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An integrated approach of flood risk assessment in the eastern part of Dhaka City

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Abstract

The flood risk is a function of the flood hazard, the exposed values and their vulnerability. In addition to extreme hydrological events, different anthropogenic activities such as extensive urbanization and land use play an important role in producing catastrophic floods. Considerations of both physical and social dimensions are therefore equally important in flood risk assessment. However, very often the risk assessment studies either focus on physical or social dimensions. In addition, the available studies often focus on economic valuation of only direct tangible costs. In this study, we provide an integrated flood risk assessment approach that go beyond valuation of direct tangible costs, through incorporating physical dimensions in hazard and exposure and social dimensions in vulnerability. The method has been implemented in the Dhaka City, Bangladesh, an area internationally recognized hotspot for flood risk. In this study, flood hazards for different return periods are calculated in spatial environment using a hydrologic model, HEC-RAS. Vulnerability is assessed through aggregation of various social dimensions i.e., coping and adaptive capacities, susceptibility. We assess vulnerability for both baseline and improved scenario. In the baseline scenario, current early warning for study area is considered. In the alternative scenario, the warning system is expected to improve. Aggregating hazard, exposure and vulnerability, risk maps (in terms of both tangible and intangible costs) of several return period floods are produced for both baseline and improved scenario. Compared to traditional assessments, the integrated assessment approach used in this study generates more information about the flood risk. Consequently, the results are useful in evaluating policy alternatives and minimizing property loss in the study area.

Keywords: *integrated assessment, flood risk, vulnerability, intangible costs, indirect costs, Dhaka City*

1 Introduction

Given the inertia generated by the various chemical and physical processes, the Earth's climate system is facing the risk to cross some critical thresholds, at which even a tiny perturbation can determine substantial alterations of the system equilibrium and let it shift to a new system regime (Gladwell 2000). Lenton et al. (2008) concluded that a variety of critical thresholds could be overpassed within this century due to anthropogenic climate change. Most notably, the frequency and intensity of some type of extreme events (e.g., floods, heat waves, tropical cyclones, and droughts) might increase globally as reported in the fourth and fifth assessment reports of the Intergovernmental Panel on Climate Change (IPCC), determining possible shifts of Earth system regimes with dramatic consequences on socio-ecosystems in various parts of the world (Solomon et al. 2007, Stocker et al. 2013). Looking at the recent past we found that the total economic damage from floods during 1970-1989 was US$ 51.8 billion while the economic damage during 1990-2011 was US$ 496 billion (Dewan, 2013; EM-DAT 2013). In coming decades, the number of people at risk from climate change induced extreme events is expected to increase (Bouwer et al. 2007; McBean and Ajibade 2009; Bouwer 2011).

'Disaster risk' by definition, is a product of the interaction of the hazardous natural event and the vulnerability conditions of the combined natural and human elements exposed to the event. Floods are among the most risky natural disasters in terms of threat to human lives and economic costs. Using a global sample of 184 disasters over the previous 47 years, Okuyama and Sahin (2009) demonstrated that 25% of the total economic losses came from hydro-meteorological disaster, while 40% were due to geophysical disasters such as earthquakes. However, flood risk is not only rooted in the extreme hydro-meteorological events. There are key social factors such as population growth, land use change, settlement patterns, and poverty distribution that hugely exacerbate flood risk.

The impacts of floods could be significantly reduced through a holistic approach to 'floor risk management' (Merz et al. 2010). Flood risk assessment is the first and foremost step of risk management processes. Ideally, a flood risk analysis should take into account all relevant flooding scenarios, their associated probabilities as well as possible consequences (Apel et al. 2004, 2006; Gain and Hoque 2013). In order to provide a realistic estimation of expected risk, detailed risk analyses are required (Apel at al. 2009). The assessment of risk related to floods should not be limited to the study of the physical processes, but require also the explicit consideration of several socio-economic phenomena including poverty, inequality, governance and policy making.

Given that flood risk is defined as the expected losses in terms of lives, health status, livelihood opportunities, assets and services resulting from interactions between natural or human induced hazards and vulnerable condition of exposed elements (UNISDR 2004), ideal flood risk assessment should comprise all possible dimensions of consequences, including economical, social, psychological and environmental damages (Merz et al. 2010). Depending on the degree of monetisation (i.e. characterised by market value) and the degree of physical contact of the hazard event, flood damages can be classified into four categories: direct tangible, direct intangible, indirect tangible and indirect intangible (Giupponi et al. 2015). The available methods of flood risk assessment are mainly limited to the estimation of direct tangible damages. Very few studies provide comprehensive assessment on remaining categories of damages. Jonkman et al. (2008) and Ahern et al. (2005), for example, estimate loss of life and health impacts respectively. However, until recently, consideration of tangible-intangible-direct-indirect categories of damages in a single risk assessment framework is rare (Merz et al. 2010; Balbi et al. 2013; Giupponi et al. 2015).

Considering all four categories of damages, the integrated assessment of risk is currently an urgent need in water resources management. For assessing flood risks, integration of both physical and social dimensions is required to 'go out of the water box' (Biswas 2005; WWAP 2009; Varis et al. 2012). To 'go out of the water box' is a response to the recent emphasis, which refers the extension of water resources discussion out of the conventional water sector centred discourse (Biswas 2005; WWAP 2009). Recently, a few studies considered socio-economic and environmental issues when assessing flood risk. Cutter et al. (2013), for example, propose a methodology for incorporating social vulnerability into federal flood risk management planning of United States. Similarly, Escuder-Bueno et al. (2012) and Ballesteros-Cánovas et al. (2013) provide an integrated assessment of flood risk in the European context. These studies have been implemented in the developed parts of the world.

In the developing parts of the world such integrated assessments of risk are still rare. In a recent study, Dewan (2013) describes geospatial techniques for assessing risk and vulnerability. Among the developing countries, Bangladesh is internationally recognized as a flood prone country. The climate change induced seasonal monsoon rainfall, upstream flow, and sea level rise (Gain et al. 2011, 2013a) makes the area vulnerable to severe flooding. In addition to climatic changes, unplanned economic development, significant population pressure, rapid urbanization and land use changes, poor governance are responsible for increased flood risk in Bangladesh (Gain et al. 2012; Gain and Schwab 2012; Dewan, 2013; Rouillard et al. 2014). Considering both climate-change induced hydrologic extreme events and socio-economic condition, the integrated methods of flood risk assessment are required for the study area.

The objective of this study is to provide an assessment of tangible-intangible-direct-indirect categories of flood damages taking into account physical hazards and social vulnerabilities.

We apply the methods in the eastern part of Dhaka City, Bangladesh, where flooding problem is severe. To assess flood risk of the study area, the proposed method incorporates several novel approaches. First, the assessment of flood risk includes the broader context considering not only physical factors, but also socio-economic factors. For assessing the combined effect of different physical and socio-economic variables, risk is conceptualized through a recently developed theoretical framework by Giupponi et al. (2013a). Second, the risk assessment considers four categories of damages (direct tangible, direct intangible, indirect tangible and indirect intangible). For assessing four categories of damages, different available approaches are systematically incorporated in the proposed risk assessment framework. Third, the policy alternative for baseline and improved scenario of vulnerability are evaluated. For evaluating policy alternatives, one of the main non-structural measures i.e., an early warning system (EWS) is considered in this study (Basher 2006). Non-structural measures are considered as the sustainable long-term flood mitigation strategies for Dhaka City, while structural measures create mixed benefits (Faisal et al. 1999). In the base line condition, the current early warning system (EWS) of study area is considered, whereas, in the alternative scenario, the EWS is expected to improve.

In the remaining part of the paper, we first describe the study area, and the methodology developed to estimate flood risk. Then we present out results. The paper is concluded by discussing the major findings.

2 Study Area

Dhaka is the most populous city in Bangladesh and the tenth-largest city in the world, with a density of 44,000/km^2 (Demographia, 2014). The city is surrounded by a network of rivers: the Turag on the west, the Buriganga on the south, the Balu on the east and the Tongi Khal on the north. The combined effect of seasonal monsoon rainfall due to climate change (Gain et al. 2011) and upstream flow due to trans-boundary water governance (Gain and Schwab 2012) makes the city vulnerable to flooding. In recent times, four severe river floods have occurred in 1987, 1988, 1998 and 2004. The total amount of the reported flood damages was BDT (Bangladesh currency) 781.2 million (equivalent to 11.16 million US$) in 1988 and BDT 347.2 million (about 4.96 million US$) in 1987 (Gain and Hoque 2013). After the 1988 flood, the western part of Dhaka City was protected from river flooding by embankments and raised roads (Khan 2006). However, the eastern part of the city remains unprotected from flooding. Therefore, the eastern part of Dhaka City is considered as study area (see Figure 1). The study area, surrounded by a network of rivers, covers an area of 124 km^2 (Gain and Hoque 2013). It is observed that about 60% study area regularly goes under water every year due to flooding by the Balu river in the east and the Tongi Khal in the north (See Figure 1). The average recorded discharge in dry season (February and March) and in monsoon (August) is 60 m^3s^{-1} and 744 m^3s^{-1} respectively (Khan 2006; Gain and Hoque 2011; 2013). The average annual rainfall is about 2,000 mm, of which 80% occurs during the monsoon season (Dewan, 2013). The temperature during the summer months ranges between 28 and 34°C. In winter, the temperature ranges between 10 and 21°C. The ground elevation of Dhaka megacity is very low. Lands along the study area are at elevations between 0.5m and 7m PWD (Public Works Datum, a national datum). Moreover, recent unplanned urbanization (Dewan and Yamaguchi 2008; Hossain et al. 2013) which are now mainly through earth-filling on alluvial deposits, is elevating the potential of flood and earthquake risks related to soil liquefaction (Corner and Dewan, 2014). In addition to these physical features, low response capacity, poor infrastructure, and high poverty of the city make the effects of floods more devastating (Dewan, 2013; Masuya 2014). The land use of the study area is also shown in Figure 1. In the Figure, green dot indicates important locations or urban agglomerations.

3 Methods

For assessing flood risk in the eastern part of Dhaka City, risk is conceptualized as a function of hazard, vulnerability, and exposure (UNDRO 1980; Crichton 1999). This study combines physical, social and ecological dimensions. The risk is calculated based on the following steps.

3.1 Concept of risk and framework for assessment

The notions of vulnerability and risk differ greatly according to various schools of thought such as climate change adaptation (CCA) and disaster risk reduction (DRR) (Gain et al. 2012). For achieving greater synergy between the two communities (e.g., DRR and CCA), recently the IPCC has released a special report (IPCC-SREX Report) in which a substantial move from the CCA community towards the concepts and definitions consolidated in the DRR could be observed (Field et al. 2012).

