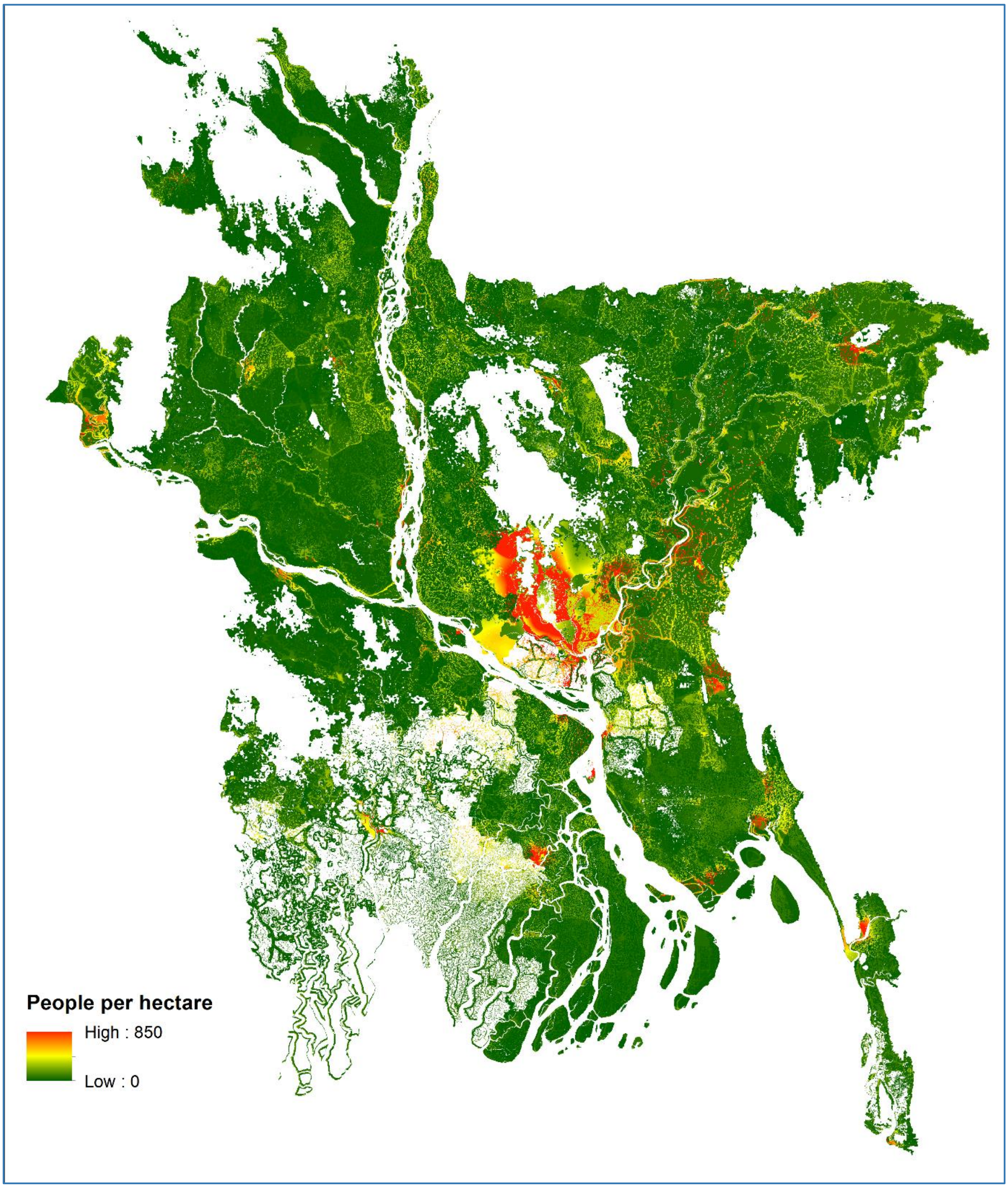

Figure 21: Annual expected affected people per hectare - Base variant - Stagnation scenario 2050

Figure 22 shows quite a different result, overall much fewer people are affected. Mostly due to a lower national population figure, but in the Resilient scenario the urbanized population is higher, so there are also relatively fewer people living in rural areas, which also explains the overall less green image.

