

Adapting to urban flooding: a case of two cities in South Asia

Ismat Ara Pervin^a, Sheikh Mohammad Mahbubur Rahman^a,
Mani Nepal^{b,*}, Abdul Kalam Enamul Haque^c, Humayun Karim^a
and Ganesh Dhakal^d

^a*Institute of Water Modelling, Dhaka, Bangladesh*

^b*South Asian Network for Development and Environmental Economics at the International Centre for Integrated Mountain Development, Kathmandu, Nepal*

^{*}*Corresponding author. E-mail: mani.nepal@icimod.org*

^c*Asian Centre for Development, Dhaka, Bangladesh*

^d*Freelance researcher, Kathmandu, Nepal*

Abstract

Cities in South Asia are experiencing storm water drainage problems due to a combination of urban sprawl, structural, hydrological, socioeconomic and climatic factors. The frequency of short duration, high-intensity rainfall is expected to increase in the future due to climate change. Given the limited capacity of drainage systems in South Asian cities, urban flooding and waterlogging is expected to intensify. The problem gets worse when low-lying areas are filled up for infrastructure development due to unplanned urban growth, reducing permeable areas. Additionally, solid waste, when dumped in canals and open spaces, blocks urban drainage systems and worsens urban flooding and waterlogging. Using hydraulic models for two South Asian cities, Sylhet (in Bangladesh) and Bharatpur (in Nepal), we find that 22.3% of the land area in Sylhet and 12.7% in Bharatpur is under flooding risk, under the current scenario. The flood risk area can be reduced to 3.6% in Sylhet and 5.5% in Bharatpur with structural interventions in the drainage system. However, the area under flood risk could increase to 18.5% in Sylhet and 7.6% in Bharatpur in five years if the cities' solid waste is not managed properly, suggesting that the structural solution alone, without proper solid waste management, is almost ineffective in reducing the long-term flooding risk in these cities.

Keywords: Climate change; Hydraulic modelling; South Asia; Urban flooding; Waste management; Waterlogging

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1. Introduction

Unplanned urban growth and development interferes with the natural flow of water and hence usually increases the risk of urban flooding (Booth, 1991; Douglas *et al.*, 2008). For the purposes of this paper, there are two consequences of urban development in South Asia: (i) it augments run-off and hence increases the risk of the breaching of embankments if a city abuts a river; and (ii) it reduces the flow of drainage by gravity due to drainage congestion, as urban drainage systems are unable to keep pace with urban development. In general, urban development, if unplanned, often reduces the effectiveness of urban drainage systems and increases the risk of flooding and waterlogging (Clemens & Veldhuis, 2010). Developing countries are particularly susceptible to urban flooding because their drainage systems are limited, mismanaged and often congested for a variety of reasons, including because of the dumping of solid waste in drains and canals (Zurbrugg, 2003; Haque, 2013).

Solid waste dumping in drainage routes reduces the carrying capacity of the drainage system, resulting in unwanted waterlogging in the event of heavy rainfall. Waterlogging due to drainage congestion contaminates ground water, which in turn creates a public health problem if cities use ground water or polluted surface water for domestic purposes (Phanuwan *et al.*, 2006; ten Veldhuis *et al.*, 2010). Most of the fast-growing cities in South Asia are located on riversides and developed without proper urban planning and appropriate drainage routes. Urban flooding is exacerbated as a result of rapid but unplanned urbanization and the resulting increased impervious surface (Huong & Pathirana, 2013).

Evidence suggests that poor households are disproportionately affected by seasonal flooding, as they mostly settle in flood-prone, low-lying marginal land, where land prices are relatively cheaper and the areas are unrestricted, allowing for unplanned settlement (IPCC, 2007; Nchito, 2007; Douglas *et al.*, 2008). With high-intensity and high-frequency climate and weather events such as excessive rainfall in short duration, waterlogging and flooding pose a serious risk for such unplanned and unprepared cities in terms of property damage, disruption of the daily lives of the residents, and water contamination and the resulting health problems (Patz *et al.*, 2005). Alderman *et al.* (2012) reported an increased risk of post-flood disease outbreaks in areas with poor hygiene and displaced populations. Potential diseases include hepatitis E, gastrointestinal diseases and leptospirosis. The rapid rural to urban migration, land use change and poor urban infrastructures in developing countries exacerbate flooding and waterlogging. Cities need to prepare climate-resilient development pathways to adapt to extreme climate events and disaster risk reduction, as planned adaptation helps to reduce disaster risk significantly (IPCC, 2018).

Lele *et al.* (2018) elaborated on a framework by Srinivasan *et al.* (2013) which illustrates how multiple stressors, multiple concerns and links between the basin, water supply and sewerage utility and household scales of analysis are explicitly incorporated in the climate change adaptation debate in an urban context. The authors put emphasis on pre-existing conditions, the urban water infrastructure, equity and institutions as the major normative issues that need to be considered when analysing water-related outcomes (drinking as well as wastewater) in the urban environment. In order to maintain good environmental conditions in cities, some of the main adaptation options include constructing an adequate drainage system, and a comprehensive solid waste collection and disposal system, amongst others (SANDEE & ACD, 2017). There is, however, very little literature examining the effectiveness of soft interventions such as proper management of solid waste by changing human behaviour to reduce the risk of urban flooding and waterlogging in the context of extreme climatic events in South Asia.

In this paper, we examine the existing designs of the drainage systems in Sylhet (in Bangladesh) and Bharatpur (in Nepal) to understand how the inadequate capacity of a drainage system and the unplanned dumping of solid waste result in higher risks of waterlogging and flooding in the low-lying areas of two South Asian cities. We develop drainage network models and use different scenarios to analyse how improved drainage infrastructure and management combined with the proper management of solid waste, as adaptation strategies, could reduce the risk of urban flooding and waterlogging under different climatic and non-climatic scenarios.

2. Methodology

2.1. Description of study area

For research purposes, we selected two medium-sized South Asian cities (with populations close to half a million or less) which are situated by rivers and foothills. The selection of these cities was guided by the idea that the research could influence the adaptation policies of these cities, as they are growing fast but are still manageable given their size, and there is a willingness amongst the city officials to be guided by research outcomes while preparing adaptation plans.

There are a number of areas in both Bharatpur and Sylhet that suffer from waterlogging and standing water after heavy raining during monsoon. Due to socioeconomic development and rural to urban migration, land use in these cities is changing continuously from agriculture to a built-up environment, leading to an increased volume and speed of run-off. The existing drainage systems fail to carry the huge volume of the increased amount of storm water, increasing the risk of flooding and waterlogging.

2.1.1. Sylhet. Sylhet city was declared a metropolitan area in 2002 with an area of 508.7 km². The Surma River divides the Sylhet City Corporation (SCC) area into two parts: the northern part, with an area of 18.18 km², and the southern part, covering 6.52 km². Only the northern core city area has been considered in this study, as it is a relatively high flood-risk area (Figure 1).

2.1.1.1. Climate. Sylhet has a tropical climate. In summer (March–May), the mean temperature reaches around 27°C, while in winter, the mean temperature stays at around 20°C. The mean annual rainfall is 4,000 mm. Most of the rainfall occurs during the summer monsoon season (June–August).

2.1.1.2. Flooding and drainage system. In Sylhet, two types of flood risks occur: flash floods in the Surma River, and localized floods caused by heavy monsoon rainfall. As the main drainage canals flowing through the city originate from sloped hills, the run-off from upstream areas travels fast towards the urban area, which is comparatively less sloped. Therefore, during heavy rainfall events, the rainfall–run-off causes flash floods.

Every year, the riverbed gets higher due to heavy siltation. Consequently, during events of moderate to high rainfall, the run-off cannot be evacuated through the canals (that are ultimately linked to the Surma River) due to the backwater effect. The run-off spills over into surrounding areas, causing widespread flooding and waterlogging. The waterlogging remains for 5–8 hours when the water level of the Surma River is low. However, when its water level is more than the danger level, which is 10.05 metres above mean sea level (mMSL), the backwater effect becomes very pronounced and the waterlogged situation continues for about 7–10 days until the water level of the river declines.

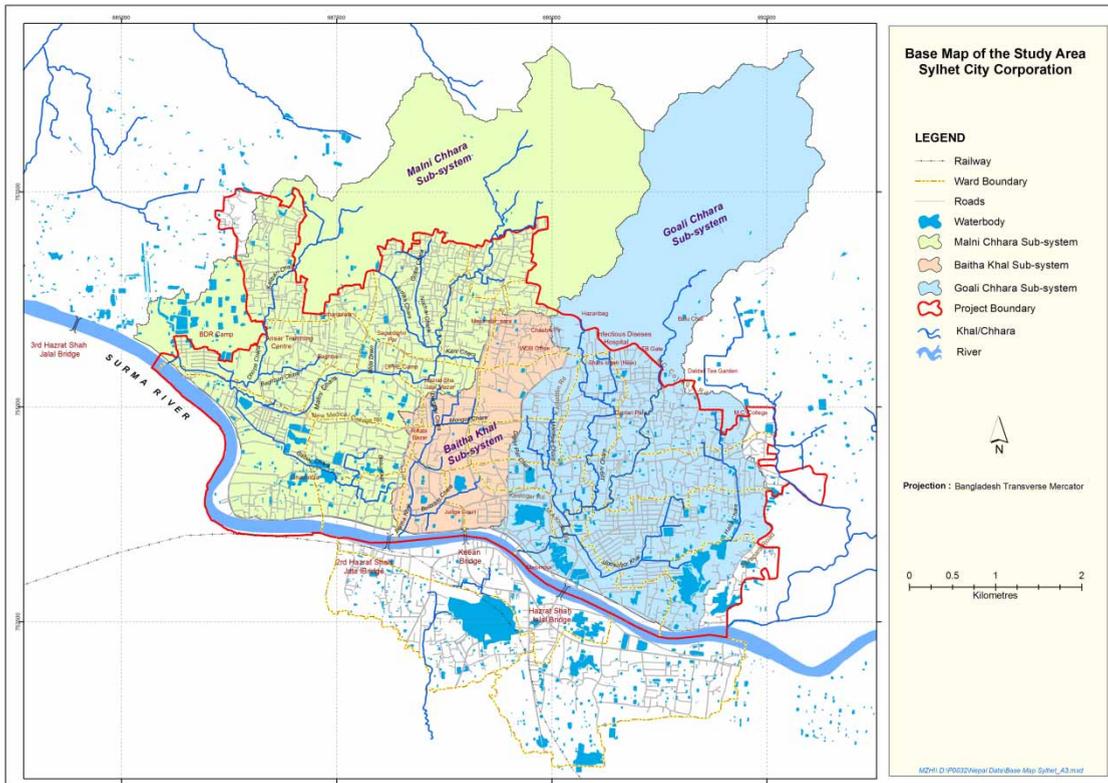


Fig. 1. Study area, Sylhet. (Source: the authors).

