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A megacity in a changing climate: the case of Kolkata

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Abstract Projections by the Intergovernmental Panel on Climate Change suggest that there will be an increase in the frequency and intensity of climate extremes in the 21st century. Kolkata, a megacity in India, has been singled out as one of the urban centers vulnerable to climate risks. Modest flooding during monsoons at high tide in the Hooghly River is a recurring hazard in Kolkata. More intense rainfall, riverine flooding, sea level rise, and coastal storm surges in a changing climate can lead to widespread and severe flooding and bring the city to a standstill for several days. Using rainfall data, high and low emissions scenarios, and sea level rise of 27 cm by 2050, this paper assesses the vulnerability of Kolkata to increasingly intense precipitation events for return periods of 30, 50, and 100 years. It makes location-specific inundation depth and duration projections using hydrological, hydraulic, and urban storm models with geographic overlays. High resolution spatial analysis provides a roadmap for designing adaptation schemes to minimize the impacts of climate change. The modeling results show that de-silting of the main sewers would reduce vulnerable population estimates by at least 5 %.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC), in its overview of global trends of extreme weather events up to 2006, notes that the frequency of heavy precipitation events has increased over most land areas (IPCC AR4 2007). Historical evidence highlights the dangers associated with such intense precipitation events in developing countries.[1] Flood-related deaths increased steadily from 17,000 in the 1960s to more than 58,000 in the 1990s in developing countries (EM-DAT 2010). Floods affected billions of people who were injured, made homeless, or forced to seek emergency assistance. Recent examples of devastating extreme precipitation impacts in developing countries include the following: floods[2] in Pakistan (1,600 people died

[1] Countries identified by the World Bank as Low Income or Lower Middle Income.

[2] http://www.dartmouth.edu/~floods/dbtop.html, accessed December 2011.

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and 14 million people were displaced in July 2010), India (24 died and 1.1 million people were displaced in July 2010), China (12 died and 300,000 people were displaced in Hubei, Sichuan, and Shananxi provinces in May 2010; 60 died and 4.7 million people were displaced in southern China in July 2010), and Mozambique (35 died and 130,000 people were displaced in February 2010); tropical cyclone Nargis[3] in Myanmar (100,000 people died and the livelihoods of 1.5 million people were affected in May 2008); and cyclone Sidr[4] in Bangladesh (243 people died and the livelihoods of 7 million people were affected in November 2007). The impacts are particularly disastrous when extreme weather strikes densely populated urban centers.

The IPCC and the Asian Development Bank specifically identify the heavily urbanized megacities in the low-lying deltas of Asia as hotspots for climate risks (ADB 2008; IPCC AR4 2007). In many such cities, flooding is a recurrent annual feature. Based on various emissions scenarios, the IPCC and the World Meteorological Organization have projected an increase in the frequency and intensity of climate extremes during the 21st century (WMO 2010; IPCC AR4 2007). With the addition of the increased risk of storm surges, cyclones, and intense precipitation induced by climate change effects, such flooding conditions and associated impacts caused by weather related events may worsen dramatically and become disasters (World Bank 2010a, b). Furthermore, the poor inhabitants of these cities are among the most vulnerable, because large and densely populated conglomerations of slums in most of these cities are located in areas of unplanned and unregulated development with scant attention to environmental issues (World Bank 2010b; UNFCC 2008).

Hence, adaptation to face the challenges posed by climate change in megacities in the low-lying deltas of Asia, most of which are rapidly growing, is critical. Although a number of cities are taking steps to mitigate their carbon footprint, less attention has focused on how cities in developing countries can adapt and respond to climate change risks (Dickson et al. 2010). Setting a new course requires better understanding of expected changes in local weather patterns and the associated damages in the future. Currently, few studies have been carried out in developing countries on future climate patterns and location-specific impacts. This paper is an attempt to narrow that gap.

We present a study undertaken for Kolkata, a megacity in India, to assess the impacts of climate change. Kolkata is vulnerable to a number of natural hazards that lead to water-logging and flooding, including cyclones, tidal upsurges, storms, and intense local precipitation. The scope of the paper is restricted to urban flooding mainly arising from increases in intense precipitation due to climate change. The remainder of the paper is organized as follows: Section 2 describes the study area, Kolkata, and provides background information. Section 3 describes the modeling of climate change to determine the timing and magnitude of floods of different return periods. Section 4 presents the vulnerable area and population estimates resulting from such flooding. Section 5 illustrates adaptation options and discusses local coping strategies. Section 6 concludes the paper.

2 The city of Kolkata

This study of Kolkata is based on the urban agglomeration, the Kolkata Metropolitan Area (KMA), as defined in the Vision 2025 document (KMPC 2004). However, given the paucity of available data for the entire area for all aspects of the study, some of the more detailed analysis is confined to the Kolkata Municipal Corporation (KMC), the more urbanized heart of the KMA. Background information on the KMA and the KMC is provided below.

[3] http://www.dartmouth.edu/%7Efloods/Archives/2008sum.htm, accessed December 2011.
[4] http://www.reliefweb.int/rw/RWB.NSF/db900SID/EDIS-79BQ9Z?OpenDocument, accessed December 2011.

2.1 Kolkata Metropolitan Area

The KMA, the capital of the State of West Bangal, has an area of 1,851 km^2 that covers a complex of administrative entities comprised of three municipal corporations. These include the KMC, 38 other municipalities, 77 non-municipal urban towns, 16 suburban areas, and 445 rural areas. The KMA is one of Asia's largest urban centers. It is among the 30 largest megacities in the world, having population in excess of 10 million (UN Department of Economic and Social Affairs 2005). As per the 2001 Census, the population of the KMA was 14.72 million. The average population density in the KMA is 7,950 persons per square kilometer. Its annual population growth rate was in the 1.8–2.6 % range by 2001, and its population was projected to rise to 17 million in 2011, 20 million in 2021, and 21.1 million in 2025 (KMDA 2010).

Although Kolkata (KMA) is often perceived as a coastal city, in reality it is about 145 km away from the Bay of Bengal (see Fig. 1). The KMA is 1.5 to 11 m above mean sea level (MSL), with an overall average of about 8 m above MSL.

The KMA has a tropical wet-and-dry climate, with annual mean temperature 26.8 °C and monthly mean temperature 19–30 °C. The region around the KMA is subject to short, high intensity precipitation, especially during the monsoon months between June and September. This, along with the occasional coincidence of high tide, is the usual cause of urban flooding. Annual rainfall is about 1,600 mm, and the greatest rainfall usually occurs during the monsoon in August.

Urban built-up land constitutes 54.2 % of the current total area of the KMA, with the remaining area under non-urban use, mainly as agricultural land in peripheral areas and wetlands in the eastern parts. In urban areas, residential use is predominant, with a share of about 31.2 % of the total area.