In this study, flood risk is assessed based on an integrated risk assessment framework, recently developed within an EU funded research project, Knowledge-based approach to develop a cULTUre of Risk prevention (KULTURisk, http://www.kulturisk.eu/). The main innovations of the frameworks are: (i) the integration of physical/environmental dimensions and the socio-economic ones; (ii) the consideration of social capacities of reducing risk, and (iii) the systematic assessment of four categories of damages (direct-indirect-tangible-intangible) for decision support on risk mitigation measures. The framework is shown in Figure 2. The detailed description of framework can be found in Giupponi et al. (2013a) and Mojtahed et al. (2013). In brief, risk is considered as the result of the combination of hazard, exposure, and vulnerability. These components allow calculating the expected damages related to the risks. Risk is composed of four components constituting the Total Cost Matrix (TCM) and deriving from the combinations of indirect/direct tangible/intangible costs. Tangible costs refer to damages receptors that have a market value; intangibles have intrinsic value but no market value. Direct costs include all the tangible/intangible costs in the geographical location during the hazardous event. All the costs generated outside the affected location of the hazardous event is represented by indirect costs.

Similar to recent IPCC reports, in the framework, 'hazard' refers to the occurrence or intensity of natural or human-induced physical events that may cause adverse effects on vulnerable and exposed elements (Field et al. 2012; 2014). In this study, flood is considered as a 'natural hazard' calculated by flood inundation maps through hydrological analysis and modelling and expressed in terms of the expected frequency of 10-, 20-, 50-, 70- and 100-year flood (Gain and Hoque 2013).

'Exposure' refers to the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected. In this study, people and economic activities are used as exposure elements.

Vulnerability is defined as the propensity or predisposition of exposed receptors to be negatively affected by hazard events (Field et al. 2012). Vulnerability considers both human and physical dimensions. In this study, the physical dimension of vulnerability encompasses the susceptibility of man-made structures and infrastructure, which is the likelihood of these receptors to be negatively affected by a hazard event. The human dimension of vulnerability consists of both adaptive (ex-ante) and coping (ex-post) capacities. 'Coping capacity' is the ability to react to and reduce the adverse effects of experienced hazards. This is the ex-post skills to cope with the impacts of the hazards. ‘Adaptive capacity’ is the ability to anticipate and transform structure, functioning, or organization to better survive hazards. Adaptive capacity is the ex-ante preparedness of society given their risk perception and awareness, to combat hazard and reduce its adverse impact. For different components of risk, specific indicators are identified and for each of the indicators quantitative data are collected from different sources. For each of the indicators, collected data are converted into raster map with a resolution of 20 m. Flood inundation maps of 20 m resolution, for example are assessed through hydrologic model and geographic information system (GIS) software using spot height data and hydrologic data (see sub-section 3.2). Socio-economic data are collected at lowest administrative level (mouza for rural portion and ward for urban portion of the study area). This data are then converted into 20 m resolution raster maps.

3.2 Assessment of hazards

Flood inundation depths for several return period floods are usually considered as hazards. Onishi et al. (2013) assessed flood hazards using two-dimensional numerical method. Recently, Masuya et al. (2015) developed flood hazard map based on multi-temporal flood-affected frequency and floodwater depth maps. However, in this study, flood inundation maps are assessed based on freely available hydrologic model. The flood hazard maps of Balu-Tongi Khal River system (see Figure 1) within the eastern part of Dhaka City are prepared using geo-processing tools (e.g., geographic information system software and HEC-GeoRAS) and the hydrologic model HEC-RAS. HEC-RAS is a hydrologic model developed by US Army Corps of Engineers (USACE) and is commonly used to predict flood stage and to map flood inundation by extrapolating flood stage predictions to over bank areas. To process spatial input and output data of HEC-RAS, a geo-processing tool HEC-GeoRAS is used. HEC-GeoRAS is a set of geographic information system (GIS) tools specifically designed to process geospatial data for use with HEC-RAS (USACE 2005). The detail description for the assessment of flood hazards can be found in Gain and Hoque (2013).

In brief, the required topographic input data in HEC-GeoRAS is existing digital terrain model (DTM) of the study area in the ArcInfo triangulated irregular network (TIN) format that can well-represent rivers and flood plain. In order to prepare the TIN, we have used: a DEM of 25 m resolution developed by Institute of Water Modelling (IWM), spot height point data from DAP (2010), river cross sections from Bangladesh Water Development Board (BWDB). The

DEM with 25 resolution alone is not sufficient to represent rivers and floodplain. Therefore, we have also collected spot height point data and river cross section. River cross sections represent depth of river (similar to spot height point data) for different locations. The triangulated irregular network (TIN) surface is then created from contour of the DEM and spot height point data. The prepared TIN is shown in Figure S1, of online supplementary material.

TIN represented the topographic features of the study area including river system. Following flood frequency analysis of hydrologic discharge and water level, standard hydrographs for several return periods were generated to determine inundation levels of the study area (Apel et al 2006; Gain and Hoque 2011; Gain and Hoque 2013). The standard hydrographs for various return period floods were provided as inputs in the HEC-RAS. An initial flow value was given at the upstream boundary of the channel Balu river and Tongi Khal. The flood inundation water levels obtained by HEC-RAS model for various return periods were exported in the geographic information system (GIS) and overlain into each cross-section of triangulated irregular network (TIN) of the study area. Thus, flood inundation maps of various return periods were generated. The flood inundation map for 100-year return period is shown in Figure 3. The resolution of the flood inundation maps are 20 m. The detail procedure for the assessment of flood inundation maps considered in this study is described in Gain (2008) and Gain and Hoque (2011, 2013).

3.3 Assessment of vulnerability

The choice of indicators for vulnerability components depends on the application context and mainly varies with hazard types, the spatial scale considered for the study and data availability (Gain et al. 2012). For example, the indicators for assessing flood risk are different from the indicators of seismic risk. As this work is focused on flood hazards, we referred to Giupponi et al. (2013a) and Mojtahed et al. (2013), who proposed a generalized list of indicators representing adaptive capacity, coping capacity and susceptibility. The most appropriate indicators for the study case were selected considering the data availability and the spatial extent of the study area. The data source for each of the selected indicators is provided in Table 1, whereas definition of the indicator is given in Table 2.

A preliminary step for the aggregation of indicators is normalization, as the indicators in a data set often have different measurement units. For normalizing selected indicators, we use a generalized approach of value function. Value function is a mathematical representation of human judgments through determining upper and lower thresholds and a series of values representing different significant levels of performance with reference to defined goals (Beinat 1997). The indicators are benchmarked according to the definitions of the indicators provided in Table 2 along with qualitative judgement provided in literature (Kreibich et al. 2005, 2010; Thieken et al. 2005, 2007; Merz et al. 2010). The indicator values are normalized and then categorized into five classes (see Table 3). Normalization functions and values for the selected indicators are represented in Figure 4, through the procedure described in Giupponi et al. (2015) and Gain and Giupponi (2015).

The vulnerability index is the result of the combination of several indicators for adaptive capacity, coping capacity and susceptibility. To combine sub-sets of indicators in each node where they converge, a hierarchical aggregation tree is shown in Figure 5. Several weighting and aggregation algorithms are available to aggregate them (OECD 2008). Commonly used weighting procedures are mainly based on either statistical methods (Aleksandrova et al. 2015) or participatory methods (Giupponi et al. 2015). Based on statistical methods of Pareto ranking, Rygel et al. (2006) and Karmakar et al. (2010), for example, demonstrated a method of aggregating vulnerability indicators that avoids the problems associated with assigning weights. The statistical based methods does not incorporate stakeholders' attitude in aggregation. Recently, Giupponi et al. (2013b) and Gain and Giupponi (2015) demonstrated participatory based non-additive aggregation procedure. In this study, we do not have statistical basis of developing causal relationships among indicators. In addition, stakeholder involvement in the aggregation procedure was not possible in this study. Therefore, among different aggregation methods, we apply weighted averages (WA) method considering equal weights for each of the selected indicators in each convergence node. We apply the widely used WA method, as this is very simple and effective. However, we have selected very common indicators and we assume that all indicators in same aggregation node are "worth" the same in the composite. Similar assumption has been considered by Birkmann et al. (2010) for assessing tsunami vulnerability index in Spain using equal weights.

By applying equal weights to normalized indicators and aggregating them by means of the preferred aggregation rule, the vulnerability index is obtained with a score ranging between 0 and 1, where 0 represents no vulnerability and 1 represents high vulnerability. We assess vulnerability for baseline and alternative scenarios. In the baseline condition, current state of the art for early warning system (EWS) of study area is considered. However, in the alternative scenario, an improvement of current EWS is considered keeping all other indicator values constant. This is mainly due to the global emphasis on EWS as one of the major non-structural risk reduction measures (Basher 2006). Description of current and improved EWS is described below.

The Flood Forecasting and Warning Center (FFWC) of the Bangladesh Water Development Board (BWDB) is responsible for monitoring floods in unified and multipurpose basis throughout the country. The rise/fall of the water level with respect to the danger level of the major rivers is the basis of the existing warning message preparation by the FFWC (Paudyal 2002; Chowdhury 2005). Although current EWS provides this flood forecasting with 72-hrs lead-time, but forecasting is less reliable beyond 48 hrs (ADB 2006; Rahman et al. 2013). The forecasting model provides good results for the 24-hrs forecasts with a correlation of 0.987 and a mean absolute error of 6 cm whereas the results of 72-hrs forecasts are subject to more variation with a correlation of 0.866 and a mean absolute error of 23 cm (ADB 2006). The success rate of predicting the correct trend (that is whether water levels are rising or falling) is 89% for the 24-hrs forecasts and 49% for the 72-hrs forecasts (ADB 2006). In addition, the current early warning messages are prepared in technical terms i.e., 'the rise/fall of the water level with respect to the danger level' (Paudyal 2002). It is difficult to interpret the meaning of technical dissemination for a person who is illiterate and resides far away from the river (Dewan, 2013). In addition, warning messages in their present form remain difficult for people to grasp and thus respond effectively to an approaching flood. This message is disseminated to the national level and not in the local or community level (Chowdury 2000, 2005; Rahman et al. 2013). This technical forecast is unclear, and also not equally accessible to all users.