Subsidiary canals are locally called chhara or khal, and there are three main drainage sub-systems in the study area of Sylhet: Malni chhara, Baitha khal and Goali chhara (Figure 1). These subsidiary canals drain from north to south and fall into the Surma River. Malni chhara and Goali chhara originate in hilly areas. Brief details of the drainage sub-systems are given in Table 1.

The capacity of these drainage canals is not sufficient in many areas to carry even moderate rainfall–run-off mainly due to unauthorized land use and solid waste dumping. Sylhet City Corporation sometimes cleans the existing chhara/drain when the situation becomes very bad but the city does not have a regular cleaning programme. After heavy rainfall, the roads and outside areas around housing become inundated in many places. Sometimes people build temporary brick walls around their houses as flood

Table 1. Sylhet city drainage sub-systems.

Canal	Number of tributaries	Total length, including tributaries (m)	Watershed area (km ²)
Malni chhara	17	23,600	16.26
Baitha khal	5	4,245	2.79
Goali chhara	12	18,013	12.98

Note: The number and length of tributaries are based on a survey and watershed areas are estimated after analysis of a Digital Elevation Model (DEM).

protection. Recently, Sylhet City Corporation adopted a 5-year Capital Investment Plan to improve environmental conditions, tourism facilities and infrastructure development, etc. Reducing waterlogging by constructing reinforced cement concrete drains, regulators and pumps is a major component of the project.

2.1.1.3. Land use patterns. Residential areas, agricultural plots and tea gardens dominate land use in Sylhet city. The agricultural and vacant areas are expected to change into residential and commercial land use in the future due to population pressure (Table 2). This will add more impermeable surfaces and increase the volume and speed of run-off, thus increasing the risk of flooding. The land use maps for the present situation (2010) and future conditions (2030) for Sylhet are presented in Figure 2.

2.1.1.4. Solid waste management. The Sylhet City Corporation's solid waste management programme requires improvement. Households pay for waste collection services that are managed by private clubs. The payment per household ranges between Bangladeshi taka (BDT) 50–150 per month, and about 80% of households participate in the waste collection service. The clubs pick up waste from households six times a week. However, they only take it to transfer stations; final disposal is done by the city. Currently, households and institutions that generate waste do not segregate it at source, and hence there has been no practice of composting, few materials are recovered and there is a low rate of recycling. The city provides large street bins but the collection is not regular so the bins are over-filled and the waste gets scattered, ending up in the streets and ultimately in the drains, which reduces the conveyance capacity of the drainage system and often blocks the flow of water. Households that do not subscribe to the collection services also dispose of their solid waste in open spaces, which ultimately lead to the drainage canals.

Moreover, the utility tunnels at canal crossings also decrease the conveyance capacity of the drainage network below the culverts and obstruct the free flow of water, which results in local flooding. The city does not have enough capacity (both technical and financial) to manage solid waste; it does not fully cover the residential areas to pick up waste from residents, and it does not have a sanitary landfill site for safe disposal. To improve the capacity of Sylhet City Corporation, additional resources (human, material and financial) and proper training of human resources are required. In the case of segregating waste at source, the resources needed for collection and disposal of the waste will be less, since proper segregation at source means more material recovery (for reuse and recycling) and less waste for disposal when organic wastes are composted at the community or household level (suitable for those who have kitchen gardens). The research team set up a community level demonstration of composting organic waste in a few areas on an experimental basis. After the demonstration, residents expressed their willingness to adopt the technology if provided with suitable training and technological support.

Table 2. Existing and proposed Sylhet city land use. (Source: Government of the People's Republic of Bangladesh, 2010.)

Land Type	% of area		Land Type	% of area	
	Existing	Proposed		Existing	Proposed
Residential	39.4	54.3	Vacant Land	13.3	–
Agriculture	7.2	3.4	Education & Research	4.4	4.5
Tea Garden	4.9	4.7	Transport & Communication	5.0	7.5
Others	26.0	25.7			

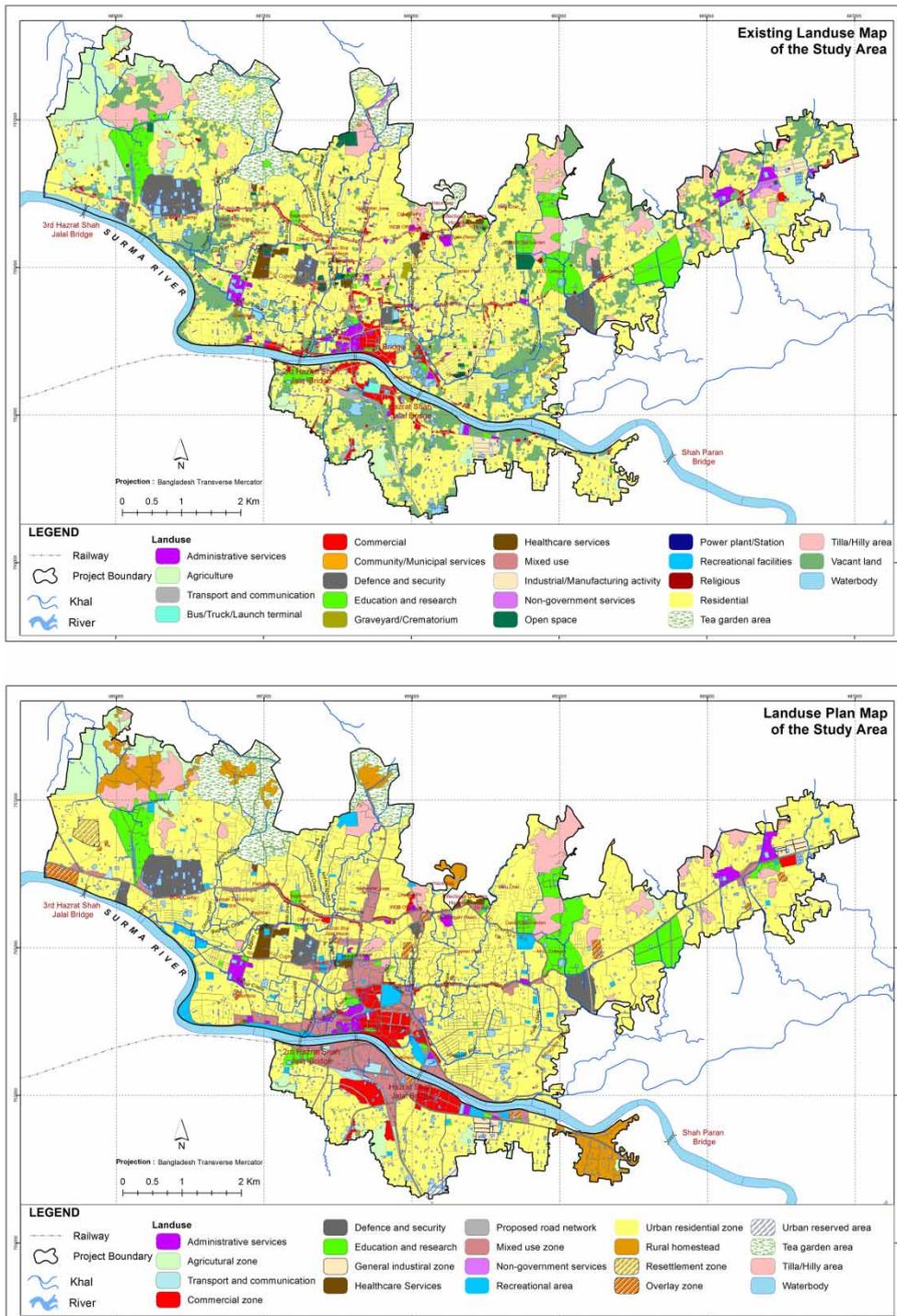


Fig. 2. Existing land use map (2010) (top) and proposed land use map (2030) (bottom) for Sylhet. (Source: Urban Development Directorate (UDD), 2010.)

2.1.2. Bharatpur. Bharatpur city is situated in south-central Nepal, in Chitwan district, which lies on the left bank of the Narayani River. Bharatpur municipality was declared a sub-metropolitan city in 2014 (with a total area of 77.91 km²) and then a metropolitan city in 2016 (with a total area of 418.8 km²). The study area is located in the then municipality area, which is the core area of the current metropolitan city (Figure 3).

2.1.2.1. Climate. Bharatpur has a humid, subtropical climate. The temperature peaks in June–August, when the mean temperature is approximately 28°C. During the winter season (December–February), the mean temperature is around 19°C. The mean annual rainfall is around 2,100 mm. The heaviest rainfall occurs during June–September.