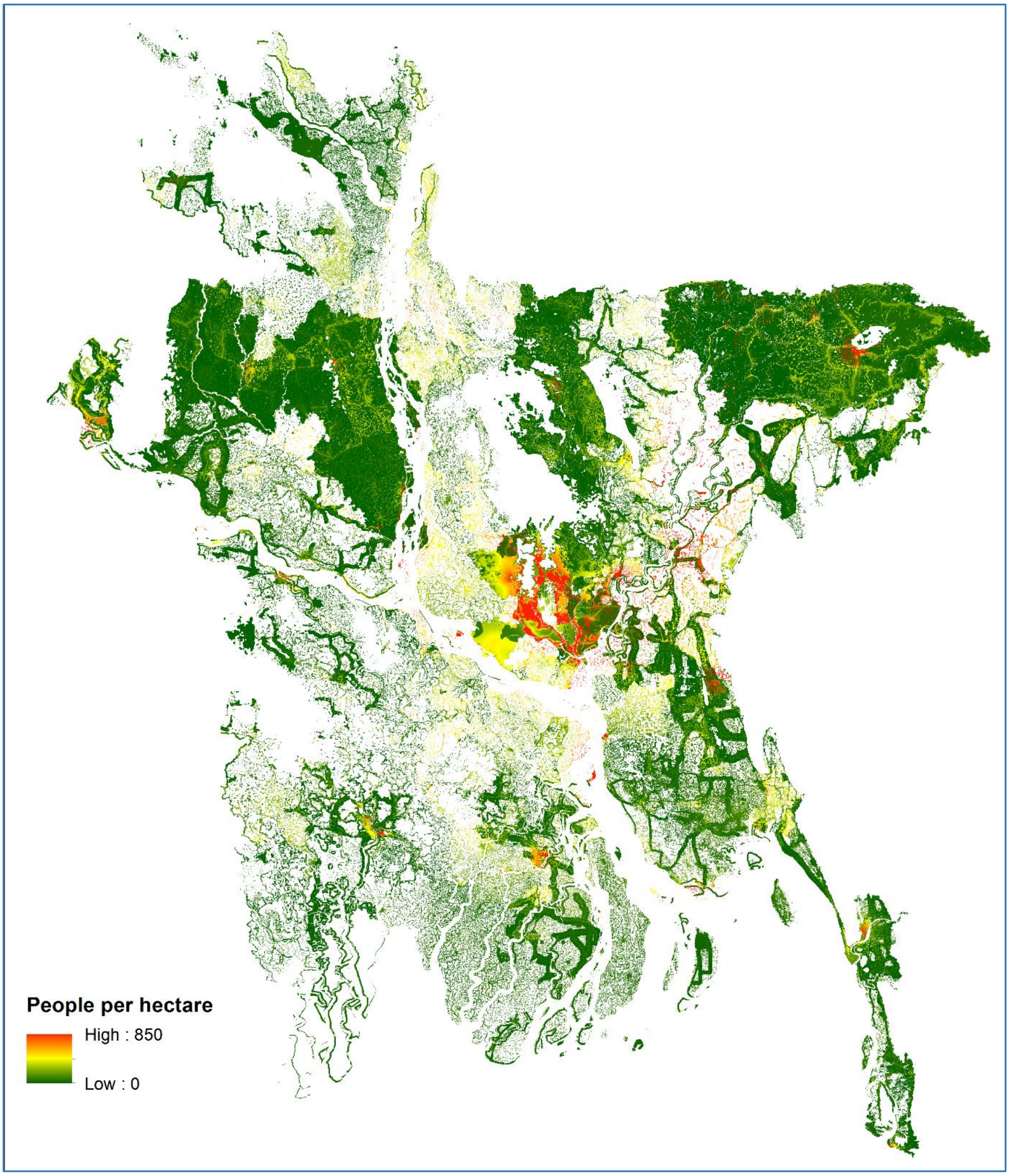

Figure 22: Annual expected affected people per hectare - Base variant - Resilient scenario 2050

Figure 23 shows the same maps as in Figure 21 and Figure 22, but the affected people per cell are averaged over Upazilas, which gives a clearer image. But it gives a slightly different image because it now visually ignores the cells that do not have affected people in it (the white areas in the previous maps).

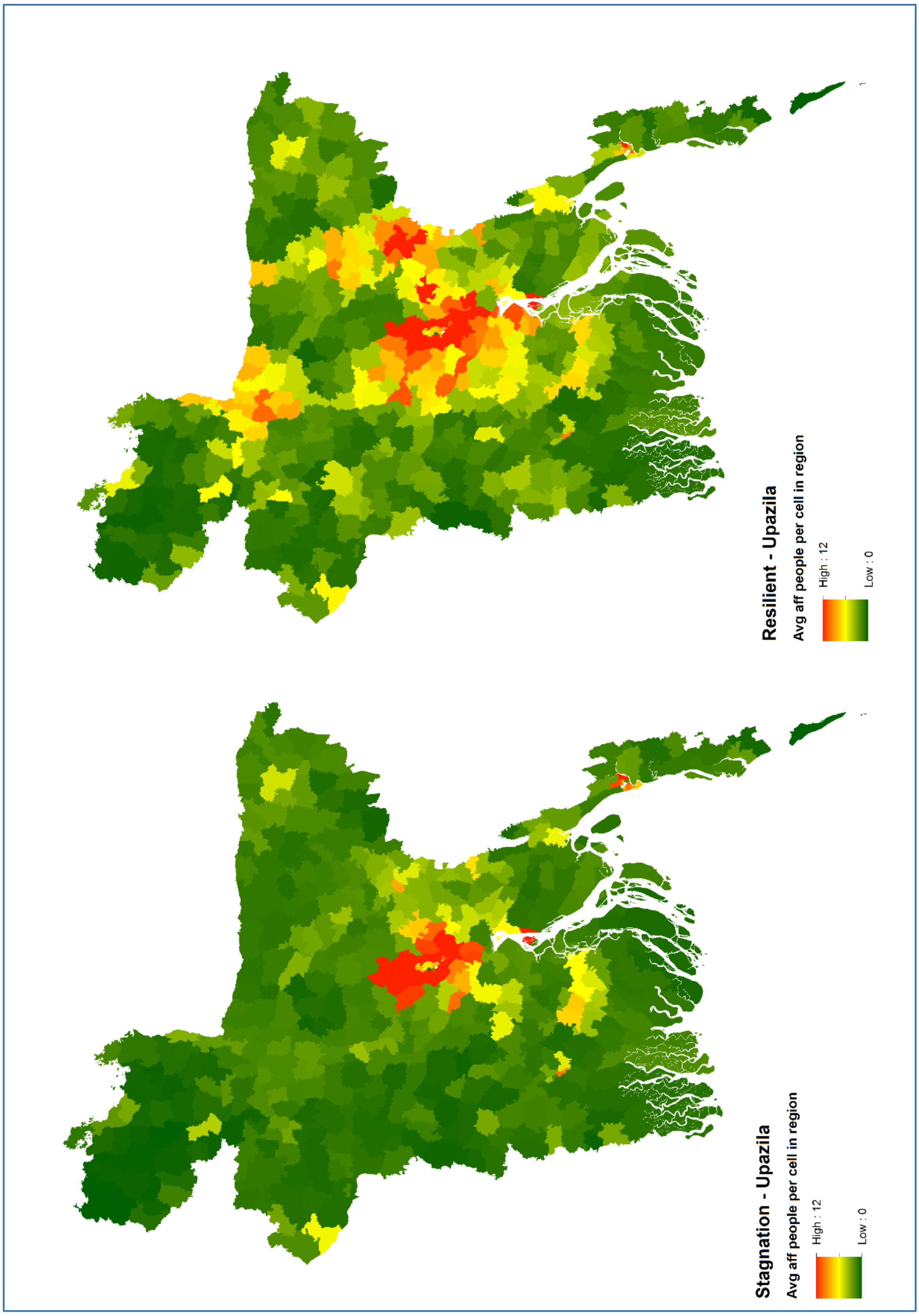

Figure 23: Affected people per cell averaged over Upazilas for the Stagnation and Resilient scenario in 2050 for the base variant

The results from the flood impact assessment are also numerically shown in the following table. The table shows the amount of annually expected affected people per time step in each scenario. It shows that the number of annual expected affected people is particularly low for the resilient scenario while on the other hand, the stagnation scenario has the highest number of annual expected affected people. This is mostly due to the difference in the national population.