The drainage and sewer network in the KMA is sparse and not commensurate with its area of 1,851 km^2. Where the network exists, it is mostly comprised of a century-old drainage and sewer system. The drainage system is divided into 25 drainage basins (catchment areas), and the entire metropolitan area is divided into 20 sewer zones (zones for the sewer network). Of the 41

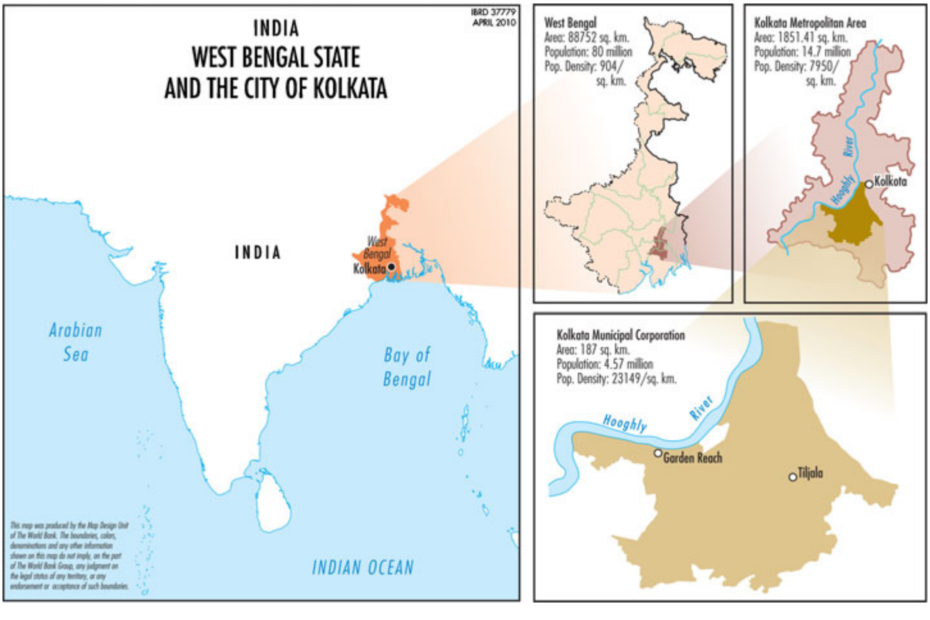


Fig. 1 Geographical context of the study

municipal towns in the KMA, the piped sewer network is confined mainly to the KMC, Panihati, Titagarh, Bhatpara, and Kalyani on the East Bank and Howrah MC, Bally, Serampore, Chandannagar, and Hooghly-Chinsurah on the West Bank. However, it is intended that all municipal towns will be connected with sewer lines by 2025.

At present, systematic studies of land subsidence for the KMA are scarce. Land subsidence is perceived to be a localized problem for the KMA, largely connected to the increasing pressure on ground water extraction tapped by hand-pumps and heavy-duty tube wells installed by private industries, housing estates, and high-rise apartment blocks. The driving force is the increasing population pressure that has led to the back swamp and marshy land in the eastern part of the KMA, especially the Salt Lake and Rajarhat areas, being encroached upon and becoming urbanized largely without planning (Nandy 2007).

2.2 Kolkata Municipal Corporation

The KMC, which covers 185 km^2 and is divided into 141 wards, is the core component of the KMA (KMC 2010). As per the 2001 Census, the population of the KMC is 4.6 million people. The average population density of the KMC is 24,760 persons per sq. km. The KMC accounts for 31 % of the KMA's population, with only 10 % of its area. More than a third of the KMC's population lives in slums.

Within the KMA, the KMC lies along the tidal reaches of the Hooghly River, which were once mostly a wetland area. The slope and the transformation of the marshy land into an urban area have made drainage difficult. The elevation of the KMC area ranges from 1.5 to 9.0 m above MSL with an average elevation of 6 m above MSL.

Compared with the land use pattern in the KMA, the land use pattern in the KMC is more urban, reflecting 300 years of organic growth. With almost nonexistent land-use planning or control, residential and non-residential land use is co-mingled in most areas, with little or no demarcations. In the KMC, residential or mixed residential areas account for 68 % of land use. Slums in the KMC are the hub of many informal manufacturing activities, some of which involve highly toxic industries that generate or use acids and other chemicals.

The sewer network in the KMC covers 55 % of the total area. The KMC is divided into nine major drainage basins, each with an independent sewer network and a terminal pumping station. Three of the basins drain into the Hooghly River on the west and six drain into the Kulti system in the east. Eleven sluice gates on the Hooghly River prevent tidal ingress into the sewer system during heavy storms and high tide. The existing sewer network covers a length of 1,610 km and the length of open drains is about 950 km. However, the central part of the KMC sewer network system (town system) is almost 140 years old. Heavy siltation and inadequate maintenance of the channel outfall structures have resulted in a significant reduction in the hydraulic capacity of the KMC sewer system (Kolkata Municipal Corporation 2007).

The literature indicates that some areas of the KMC had been undergoing subsidence ranging from 6.52 to 13.0 mm per year on average for a period of 42 years from 1958 to 2000 (Chatterjee et al. 2006). If such subsidence continues over a longer period of time and occurs over a wide area, land subsidence will be an important cause of flooding in the KMC in the future.

The city of Calcutta (Kolkata), as described by Kipling, was "chance directed and chance erected." The description is appropriate because of the challenges presented by its location and its exposure to flooding. Flooding in Kolkata is an annual feature during the monsoons. Any past incidence of high intensity rainfall synchronized with high tide in the Hooghly River has almost always resulted in water-logging in Kolkata. Yet there has been no mass exodus from Kolkata during temporary floods, possibly because the magnitude of most such floods has not been very large or long lasting, and the population has learned to adapt to floods by taking precautions to protect critical assets and prepare for health risks. However, the situation may change if flooding becomes more severe as a result of climate change. The causes of flooding in the KMC and the KMA can be categorized as follows:

- *Natural factors*: The area's flat topography, low relief, and natural subsidence cause flooding in the KMA. The sources of such flooding are high intensity rainfall, storm surges, and cyclonic storms.
- *Developmental factors*: These include unplanned and unregulated urbanization, low capacity drainage and sewer infrastructure that have not kept pace with the growth of the city or demand for services, siltation in available channels, uncontrolled construction in natural drainage areas (marshlands), human-induced subsidence of the area, etc.
- *Climate change aspects*: Changes such as increased intensity of rainfall, sea level rise,[5] and increased storm surges[6] may increase the intensity and duration of flooding events.

3 Modeling climate change

The effect of climate change in the KMA can manifest in several ways. The present analysis studies the hydrological and hydraulic impacts resulting from increased precipitation in a changing climate, because they are likely to be the most significant climate change effects in an urban area like the KMA. In addition, sea level rise from climate change is included because it can increase storm surges. Intense precipitation occurring concurrently with high tide and extreme storm surge can cause increased flooding in the KMA; the results can be especially devastating for areas that are already vulnerable to flooding.