2.1.2.2. Flooding and drainage system. There are two main drainage canals flowing through Bharatpur city: the Pungi canal and Kerunga canal. Both canals originate in the northern hilly areas and travel in a southwesterly and southerly direction, and finally meet the Narayani and Rapti rivers, respectively. There is no backwater problem in Bharatpur. However, even after moderate rainfall, run-off cannot find a proper drainage route to reach the existing canals, which causes flooding. The waterlogged situation

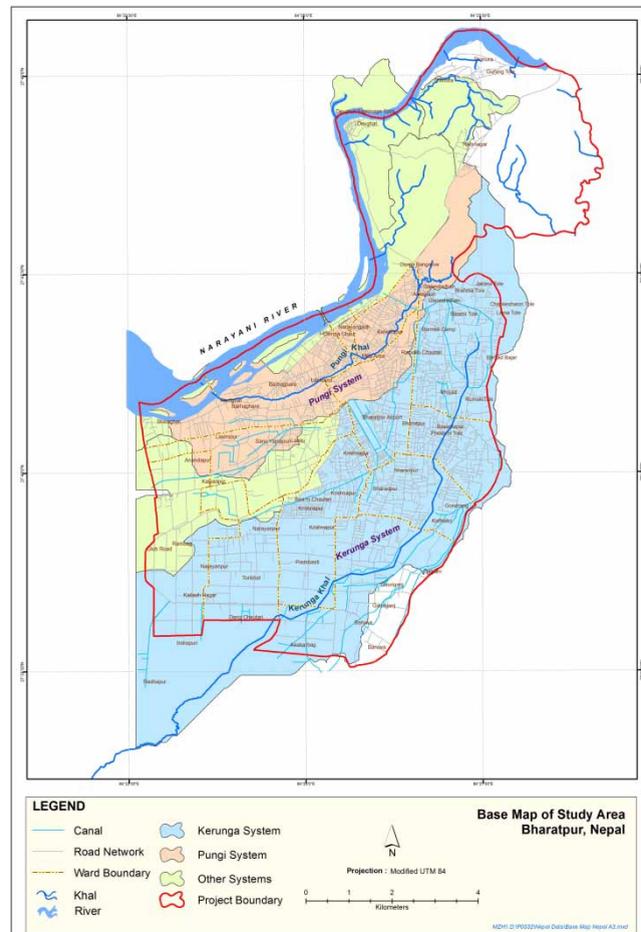


Fig. 3. Study area, Bharatpur. (Source: Sayenju & Talchabhandari, 2008.)

persists for a period ranging from a few hours to 1–2 days in some parts of the city. After the rain stops, the run-off flows slowly through natural drainage routes and reaches the canals.

The Pungi canal is 6.6 km long, extending from Aptari Bishal Marg to the outfall at Ramghat on the Narayani River. The length of the Kerunga canal is 28.4 km, extending from Shahid Dharma Bhakta Marg to the outfall on the Rapti River. About 14 km of the Kerunga canal lies within the study area. There are some underdeveloped areas on the western side of the study area, where no defined drainage system exists. The storm water from these parts flows to the western low-lying areas and ultimately into the Narayani River. The watershed of the Pungi canal covers 13.03 km², while that of the Kerunga canal covers 41.75 km².

2.1.2.3. Land use patterns. Most of Bharatpur city's land area is characterized by agricultural (52%) and forest land (21%). The economy of Bharatpur is mainly dependent on agriculture. Nevertheless, some agricultural lands are converting into residential areas due to rapid population growth in the city and the resulting change in economic activities. The extent of land use change is quite substantial, as the population growth rate is over 6% annually, but there is no definite plan in Bharatpur city for urban development and thus there is a risk of erratic urbanization. A land use map from 2008 is shown in Figure 4.

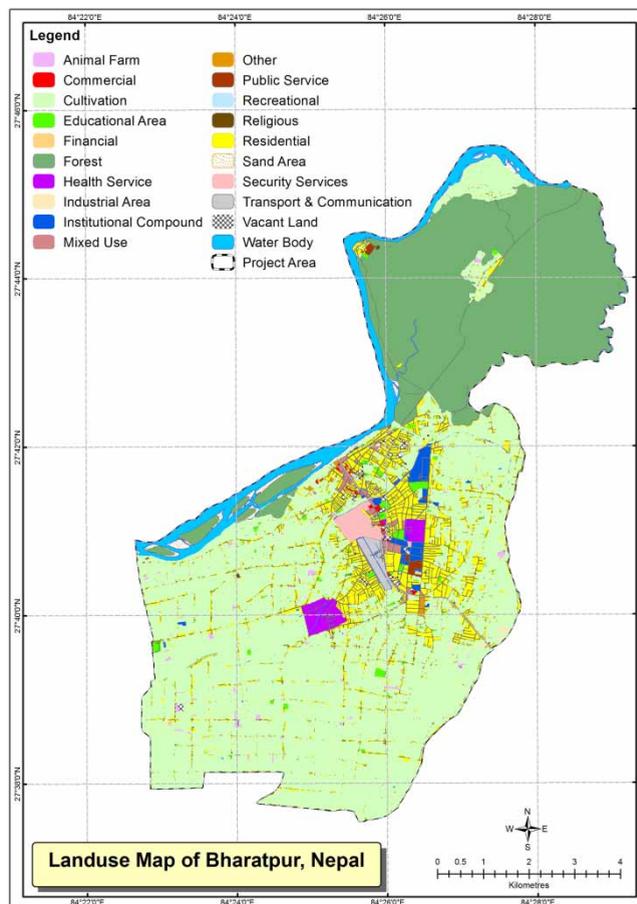


Fig. 4. Land use map for Bharatpur city. (Source: Sayenju & Talchabhandari, 2008.)

2.1.2.4. Solid waste management. In Bharatpur, solid waste is managed based on a public-private partnership approach. Two private firms are responsible for collecting and disposing of solid waste from the study area. They provide a door-to-door collection service and charge a certain amount based on the frequency of service provided (to the households) and the amount of waste generated (in the case of hotels, business and institutions). For households, the fee ranges between Nepalese rupee (NPR) 30–100 (which is close to US Dollar (USD) 0.30–1.00) per month. The money collected is not sufficient to manage the municipal solid waste and the city provides an additional budget to the private firms. As the collection service is based on a service charge payment and is voluntary, not all households pay the fee and the participation rate is reported to be around 70%–80%. The rest of the households do not pay the service fee and mainly dispose of their waste in open spaces and drains.

Households who pay the service fee reported that the waste pick-up service is often irregular and they do not know the exact time. The contractors reported that the resources they have generated from the users, on top of the transfer from the city, are not enough to properly manage the municipal solid waste and, therefore, they cannot provide the service at a pre-determined time. Due to the mismatch between the time households put their waste outside for collection and the exact collection time by the collectors, rag pickers often scatter the waste in search of reusable and recyclable materials and the waste ends up in open spaces, on streets and in drainage canals.

2.2. Data collection

The research team visited both cities to get first-hand information on existing drainage networks, episodes of flooding and potential causes, and solid waste management practices. Meetings with city officials, community leaders and private companies who collect and dispose of solid waste were used to get necessary background information. Several focused group discussions with residents were organized in order to understand the flooding and waterlogging issue and their perceived causes in both cities. After rounds of such meetings, the research team determined the study area within each city in consultation with city officials.

Since there was a lack of necessary data, the research team collected field level data in the summer of 2017 from both cities to develop the drainage model. Data pertaining to the primary water level, water discharge, and existing drainage networks and their cross-sections were collected from the field. The primary data were used for both model development and calibration. Moreover, historical water-level data (from 1938 to 2015) for the Surma River and rainfall data at Sylhet recorded by the Bangladesh Water Development Board (BWDB) (from 1957 to 2011) and the Bangladesh Meteorological Department (BMD) (from 1957 to 2015) were collected (Table 3).

Our model included rainfall data recorded by the Department of Hydrology and Meteorology (DHM) for Bharatpur city at the Bharatpur station (from 2000 to 2016; Table 3), water-level data for the Narayani River at Devghat station, and for the Rapti River at Rajayia station. The bankfull levels of the Narayani and Rapti rivers were considered as the design water level for Bharatpur. The surveyed cross-sections of the Narayani and Rapti were interpolated to generate bankfull water-level data at the outfalls of the Pungi and Kerunga canals. For Sylhet city, the research team had access to water and rainfall data. Therefore, a once in 50 year return period was considered as the design flood level for the Surma River, for the design of the regulator and pumps (see section 2.3.3).

Table 3. Historical data analysis of rainfall and water level.

Return period	Sylhet station			Bharatpur station			Surma River Maximum water level (mMSL)
	1-day max rainfall	2-day max rainfall	5-day max rainfall	1-day max rainfall	2-day max rainfall	5-day max rainfall	
2	191	278	804	141	208	282	10.03
2.33	201	291	835	152	221	297	10.07
5	249	345	987	202	275	361	10.36
10	289	389	1,114	246	313	407	10.53
25	343	445	1,278	304	355	462	10.72
50	385	486	1,404	349	383	500	10.84
100	428	528	1,531	395	410	536	10.95

Note: Rainfall values are in mm; the 2-day and 5-day max rainfalls indicate cumulative maximum rainfalls for that duration.

2.3. Data analysis

The study developed mathematical models for urban drainage systems and calibrated the models to represent the present situation (as of 2017). Once the model was tested for robustness, climate change and other scenarios were superimposed on them. The following steps were taken while developing and applying the models: (i) understanding the existing drainage system and the causes for drainage congestion; (ii) cross-verification of the collected data; (iii) developing a one-dimensional drainage model and calibrating/validating it; and (iv) simulating different scenarios using the calibrated/validated model to analyse the impact in the cities, and suggest measures for drainage improvement.