Table 10: Total annual expected affected people in base variant

Base	Productive	Resilient	Congestion	Stagnation
2020	5,613,511	5,492,019	5,696,001	5,838,033
2050	6,851,265	5,651,961	7,205,516	7,891,599
2070	6,701,416	5,173,967	7,349,476	8,365,351
2100	5,696,799	4,083,226	6,609,934	8,385,403

The differences between the scenarios are easier to see when you compare them to the 2010 value (4,782,245 affected people), the following table shows the percentage compared to 2010. This highlights the especially large difference between the Resilient and Stagnation scenario, due to different population figures.

Table 11: Change in annual expected affected people in base variant as compared to 2010 (in %)

Base	Productive	Resilient	Congestion	Stagnation
2020	+17%	+15%	+19%	+22%
2050	+43%	+18%	+51%	+65%
2070	+40%	+8%	+54%	+75%
2100	+19%	-15%	+38%	+75%

Table 11 shows that for three of the four scenarios, the number of affected people drastically increases over time, and decreases for some after 2050. Most population increases occurred in urban areas, so one might say that urbanization, which is analogous to population growth, increased the flood risk in Bangladesh. Only in the Resilient scenario does the amount of affected people by flooding decrease, but it does so only by 2100, since it follows the population decrease.

This study suggests that future flood risk, without interventions, may increase with 18 – 65% in 2050, compared to the current situation, attributable to socio-economic change. Moreover, in the same period the population increases with 13 – 52%, hence, the flood risk increases disproportionally compared to the population growth.

4.5 Policy Interventions

The effects of some potential policy interventions are calculated and its results are shown in the following tables. The first variant to discuss is the case when all the existing dikes are upgraded from 1:25 to a height to withstand a once-in-fifty-year flood event (Table 12). When the dikes are upgraded, only a small change can be seen compared to the previous table, this is a decrease of about 10% compared to the value of the same scenario and time step in the base variant.

Table 12: Annual expected affected people when all existing dikes are upgraded to 1:50, and the % change compared to the current situation.

EI_a-dike 1:50	Productive		Resilient		Congestion		Stagnation	
2020	5,026,559	(+5%)	4,917,184	(+3%)	5,103,225	(+7%)	5,237,369	(+10%)
2050	6,179,552	(+29%)	5,089,933	(+6%)	6,507,401	(+36%)	7,147,218	(+49%)
2070	6,062,874	(+27%)	4,666,005	(-2%)	6,660,174	(+39%)	7,607,672	(+59%)
2100	5,161,625	(+8%)	3,681,141	(-23%)	5,999,367	(+25%)	7,649,366	(+60%)

However, when not only the existing dikes but the entire country will be embanked to withstand once in fifty-year flood events, the number of affected people drastically goes down (Table 13). This is about 88% less compared to the value of the same scenario and the time step in the base variant. This scenario is only indicative, and not realistic because in this scenario water is hardly able to run off. But it is important to note that there might be more gains in protecting non-protected areas for such events than in improving already protected areas.

Table 13: Annual expected affected people when the entire country has 1:50 dikes, and the % change compared to the current situation.

EI_b-dike 1:50_all	Productive		Resilient		Congestion		Stagnation	
2020	698,813	(-85%)	683,252	(-86%)	706,860	(-85%)	721,276	(-85%)
2050	803,317	(-83%)	676,944	(-86%)	840,039	(-82%)	902,788	(-81%)
2070	769,911	(-84%)	614,014	(-87%)	835,775	(-83%)	929,242	(-81%)
2100	648,421	(-86%)	486,859	(-90%)	741,704	(-84%)	907,428	(-81%)

Another way to limit the number of affected people is to change the way people are affected by floods, inundated houses are a big factor in this. So what if houses are built at a different height above ground. Table 14 shows the number of affected people for each scenario in 2050, with different building heights, but also for the different variants; Base, upgrading existing dikes to 1:50 (EI-a), and embanking the entire country at 1:50 (EI-b). As one would expect, the number of affected people goes down when their houses are built higher off the ground.

Table 14: Annual expected affected people at different building heights in 2050

	Productive			Resilient		
	Base	EI-a	EI-b	Base	EI-a	EI-b
FP - 0 cm	7,435,866	6,711,798	829,832	6,163,857	5,555,806	700,586
FP - 30 cm	6,851,265	6,179,552	803,317	5,651,961	5,089,933	676,944
FP - 60 cm	6,123,452	5,522,405	767,792	5,017,888	4,517,643	645,356
FP - 90 cm	5,165,869	4,639,636	722,115	4,197,370	3,763,037	604,962
FP - 120 cm	3,958,773	3,507,722	663,781	3,211,748	2,843,373	553,298

	Congestion			Stagnation		
	Base	EI-a	EI-b	Base	EI-a	EI-b
FP - 0 cm	7,817,402	7,064,191	867,598	8,537,152	7,735,072	932,032
FP - 30 cm	7,205,516	6,507,401	840,039	7,891,599	7,147,218	902,788
FP - 60 cm	6,443,468	5,819,924	803,064	7,088,850	6,423,247	864,072
FP - 90 cm	5,436,668	4,891,360	755,443	6,007,313	5,423,590	814,228
FP - 120 cm	4,169,336	3,702,035	694,811	4,606,746	4,104,174	751,016

Building houses higher above ground can be a relatively easy measure to mitigate the increasing flood risk. The number of affected people increases by 43% in 2050 in the production scenario compared to 2010, and this number of affected people can be decreased compared to the current situation (-17%), if all the houses would be built 120 cm above ground level instead of the current 30 cm (Table 15). For the Stagnation scenario, this percentage could be brought down from 65% to -4%. Flood proofing has a similar effect in the EI-a variant, in the Stagnation scenario, the number of affected people in 2050 is 49% more than in 2010, flood proofing to 120 cm would reduce this percentage to -14% compared to 2010, even with the enormous population growth of 52% in that period.