3.1 Modeling scenarios

I. *Baseline*: In order to model the impact of climate change on intense precipitation events, we model the baseline (without climate change) scenarios of flooding for occurrence at 30, 50, and 100 years[7] using historical rainfall data from continuous recording rain gauges for 25 years. The rainfall data underlying the baselines cover the monsoon period (April to September) from 1976 to 2001. We processed the data to get rainfall at each successive 15-minute interval, and then further processed it to extract maximum rainfall events corresponding to different storm durations for the two recording stations. Hyetographs

[5] The most recent evidence suggests that sea level rise could reach 1 m or more during this century (Hansen and Sato 2011; Vermeer and Rahmstorf 2009; Pfeffer et al. 2008: Hansen 2007; Rahmstorf 2007; Overpeck et al. 2006; Hansen 2006). This more recent research has focused on the dynamic implications of ice sheet instability, and their results include estimates significantly beyond the upper limit of the range cited by the IPCC's Fourth Assessment Report (2007): a 90 % confidence interval of 18–59 cm based principally on thermal expansion, with an additional 10–20 cm allowed for a potential dynamic response from the Arctic and Antarctic ice sheets. If such sea level rise occurs, it will have a significant impact on tidal surges and drainage in the KMA.

[6] An increase in sea surface temperature is strongly evident for all latitudes and oceans. The current scientific consensus, summarized by IPCC (2011), holds that a warmer ocean is likely to intensify cyclone activity and heighten storm surges. For the Bay of Bengal, Karim and Mimura (2008) estimate that with a 1 m SLR and an increase of 2° in ocean surface temperature, storm surges in neighboring Bangladesh would increase by 13 %. The KMA would experience intense flooding with intensification of cyclonic storm surges.

[7] This is an estimate of the time interval between two precipitation events of a particular intensity. It is a statistical measure of the average recurrence interval over a long period of time and the inverse of the probability that the event will be exceeded in any one year. Hence, a 30, 50, or 100-year precipitation level has a 3.3, 2, and 1 % chance, respectively, of occurring in any given year.

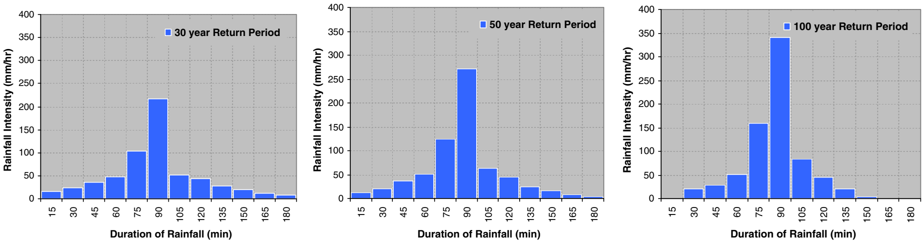


Fig. 2 Rainfall Hyetograph based on Alipore rainfall data

(graphs of the distribution of rainfall over time) provided data from the storm intensities for each 15-minute period for the 30, 50, and 100-year return period storms (see Fig. 2).

II. *Climate change*: Inputs for the climate change scenarios for Kolkata were based on analysis of a subset of models and emission scenarios used for the IPCC Fourth Assessment Report (JICA 2008). Pattern scaling techniques were applied to 16 Atmospheric-Ocean General Circulation Models used for the IPCC AR4.[8] We considered high (A1FI) and low emission (B1) scenarios to assess impact due to uncertainties in projecting future climatic conditions. (See Nakicenovic and Swart (2000) for a description of the emission scenarios.) The scenario projections include a temperature increase in Kolkata of about 1.8 °C for the A1FI scenario and 1.2 °C for the B1 scenario by 2050. Precipitation projections for 2050 are provided as a fractional increase in the precipitation extremes of about 16 % for the A1FI scenario and 11 % for the B1 scenario imposed above the baseline distribution of precipitation. A conservative estimate of expected sea level rise of 27 cm by 2050 is also included in the climate change scenarios.[9]

In each scenario, the study assesses the impact in terms of the extent, magnitude, and duration of flooding.

3.2 Models

In assessing the magnitudes of flooding events, the key factors are the inflow and outflow of water in and around the KMA area. The inflow depends on the precipitation in the KMA area, the over-topping of the Hooghly River due to water inflow from local precipitation as well as that from the catchment area, and storm surge effects. For the outflow, important considerations are the natural discharge through drainage basins and sewer systems in place as well as installed pumping capacity. Tide levels and storm surge effects also affect the rate of discharge. An imbalance between inflow and outflow, especially caused by short-duration intense precipitation, results in local flooding as the water inflow overwhelms normal drainage, sewer, and pumping capacity.

We use three models to capture the effects of all factors that lead to flooding in the KMA. A *hydrological model* develops the flow series for the whole Hooghly catchment. The

[8] For details, see Sugiyama (2008).

[9] In the absence of scientific sea level rise estimates corresponding to various emission scenarios for the Bay of Bengal near the coast of India, upon consultation with the government of West Bengal, an estimate of 27 cm sea level rise by 2050 was adopted from the World Bank-led *Economics of Adaptation for Climate Change* study for neighboring Bangladesh (World Bank 2011). This 27 cm sea level rise is a point estimate of "medium sea level rise" by 2050 derived from Rahmstorf (2007). See Neumann (2009) for details.

generated data are then fed into a *hydraulic model* to analyze the implications of the flood passing through the river stretch. Finally, an *urban storm model* is deployed to determine the flooding that will result once the river flooding is combined with local precipitation and the drainage capability of the urban area under an extreme flood situation. Here we provide a description of the models:

I. *The hydrological model*: Soil and Water Assessment Tool (SWAT). As a first step, we estimate the water flow in the Hooghly River system by using the SWAT hydrological model. The water flow in the river arises from high rainfall occurring in the whole Hooghly River catchment. The river flow is modeled using the rainfall and temperature data obtained from the India Meteorological Department for a 25-year period. Water flow from diversions made into the Hooghly from the Ganga River upstream is added while estimating the total flow in the Hooghly River. The SWAT model generates daily water flow series at various locations along the Hooghly River. For details on the inputs in the SWAT model, see Box 1.

Box 1: SWAT Model Inputs

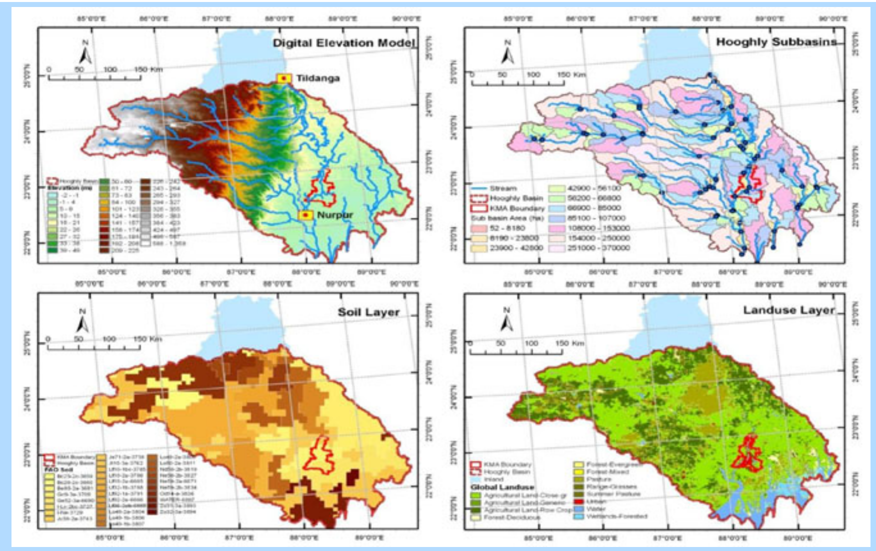
SWAT uses daily precipitation and temperature data along with spatial data to derive the flow series for the river. The spatial data as listed below were obtained from global data sources because of ready availability and reliability:

Digital Elevation Model: SRTM of 90m resolution[1]
Drainage network[2]
Soil maps and associated soil characteristics[3]
Land use[4]

Precipitation and temperature data were obtained from the India Meteorological Department.