MIKE11 modelling tools from the Danish Hydraulic Institution (DHI) were used to develop the drainage models for Sylhet and Bharatpur. MIKE11 is a one-dimensional modelling system suitable for rivers and channels. The drainage model contains two main systems: a hydrological and a hydrodynamic system. The hydrological model was developed using Mike Urban A, a lumped hydrological model. It uses the ‘Time–Area’ method, by which the run-off amount is controlled by the initial loss, size of the catchment area, percentage of the impervious area in the catchments, and losses due to evapotranspiration and depression storage. The output of the hydrological model was used as an input for the hydrodynamic model.

The delineation of the catchments for Sylhet and Bharatpur were made based on Digital Elevation Models (DEMs) (Figure 5). Seventy-seven sub-catchments were delineated for the three Sylhet drainage systems. There are no defined drainage routes in Bharatpur other than the Pungi and Kernga canals. There are two main catchments (watersheds) for Bharatpur city and some minor catchments, from where water flows into the Narayani River directly, or into low-lying areas following the natural gradient.

The catchment parameters were chosen to reflect their characteristics. Using a spatial analysis based on aerial images and land use data, impervious areas were determined for each of the catchments.

Three individual sub-models (the Malni chhara, Baitha khal and Goali chhara sub-models) were developed for Sylhet. The sub-models consist of major canals/drainage channels, along with their tributaries, on the right bank of the Surma River. The drainage network for each individual canal was developed using the survey data of the canal’s cross-sections and its topography in 2016 by the Institute of Water Modelling, Dhaka. The boundary data consist of hydrometeorological data, including rainfall

and evapotranspiration data from the Sylhet station, and downstream water-level data for the Surma River.

For Bharatpur, two sub-models (the Pungi canal and the Kerunga canal sub-models) were developed using surveyed cross-sections of these canals. The boundary data consist of hydrometeorological data, including rainfall data from the Bharatpur station and evapotranspiration data from the Kaligandaki station, and downstream bankfull water-level data for the Narayani and Rapti rivers as water levels.

2.3.1. Model calibration and validation. The Sylhet model was calibrated and further validated against water-level data from 2016 and 2017, respectively. The Bharatpur model was calibrated against collected water-level and discharge data for 2017. Calibration and validation plots are shown in Figures 6–10. In both cities, the catchments are rapid response catchments, due to their steep gradients from hilly areas. For calibration/validation of steep slope catchments, 10 min or 30 min interval rainfall data are necessary to match the peak flows. However, such shorter interval rainfall data are not available. Therefore, the calibration/validation of the models are not as accurate as expected since we used three-hour interval data for Sylhet and daily data for Bharatpur.

2.3.2. Climate change and socioeconomic scenarios. According to the synthesis of the IPCC’s (Intergovernmental Panel on Climate Change) *Fifth Assessment Report (IPCC, 2014)*, climate change will lead to three major changes in Asia: (i) changes in glaciers, snow, ice and permafrost; (ii) flooding of rivers/lakes and/or droughts; and (iii) coastal erosion and/or sea level rise and other effects. However, Sylhet and Bharatpur are not coastal cities: Sylhet city is about 350 km north of the Bay of Bengal and sea level rise will not affect water levels in the Surma River; a similar situation applies to Bharatpur city which is away from any coastal area. Therefore, we developed climate change scenarios focussing solely

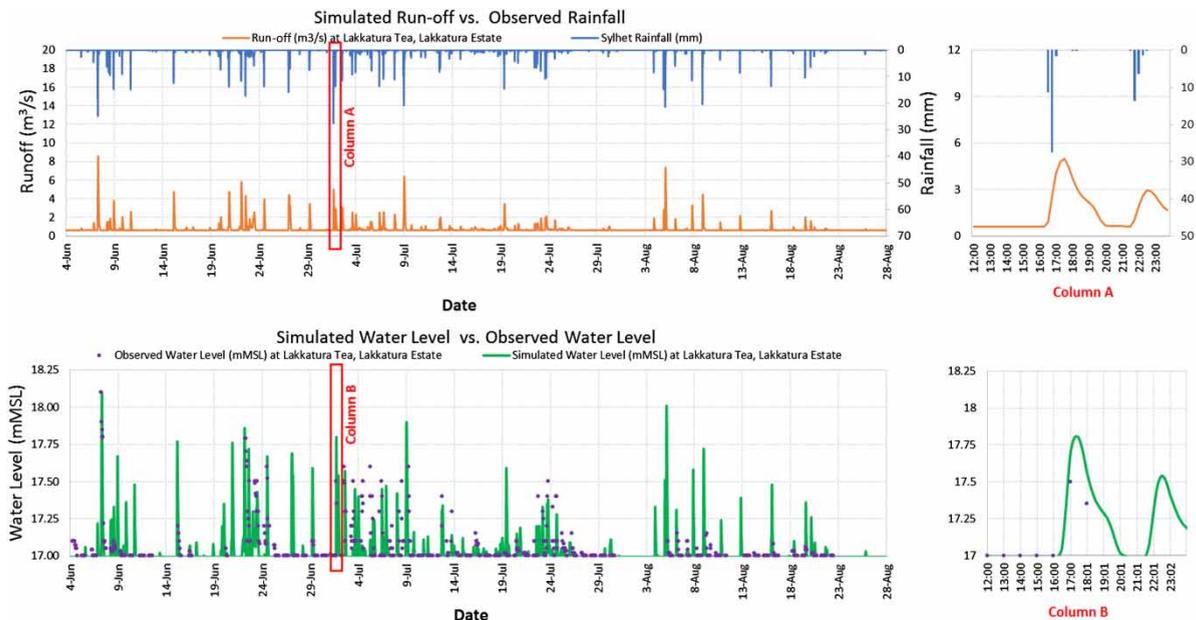


Fig. 6. Model calibration plot for the Lakkatura Tea Estate on Lakkatura Chhara, Malni Chhara sub-system.

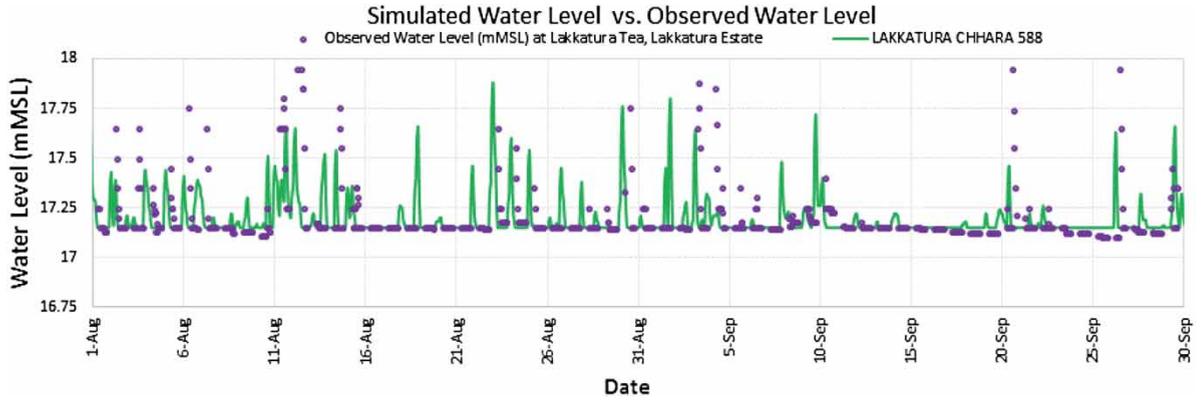


Fig. 7. Model validation plot for the Lakkatura Tea Estate on Lakkatura Chhara.

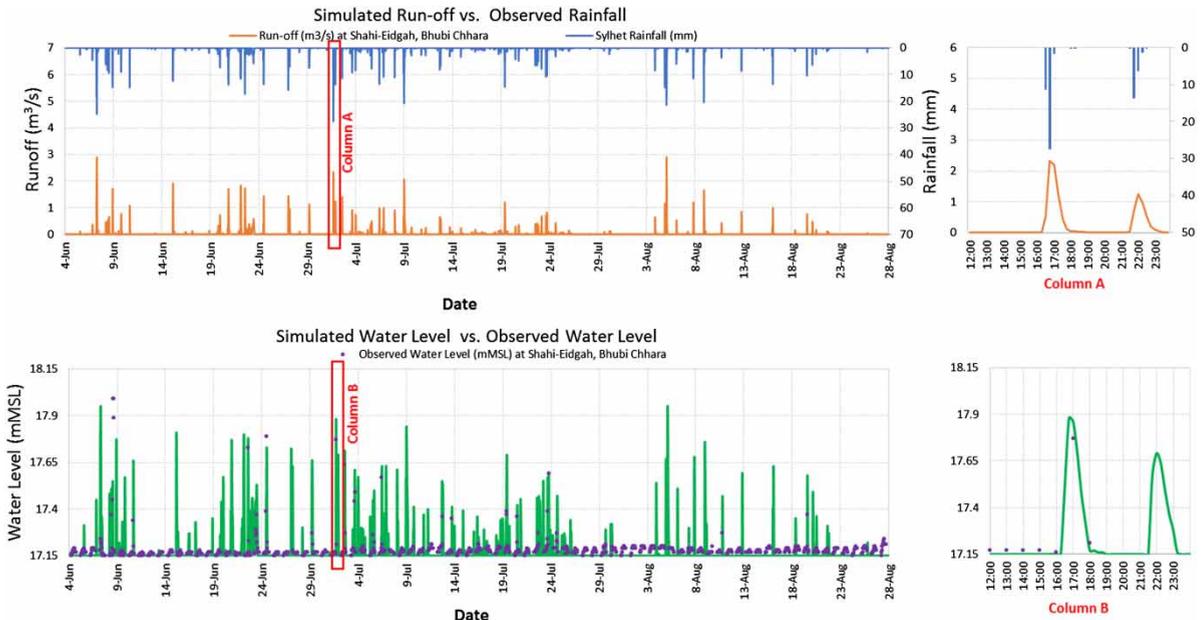


Fig. 8. Model calibration plot for Arambag on Goali Chhara, Goali Chhara sub-system.

on changing rainfall patterns. Climate change is happening and many climate models show that, due to climate change, the volume of rainfall will increase during the summer monsoon (May–October). The models also indicate reduced rainfall during the dry period (December–March).