Table 15: Change in annual expected affected people in each variant for different building heights as compared to the 2010 value (in %).

	Productive			Resilient		
	Base	EI-a	EI-b	Base	EI-a	EI-b
FP - 0 cm	+55%	+40%	-83%	+29%	+16%	-85%
FP - 30 cm	**+43%**	+29%	-83%	+18%	+6%	-86%
FP - 60 cm	+28%	+15%	-84%	+5%	-6%	-87%
FP - 90 cm	+8%	-3%	-85%	-12%	-21%	-87%
FP - 120 cm	**-17%**	-27%	-86%	-33%	-41%	-88%

	Congestion			Stagnation		
	Base	EI-a	EI-b	Base	EI-a	EI-b
FP - 0 cm	+63%	+48%	-82%	+79%	+62%	-81%
FP - 30 cm	+51%	+36%	-82%	**+65%**	**+49%**	-81%
FP - 60 cm	+35%	+22%	-83%	+48%	+34%	-82%
FP - 90 cm	+14%	+2%	-84%	+26%	+13%	-83%
FP - 120 cm	-13%	-23%	-85%	**-4%**	**-14%**	-84%

In Figure 24 the effect of the proposed policy measure of flood proofing is spatially displayed. It shows that when, in the base variant for the production scenario in 2050, the houses are built at 120 cm instead of 30 cm above ground. The number of affected people drops with nearly 3 million, with the largest portion being in the district of Dhaka. Flood proofing is a relatively easy measure to mitigate the flood risk and the most gains would be obtained in the district of Dhaka, outside the current flood protection measurements around the city of Dhaka.

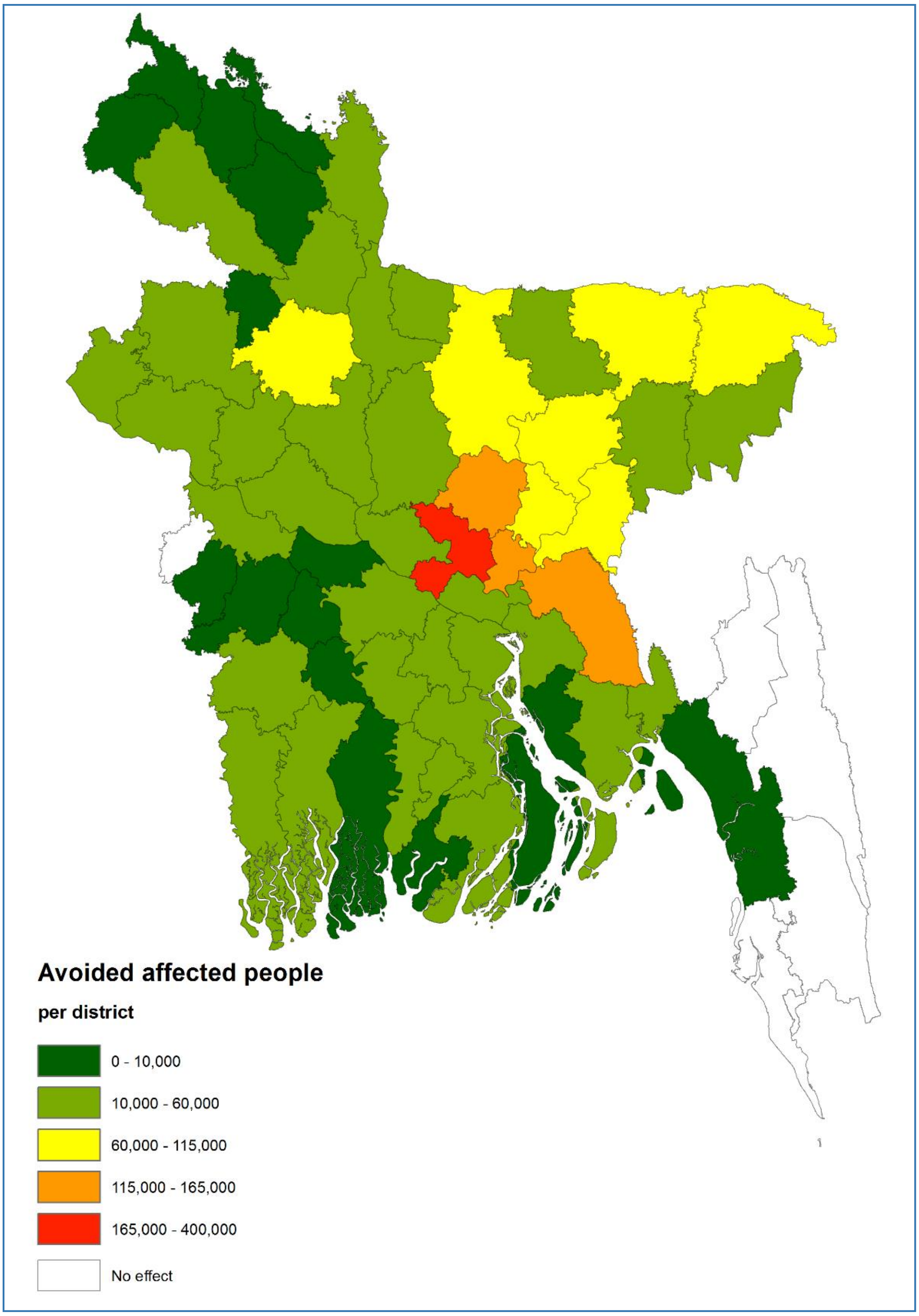

Figure 24: Avoided affected people when all the houses are flood proofed to 120 cm above ground level in the base variant for the production scenario in 2050

SECTION V: DISCUSSION

In this section, the results of the research, which were presented in the previous section, will be discussed. A recurring problem throughout this research was often the poor availability and quality of data, compromises and assumptions had to be made in order to conduct this research.