The main weaknesses of current EWS of the country are difficulties in obtaining reliable water level and rainfall data from upstream countries as there are no data sharing mechanisms among the countries (Webster et al. 2010). However, lead-time and reliability of current EWS can be increased through technological advancement. The computer system and the software used for preparing forecasts can be improved with the installation of new equipments and programmers. A study by ADB (2006) suggests that a 7-day flood forecast with high reliability has the potential of reducing post-flood household and agricultural costs in Bangladesh by 20% compared to 3% for a 2-day forecast. In order to improve lead-time and reliability of existing forecasting, several explorative studies have been undertaken. Hopson and Webster (2010) and Webster et al. (2010), for example, provided reliable probabilistic forecasts with the lead-time of 10-days. In addition, government has identified limitations of current dissemination mechanisms. The government is now approaching to improve these limitations (ADB 2006; Rahman et al 2013). Considering the current progress in EWS of Bangladesh, an alternative scenario is set for this study. The lead-time of the alternative scenario is expected to increase at least 5-days, reliability will be high and forecasted information should be understandable and equally accessible by all users.

Normalized values of early warning system for both baseline and improved scenario are given in Table 4. Assessment of vulnerability considered in this study is similar to indicator based approach of Dewan (2013). However, in our assessment, we define vulnerability based on recent literature (Giupponi et al. 2015) and IPCC report (Field et al. 2014). In addition, we assessed vulnerability for both baseline and improved scenario. The result of vulnerability for the baseline condition of EWS is provided in Figure 6a. Figure 6b depicts the results for improved condition of early warning system. In the improved scenario, the affected area of high vulnerability (with the value greater than 0.4) has been reduced compared to base line scenario (see Figure 6).

3.4 Selection of exposed elements for different cost categories

Characterized by market values and degree of physical contact with hazard, the consequences of hydro-meteorological disasters can be categorized into direct tangible, direct intangible, indirect tangible and indirect intangible costs (Balbi et al. 2013). A comprehensive summary of different category of damages is provided in Balbi et al. (2013) and Giupponi et al. (2013a). In order to determine the overall burden on a social and ecological system imposed by flood, considerations of these categories of damages are important. The estimation of flood risk in this study is therefore considered for direct tangible, direct intangible and indirect tangible and indirect intangible costs.

Among different types of direct tangible costs, damage to agriculture, industry, business, and private buildings, vehicles, evacuation and rescue costs, clean up costs, and health costs are important (Balbi et al. 2013). Consideration of all these categories in a single assessment study is very difficult mainly due to unavailability of consistent calculation methods and high data requirements. In the context of a developing country like Bangladesh, where our study focuses, unavailability and inaccessibility of required data are the major impediments. For example, required data for evacuation and rescue costs, clean up costs, health costs are not available and accessible. For these reasons, direct tangible damages for eastern part of Dhaka city is calculated for land use classes and vehicles. Damages to land use types allows risk assessment to important economic sectors from above categories e.g., residential, commercial, industrial, agricultural, roads and infrastructures. In addition, damage to vehicles is another important economic component, which is traditionally not considered for flood risk assessment. For assessing damages to vehicles, total number of vehicles was collected from Bangladesh Road Transport Authority (BRTA). In this study, we choose only Sedan cars, as the most common type of vehicle. Based on this data, we have calculated average number of cars per household. Then, we have calculated number of cars per grid *i* (resolution 20m), (See *section 4.1*, *Economic Damages to Vehicles* for detailed description).

Similarly, among different categories of direct intangible damages (Giupponi et al. 2013a), this study includes assessment for the number of exposed and injured people, and loss of life. These are the major categories of risk to people. Other types for example, psychological distress, effects on ecosystem services are difficult to assess as consistent and quantitative assessment methods are not available.

Among indirect tangible costs, disruption of public services, disruption of traffic, induced production losses to agriculture and companies outside the flood-affected area, loss of tax revenue and costs associated with temporary housing of evacuees are important (Balbi et al. 2013; Giupponi et al. 2013a). In the context of Dhaka City, induced production losses to garments industries are one of the main types of indirect tangible damages, as the importance of garments in the economy of Bangladesh is high (Islam et al. 2013). Similarly, indirect loss of paddy production is another important category of damages as rice is the main crop for Bangladesh. Although loss of taxes, costs associated with temporary housing, disruption of public sectors are relevant, required data for these assessments are not available. Therefore, we have considered indirect damages to garments industry and paddy production only. Indirect intangible categories include all the damages mentioned in direct intangible but spatial scale should be outside the project area. In Bangladesh, spread of vector and water borne diseases (e.g., diarrhoea, typhoid) due to flood is one of the major problems that also affect outside the flood-prone community (Huq et al. 2005; Schwartz et al. 2006; Reiner et al. 2012). Therefore, in this study, indirect intangible damages include assessment of spread of diseases. The elements exposed to flood risk in different cost categories considered in this study are shown in Figure 7. The results for each category of risk are discussed bellow.

4 Assessment of risk for different cost categories

Combining flood inundation maps (hazards), vulnerability index (aggregation of adaptive capacity, coping capacity and susceptibility) and exposure elements, the aggregated notion of flood risk is calculated for both baseline and improved scenarios of vulnerability.

4.1 Direct tangible costs

In this study, flood risk assessment for direct tangible costs is restricted to monetary damages to various land use classes and vehicles.

Economic damages to land use types

Consideration of damage to land use types allows risk assessment to important economic sectors of urban environment. For calculating monetary damage to different land-use categories such as residential, commercial, industrial, agricultural etc. (see Figure 1), the following equation (Eq. 1) similar to Gain and Hoque (2013) and Mojtahed et al. (2013) has been used.

$$DTLU_{ij} = p_j \left(Vul_i \times DDD_j \times P \times A \right) \qquad \text{(Eq. 1)}$$

where *DTLU* is raster-based total direct tangible damage for different land use classes, p_j is the exceedance probability of return period j, *Vul* is the vulnerability map calculated through the method described in section 3.3, *DDD* is the empirical depth-duration-damage functions for different categories of land uses in Dhaka city taken from Gain and Hoque (2013); *P* is the raster based property value in monetary terms (BDT, currency of Bangladesh); and *A* is the area of each raster cell in m^2, which is 400 m^2 as cell size is 20 × 20. i refers to different scenario of vulnerability, where i = 1 is baseline scenario of vulnerability, and i = 2 is the improved scenario of vulnerability. Similarly, j refers to the return period of flood. Detailed description for calculating depth-duration-damage function (DDD_j) can be found in Gain and Hoque (2013). Raster based property value (P) is calculated through collecting recent monetary value of different land use categories. DAP (2010) provide monetary values for lands of different locations, but not for land use categories. For providing monetary value of land use category, we have considered a recent study by Sharif and Esa (2014). Based on overall monetary value provided by DAP (2010), we have allocated monetary values for land use categories considering the assumption of Sharif and Esa (2014). Expected direct tangible damages to land use categories for 100 year return period flood is shown in Figure 8a, 8b, 8c. Figure 8a and 8b show damages for baseline and improved scenario of vulnerability respectively, whereas Figure 8c shows the benefits of improved scenario, given by the difference of previous two maps. In brief, the total costs of damages to land-use categories in baseline and alternative scenarios are 1.22 billion BDT and 990 million BDT respectively. According to this study, the gross benefit of investing in EWSs is a reduction of 18.5% in damages to land use categories. From the developed figure it is evident that in the improved EWS, expected damages may be reduced significantly.

Economic damages to Vehicles

In addition to the economic assessment of land use types, we considered the damage to vehicles (only Sedan cars) following the Eq. 2. Total number of sedan cars for Dhaka city was collected from Bangladesh Road Transport Authority (BRTA). Using the data about the sedan cars coming from BRTA and the household size (from BBS 2011), we calculated the average cars per household only for Dhaka city. We have used this average value for calculating (grid based) number of cars in the study area.

Based on this data, we have calculated average number of cars per household. Then, we have calculated number of cars per grid i (resolution 20 m).

$$DTV_j = p_j\left(DD_j \times C \times P\right) \qquad \text{(Eq. 2)}$$

where *DTV* is raster-based total direct tangible damage for vehicles, p_j is the probability of return period *j*, *DD* is the empirical depth-damage functions for different types of vehicles (USACE 2009), *C* is the number of cars per unit raster cell (400 m^2), *P* is the average monetary value (BDT, currency of Bangladesh) per car and *j* refers to return period of flood.

We understand that this can be upper estimate given that many households might not own sedan cars in the Eastern part of Dhaka city. However, we feel that this is a first approximation for trying to tackle measuring the impact of flood on mobile assets such as cars, in a data scarce area.

According to USACE (2009), households usually are able to move their vehicles to safe places with higher elevation if they are warned in advance. We have taken into account this information in estimating the damages to vehicles based on how much time the households have in advance before flood happens when EWS is active.

In the assessment, first, we calculated the number of vehicles per household for the considered area. Second, we applied the generic depth-damage functions reported by US Army Corps of Engineers, USACE (2009). Although the depth-damage functions are varying for each type of vehicle, we focused only on sedans, which are the dominant type of vehicle in Bangladesh. The depth-damage (*DD*) function is provided in Eq. 3.

$$DD_j = 34\ln(D_j) - 87.175 \qquad \text{(Eq. 3)}$$

where, D_j is the flood depths map of j return period event.

Applying the above method, we assess total amount of calculated damages to vehicles for 100 year-return period floods, which is 7.23 million BDT. For any warning sent at least 12 hours in advance by the EWS, it appears that only 11.9% of household will not be able to move their vehicles to the higher ground. Similarly, we have also calculated damages in the presence of EWS with 120-hour lead-time. We found total amount of damages for vehicles for 100 year flood as 0.85 million BDT.

4.2 Direct intangible costs

In this study, direct intangible damages are restricted to the assessment of risk to people. Risks to people include three categories of intangibles damages: number of exposed, injured and dead people due to flood risk. For calculating these intangible damages, first flood severeness (Eq. 4) is calculated following the method presented in DEFRA (2006) and Mojtahed et al (2013).

$$FS_i = \frac{\left(d_i \times \left(v_i + 0.5\right) + DF_i\right)}{10} \qquad \text{(Eq. 4)}$$

where d_i is the depth of water measured in meter, v_i is the velocity of flood (m/s) and DF_i is debris factor (1= Urban, 0.5 = Woodland) all considered for raster cell *i*. The above formula is estimated for human receptor based on field experiments and the coefficients are subject to variations based on characterization of body masses of the samples. Following the characterization of flood severeness, we identify the number of people exposed to risk, $n.p.r._i$ (Eq. 5).

$$n.p.r._i = N_i \times FS_i \times Vul_i \qquad \text{(Eq. 5)}$$

where N_i is the number of people, and Vul_i is the overall vulnerability index in raster cell *i*. The number of injuries, $n.inj._i$, is calculated following Eq. 6.

$$n.inj._i = n.p.r_i \times \alpha \times Vul_i \qquad \text{(Eq. 6)}$$

where α is calibrated by means of the historical data for a given hazard with certain return time, and then rounded to the closet integer. The number of deaths is calculated as Eq. 7.

$$n.dth._i = \frac{(n.inj._i \times \beta + FS_i)}{10} \qquad \text{(Eq. 7)}$$

where β is also calibrated with the historical data. For this assessment, we assumed α =1 and β =1.5.