The figure below provides a snapshot of all the spatial layers used for the SWAT modeling. Daily gridded (0.5° × 0.5°) rainfall data and daily gridded (1.0° × 1.0°) temperature data for the catchment of the Hooghly River are from the Indian Meteorological Department. The gridded data were developed based on the observed data that were available from 1976-2001.

Spatial data for the Hooghly basin used for the SWAT modeling



[1] http://srtm.csi.cgiar.org/ . [2] Digital Chart of the World, 1992, http://www.maproom.psu.edu/dcw/.
[3] FAO Global soil, 1995, http://www.lib.berkeley.edu/EART/fao.html. [4] Global land use, Hansen et al. (1999) http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp.

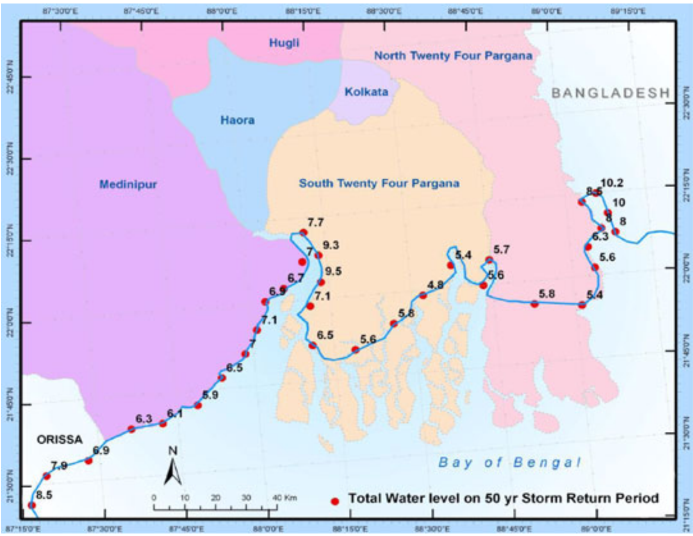
II. *The hydraulic model*: Hydrologic Engineering Centre-River Analysis System (HEC-RAS).[10] For the second step, daily water flow along the Hooghly River is obtained from the SWAT and used to generate flood waves moving through the river channel using the hydraulic model HEC-RAS. These flood waves cause inundation when the carrying capacity of the channel is exceeded by the volume of the wave. The tidal and storm surge effects are fed into the HEC-RAS model as boundary conditions. Output from the model provides the water surface profiles along the river coupled with change in flow depth during the flood period. For details on the inputs in the HEC-RAS model, see Box 2.

Box 2: HEC-RAS Model Inputs

Input parameters for the HEC-RAS include topographic data in the form of river cross-sections, a friction parameter in the form of Manning's n values[1] across each cross-section, flow data including flow rates, flow change locations, and tide and storm surge data as boundary conditions. In addition, flood hydrographs from September to October for different return periods were also used as inputs for each relevant scenario.

The storm surge data used in the analysis are based on available literature. Kolkata is about 120km from the open sea and does not experience storm surge as frequently as the lagoon areas of the Hooghly River. The highest tidal height experienced in the area is around 6m. A surge of around 3 to 4m (Dube et al., 1997) has been observed a few times above high tide value and these data were used for the simulation (see the table below). The water level on a 50-year storm return period in the coastal area downstream from Kolkata is shown in the figure below.

Peak water level rise in the event of a 50-year storm for the coastal districts of West Bengal



Maximum storm surge for various return periods for the average coastal length of West Bengal

	Return Period (years)			
	10	**25**	**50**	**100**
Maximum wind speed (kmph)	*167*	*195*	*215*	*231*
Maximum storm surge height (m)	*4.5*	*6.3*	*7.8*	*9.2*

Source: Figure adapted from Jaine et al. (2010); table: Jain et al. (2010).
[1] http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm

[10] HEC-RAS is a one-dimensional steady and unsteady flow hydraulic model developed by the U.S. Army Corps of Engineers (U.S Army Corp of Engineers 2002).

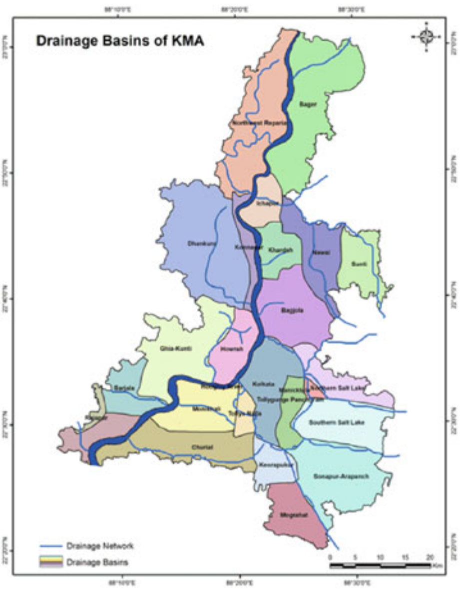
III. *The urban storm model*: Storm Water Management Model (SWMM).[11] For the third step, the urban storm model SWMM is used to simulate flooding due to local rainfall by incorporating the prevailing urban characteristics of the area, such as built-up and paved areas and other specific structures, such as sewers in place, pumping capacity of drainage pumps,[12] and likely operation of lock gates during flooding. The intense local rainfall and the flow of water determined by HEC-RAS provide the inflow in the model. For details on the inputs in the SWMM model, see Box 3.

Box 3: SWMM Model Inputs

The primary inputs in the SWMM are the characteristics of the 25 drainage basins, of which 18 are on the east bank and 7 are on the west bank of the Hooghly River (see the figure below). All drain shapes were taken as open rectangular drains and their depth, width, and invert elevation were derived using Digital Elevation Model and Google Earth Images. It was assumed that no interventions like pump, sump, weir, gates, diversions, etc. existed in the flow path in the rest of the KMA outside the KMC. Because of lack of availability of short-interval rainfall data for the whole of the KMA, data available for the KMC area (Dumdum in the North and Alipore in the South) were used for the rest of the KMA. The Manning Roughness coefficient was taken as 0.035 for open natural channels. The flow in the Hooghly at the entry point to the KMA simulated by the HEC-RAS model was used as the inflow into the Hooghly. Since the KMA boundary is not the natural watershed boundary, to balance rainfall runoff generation, an area adjustment was made for other natural drains.