5.1 Population Projections

The population projections are based on a method that is used often in other research but showed that some alterations were necessary to make the projections more realistic. Extending historical trends so far into the future resulted in highly improbable outcomes. Several districts that showed large growth rates in the last 20 years, needed their growth rate to diminish over time. The size of these reductions has been determined using factors from the Delta scenarios.

The projections for some districts with low growth rates were also adjusted. These districts are expected to grow in the coming decades either because they are district capitals, because sea ports are planned to be built that will stimulate economic activity, or because they are likely to become major hubs in an infrastructural corridor.

5.2 Urban Driver Analysis

An important factor to consider in the urban driver analysis is that all created variables are from 2010 to 2014 data sources. So, for example, the distance to a road is included to look at urban developments between 1989 and 2014, while that road might have been built as late as 2009, and may have actually followed urban development rather than causing it. The same endogeneity issue may hold for the administrative borders, like City Corporations, that change nearly every year.

On top of this, the original land-use maps from 1989 and 2014 might not give a realistic representation. During discussions about the land-use maps with different experts (both in the Netherlands and in Bangladesh), some experts pointed out that the built-up areas might have been over-represented in these land-use maps and others say that it is actually quite plausible. Other data sources also show comparable representations (also a LANDSAT-source land-use map obtained from CEGIS, see Subsection 4.1), and personal observations somewhat confirm this view.

An important addition to the Urban Driver Analysis should be to have a land-use map from a period in the middle of these two periods, in that way the period 1989 to 2001 can be used to model the coefficients, and the second period, 2001-2014, can be used to calibrate the model. However, such dataset was unavailable.

5.3 Urbanization Model

During the research, it occurred that the population allocation per district in the population projections have the largest impact on the results in the urbanization model. Therefore, the population projections are the main driver throughout this research, having a stronger impact on simulated urban development than the other variables. These population projections use historic trends to distribute regional population numbers adding up to the national totals provided by the Delta scenarios. One could challenge if this method is the best method, but it is commonly used in similar research (Wilson & Rees, 2005) and moreover, it was the easiest to use. A method that could be explored in future research is to allocate population not over districts, but at a national level based only on local suitabilities.

The translation of the coefficients from the urban driver analysis to usable weights in the urbanization model proved quite difficult and is to a large extent based on expert judgment. The final weights can be seen in Table 16 in Appendix B. The coefficients from the Urban Driver Analysis are mostly used to provide relative differences while trial and error showed what the magnitude of the weights should be, to have a noticeable effect on the output. In further research, a sensitivity analysis should be carried out to validate these results.

Furthermore, the resulting maps showed less variation between the scenarios than expected. During the research, the aim was to try and produce maps comparable to those presented in the Delta Scenario Report. Especially the maps for 2050 show few variations between the different scenarios, and are as previously mentioned primarily influenced by the population projections. In further research additional effort should be put in improving the different scenarios to create scenarios that are more distinct.

5.4 Flood Impact Assessment

An important addition to the flood impact assessment is to express damages also as monetary values, like in the Dutch HIS-SSM model (HKV, 2000). However, this proved quite difficult due to the lack of data; there is no actual property value data available or even the location of industrial areas.

A crucial assumption that is made for the flood assessment is based on the assumption that the average building in Bangladesh is built at 30 cm above the ground. This means that if the inundation depth is below 30 cm in a certain area, there are no affected people. But if the inundation depth is 31 cm or more every building in the area is affected. Since there is no building data or household location available, this only depends on the population density in a particular cell (50x50m). This threshold of 30 cm is a value that is common practice for flood-related research in Bangladesh. However, actual research for this value was not found.

Another issue that should be addressed in this section is that the water depth maps used in Delft-FIAT, do not contain the climate-related properties that are mentioned in the Delta Scenario Report. This means that this flood impact assessment does not account for climate change. Moreover, there are significant uncertainties in these flood maps.

An important assumption that is made in this thesis is that it considers future population densities and possible interventions, but do not consider the tendency of people to adapt to different circumstances by themselves. Therefore, the results are probably an overestimation since people will always try to adapt and minimize their damages. When certain areas keep getting flooded more and more each year, they might try to relocate to less severe locations.

It is very difficult to compare the findings of this study to those of other studies since there has not been a countrywide flood impact assessment for Bangladesh. Furthermore, the results are very country specific and heavily dependent on the constructed scenarios. However, a study from the Netherlands did also found that the flood risk grows disproportionally compared to population growth (Maaskant, Jonkman, & Bouwer, 2009).

A test was run to assess if actually all the people were properly allocated in the urbanization model and again if all the people were included in the flood impact assessment. This resulted in a loss of 3% of the population, this is assumed to be an acceptable loss in the allocation processes.

5.5 Policy Interventions

The policy interventions that are calculated in this research are very rudimentary and just show some indicative values for some what-if scenarios. An important aspect to note is the realism of such measures. The EI-b variant, wherein the entire country would be embanked at 1:50, is quite unrealistic. The cost of this would be immeasurable since there is a lack of suitable resources in the entire country, and the logistics would make it near impossible to construct, because most rivers that should be embanked are not navigational, especially for large ships that would be carrying the materials.