Using above methods, three categories of intangible damages are calculated. Summary results for total number of exposed, injured and death people of study area are shown in Table 5. The results indicate intangible damages for 100-year return period flood of both baseline and improved scenario. In the improved scenario, number of exposed, injured and dead people has been reduced significantly, as provided in Table 5.

4.3 Indirect tangible costs

Economic damages to garments industry

Garments factory is the most important economic sector in Bangladesh for export value (Keane and te Velde 2008; Islam et al. 2013). Flood risk assessment for indirect tangible damages is assessed for garments factory, which is not directly affected by flood. Part of the labor force of the garments factory is impeded to reach the workplace. The indirect effects can be computed by estimating the daily lack of production in a labor-intensive activity such as the one occurring in the garments factory in Dhaka city. According to recent estimate, nearly 4,500 garment factories are available in Bangladesh, although around 3,500 are currently operating (Wadud et al. 2014). Over 70% of these factories are located in Dhaka, the capital of Bangladesh (Muhammad, 2011). Although Bangladesh government is planning to relocate some of these factories, it has not been relocated yet.

In this study we focus on two areas on the west side of the embankment. They host two relevant clusters of firms: not the only ones in Dhaka, but they are among the closest to the flood affected area. One of them is located in Motijheel, in the south of the Dhaka City. This part is in the western part of the study area and is flood-secured by the embankment and raised road. Motijheel hosts a cluster of 225 garment factories (Hoque et al. 2006, 2007) with more than 94,000 workers. The second cluster is located between Dhanmondi and Tejgaon – and we call it the Northern cluster (N) – and it is a few km farther away from the embankment than Mojtheel (M), see Figure 9. Around 35,000 employees are employed by 75 firms in the area of N (for the location of clusters and the summary of data see Figure 9 and Table 6).

We assume that the distribution of workers in the garment industry is uniform across the territory of Dhaka City and workers may flow into their workplace from all directions. Yet, commuting on foot (see for instance Table 2.1 in Ahmed et al. 2014), they will generally prefer living close to the working place. This is confirmed by a preliminary study on workers' travel pattern carried out in 2006 (Hoque et al. 2006) and holds nowadays (Ahmed et al. 2014; Nahiduzzaman 2012): "those who are employed in formal jobs such as garment industries … do not commute more than 12 km" (Ahmed et al. 2014:37). We estimate people's mobility using two different models that embed the preference for individuals to shorten their commuting distance (Clark et al. 2003), for the absence of detailed data on traffic flows of the urban population in Dhaka. The results from the gravity model (relative preference of workers to commute to two different workplaces on the secure side of the embankment) are validated by the radiation model (Simini et al. 2012) that is less biased towards short commuting distances. Grounded in physics, gravity models are used to predict flows of goods and people (Vanderkamp 1971; Eaton and Tamura 1995). The gravity model shows the force of attraction of the two clusters M and N on workers of the area depicted in Figure 9. The force of attraction is proportional to the size of firms, i.e., number of employees, and decays strongly with the distance. We compute the attraction of the two cluster of firms M and N to estimate the flow of people moving from the flood impacted eastern part (here forth K, denoted also in Figure 8) that is situated on the eastern and non-secured part of Dhaka to the workplaces located in M and N. We divide the zone around K in three parts, north, centre, and south to accurately estimate the attraction force, see Table 6.

The force of attraction, a of the cluster i is

$$a_i = \frac{size_i}{f(r)} \qquad \text{(Eq. 8)}$$

where r is the distance to a cluster of firms, and size is the number of employees within the cluster. We compute this with r^2 that seems to be conservative with respect to walking as means for commuting – the higher the exponent of r, the higher is the preference for a closer location (see Simini et al. 2012 for a brief discussion on f(r) in western society). Due to the proximity to the unsecured area, the attraction for the M cluster with respect to the N cluster is between 7.5 and 8.5 times higher, with higher values in the north and centre, due to the proximity with M and the exponential decay with the distance. The force of attraction can be seen as a proportion of workers moving from the unsecured area towards M rather than in N.

To understand the amount of workforce living in K and moving west towards the clusters of M and N, we need to assume that the proportion of workers in the garments industry who live in the eastern part of Dhaka does not differ from that of the whole city, i.e., 8.9% of the population. In this case nearly 25670 workers in the garments factory live in K: around 22800 commute to the M district, while the remainder go to N. A shrunk of workforce will negatively affect the output of the firms in the cluster. In the M cluster, a reduction of nearly 22800 workers will decrease the total workforce of 24.2%, whereas in N the reduction is of 8.4%. These proportions, along with the capitalization of the garment industry (SHDU 2000) averaged over the number of Bangladeshi workers in the industry (BBS 2010), and the yearly labour input in working hours (50-hour week) in M and N before and during a flood, we feed a Cobb-Douglas production function recently estimated for Bangladeshi industries (Hossain et al. 2012). Results show that in the cluster of M, the reduction in production is of 13% for each day of flood, whereas in N of 4.3%.

The estimated percentages of loss of production are the upper bounds since for floods with duration of over three weeks; firms can eventually substitute the less skilled labour forces easily. Another observation that leads us to believe that the above estimation is high, is due to the adaptation strategies of people living in flood prone areas like Dhaka city. People living in these areas have eventually learned to use backup methods of transportation such as boats.

Economic damages to paddy production

Damages to agricultural products are one of the major categories of flood damages, as the agricultural lands can easily exposed to flood waters and products can be spoiled. However, in this section we demonstrate how economic production functions can be used instead of typical depth-damage functions to assess the damages. In the next step, we use the Input-Output (I-O) tables to evaluate the ripple effects of damages to other sectors.

In the area under study, one of the main economic activities is agriculture with 33% of workers being employed in this sector (BBS 2011). Therefore, we have limited our consideration to agriculture sector and in particular paddy, which is the dominant crop cultivated in the area. This is a sector where both factors of production meaning labor and capital (i.e. land) are exposed to risk. The flood happens to occur during the period of planting 'aman' paddy, which is the monsoon seasons and lasts from June to October. The inundation and timing of the event prevents farmers from being able to cultivate their lands.

Input data for this assessment are: land used for agriculture and people dependent on agriculture. These data are collected from BBS (2011) and DAP (2010). The first step is to estimate the effects of the direct shock to agricultural production. Due to this shock, certain restriction on forwardly or backwardly linked sectors such as shipments or purchases is imposed, which when computed we can derive the excess demand or supply. For example as a result of the shock to production of paddy, the demand for fertilizer will decrease. The same shock would also limit the shipment to other sectors, for instance rice-milling sector will receive less products from the paddy sector. This first-round effect produces excess demand and supplies of other resources.

It is noteworthy to mention that such assessment is static and does not consider the dynamic changes in prices and subsequent substitutions that can take place in a market or by producers and households. Moreover, the I-O analysis is more suitable for short-term shocks e.g. sudden change in demand while in the long-run often factors of production can be substituted with each other or import and exports can act as shock absorbers or new plants can be built which eventually mitigates the adverse impacts of natural disasters and change the internal structure of the I-O tables (See Bess and Ambargis (2011) for review of important assumption of I-O analysis).

The generic I-O table represents the flows of goods and services among industries and from industries to households, government, and import/exports. This flow is represented by Eq. 9:

$$X_i = \sum_{j}^{I} X_{ij} + Y_i \qquad \text{(Eq. 9)}$$

where X_i is the total output of good i, X_{ij} is the amount of good i sold as intermediate input to sector j, Y_i is the amount of good i sold as final good. The above equation is rearranged similar to Eq. (10) so that it comprises technical coefficients representing the ratios of inputs to outputs.

$$X_i = \sum_{j}^{I} a_{ij} X_j + Y_i \qquad \text{(Eq. 10)}$$

where a_{ij} is equal to input value of sector i to sector j divided by total output of sector i. In matrix form, we can write the above as $X=AX+Y$.

Rearranging the above, we arrive at Eq. (11).

$$(1-A)^{-1} Y = X \qquad \text{(Eq. 11)}$$

The term (I-A)$^{-1}$ is called Leontief Inverse, which represents how much each sector's output must increase as a result of (direct and indirect) demands to produce an additional unit of final good of each type (Miller and Blair 2009).

In order to calculate the indirect damages, we first estimate the direct damages (ΔX_i) to sector i in terms of loss of capacity, production, or labor. We then utilize this result to calculate the loss of direct/indirect demand (ΔY) of intermediate products. Once the loss of demand is known, we use Equation (11) to calculate the value of business interruption to all sectors (ΔX) due to loss of demand as a result of direct damage to the sector of interest (Cochrane 1999). The estimated value comprises both the direct and indirect damages.

Based on our calculations in the previous section, 2.4% of the labor force and 38.8% of land will be affected during the flood (Table 7).

Using this result and the production function from Shahadatullah (1974), we estimate the loss of paddy production by using Eq. 12

$$\log(Q) = 0.279 + 0.244\log(L) + 0.611\log(N) - 0.159(\log(L) - \log(N))^2 \qquad \text{(Eq. 12)}$$

where Q is production in maund (where, 1 maund = 37.32 kg), L is the land in acre, N is number of workers in standard unit. Given the loss of land and labor, 425,230 BDT (Bangladesh Currency Unit) worth of paddy will be ruined in case of a flood.

Now that we know the direct damage to production of paddy, we can proceed to estimate the change in demand (ΔY) of other sectors goods and services. This is simply done by multiplying the multiplier matrix (I-A) by the vector X, which represents change in gross productions. Finally, we use Equation (11), to evaluate the damages to other sectors given the shift in the final demand. Our calculation shows a direct and indirect damages equal to 1,063,525 BDT out of which 638,295 BDT is indirect damages.

In this exercise, we limited our assessment to only the inter-industry damages and not damages to households since past studies regarding the effects of disasters (Rose and Lim 2002) has shown that i) spending patterns of households will not change ii) relative prices do not change significantly in the short run.

Nevertheless, our estimate is an upper bound to the true value of damages. For instance, damage to a farm may not necessarily always trigger the change in demand for some intermediate products like machinery (please see online supplementary material, Table S1). The reason is usage of machinery is not always in form of renting from outside and may be owned by the farmer. In such cases, it can be rented out to unaffected farms during the flood event. In some other cases, a damage to products of one sector can be substituted by the products of the competing firms in another area especially if there are empty capacities to increases the production and hence this reduces the estimated damages.