For the KMC, the SWMM inputs came from the prevailing urban characteristics of the area. Thus, the existing extensive sewer network data for the KMC area were used in the SWMM model. It also included other specific structures, such as lock gates, drainage pumps, etc., that make a difference in the water flow. The brick sewers built over many phases in the city's development were an important input in the model. Since the hydraulic capacity of the sewer system and discharge canal systems has been considerably reduced due to the build-up of silt, the simulation was run with an overall siltation level of 30 percent. The simulations were also repeated later with the assumption of no siltation to test the effects of adaptation measures. The model used the current system of storm water passage (drain → sewer lines → pumping stations → main sewers → canals Hooghly River or Wetland/Kulti River).

Drainage basins in the KMA



Data Source: Vision 2025 perspective plan of KMA, 2005

[11] SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of water runoff from primarily urban areas.

[12] The KMC area covered by town and suburban sewer systems has a total installed pumping capacity of 82 cubic m/s with a current working capacity of 59 cubic m/s.

3.3 Model calibration and validation

In order to calibrate and validate the models, we compare the theoretical distribution of rainfall patterns for a 100-year return period with observed 15-minute rainfall intensities in the study area from 1976 to 2001. A comparison with the 1978 rainfall pattern on September 27, 1978 from 5:03 PM to 8:00 PM—the period with the highest rainfall intensity in recent times—shows a good match with the theoretical 100-year return period rainfall. Thus, the return period for the precipitation event of 1978 can be used for the 100-year return period precipitation.

We matched the flow obtained from the SWAT model for flood peaks with the theoretically generated flow from a number of distributions. Of these, the distribution that fits best is the Gumbel Extreme Value Type I distribution (NIST/SEMATECH 2010). With a resultant R^2 of 0.98 between the two variables—the simulated flow using the SWAT flow and the synthetic flow using the Gumbel distribution—the match is nearly perfect. The peak flows for all other return periods are therefore based on the Gumbel distribution.

Analysis of the flood events requires data on the complete rainfall distribution (rather than just the peak used to fit the theoretical distribution). To remedy this, we apply a ratio of rainfall corresponding to the respective return periods, derived using the rainfall analysis. We then update the observed rainfall time series with these ratios, and carry out the SWAT simulations for each of the return periods.

3.4 Model simulation

We set up the SWAT model and run it for the baselines of 30, 50, and 100-year return period rainfall for the baseline as well as for the A1FI and B1 climate change scenarios. We then use the results from the SWAT model, the water flow series along the Hooghly River for 30, 50, and 100-year return periods for the baseline and climate change scenarios A1FI and B1 as inputs into the HEC-RAS model. In addition, we feed the tidal and storm surge effects into the HEC-RAS to get the water flow profiles and the consequent inundation of the areas in and around the KMA. We set up the urban hydrological model SWMM using the flow profiles from the HEC-RAS model as inputs to simulate the flooding conditions of various magnitudes during the flood events under all the scenarios. Since sewer networks are sparse in the KMA outside the KMC, we model the KMA and KMC areas separately and run the KMA without any sewer network and the KMC area with sewer networks in position.

4 Results

The impacts of climate change through greater area inundation show up in two ways, higher total inundation at all depths and higher inundation at greater depths given the topography of the area. The percentage of the KMA (excluding the KMC) area inundated under different flood depth categories—as shown in the top panel of Table 1—clearly indicates that although a large segment of the KMA is inundated under all the flooding scenarios, the majority of the affected area belongs to the low-threat depth categories below 0.25 m.[13] One reason is that the KMA area is mainly peri-urban and does not have a formalized network of

[13] It has been found that a depth level below 0.25 m produces little damage in most affected areas as people have learned to adapt to this level of flooding as a common occurrence every year. Buildings in the KMA are generally raised to avoid flooding up to a water depth level of 0.25 m.

Table 1 Percentage of area inundated

Flood depth range (m)	30 year	30 year + A1FI	30 year + B1	50 year	50 year + A1FI	50 year + B1	100 year	100 year + A1FI	100 year + B1
KMA outside KMC									
0.00–0.10	56.5	46.7	49.1	47.8	38.7	41.2	40.6	29.4	34.1
0.10–0.25	21.4	22.1	22.4	22.2	24.1	23.8	23.8	26.8	24.5
0.25–0.50	9.4	15.8	14.4	14.9	16.6	16.7	16.7	16.0	16.4
0.50–0.75	1.6	3.6	3.0	3.1	6.9	5.4	5.4	10.5	9.2
0.75–1.00	0.0	1.1	0.6	0.8	2.2	1.9	1.9	3.7	2.9
1.00–1.50	0.0	0.1	0.0	0.0	0.9	0.4	0.4	2.2	1.6
1.50–3.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1
KMC									
0.00–0.10	1.0	0.3	0.3	0.7	0.3	0.3	0.3	0.2	0.2
0.10–0.25	4.7	1.7	1.7	3.9	1.5	1.4	2.8	1.9	2.2
0.25–0.50	13.6	7.3	8.5	11.3	6.4	6.9	10.4	7.6	8.1
0.50–0.75	9.3	12.1	9.9	11.9	11.9	12.2	15.5	13.9	15.1
0.75–1.00	2.7	6.3	5.1	4.0	8.2	7.4	7.2	11.1	10.0
1.00–1.50	2.2	3.5	3.6	2.5	4.4	3.9	4.1	5.9	5.3
1.50–3.00	1.1	1.5	1.3	1.4	1.8	1.7	2.0	2.2	2.1
>3.0	0.0	0.1	0.1	0.0	0.3	0.2	0.2	0.4	0.3

sewers covering the entire area. Water is therefore expected to follow the natural drainage patterns. The less-paved area in the KMA also contributes to less surface flow of water.

In the KMC, by contrast, the largest affected area for the 30, 50, and 100-year scenarios belongs to two depth categories—0.25–0.50 m and 0.50–0.75 m—without climate change. However, when the B1 and A1FI climate change scenarios are added, flooding depth goes up by one notch, with the depth categories 0.50–0.75 m and 0.75–1.00 m accounting for the largest affected areas for all three return periods. This is in sharp contrast with the rest of the KMA area, where the greatest percentage of inundated area is in the two lowest-depth categories. The depth of flooding in the KMC is higher mainly due to its topography, which prevents natural drainage. See Table 1.