SECTION VI: CONCLUSION

This research tried to give an answer to the question: *To what extent may future urban development, change flood risk in Bangladesh?* To answer this, for the first time a national-scale flood risk assessment, for four scenarios up to 2100, has been applied to the entire country of Bangladesh. In order to make this assessment, population projections are made, making use of the four Delta scenarios. Furthermore, an urban driver analysis has been conducted to quantify historical urbanization patterns. Then a land-use model has been altered to model population densities up to 2100 for the four scenarios, using the population projections and the results from the urban driver analysis. The output from the urbanization model is used in a flood impact model in combination with water depth maps, resulting in flood impact maps and tables for each of the four scenarios and for each decade up to 2100 at a resolution of 50x50 meters.

As a result, there are four main products in this research; the population projections, the urban driver analysis, the urbanization model and its resulting population density maps and the flood impact assessment. The population projections appeared to be highly influential for further results in this research. The urban driver analysis was quite time-consuming while it only has little effect on the results. The urbanization model is built to be as general as possible so that it could easily be altered and used for different study areas.

This study suggests that future flood risk, without interventions, may increase with 18 – 65% in 2050, compared to the current situation, attributable to socio-economic change. Moreover, in the same period the population increases with 13 – 52%, hence, the flood risk may increase disproportionally compared to the population growth. Most population increases occur in urban areas, so one might say that urbanization, which is analogous to population growth, increased the flood risk in Bangladesh. Only in the Resilient scenario does the amount of affected people by flooding decrease compared to the current situation, but it does so only by 2100. For the Productive, Congestion and Stagnation scenarios this increased flood risk is between 43% and 65% in 2050 and between 19% and 75% in 2100 while 18% and -15% correspond to the same time periods in the Resilient scenario. The proposed policy interventions show that the increase in flood risk may better be mitigated by embanking non-protected areas rather than improving already protected areas. While another policy intervention, building houses higher of the ground, may even have a stronger effect on mitigating flood risk.

There are some parts in this research that could be expanded or improved in further research. For example; monetary values could be added to the flood impact assessment, and more planned developments in infrastructure or proposed building sites can be incorporated in the urbanization model. Furthermore, there could be more validation steps and sensitivity analyses in the urban driver analysis, urbanization model and the flood impact assessment. Moreover, the population doubled in the last 25 years, it would be interesting to see if the flood risk also doubled, or more than doubled in the past 25 years.

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APPENDICES

Appendix A

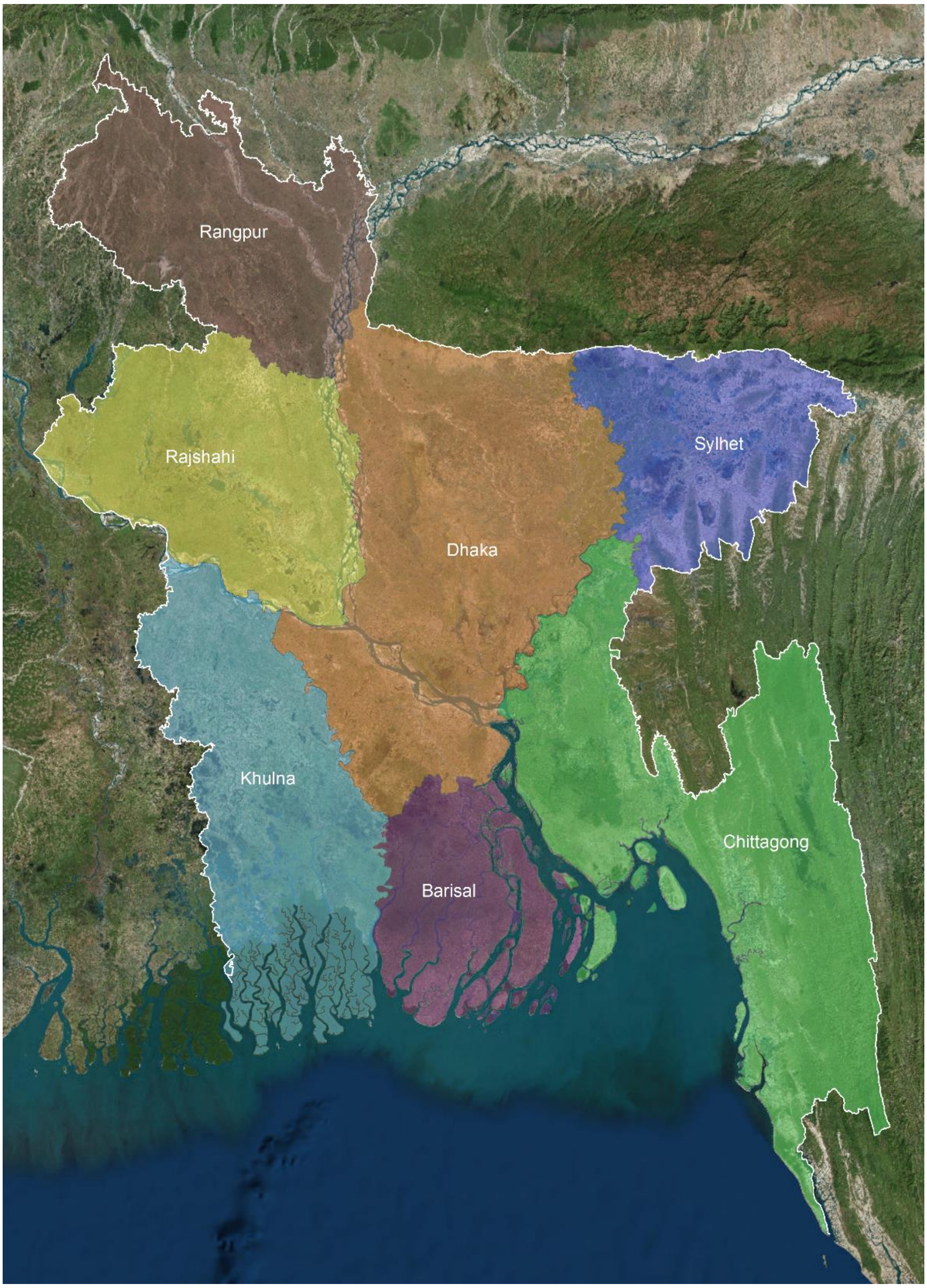

Figure 25: Satellite map of Bangladesh with Divisions (satellite image from ArcGIS basemap)