4.3 Indirect intangible costs

The effects of floods on water and vector borne diseases may be of significant public health concern for Bangladesh (Hashizume et al. 2012; Dewan et al. 2013; Corner et al. 2013; Zanuzdana et al. 2013; Ali et al. 2014; Banu et al. 2014; Dewan et al., 2014; Khan et al. 2014). Especially diarrhoeal disease is one of the leading causes of morbidity and mortality, especially among children in low-income countries (Kosek et al. 2003; Hashizume et al. 2014). There is a potential for increased transmission of diarrhoeal diseases during flood and post-flood conditions (Kondo et al. 2002). Hashizume et al (2008) confirm that low socio-economic groups and poor hygiene and sanitation groups are the most vulnerable to flood-related diarrhoea. One of the quantitative measures for epidemiological effect is the calculation of incidence rate. The incidence rate for diarrhoea disease in any given spatial (e.g., lowest administrative level) and temporal unit (e.g., month, season or year) can be calculated using Eq. 9.

$$IR = \frac{tdc}{tp} \times 100{,}000 \qquad \text{(Eq. 9)}$$

where IR is incidence rate per 100,000 population, *tdc* is total diarrhoea diseases, *tp* is total population.

To investigate the effect of flooding, the temporal unit can be considered as season. In Bangladesh, monsoon (July to October) is the important season when spread of diarrhoea is noticed. There were extensive floods during the monsoons of 1988, 1998, 2004 and 2007 (Schwartz et al. 2006; Harris et al. 2008). During these periods, 25-50% of Bangladesh was submerged, resulting in the destruction of infrastructure, contamination of water, and epidemics of diarrhoeal illness. Waterborne outbreaks of diarrhoeal illness in the flood affected community after floods are thought to result primarily from contamination of water caused by disruption of water purification and sewage disposal systems (Schwartz et al. 2006). The diarrhoeal diseases can be spread in the surrounding area through secondary effects of flooding. In order to understand the indirect effect on diarrhoeal epidemiology, investigation on transmission mechanism of diseases is required.

Diarrhoeal diseases are transmitted via the faecal-oral root. The pathogens discharged in the faces of an infected person may enter the body of another susceptible person through the mouth. This may occur through ingesting food or water contaminated with human excreta. Direct transmission among persons in close contact is also possible through unclean hands and contaminated objects such as bed linen, kitchen utensils, and tableware. Flies and cockroaches play a role as vectors of the infectious agents of faecal origin.

Most of the people from the flood affected eastern part need to go western part for daily activities e.g., services, business, rickshaw pulling etc as western part is more urbanized and has economic attraction. The diarrhoea affected people (who are at initial stage) from eastern part and work in unhygienic environment of western part are the primary agents to spread the disease in the flood unaffected part. In addition, flies and cockroaches directly spread the vectors of the infectious agents of faecal origin. Once infectious pathogens enter into urban part, it spreads quickly as population density is high where slums and squatters are situated (Chowdhury et al. 2011). However, in the absence of data, in this study we do not provide any quantitative figure of diarrhoea incidence rate in the flood-unaffected community.

5 Discussion

As stated in the introduction to this paper, there is an urgent need to 'go out of the water box' in water resources management. In this direction, integrated flood risk management is an approach that explicitly recognizes the interrelationships between multiple risk management measures, and the analysis of their costs and effectiveness, within changing social, economic, and environmental contexts (Hall et al. 2003; Hall and Borgemeo 2013). Despite their evident relevance, the links between physical and social dimensions of flood risk have rarely been explored in detail and sectoral and technocratic approaches to flood risk management have been preferred (Brown and Damery 2002). To go beyond technocratic approaches, in this study we apply an integrated assessment framework of risk (see Figure 2) recently developed by Giupponi et al. (2013a) and Mojtahed et al. (2013) that combines various social and ecological indicators of risks related to floods. The framework has been implemented in the eastern part of Dhaka city, Bangladesh, extremely prone to detrimental flooding. Risks associated with flooding in the study area are expected to increase further in the coming years due to global change impacts as well as the high rate of urbanization the city is facing (Haque et al. 2012).

In this study, flood risk risks are calculated for different categories of damages. Direct tangible damages are calculated for land-use classes, whereas direct intangible costs are assessed for risks to people. In addition, indirect tangible and intangible costs are calculated for garments factory and spread of diseases respectively. The results are summarized in Table 8.

Compared to classical inundation maps in the study area (e.g., Dewan et al. 2007), expected flood damage maps generate more information about the flooding event because they take into account all the major effects of flooding (Masood and Takeuchi 2012; Gain and Hoque 2013). Therefore, for a comprehensive assessment of risk it is required to consider different categories of damages: direct-indirect-tangible-intangible (Penning-Rowsell et al. 2003; Jonkman et al. 2008; Merz et al. 2010).

Decision support based upon Cost-Benefit Analysis requires the assessment of all types of damages in monetary value. However, we argue that full monetization of all types of damages is possible only in limited cases. Already some of these damages have been considered separately e.g., estimation of loss of life by Jonkman et al. (2008), health impacts by Ahern et al. (2005), but assessment of different categories of damages in a single study is new.

In this study, we evaluated the quantitative performance of alternative risk reduction measures. Compared to structural measures, it became evident that non-structural measures contributed to flood damage reduction (Faisal et al. 1999). Among the non-structural measures, improvement of EWS, adoption of flood insurance, land use planning, emergency services are important (Faisal et al. 1999; Haque et al. 2012). Among these measures, we evaluated only the performance of EWS for direct tangible and direct intangible damages. Our results suggest that flood risk and related damages are expected to reduce significantly in the improved scenario compared to the base line scenario (i.e., current EWSs). We believe that EWS has little effect on indirect damages of floods. Therefore, we do not provide assessment of improved EWS for indirect damages.

6 Conclusion

Dhaka megacity, the capital of Bangladesh is an internationally recognized hotspot for flood risk due to both natural and anthropogenic conditions. Therefore, the eastern part of Dhaka city is selected to apply an integrated assessment approach through readily available secondary data to provide initial estimation of the expected effects of risk reduction measures.

In this study, we provide a comprehensive flood risk assessment combining flood hazard maps, vulnerably assessment and direct-indirect-tangible-intangibles damages estimation. Flood hazard maps for different return periods are developed through geographic information system and a hydrologic model, HEC-RAS. Vulnerability is assessed through aggregation of various social dimensions i.e., coping and adaptive capacities, susceptibility. We assess vulnerability for both baseline and improved scenario. In the baseline scenario, currently available lead-time and reliability of early warning implemented in the study area is considered. In the alternative scenario, the warning system is expected to improve through technological advancement. Considering the current progress in EWS of Bangladesh, an alternative scenario is set: the lead-time is set as 5-days, reliability will be high and forecasted information should be understandable and equally accessible by all users. Flood risk maps aggregating hazard, exposure and vulnerability, (damages to direct-indirect-tangible-intangibles categories) for several return period are produced for both baseline and improved scenario.

In this study, we provide a better understanding of total costs and their physical and social drivers, which is needed for appropriate risk management (Kreibich et al. 2014). Our results suggest that improvement of current early warning system significantly reduces all categories (direct-indirect-tangible-intangible) of damages. According to our estimation for 100-year flood, at least 18.5% in monetary damages to land use categories can be reduced if advanced early warning system is implemented. Similarly, number of injured and dead people can be reduced significantly through improving early warning system.

The urban planners and the decision-makers may find the result of this study useful for comparing the alternative scenarios with the current flood risk management plan in the eastern side of Dhaka City. This assessment provides useful information about flood risk management and should be helpful in identifying priority measures in risk prone areas. The risk maps may serve the responsible authorities to envisage the combination of physical and social drivers in the study area. This study could thus have considerable management implications for various short-term measures (e.g., emergency preparedness including aid and relief operations) and longer term measures (e.g., future adaptation plans). Spatial representation of our results may also help the local people to visualize flood risk. Although the method can be easily transferred to similar cases where secondary data are available, we need to acknowledge some main pitfall of what we presented.

In this study we do not explicitly model future climate change impact including uncertainty. Figures are presented in deterministic fashion, while the inclusion of uncertainty with probability intervals may significantly change the risk maps output (Mojtahed et al. 2014).

In addition, indicators for social and physical dimensions are aggregated through mean-average weighting factor without involving stakeholders. Stakeholders involvement is a cornerstone of current integrated water resources management practices (Gain et al. 2013b; Benson et al. 2015), and this should be included in comprehensive studies with policy implications.

Furthermore we intentionally avoided the monetary assessment of garments industry losses, because we preferred to exclusively rely on public secondary sources. However to quantify these losses, our assessment would be easily feasible if the value of the production of the garment industry in Dhaka City is known.

Optimal investment in flood risk mitigation will require in the study area. The marginal benefit of risk reduction should be at least equal to the cost of achieving that reduction. In this study, we only assess one of the non-structural measures, early warning system. However, other non-structural measures such as land use planning can play important role for reducing flood risk. Dewan and Yamaguchi (2009) and Ahmed and Ahmed (2012) provided model based estimation of future land use planning. Considering these studies, non-structural measures such as land use planning, adoption of flood insurance need to be implemented for reducing flood related damages through better understanding of total costs.