Moreover, the frequency of short duration, high-intensity rainfall is expected to increase during the monsoon in both cities. This will result in more run-off in short periods, as both cities lie at the foothills which would aggravate drainage congestion. The rainfall pattern for the high emission Representative Concentration Pathway (RCP) 8.5 scenario was used to access the worst conditions using the CNRM ARPEGE climate model, which is suitable for the Ganges basin (in which Bharatpur lies) and the

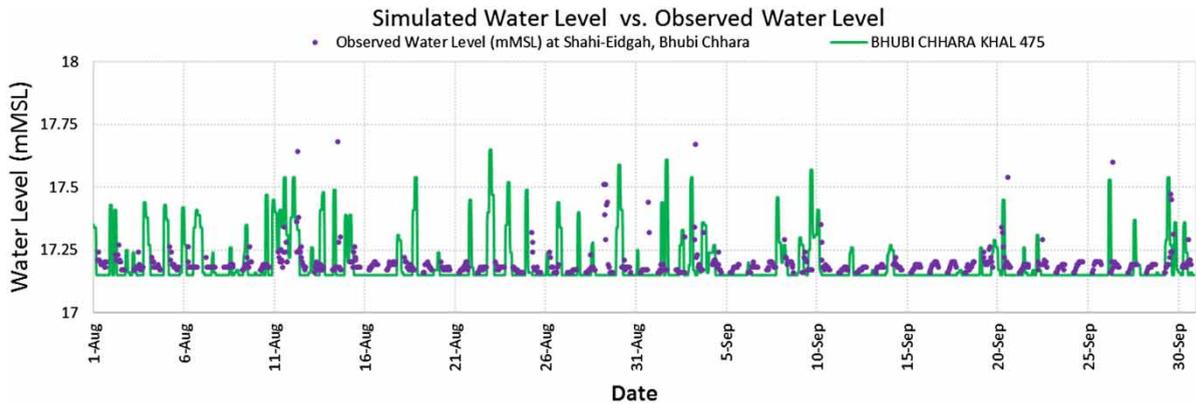


Fig. 9. Model validation plot for Shahi Eid-gah on Bhubi Chhara, Goali Chhara sub-system.

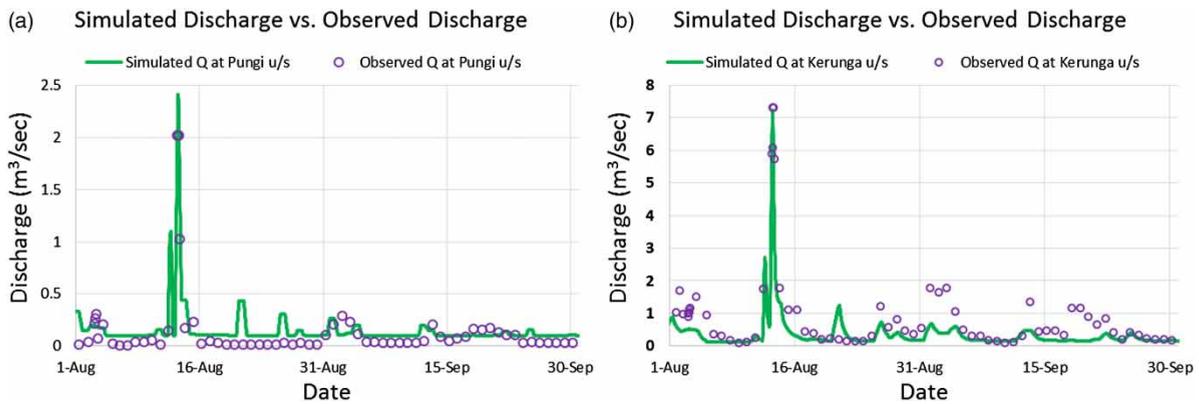


Fig. 10. Model calibration plots for locations (a) near Tinkune Chawk on the Pungi canal and (b) near Sree Naya Kiran Secondary School on the Kerunga canal.

Meghna basin (for Sylhet) (IWM, 2016). The CNRM model suggests 11% and 20% increases in rainfall intensity during the summer monsoon for Sylhet, in 2030 and 2050, respectively. The model indicates a 7% and 13% increase in rainfall intensity for Bharatpur, in 2030 and 2050, respectively, during the summer monsoon (IWM, 2016).

This study also considers socioeconomic scenarios. In terms of economic trends, both of the cities are growing fast with a population growth rate of more than 6%. High urban population growth leads to rapid changes in land use, from agriculture to built-up areas. With economic growth, the land prices in these cities have been increasing rapidly. As a result, land filling is taking place in both cities, converting low-lying agricultural land into housing and commercial spaces. The study, therefore, used urban population growth in these cities and land filling to predict land use changes in the future (in 2030 and 2050).

2.3.3. Identifying different scenarios. Calibrated/validated drainage models for Sylhet and Bharatpur were used to study different structural and non-structural adaptation options/scenarios to understand

flooding/waterlogging risks. The scenarios are presented in Table 4. The simulated results are presented in Tables 5 and 6 and, based on the results, suitable adaptation option(s) for reducing the future flooding/waterlogging risks in these two cities were discussed.

These adaptation scenarios or lack thereof were developed after having several focus group discussions and in-depth interviews with the municipal authorities, local residents and key informants in both cities. Scenario Sc-0 is the baseline scenario and simulates the current conditions of the drainage

Table 4. Scenarios for improving drainage.

Scenario ID	1. Scenarios for Sylhet	2. Scenarios for Bharatpur
Sc-0 (Baseline)	<p><i>Existing situation with design event</i></p> <ul style="list-style-type: none"> ○ Rainfall: 2-day cumulative, once in 10 year rainfall ○ Water level (WL): once in 50 year water level of the Surma River ○ Socioeconomic conditions: existing land use 	<p><i>Existing situation with design event</i></p> <ul style="list-style-type: none"> ○ Rainfall: 2-day cumulative, once in 10 year rainfall ○ Water level (WL): bankfull level of the Narayani and Rapti rivers ○ Socioeconomic conditions: existing land use
Sc-1	<p><i>Existing situation with design event and climate change</i></p> <ul style="list-style-type: none"> ○ Sc-0 + climate change impacts (in 2030 and 2050) 	<p><i>Existing situation with design event and climate change</i></p> <ul style="list-style-type: none"> ○ Sc-0 + climate change impacts (in 2030 and 2050)
Sc-2	<p><i>Rehabilitation, expansion, and re-sectioning of drainage channels</i></p> <ul style="list-style-type: none"> ○ Rehabilitation/expansion/re-sectioning of the existing inadequate channels ○ Construction of new drains ○ Two silt traps on the upstream side of Malni and Goali chharas ○ Reconstruction of the inadequate culverts ○ Solid waste disposal facilities 	<p><i>Rehabilitation, expansion, and re-sectioning of drainage channels</i></p> <ul style="list-style-type: none"> ○ Rehabilitation/expansion/re-sectioning of the existing inadequate channels ○ Construction of new drains ○ Solid waste disposal facilities
Sc-3	<p><i>Structural interventions using regulators and pumps</i></p> <ul style="list-style-type: none"> ○ Sc2 + regulators and pumping stations at outfalls 	(Not relevant)
Sc-4	<p><i>Physical interventions and climate change</i></p> <ul style="list-style-type: none"> ○ Sc-3 + climate change impacts (in 2030 and 2050) 	<p><i>Physical interventions and climate change</i></p> <ul style="list-style-type: none"> ○ Sc-2 + climate change impacts (in 2030 and 2050)
Sc-5	<p><i>Trends in economic growth</i></p> <ul style="list-style-type: none"> ○ Sc-3 + socioeconomic conditions: Future land use (in 2030 and 2050) 	<p><i>Trends in economic growth</i></p> <ul style="list-style-type: none"> ○ Sc-2 + Socioeconomic conditions: predicted land use change based on population for 2030 and 2050
Sc-6	<p><i>Trends in economic growth and climate change</i></p> <ul style="list-style-type: none"> ○ Sc-5 + climate change impacts (in 2030 and 2050) 	<p><i>Trends in economic growth and climate change</i></p> <ul style="list-style-type: none"> ○ Sc-5 + climate change impacts (in 2030 and 2050)
Sc-7	<p><i>Solid waste dumping in the drainage system</i></p> <ul style="list-style-type: none"> ○ Sc-2 + no solid waste disposal and cleaning facilities 	<p><i>Solid waste dumping in the drainage system</i></p> <ul style="list-style-type: none"> ○ Sc-2 + no solid waste disposal and cleaning facilities

Source: Developed by the authors based on information from stakeholders, including officials from the respective municipal offices.

Table 5. Summary of drainage model simulations by scenario (Sylhet).

Scenarios >>>>>>>	Sc-0 Baseline	Sc-1 Climatic change in 2050 with existing situation	Sc-2 Rehabilitation/ expansion/re- sectioning of drainage canals	Sc-3 Structural interventions	Sc-4 Structural interventions and climate change in 2050	Sc-5 Changes in socioeconomic conditions in 2050	Sc-6 Changes in socioeconomic conditions and climate change in 2050	Sc-7 No waste management
Flooded area (ha)	486	568	374	164	193	109	106	421
Percentage area of flooding in northern city (%)	22.3	27.1	15.8	3.6	5.2	2.8	2.6	18.5
Total area that benefits (ha)	–	–82	112	322	293	377	380	47
Additional area that benefits (ha)	–	–	–	210	–	55	3	–
Additional investment (USD million)	–	–	31.62	43.46	11.25	0	11.25	–
Investment per ha (USD million)	–	–	0.28	0.21	–	0	3.75	–

Note: 1 km² = 100 ha; 1 ha = 0.01 km².