Appendix B

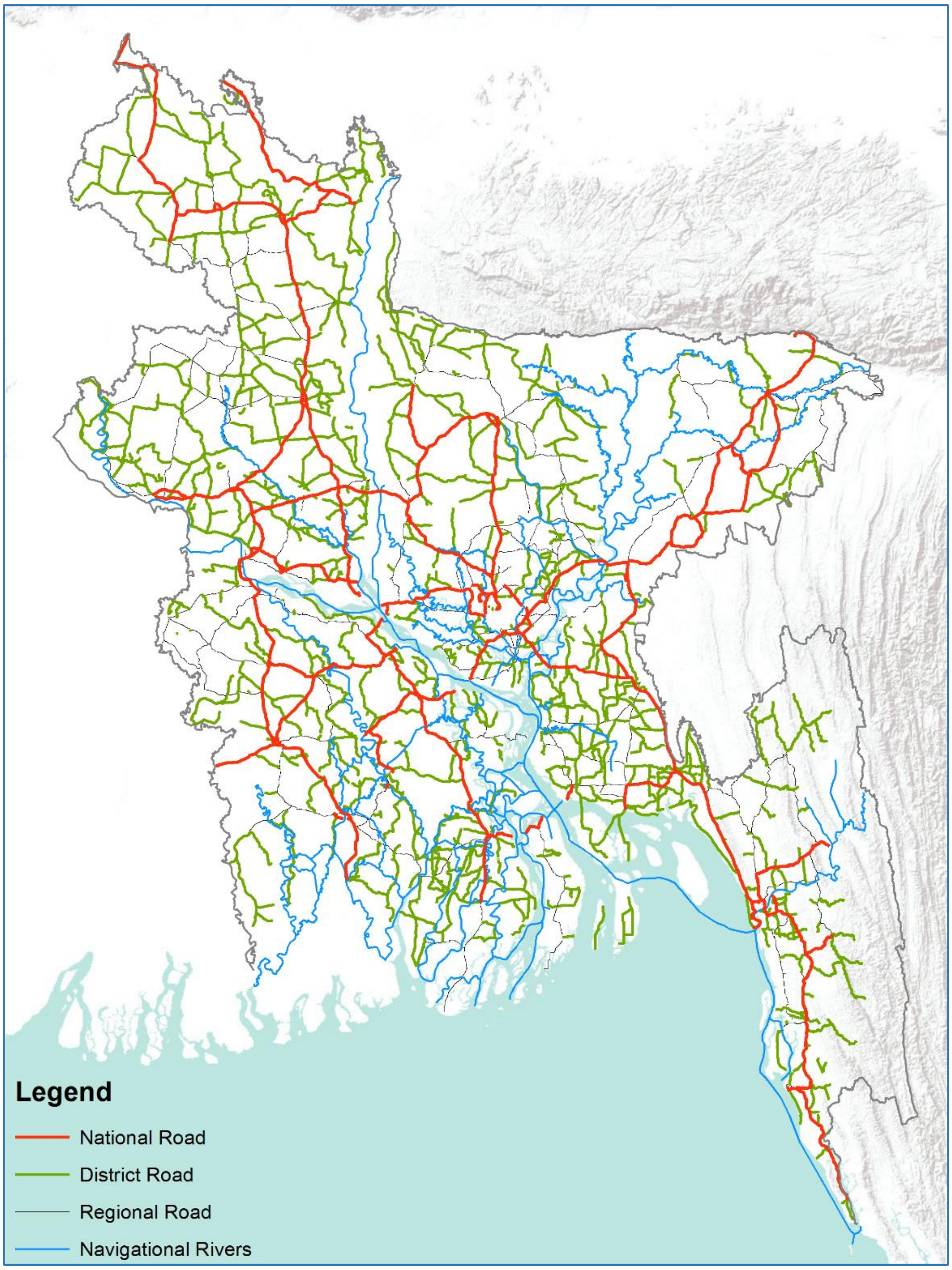

Figure 26: Map of Bangladesh with different road types (terrain map from ArcGIS basemap)