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Figures

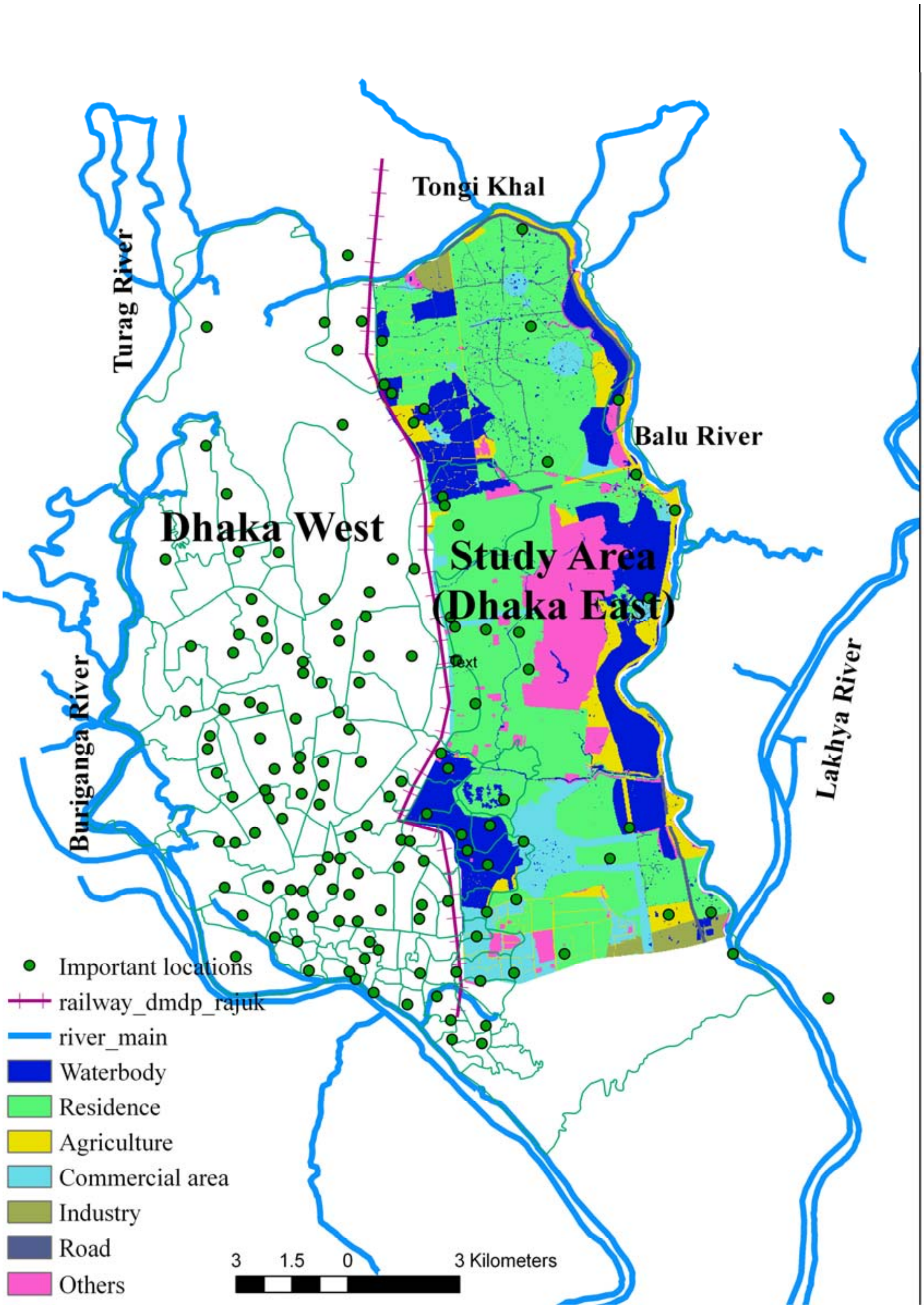

Figure 1. Location map of the study area

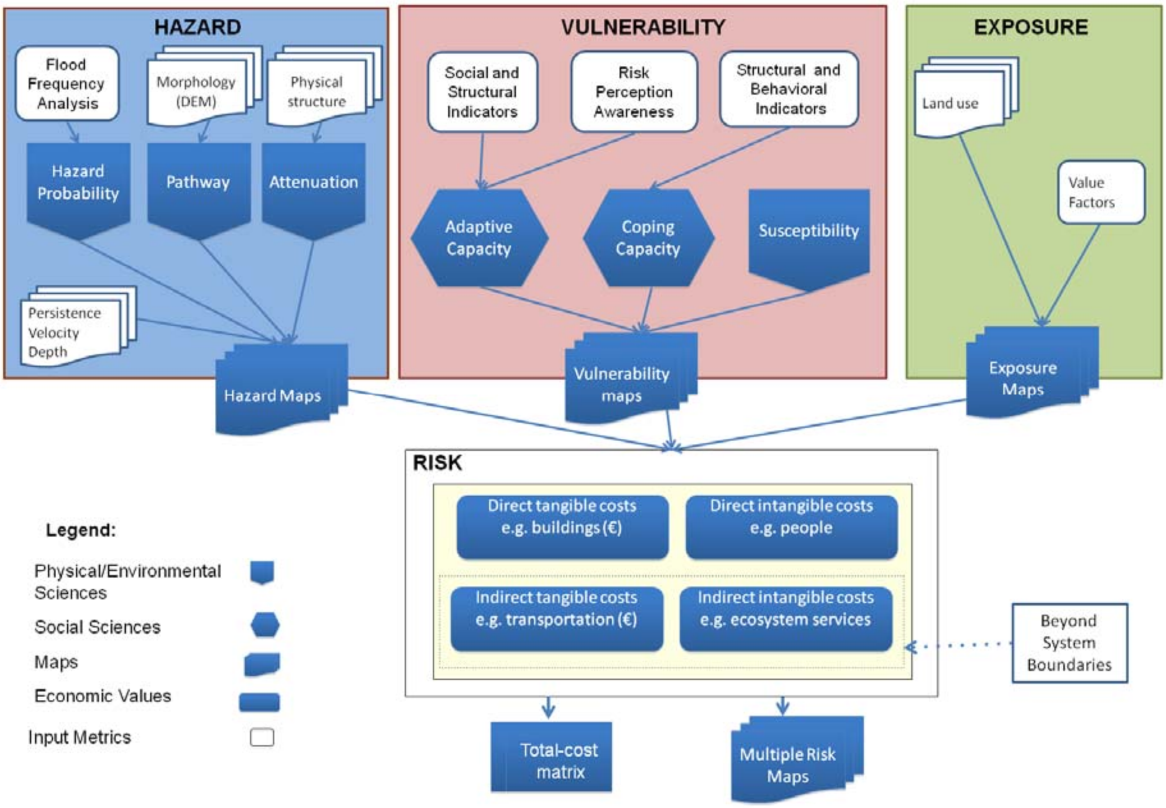

Figure 2. The KULTURisk Framework with the identification of the main sources of data