Table 6. Summary of drainage model simulation using scenarios (Bharatpur).

Scenarios >>>>>>>	Sc-0 Baseline	Sc-1 Climate change in 2050 with baseline	Sc-2 Rehabilitation/ expansion/re- sectioning of drainage channels	Sc-4 Structural interventions and climate change in 2050	Sc-5 Changes in socioeconomic conditions in 2050	Sc-6 Changes in socioeconomic conditions and climate change in 2050	Sc-7 No waste management
Flooded area (ha)	166	175	72	77	86	94	99
Flooded area (%) (Pungi catchment)	12.7	13.5	5.5	5.9	6.6	7.2	7.6
Total area that benefits (ha)	–	–	93	89	80	71	66
Additional inundated area (ha)	–	–	–	4	14	8	27
Additional investment (USD million)	–	–	0.38	–	–	–	–
Investment per ha (USD million)	–	–	0.004	–	–	–	–

Note: 1 km² = 100 ha; 1 ha = 0.01 km².

system. Scenario Sc-1 introduces climate change over Sc-0, to understand the impacts of climate change if no drainage interventions were applied. Scenario Sc-2 includes an improved drainage system that is superimposed on the baseline scenario Sc-0. Scenario Sc-3 is a further superimposition with control on backwater flows from the Surma River. This scenario applies to Sylhet but not for Bharatpur as there is no backwater effect in Bharatpur. In scenario Sc-4, climate change impacts over the improvement scenarios – Sc-3 (Sylhet) and Sc-2 (Bharatpur) – are simulated. Scenario Sc-5 considers changes in land use patterns in the future, based on current trends. Scenario Sc-6 includes changes in socioeconomic conditions (income and living standards, measured as changes in housing patterns) and climate change scenarios in terms of variability and changes in rainfall patterns. Scenario Sc-7 describes the effects of poor waste management and dumping solid waste in the chhara/khal and canals, which is superimposed on scenario Sc-2.

3. Results

3.1. Sylhet city

3.1.1. Existing situation with design event. In scenario Sc-0, due to the backwater effect of the Surma River in Sylhet, the catchment run-off cannot drain out quickly, which causes flooding and the situation can exist for about seven days (observed from historical records). The backwater effect of the Surma River progresses up to 3,000 metres inside the Malni chhara, 900 m inside Boitha khal, and 2,100 m inside the Goali chhara. The simulated area of inundation is around 486 ha, including approximately 103 ha of water bodies (ponds, lakes etc., other than canal areas) (Figure 11).

3.1.2. Existing situation with design event and climate change. Due to climate change (as described in section 2.3.2), run-off in the monsoon could increase in 2030 and 2050, which will increase the inundation area from the Sc-0 scenario. The simulated inundation area would be around 548 ha in 2030 and 568 ha in 2050, including water bodies covering 103 ha. Therefore, due to climate change, an additional 62 hectares (ha) in 2030 and 82 ha in 2050 would be inundated if no adaptation measures are taken.

3.1.3. Rehabilitation, expansion and re-sectioning of drainage channels. To improve the drainage situation from the baseline scenario (Sc-0), rehabilitation/expansion/re-sectioning of the existing inadequate channels, with the provision of some new drains and culverts, was incorporated in scenario Sc-2. The simulated inundation area would be 374 ha, which includes the 103 ha of water bodies. With these interventions, an area of 112 ha would benefit, in terms of avoiding flooding.

3.1.4. Structural interventions using regulators and pumps. For further improvement in the drainage system in Sylhet, structural solutions like regulators and pumps were considered at the outfall of Malni chhara and Goali chhara under scenario Sc-3. These regulators would prevent the backwater effect of the Surma River and would permit drainage by gravity when the outfall water level is higher than the water level in the Surma River. When the water level in the Surma River rises to 10 mMSL, the gate would close and the pump would start expelling the excess run-off generated by heavy rain. The pump capacity was estimated in such a way as to maintain the water level in the canals and channels close to this danger level (10.05 mMSL). After several trials, the optimum pump capacity for both canals was estimated at

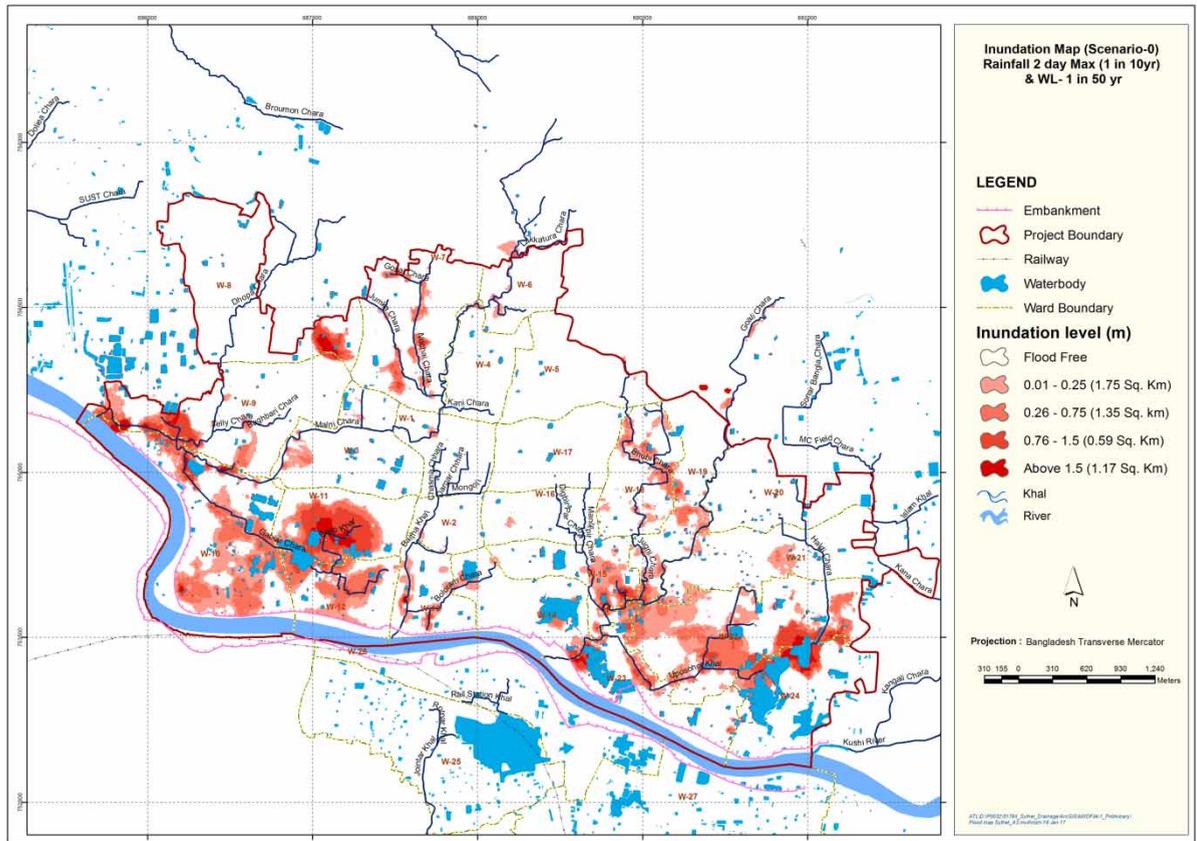


Fig. 11. Flood map for Sc-0 (baseline), Sylhet.

22 m³/sec, whereby the water level remains above the danger level for only 1.2 hours in Goali chhara and 6 hours in Malni chhara. Due to these structural interventions, 322 ha of land benefit by avoiding waterlogging. The simulated inundation area would be 164 ha, which includes the 103 ha of water bodies (Figure 12).

3.1.5. Physical interventions and climate change. Climate change impacts in 2030 and 2050 over the improved scenario (Sc-3) were simulated in scenario Sc-4. It was observed that the extent of flooding and duration of inundation both increased over Sc-3, due to additional run-off generated by climatic conditions. In order to adapt this, one additional pump of 7.33 m³/s would be required in 2030 for Malni chhara, and another pump of 7.33 m³/s in 2050. However, no additional pump is required for Goali chhara in 2030 or 2050. Due to these structural interventions, 294 ha of land would benefit in 2030, and 293 ha in 2050 in terms of avoided waterlogging. The simulated inundated area would be 192 ha and 193 ha, in 2030 and 2050 respectively, which includes water bodies covering 103 ha.