Since flood water depths below 0.25 m cause little damage to the affected area and population, we aggregate the percentage area and population exposed in the KMA and the KMC with flood depths of 0.25 m and more under various scenarios in Table 2. In the KMA, the population exposed to flood water depths above 0.25 m increases from 4 % in the 30-year return period flood to 9 % in the 100-year return period. When the climate change effects are added, the population exposed increases to 6 % in the 30-year + B1 and 7 % in 30-year + A1FI scenarios. Under the 100-year + B1 and 100-year + A1FI scenarios, it increases to 13 and 15 %, respectively. In the KMC, 39 % of the population is exposed to flood water depths above 0.25 m in the 30-year return period and 45 % in the 100-year return period. With climate change, the population affected increases to 41 % under both the 30-year + B1 and 30-year + A1FI scenarios. Under the 100-year + B1 and 100-year + A1FI scenarios, the percentage goes up to 47 %. The greater percentage of population affected by flooding in the KMC compared with the KMA is not only due to greater submerged area, but also as a consequence of the KMC's higher population density in the affected areas. See Table 2.

Table 2 Area and population exposed to flood depths greater than 0.25 m

	Flood return period scenarios								
	30 year	30 year + A1FI	30 year + B1	50 year	50 year + A1FI	50 year + B1	100 year	100 year + A1FI	100 year + B1
KMA: area affected sq km (%)	204 (11 %)	389 (%)	333 (18 %)	352 (19 %)	500 (27 %)	444 (24 %)	442 (24 %)	611 (33 %)	555 (30 %)
KMA: population affected million (%)	0.91 (4 %)	1.73 (7 %)	1.44 (6 %)	1.71 (7 %)	2.42 (10 %)	2.16 (9 %)	2.13 (9 %)	3.57 (15 %)	3.14 (13 %)
KMC: area affected sq km (%)	63 (34 %)	65 (35 %)	64 (34 %)	67 (36 %)	72 (39 %)	70 (38 %)	72 (39 %)	76 (41 %)	75 (41 %)
KMC: population affected million (%)	1.99 (39 %)	2.11 (41 %)	2.07 (41 %)	2.14 (42 %)	2.24 (44 %)	2.19 (43 %)	2.28 (45 %)	2.42 (47 %)	2.38 (47 %)

Figure 3 provides a comparison of the duration of inundation of various depths between the 100-year return period without climate change effects and with the A1FI climate change scenario added. Inundation results for only the first 10 days are compared as the area inundated with the greatest depth category of flooding (>1.0 m) reaches its peak on day 9 under the A1FI scenario and starts decreasing thereafter. The same peak under the 100-year return period occurs on day 8, although with a smaller peak percentage area compared with the A1FI scenario. The model results show that under the 100-year return period scenario, by day 30 only about 7 % of the area still faces flooding of depth of 0.25 m–0.5 m. By contrast, under the A1FI scenario, by day 30, while most areas are free from flooding of depth >1.0 m, a small area (2 %) still faces flooding of 0.5 m–1.0 m and it takes about 5 more days for all such areas to decrease to the inundation depth of 0.25 m–0.5 m.

4.1 Vulnerability of KMC

In order to evaluate the spatial vulnerability of the KMC to flooding, two separate exercises are carried out. In the first one, the vulnerability is assessed at the ward level to identify the most vulnerable wards that require specific attention while designing adaptation strategies. Since the vulnerability in different areas within a ward may differ, in the second exercise, the vulnerability analysis is extended to the sub-ward level using spatial data.

4.2 Ward level analysis

The outputs from the urban storm drainage model that quantified the depth and duration of flooding in the KMC for the 100-year return period are used to analyze the vulnerability of the KMC at the ward level. In any risk analysis, both the average magnitude of the damage as well as the variability of such damage add to risk (Emery et al. 2007). In order to take into account the increased average magnitude of damage based on inundation depth, inundation depth >1.5 m is assigned the highest vulnerability index of 3, inundation depth 0.75–1.5 m is assigned a vulnerability index of 2, and inundation depth 0.25–0.75 m is assigned a

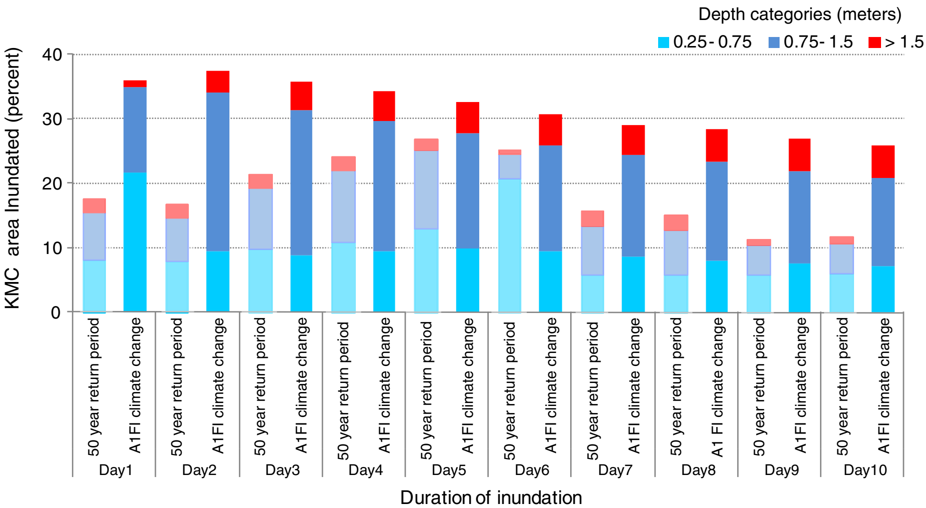


Fig. 3 Duration of inundation of various depths in the KMC for the 100-year and A1FI scenarios

vulnerability index of 1. Inundation depth below 0.25 m is assigned a vulnerability index of 0 because people in flood-prone areas have learned to adapt to the recurrence of such flooding during the monsoons. The increase in risk caused by variability is captured by using the standard deviation of the percentage of area flooded to weight the vulnerability index. The cumulative flood vulnerability index of a ward is then computed as the weighted sum of the percentage area under different flood water depths for each consecutive day up to the 10th day of flooding. The vulnerability rankings of the top 10 wards (wards 76, 105, 62, 77, 51, 137, 52, 134, 73, and 87) in the KMC are shown in Fig. 4.[14]

Flood vulnerability can be accentuated by the nature of the land use as well as the socio-economic characteristic of the population. To examine these aspects, the wards are ranked by five socio-economic characteristics (population density, percentage slum population, percentage illiterate, percentage unemployed, and low road density) and by two land use characteristics (number of highly polluting industries and low percentage of open land area). The top 10 flood vulnerable wards are examined to see whether they are also in the top 20 % of wards based on land use and socio-economic vulnerability. The wards found to have added vulnerability based on these criteria are the following:

Ward 51: Number of highly polluting Industries
Ward 52: Population density
Ward 73: Low percentage open land area
Ward 76: Low percentage open land area
Ward 77: Low percentage open land area, population density, and percentage unemployed
Ward 87: Number of highly polluting Industries
Ward 105: Percentage unemployed
Ward 134: Population density, percentage slum population, percentage illiterate, and percentage unemployed
Ward 137: Percentage slum population, percentage illiterate, percentage unemployed, and low road density

In sum, nine of the top ten identified flood vulnerable wards are also found to be vulnerable due to either land use or social vulnerability or both.