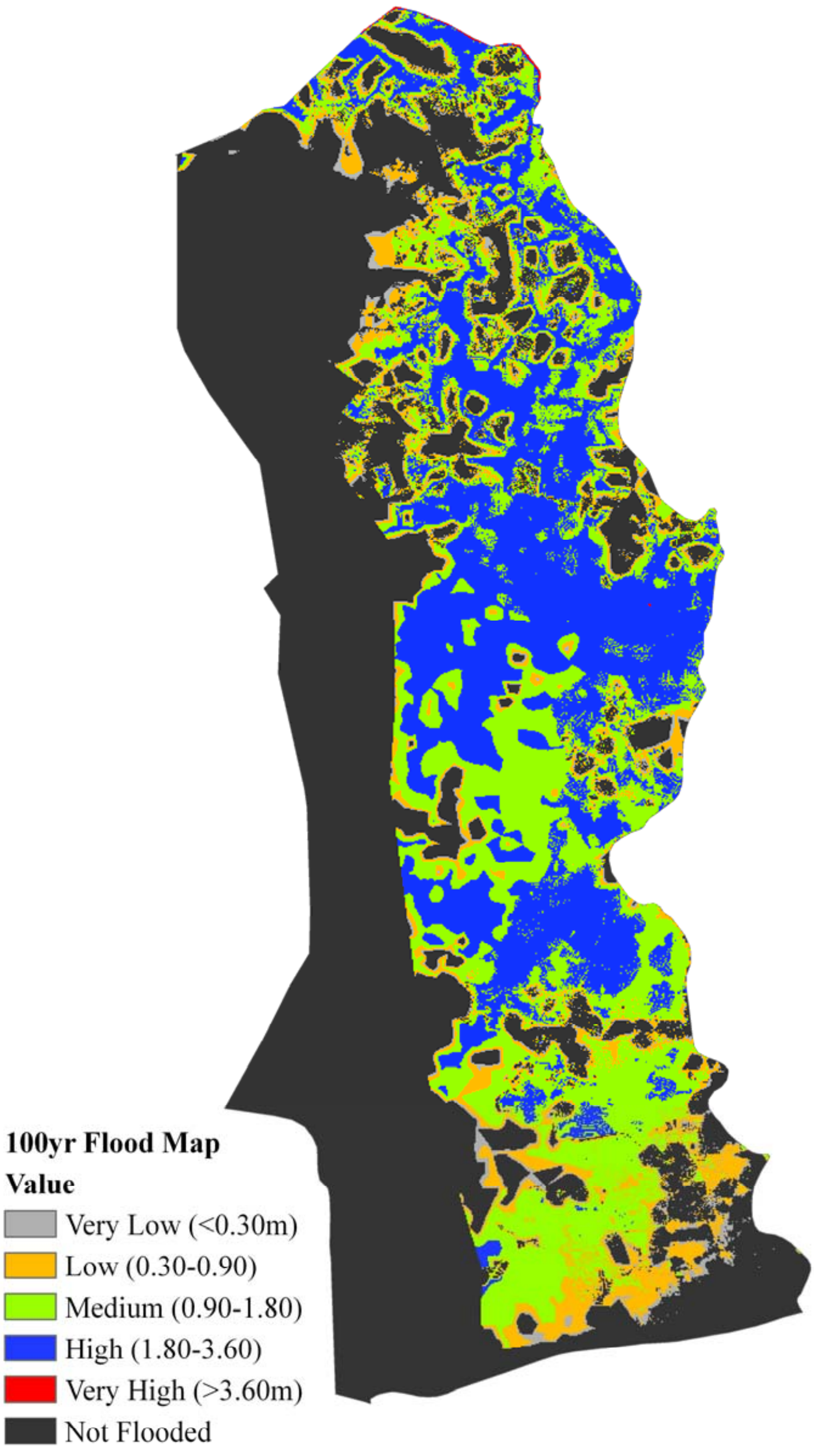

Figure 3. Flood inundation map of 100-year return period

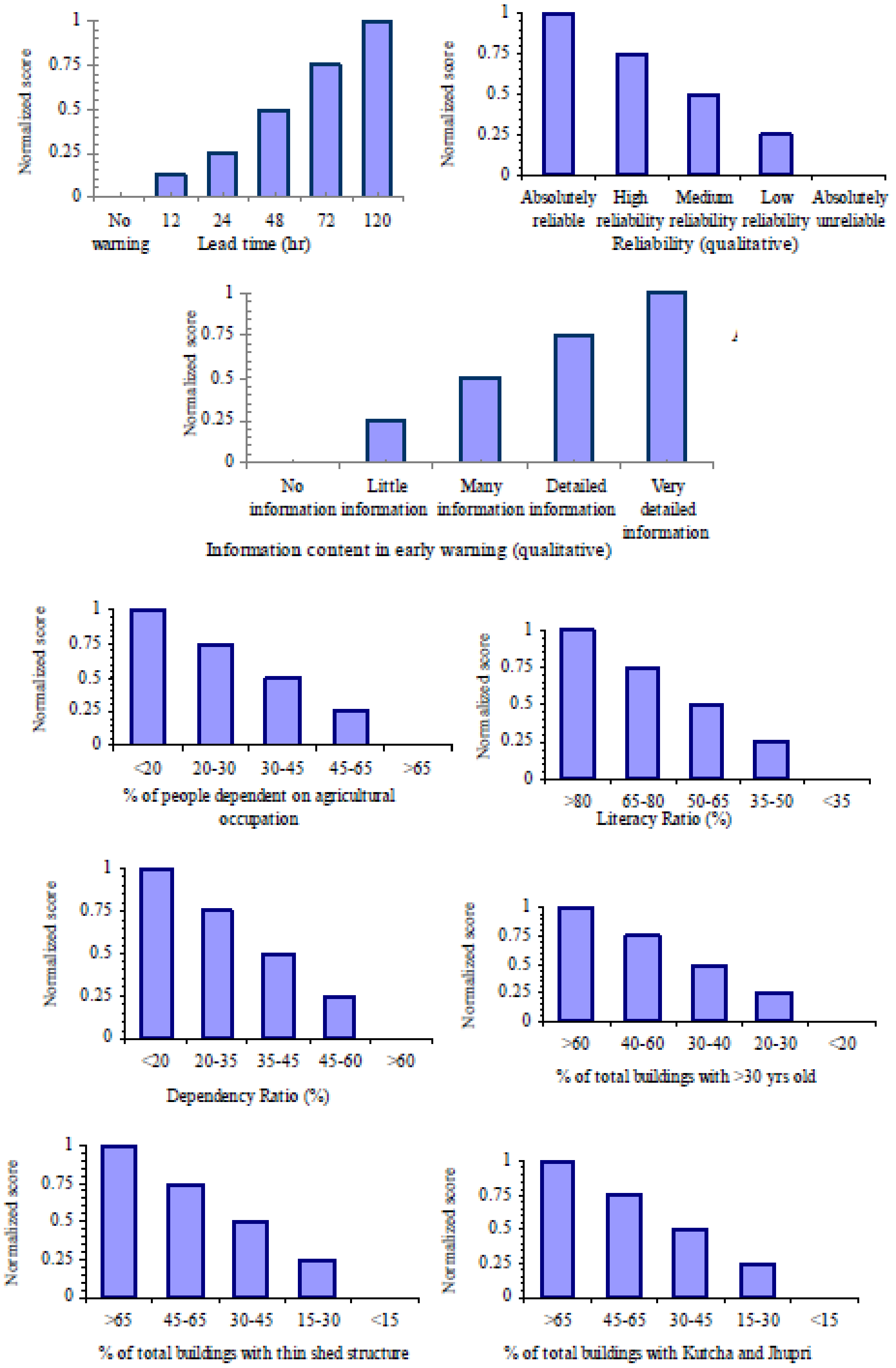

Figure 4. Normalization for the selected indicators of adaptive capacity, coping capacity and susceptibility

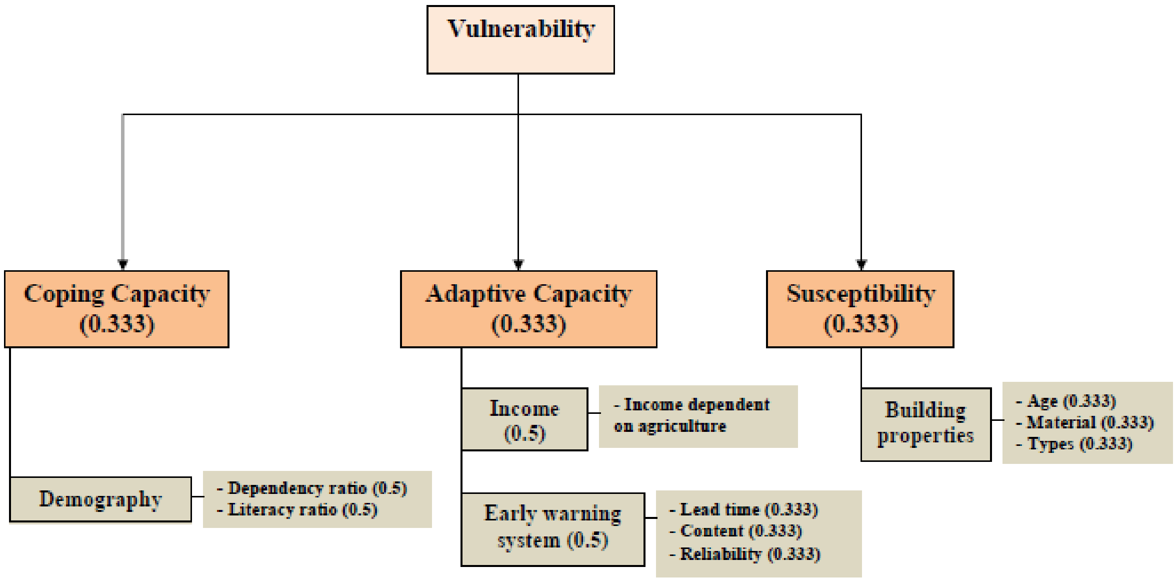

Figure 5. Hierarchical aggregation for the selected indicators of adaptive capacity, coping capacity and susceptibility

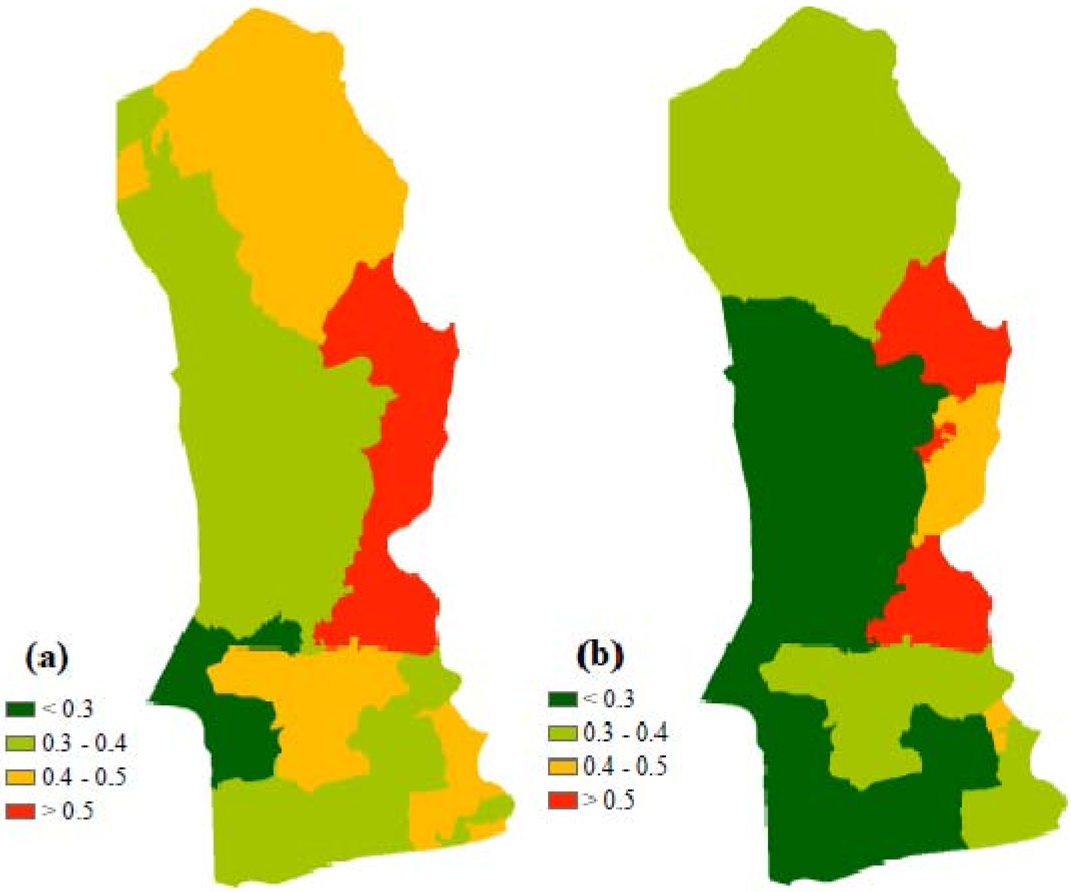

Figure 6. The results of aggregated vulnerability for (a) baseline condition and (b) improved scenario of early warning system and flood insurance. In the bracket, affected area (in hectare, ha) is indicated for each class of vulnerability

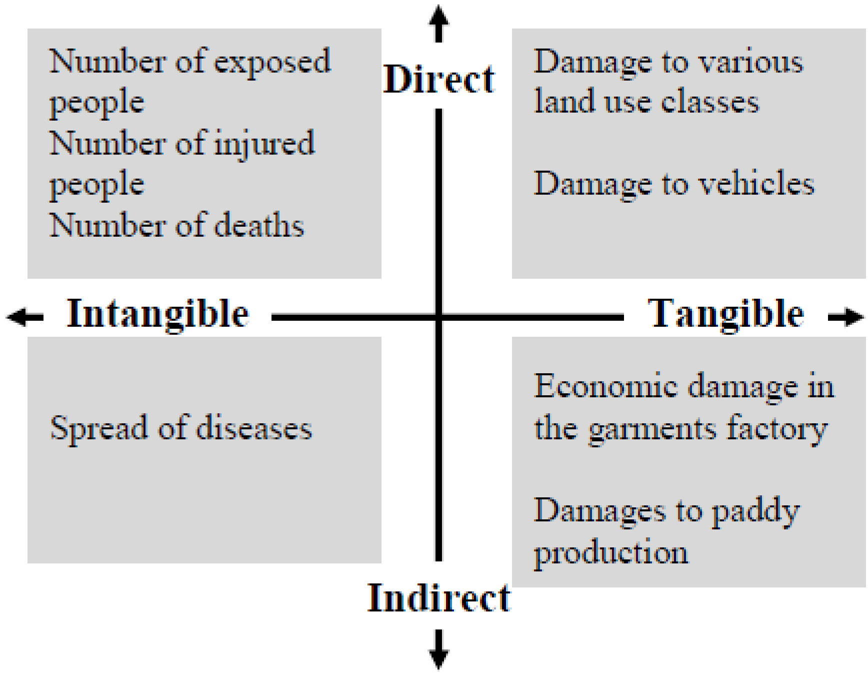

Figure 7. Distribution of considered exposures in different categories of damages