3.1.6. Trends in economic growth. Socioeconomic development would alter land use. The land use plan for 2030 proposed by the city was considered for Sylhet city. The land use plan will increase

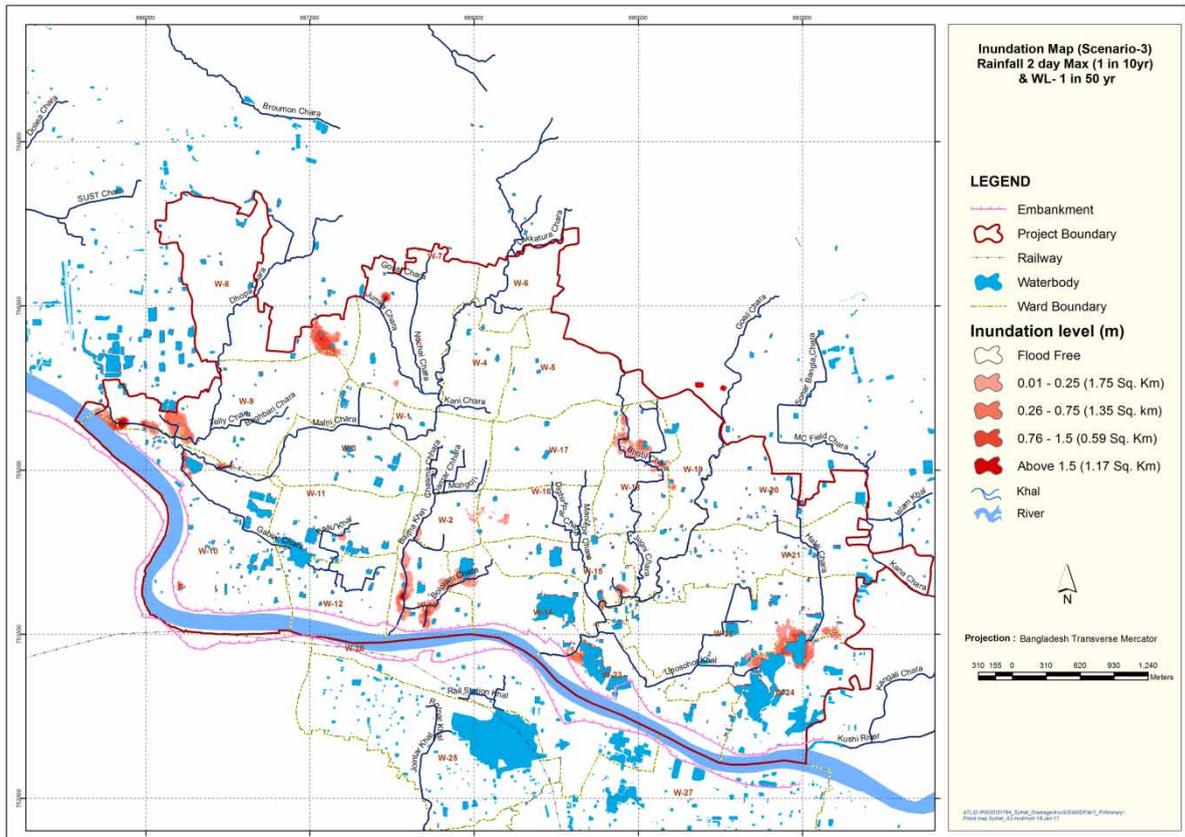


Fig. 12. Flood map for Sc-3 scenarios, Sylhet.

the extent of the impervious area in each sub-catchment, and will increase run-off patterns, which were simulated in scenario Sc-5. In 2030, the elevation of the land would increase to a level of 12 mMSL due to land development and land use changes. The land development level is considered 1.15 m above the once in 50 year water level of the Surma River. Due to land development, which is one form of adaptation, the inundated area would be reduced in 2030, and no additional pump (as estimated in Sc-3) would be required for both Malni chhara and Goali chhara. About 377 ha of additional land area would be free from waterlogging as a result of land development, but the duration of the water above the danger level would increase to 7 hours in Malni chhara and 3 hours in Goali chhara. The simulated area inundated would be 109 ha, which includes water bodies covering 60 ha (the area covered by water bodies declines due to land use changes by 2030).

3.1.7. Trends in economic growth and climate change. Future climate change, superimposed over an altered socioeconomic condition, was simulated in scenario Sc-6. It was considered that the proposed land use plan would be implemented in 2030, even as the city would simultaneously experience the effects of climate change with increased economic activities. To cope with the excess storm water that would ensue due to climate change and to ensure adequate drainage facilities, an additional pump (7.33 m³/s) would be required for both Malni chhara and Goali chhara in 2030. Yet another pump

would be required in 2050. The land area that would benefit by being free of inundation would be 380 ha. The simulated inundated area would cover 1.06 km², including water bodies covering 60 ha.

3.1.8. Solid waste dumping in the drainage system. Solid waste dumping in the drainage canals reduces conveyance capacity (Figure 13). It was observed from the field survey that due to the dumping of waste, the depth of the canal decreased by 11 cm, 10 cm, and 20 cm in Malni, Baitha and Goali canals, respectively, in a one-year period. If no cleaning or dredging operation is carried out with the rehabilitation/expansion/re-sectioning of existing canals, the depth will decrease continuously. The possible effects after five years of solid waste dumping in the canals were simulated under scenario Sc-7. It was observed that the inundated area would be 421 ha, including water bodies spread over 103 ha. Therefore, the area that would benefit after rehabilitation/expansion/re-sectioning would decrease by approximately 47 ha.

Since the indiscriminate dumping of solid waste critically impairs the conveyance capacity of the drains, improving the drainage infrastructure alone without considering solid waste management would be a waste of resources. Therefore, improving waste management systems by adding segregation at source and placing waste collection bins in the streets are important adaptation activities. Waste collection bins were considered in improvement scenarios Sc-2 to Sc-6, at a cost of USD 0.51 million.

Therefore, the important adaptation options include both infrastructural change and behavioural change. Infrastructural changes in Sylhet include: (i) the rehabilitation/expansion/re-sectioning of existing drainage canals; (ii) the construction of new drains; (iii) reconstruction of culverts; (iv) the construction of silt traps; (v) the placement of solid waste collection bins; (vi) regulators; and (vii) a drainage pumping station. The behavioural change includes improved solid waste management with segregation at source and separate collection of different types of waste for proper disposal. The extent of flooding and the cost of investment for each scenario are given in Table 5.

3.2. Bharatpur

3.2.1. Existing baseline situation with design event. In the baseline scenario for Bharatpur, Sc-0, the existing situation of the canal, bankfull water levels for the Narayani and Rapti rivers, and cumulative

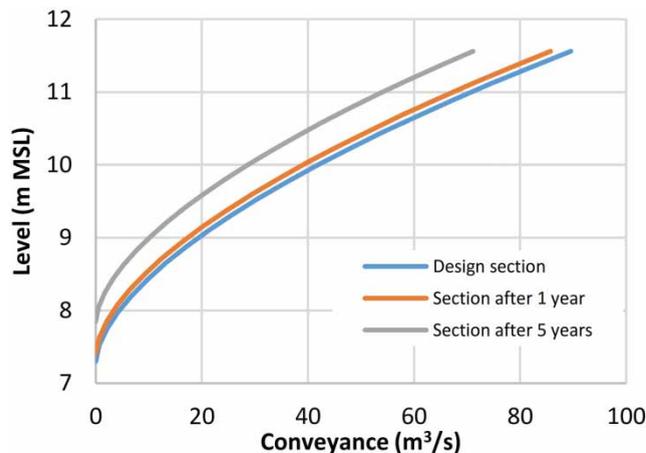


Fig. 13. Change of conveyance capacity due to solid waste dumping.

two-day, once in 10 year rainfall data were used. As there is no backwater effect, water flows through the canals by gravity. The drainage capacity of the Pungi canal is insufficient in some places, which contributes to flooding in a number of areas. The drainage capacity of the Kerunga canal is sufficient to carry the storm water it receives and hence no flooding occurs in the Kerunga canal catchment. The simulated inundated area is around 166 ha, which falls mainly in the Pungi canal catchment under this scenario (Figure 14).

3.2.2. *Existing situation with design event and climate change.* Due to climate change, the run-off during the monsoon season would increase in 2030 and even more in 2050, which would increase inundation over the Sc-0 scenario. The simulated inundated area is almost the same in 2030 and in 2050, being roughly 175 ha, meaning that an additional 9 ha area, in addition to the 166 ha flooded area under Sc-0, would be inundated in 2030 and 2050 due to climate change, if no adaptation measures are taken.

3.2.3. *Rehabilitation, expansion and re-sectioning of drainage channels.* To improve the drainage situation from the baseline scenario, rehabilitation/expansion/re-sectioning of the existing inadequate

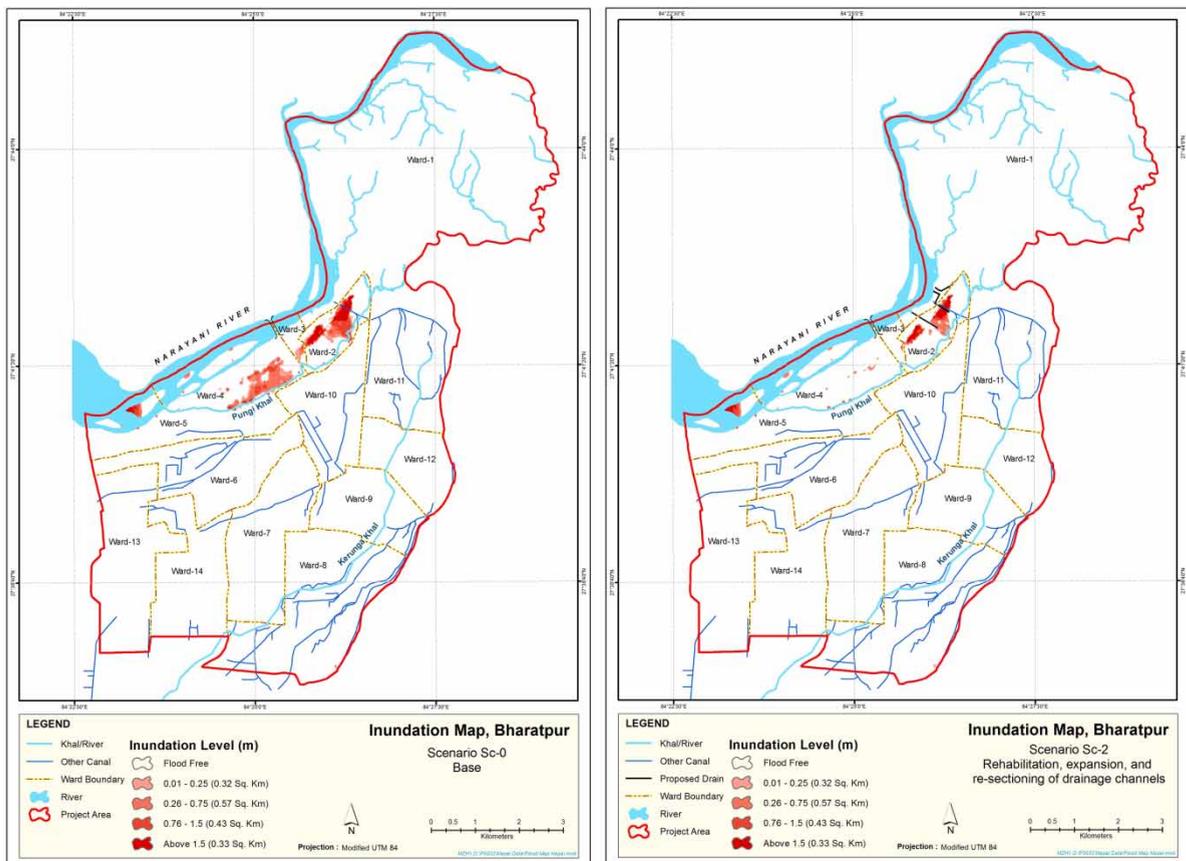


Fig. 14. Flood maps for scenarios Sc-0 and Sc-2, Bharatpur.

canals and the construction of some new drains in the Pungi canal system were incorporated into scenario Sc-2. The bottom level of the canal becomes silted up in some places, or the channel sections become narrow due to encroachment. While designing the section, a gentle slope is maintained along the canal and widened at places where necessary. These improvement works would increase the canal's water-carrying capacity and would make 94 ha land free of waterlogging in the Pungi catchment area, and the simulated inundated area would be about 72 ha (Figure 14). The areas that are flooded are mainly agricultural lands at a lower elevation.