4.3 Sub-ward level analysis

Even in a ward with very high vulnerability, not all areas in the ward may be equally vulnerable. To capture such details, in Fig. 5 the spatially distributed Geographical Information System (GIS) layers of flood depth and duration are used on a scale of 1:5000, ignoring artificial administrative boundaries imposed by the wards. This exercise helps in identifying the actual pockets of vulnerable areas in the whole KMC, especially in the eastern parts, which are generally found to be more vulnerable.

It should be noted that land subsidence in the KMA/KMC is not included in the present analysis because of inherent uncertainties about future changes and the paucity of reliable forecast data for the KMA/KMC area. However, a recent study shows that with an estimated land subsidence of 0.5 m, the damage caused by water inundation in the KMA by 2070 may be

[14] A ranking of vulnerable wards was also done with respect to percentage of area flooded without assigning any vulnerability index by flooding depth. The results from both procedures resulted in similar findings for the ten most vulnerable wards.

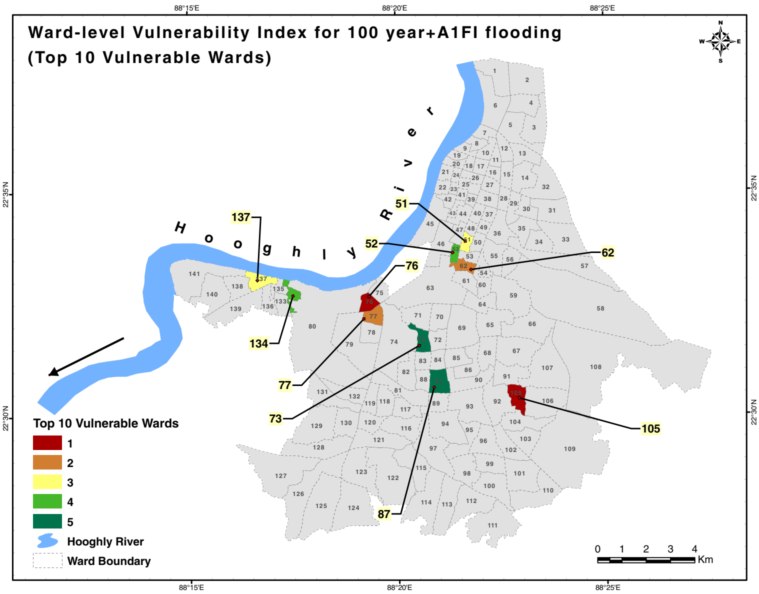


Fig. 4 Ward-level vulnerability index for 100 year + A1FI flooding (10 most vulnerable wards)

quite devastating (Hanson et al. 2011). Hence, our present study concludes with a cautionary note that land subsidence may further exacerbate the flooding caused by climate change effects.

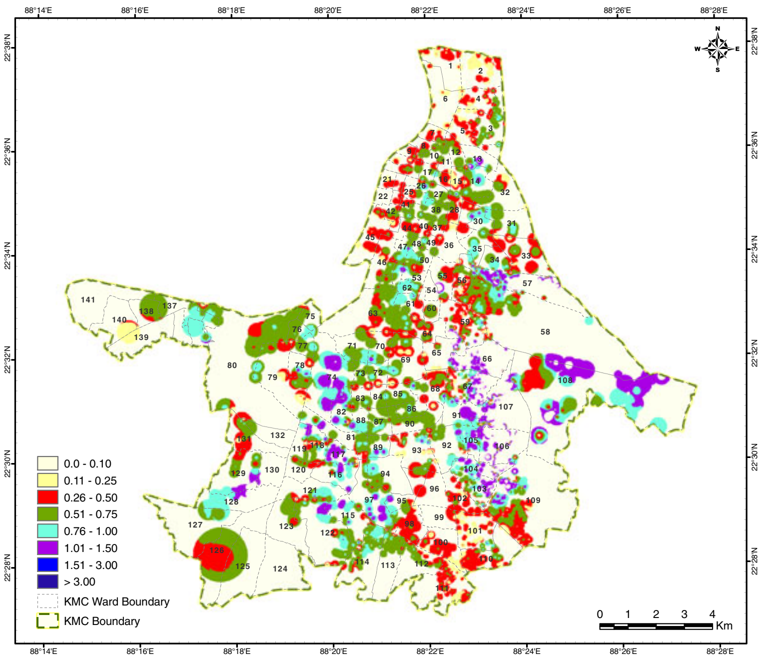


Fig. 5 KMC sub-ward vulnerability

5 Adaptation strategy

Modest flooding during monsoons at high tide in the Hooghly River is a recurring phenomenon in Kolkata. The local population has learned to adapt by developing a number of coping strategies for facing such periodic episodes of flooding. However, more intense rainfall, riverine flooding, sea level rise, and coastal storm surges in a changing climate could lead to widespread and severe flooding and bring the city to a standstill for several days.

Undeniably, a major cause of periodic flooding in Kolkata during the rainy season is the "Adaptation Deficit" the city faces at present for coping with such events. Major adaptation deficits in Kolkata currently include:

a. *Deficit in sewer network and treatment infrastructure:* Our analysis has identified areas in the KMC that have inadequate drainage and sewer infrastructure (such as wards 76, 105, 62, 77, 51, 137, 52, 134, 73, and 87) and some other localities in the KMC (such as wards 63 and 74) that have either remained vulnerable due to their topography or become more vulnerable due to development activities in recent times and inadequate maintenance of infrastructure. At present, these wards are facing the greatest adaptation deficit.

   In many places in the KMC, the capacity of the sewer systems has not kept pace with changes in population as the city has evolved. The added wards from the municipalities of South Suburban, Garden Reach, and Jadavpur suffered from inadequate sewer networks and treatment infrastructure before their inclusion in the KMC. Even after becoming part of the KMC, not enough investments were made in these areas to make up for the earlier shortfalls. Since the 1970s, the northward and southward expansion of Kolkata has slowed and the main growth has been toward the east. This has led to shrinkage of the wetlands located in the east, which may worsen the incidence of flooding in the future.
b. *Deficit in drainage infrastructure:* The major issues with the drainage system in the KMC are (i) almost all the major pumping stations operate at much less than their rated capacity due to inadequate maintenance and renovation of equipment and buildings; and (ii) the hydraulic capacity of the outfall canal system has been reduced due to siltation and deposition of solid waste.[15]
c. *Deficit in financial resources and institutional capacity:* A major reason for inadequate maintenance and renovation of the sewer/drainage systems and other infrastructure in the KMC is inadequate availability of resources. User charges for municipal services meet only a fraction of the cost involved and this is true even for the service charge recovery from institutional, commercial, and industrial users. The lack of a market-based approach in operations in the KMC has led to a consequent decrease in efficiency of utilization of both physical and human resources. There is also little private sector participation in improving day-to-day functioning. Many of the multiple government agencies responsible for maintaining the system are not under the direct administrative jurisdiction of the KMC, which in turn causes coordination problems leading to operational inefficiencies.