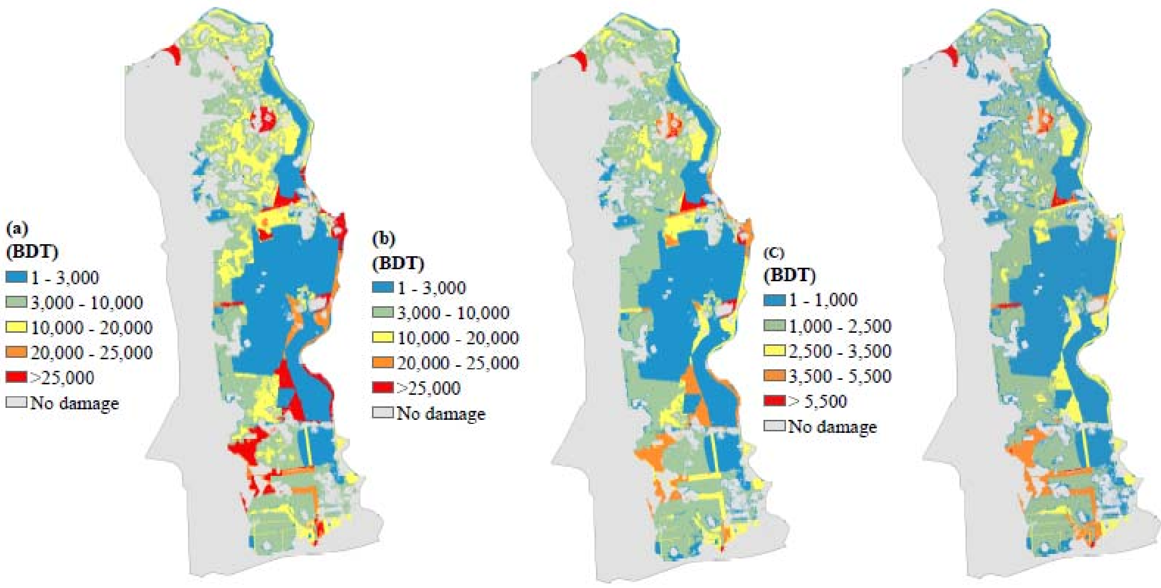

Figure 8. Economic damages to land use categories of 100-year return period flood for both baseline (a) and improved scenario (b) of vulnerability. (c) refers benefits of improved early warning system

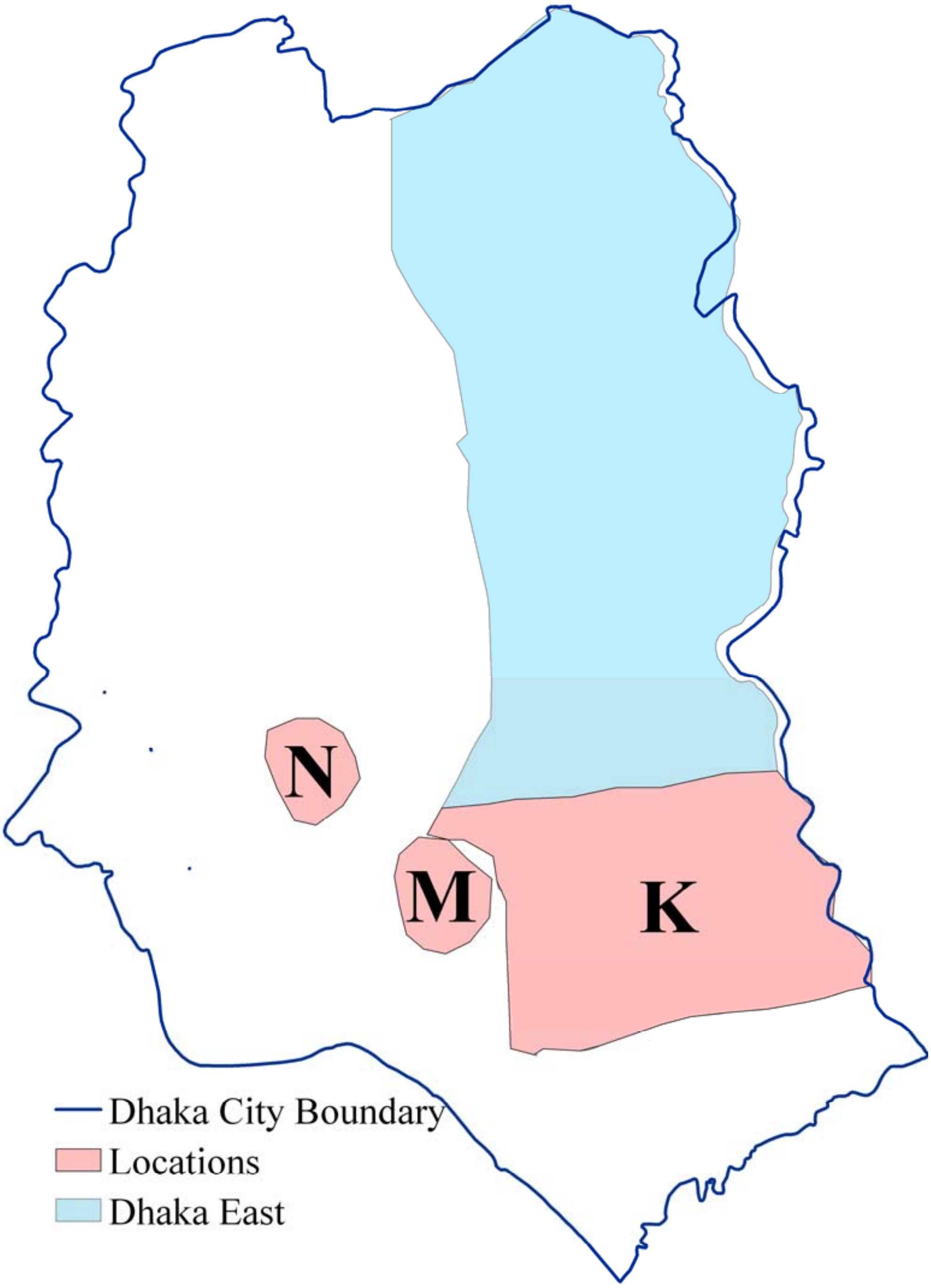

Figure 9. Position of garments factory and workers commuting from the eastern part of the City. The industries under consideration are located in N and M, while we consider workers coming from the area K that stand in the eastern part of the city.

Tables

Table 1

Required data and its sources for assessment of hazard, vulnerability and exposures

Components	Reference methods	Sub-components	Required input data	sources
Hazard	- Gain and Hoque (2011) - Gain and Hoque (2013)	--	Topographic data (spot height)	Institute of Water Modelling (IWM), Gani Bangla Limited (GBL), Design and Development Consultant (DDC), for DAP (2010)
			Topographic data (river cross section)	Bangladesh Water Development Board (BWDB)
			Hydrologic data (water level)	BWDB
			Hydrologic data (discharge)	BWDB
Vulnerability	- in this study	Adaptive Capacity	Early Warning System, EWS (lead time, 48 hrs)	- ADB (2006) - Rahman et al. (2013)
			EWS (information content)	- Paudyal (2002) - Chowdhury (2005)
			EWS (reliability)	- Webster et al. (2010)
			Income (BDT)	Extracted from DAP (2010)
		Coping Capacity	Literacy Ratio Dependency Ratio	BBS (2011) BBS (2011)
		Susceptibility	Building age Building types Building materials	BBS (2011); CDMP (2009)
Exposure (- direct tangible - direct intangible - indirect tangible)	- in this study	Direct tangible (damages to land use types)	Land use map Monetary value of land use types	DAP (2010) Extracted from DAP (2010)
		Direct tangible (damages to vehicles)	Number of total cars	Bangladesh Road Transport Authority (BRTA)
		Direct intangible (damages to exposed, injured and dead people)	Number of people	BBS (2011)
		Indirect tangible (damages garments industry)	Number of garments industry	Hoque et al (2006)
		Indirect tangible (damages to paddy production)	- Agricultural land - people dependent on agriculture	BBS (2011); DAP (2010)

Table 2

Indicators for adaptive capacity, coping capacity and susceptibility

Components	**Variables**	**Indicator**	**Definition**
Adaptive Capacity (AC)	Early Warning System (EWS)	Lead-time Information Content (absent to detailed) Reliability (low to high)	EWS with high lead-time (i.e. time in hours between the warning and the event occurrence), detail information content and high reliability leads to increase AC, and consequently decrease vulnerability
	Income	Income dependent on agriculture (% of total people)	Values with lower number leads to increase AC, as income from agriculture is more vulnerable to flood
Coping Capacity	Education	Literacy Ratio, LR (%)	Population with higher LR leads to increase CC and hence decrease vulnerability
	Demography	Dependency Ratio, DR (%)	Population with higher DR leads to decrease CC and hence increase vulnerability
Susceptibility	Building properties	Age (% of total buildings with more than 30 years old) Types (% of buildings with lower structural type) Materials (% of buildings with earthen and wood)	Values with higher percentage are highly susceptible to floods

Table 3

Definition of normalized scores

Normalized value	Vulnerability level
0	Not vulnerable
0.25	Slightly vulnerable
0.50	Highly vulnerable
0.75	Extremely vulnerable
1	Fully vulnerable

Table 4

Normalized value for baseline and improved scenario of adaptive capacity

Components	Variables	Indicators	Baseline (normalized)	Improved scenario (normalized)
Adaptive Capacity (AC)	EWS (EWS)	Lead-time (hr)	48 hrs (0.50)	120 hrs (1)
		Information Content (no to detailed)	Technical information, not understandable by local users (0.25)	Detailed dissemination information, understandable by local users (0.75)
		Reliability (low to high)	Low reliability beyond 48 hrs lead-time (0.25)	High reliability due to adoption of sophisticated tools (0.75)

Table 5

Summary results of risk to people for 100 year return flood

Types of intangible damages	Baseline Vulnerability	Improved scenario of vulnerability
Number of people exposed to risk	17,840	13,494
Number of injured people	8566	3905
Number of deaths	450	225

Table 6

Data summary for indirect tangible costs of garments factory

	West	East	
population density	25,144 people/km^2	9,861 people/ km^2	
	cluster M	cluster N	
employees	94,350	34,498	
number of firms	225	75	
	surface	distance to M	distance to N
north Khilket & Kamalapur (K)	0.6 km^2	1.9 km	3.3 km
centre K	14.3 km^2	4.2 km	7.2 km
south K	14.3 km^2	4.4 km	7.4 km

Table 7

Factors of production in Paddy sector

Factors of production	Before Flood	During Flood	% Change
Labor	98868 (man-day)	2409 (man-day)	2.43%
Capital (Land)	2264.86 acres	879.3 acres	38.8%

Table 8

Summary of results for total cost matrix (TCM)

TCM categories (1)	Exposed elements (2)	Damage for baseline (3)	Damage for improved scenario (4)
Direct tangible	Land use (BDT)	1.22 billion	990 million
	Vehicles (BDT)	7 million	0.85 million
Direct Intangible	Exposed people (#)	17900	13500
	Injured people(#)	8600	3600
	Deaths (#)	450	225
Indirect Tangible	Garments factory	13% (for M)	-
	Paddy production (BDT)	60 million	-
Indirect Intangible	Spread of diseases	-	-