3.2.4. Physical interventions and climate change. Climate change impacts in 2030 and 2050 over the improved scenario (Sc-2) were simulated in scenario Sc-4. The extent of flooding and the duration of inundation both increase slightly over scenario Sc-2 due to the additional run-off under the climate change scenario (change in rainfall pattern). The simulated inundated area was found to be 77 ha in the Pungi catchment in both 2030 and 2050. Thus, the area to benefit would be decreased (over scenario Sc-2) by just 5 ha in 2030 and 2050. As the additional inundated area is not significant, no additional structural improvement is suggested for the future.

3.2.5. Trends in economic growth in Bharatpur. Due to socioeconomic developments, land use patterns are changing continuously in Bharatpur. However, there is no land use plan for the near future in Bharatpur, even though the population has been growing at about 6% per year during the last decade. Agricultural land and vacant land is being rapidly converted into residential, commercial and service areas as development and population growth continues. The major reasons that Bharatpur attracts growing numbers of people are its proximity to Kathmandu, the capital city, and moderate year-round weather, with almost all facilities needed for urban living (health service facilities, education institutions, businesses, employment opportunities, industries and transportation, including quick air links to the major cities, Kathmandu and Pokhara). Due to rapid expansion of the built-up areas, the impervious surface area would increase by 40% in 2030 and by 70% in 2050 above the present situation, as simulated under scenario Sc-5. Considering these factors, simulated results show an increased run-off and accordingly the drainage situation was simulated under this scenario. The simulated inundated area covers 77 ha in 2030 and 86 ha in 2050, slightly higher than scenario Sc-2. Due to the increased run-off, the inundation-free area would decrease by 5 ha in 2030 and 14 ha in 2050. These areas are mainly agricultural areas. With land use changes, these low-lying areas would eventually be urbanized and developed after landfill. Stormwater drains of proper design and connected to existing canals need to be implemented to avoid waterlogging in newly developed areas.

3.2.6. Trends in economic growth and climate change. Climatic change with future socioeconomic development (as described above) is simulated in scenario Sc-6. Economic development in Bharatpur would create larger impervious areas in future and climate change would aggravate the situation by increasing the rainfall amount. The simulated inundated area would be 79 ha in 2030 and 94 ha in 2050 – higher than scenario Sc-5 due to the increase in rainfall–run-off. The inundation-free area would decrease further by 2 ha in 2030 and 8 ha in 2050 from Sc-5. However, the increase in the flooded area is not significant, so no improvement is recommended under scenario Sc-6. If the land is developed as discussed above, the extent of flooded areas would reduce in due course. An additional risk faced by Bharatpur is riverbank erosion of the Narayani River, which requires a proper embankment. However, this issue has not been considered in this study.

3.2.7. Solid waste dumping in the drainage system. There is no field level or survey data for Bharatpur regarding reduced depth of drainage due to the dumping of solid waste in the existing canals. Considering the rapid population growth in Bharatpur, it is assumed that the decrease in depth due to the dumping of waste in the canals would be 10 cm in the Pungi and Kerunga system per year (in Sylhet it is between 10 and 20 cm per year and we assumed the lowest effect of 10 cm in the absence of historical records data for Bharatpur). Solid waste dumping without any cleaning or dredging operations in the expanded canals and new drains (Sc-2) after five years was simulated under scenario Sc-7. It is estimated that the simulated inundated area is 99 ha. Therefore, the additional area that would get waterlogged is approximately 27 ha more than in scenario Sc-2.

A proper solid waste management system was considered under scenarios Sc-2 to Sc-6. The important infrastructural changes in Bharatpur for drainage improvement include: (i) the rehabilitation/expansion/re-sectioning of the existing drainage system in the Pungi canal; (ii) the construction of new drains in the areas where new development is occurring; and (iii) soft measures for improving solid waste management. The extent of flooding and the cost of investment for each adaptation scenario are given in Table 6.

4. Discussion and conclusions

The existing drainage networks, waterlogging and flooding risks were studied under different scenarios in two medium-sized Asian cities. Results from the simulation exercises show that improving the existing drainage canals through rehabilitation/expansion/re-sectioning and the construction of new canals reduces the flooding risk in the short term, but without proper management of solid waste, the flooding risks increase significantly in five years. With engineering solutions, soft measures such as changing human behaviour to properly manage solid waste and not dispose of it in canal and drainage systems would help the cities reduce flooding and waterlogging risks. This cheaper but more effective solution could potentially save city resources that otherwise would be needed to reduce urban flooding and waterlogging.

In order to properly manage a city's solid waste, an improvement in the collection and disposal system is needed. City governments should improve the current practice of non-segregation at source in order to properly managing solid waste. During our interactions, city residents suggested that they would be willing to segregate waste (organic, plastics, metals, bottles and the rest), recycle and dispose properly if the waste collection service also provided systematic collection of the waste from households (putting organic waste separately from recyclable and other waste). A social campaign regarding solid waste management would be an important accompaniment, along with awarding waste collection and management contracts to private firms that are willing to compost the organic waste, and to recover and recycle useful materials.

Sylhet city faces the issue of backwater flow from the Surma River which requires structural interventions in addition to improving the existing drainage canals and proper solid waste management. Such interventions help prevent about 322 ha of land from flooding. The structural interventions include the construction of new drains, reconstruction of culverts, construction of silt traps and regulators. The cost of such improvements is estimated to be at least USD 75.08 million (based on the project estimates that Sylhet city has been working on). This is about USD 233,000 per hectare in terms of public investment. Under the climate change scenario but without socioeconomic development (Sc-4), an additional public investment of USD 11.25 million is required to prevent flooding and waterlogging, although the area that would benefit would reduce by 29 ha from the 'no climate change' scenario.

Under scenario Sc-5, no additional public investment is required because this scenario assumes that, with improvements in economic conditions, city residents will make investments (using landfill measures) to make their land flood-free. This means that the city will gain an additional 55 ha of land without any additional burden on the public exchequer. Private owners will recover their costs, however, through the increased value of their land. For landowners, it is an investment to increase the value of their land.

Under the climate change scenario, there is a need for additional investment in Sylhet to make more land flood-free because climate change will bring in additional rainfall (Sc-6). The estimated cost of adaptation under this scenario is around USD 11.25 million. However, such measures will only make another 3 ha of land flood free, resulting in a large average cost of USD 3.75 million per hectare.

In Bharatpur, the estimated cost of improving the existing drainage channels and constructing three new drains is USD 0.38 million, which would reduce flooding over 94 ha land in the Pungi canal catchment. With urbanization, more new drains need to be constructed to avoid local flooding – which is not planned and has not been analysed in this paper.

The simulation results of scenario Sc-7 show that the carrying capacity of the drainage channels would reduce due to the poor management of solid waste even after the engineering solution. The mismanagement of solid waste would possibly result in an additional 47 ha of flooding in Sylhet and an additional 27 ha flooding in Bharatpur within five years, despite the additional investment in drainage expansion. In order to prevent such a situation, awareness-building of city dwellers, the continuous monitoring of waste management and maintaining the drainage conveyance capacity are all needed in both cities. If households cannot be motivated to practice proper solid waste management, and if they continue disposing of solid wastes in open spaces and in drainage canals, the carrying capacity of the drainage canals will be reduced and the benefit of additional investment in the drainage infrastructure will be neutralized. Our results suggest that, without the proper management of solid waste, the cities cannot maintain a congestion-free drainage environment under the climate change risk.

To be more precise, under the current scenario, about 22.3% of the land area in Sylhet and 12.7% of the land area in Bharatpur is under flooding risk. The flood risk area can be as low as 3.6% in Sylhet and 5.5% in Bharatpur with structural interventions combined with proper solid waste management. However, the area under flood risk goes back up to 18.5% in Sylhet and 7.6% in Bharatpur in five years if solid waste is not managed properly, suggesting that the structural solutions without properly integrating effective solid waste management become almost ineffective in reducing flooding risk in these cities.

Under the proper solid waste management scenarios (Sc-2 to Sc-6), we assumed that the capacities of the city councils in both cities are improved, and that 100% of the solid waste is either placed in a suitable dumpsite or composted properly as organic fertilizer and the remaining non-recyclable waste is properly managed. The strategies proposed in the scenarios include: (i) at-source separation of kitchen waste by residents; (ii) managing plastic properly; and (iii) local composting of organic waste or disposing of it properly in landfill sites by the waste collectors. These options were discussed with the concerned officials in both cities and are feasible to implement within reasonable and short time periods.

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