In addition, localized land-use, socio-economic, and environmental problems can aggravate the impact of flooding.

Investment in capital-intensive infrastructure should include (i) de-siltation of the main sewer in both the town and the suburban systems to increase hydraulic capacity and minimize flooding in the core area of the KMC; (ii) construction of additional main sewers in both the town and the suburban systems; (iii) extension of sewer and drainage facilities in

[15] There has been no regular maintenance. The dry weather flow canal was last maintained in 1999 and the storm weather flow canal was last maintained in 2003–04.

the Cossipore-Chitpur area (Borough I) and the areas that were added to the KMC limits in 1984 (Boroughs XI to XV); (iv) construction of deep sump pumps and/or rehabilitation of pumps as well as changes to shape the existing sewer (gradation) to improve the hydraulics of the major sewer approaching the major pumping stations and to increase the flow velocities in the sewer during flood conditions; (v) overall improvement in the storm water drainage system from the KMC core leading to the Kulti River; and (vi) renovation and rehabilitation of the outfall canal system.

De-siltation of the main sewer in both the town and suburban systems, for example, is critical to increase hydraulic capacity and minimize flooding in the core area of the KMC. The results from our SWMM show the changes in inundation under various flood scenarios between current conditions (30 % silting) and an Adaptation Scenario (0 % silting); these are shown in Fig. 6. The findings indicate that this simple investment could reduce the area affected by flooding by 4 % and the population affected by flooding by at least 5 %.

6 Conclusion

Urban flooding is the most critical climate-related hazard in Kolkata. It is a recurring phenomenon the city faces every year during the monsoon period. High intensity rainfall synchronized with high tide in the Hooghly River has almost always resulted in water-logging in Kolkata. Climate change is likely to intensify this problem through a combination of more intense local precipitation, riverine flooding in the Hooghly, and coastal storm surges.

In this paper, the hydrological and hydraulic impacts resulting from increased precipitation in a changing climate by 2050 were studied for Kolkata for two emission scenarios: A1FI and B1 for intense precipitation events. The estimates indicate that with a 100-year return period under the A1FI scenario, 30 % of the KMA area will witness flooding in excess of 0.25 m, affecting 15 % of the population. For the KMC area, it will affect 41 % of the area, and impact 47 % of the population. Projection of location-specific inundation depth and duration were used to address the spatial vulnerability of the KMC, the more urbanized heart of the city, to flooding. The ten most vulnerable wards in the KMC are wards 76, 105, 62, 77, 51, 137, 52, 134, 73, and 87. In addition, high-resolution GIS data on flood depth and duration were used to identify pockets of vulnerable areas within wards.

A major cause of periodic flooding in Kolkata during the rainy season is the deficit in sewer networks and drainage infrastructure. In many places in the older KMC, the hydraulic capacity of the silted main sewer systems is inadequate for drainage during the rainy season. De-siltation of the main sewer, both in the town and suburban systems, is critical to increase the hydraulic capacity and minimize flooding in the core area of the KMC. The results from the SWMM presented in this paper show that the changes in inundation under various flood scenarios between current conditions (30 % silting) and an Adaptation Scenario (0 % silting) could reduce the area affected by flooding by 4 % and the population affected by flooding by at least 5 %.

The current development plans for Kolkata are only up to 2025 and do not account for the possible long-term effects of climate change or any adaptation that may be needed to cope with the problems arising due to climate change over time. The projects currently being implemented or in the pipeline in the KMC were selected using cost–benefit analysis based on impact estimates from current weather-related data. The impacts from climate change were not included in such analysis. However,

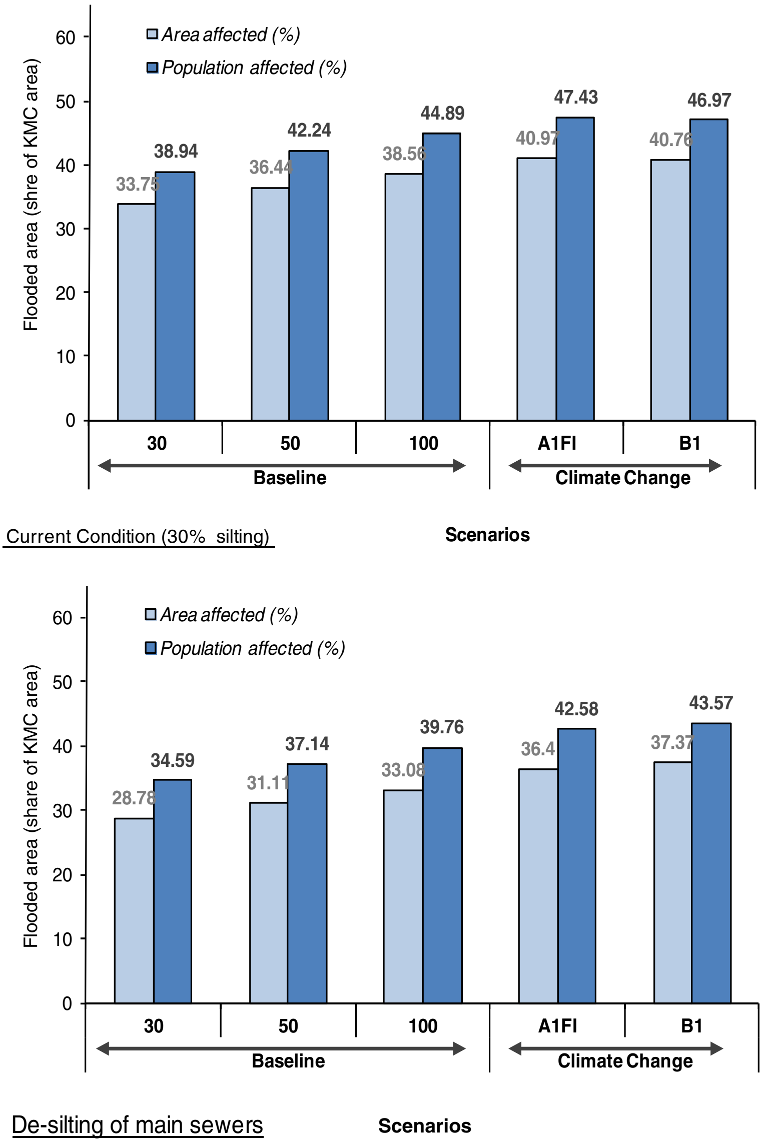


Fig. 6 Area and population affected by flooding without and with de-silting of main sewers

the likely increased precipitation intensity and sea level rise because of climate change may worsen drainage in Kolkata, causing expansion of the waterlogged areas and longer duration of annual flooding events. Due to the increased flooding and damage caused by climate change, it is likely that the use of cost–benefit analysis using a net present value approach that takes into account climate change effects will increase the viability of many projects not found viable earlier with only current weather data. Hence, there is a need for making the effects of climate an integral part of all future planning for adaptation in Kolkata.

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