Appendix C

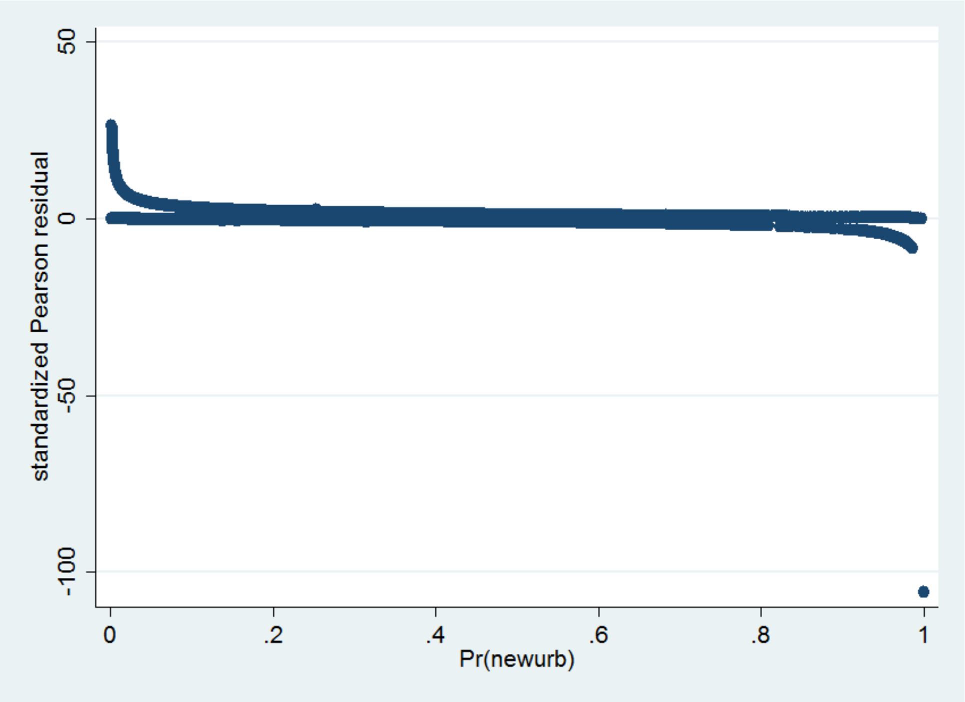

Figure 27: Scatterplot of standardized Pearson residuals against P with outlier

Appendix D

Table 16: Weights for Urbanization Model

	Productive	Resilient	Congestion	Stagnation
National Road	0.01*3*10000=300	0.01*3*10000=300	0.01*1*10000=100	0.01*1*10000=100
District Road	0.09*3*10000=2700	0.09*3*10000=2700	0.09*1*10000=900	0.09*1*10000=900
Regional Road	0.03*3*10000=900	0.03*3*10000=900	0.03*1*10000=300	0.03*1*10000=300
Upazila Road	0	0	0	0
Village Road	0	0	0	0
Union Road	0	0	0	0
Rail	0	0	0	0
River	-0.17*1*10000=-1700	-0.17*2*10000=-3400	-0.17*1*10000=-1700	-0.17*2*10000=-3400
CC	0.53*400=212	0.53*200=106	0.53*200=106	0.53*400=212
CC Gazipur	1.19*400=476	1.19*200=238	1.19*200=238	1.19*400=476
District Paura	0.04*300=12	0.04*300=12	0.04*300=12	0.04*200=8
Paurashava	0.06*300=18	0.06*300=12	0.06*200=12	0.06*100=6
Annexpo	-0.52*100=-52	-0.52*200=-104	-0.52*100=-52	-0.52*200=-104
Elevation	0.0003*1*100000=30	0.0003*2*100000=60	0.0003*1*100000=30	0.0003*2*100000=60
Settlement dyn	1*10=10			

Appendix E

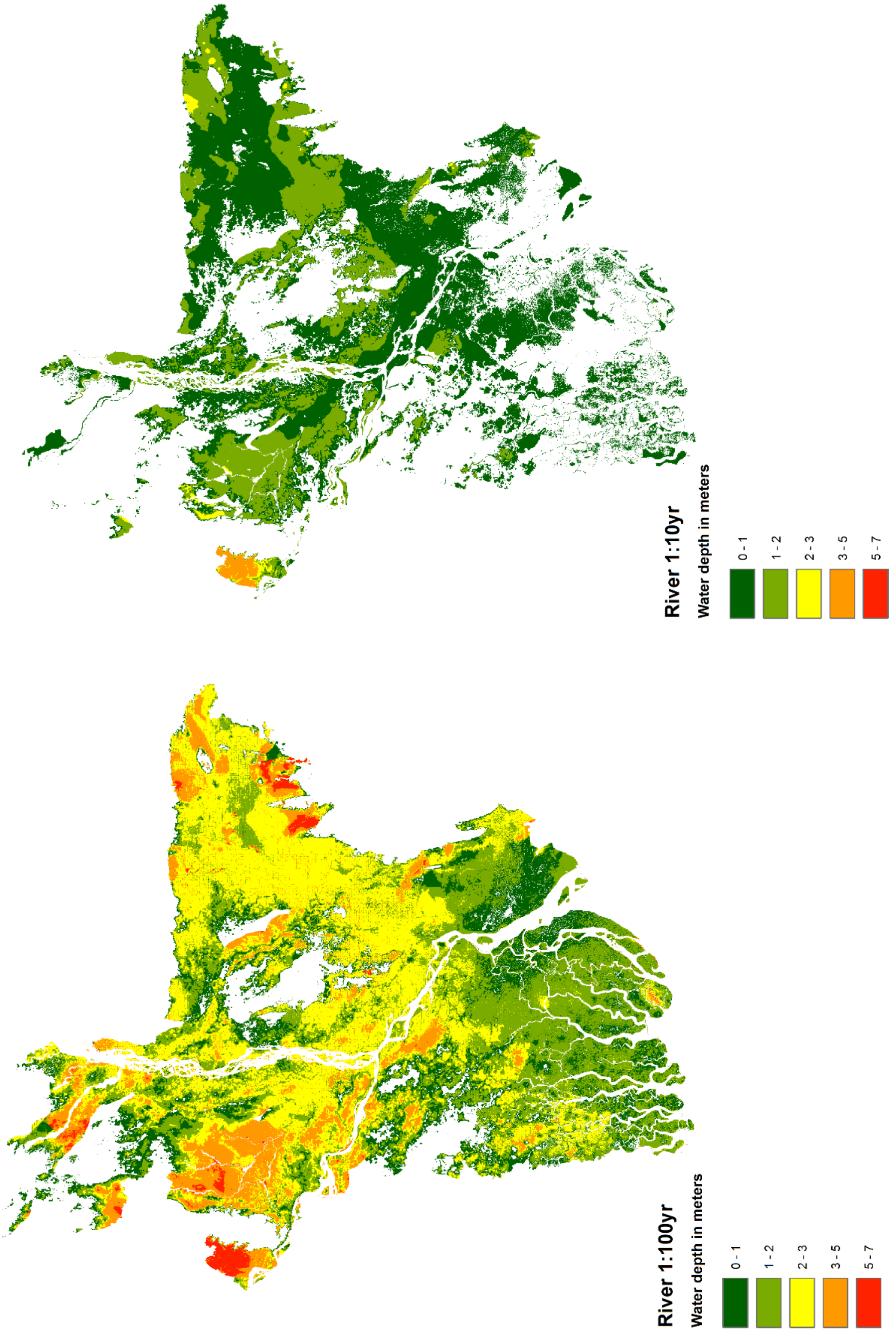

Figure 28: Water depth maps for river floods with a return period of 1:10 and 1:100 years (source IWM (2015).