Adequacy assessment of an urban drainage system considering future land use and climate change scenario
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ABSTRACT

Dhaka, the capital of Bangladesh, has been experiencing severe water-logging and urban flooding in the last few decades. In this paper, we estimate the peak storm runoff of Hatirjheel-Begunbari canal – the largest drainage system of the city – under different operational, land use and climate scenarios (2013, 2025 and 2040). Our method includes digital elevation model (DEM) reconditioning, watershed delineation, and development of future land use scenario. We apply HEC-RAS to check the adequacy of Begunbari canal cross-sections to carry peak runoff for the scenarios considered here. The Hatirjheel-Begunbari system is found to drain stormwater from ~25% of the city. Within the system, built-up areas are increasing linearly by 0.8 km²/year, whereas water body and wetlands are decreasing exponentially, which might increase the runoff coefficient by 11% in 2040 relative to 2013. Climate-induced change in rainfall intensity along with land-use change show three times higher runoff in 2040 than in 2013. Around 58% of canal cross-sections appear to be overflown at both banks while carrying a 5-year return period peak runoff under the 2013 scenario. For future scenarios, all sections seem to cause an overflow, which is alarming.

Key words | catchment delineation, climate change, Hatirjheel-Begunbari canal, land use, stormwater runoff, waterlogging

HIGHLIGHTS

- Digital elevation model (DEM) reconditioning and catchment delineation of Hatirjheel-Begunbari (HB) – the largest drainage system of Dhaka.
- Estimation of recent and future runoff intensity considering future precipitation variability due to climate change.
- Development of future land use scenario.
- Estimation of peak stormwater runoff and capacity assessment of Begunbari canal using HEC-RAS.
 Dhaka, the capital city of Bangladesh, is one of the top megacities in the world. The current population of Dhaka city is over 8.5 million. For the last couple of decades, central Dhaka has been experiencing severe waterlogging by the stormwater runoff, while the periphery of the city is being inundated by backwater flow from surrounding rivers (Barua & Van Ast 2011). This situation is more aggravated during the monsoon (May to September) when nearly 75% of the annual average rainfall of 2,200–2,800 millimeters occurs (Ahmed & Rahman 2013). Even a little rain inundates certain areas of the city for several days and causes serious problems including disruption of traffic movement and normal life, damage to structures and infrastructure, and destruction of vegetation and aquatic habitats (Alam & Rabbani 2007; Barua & Van Ast 2011; Mowla & Islam 2013). This stormwater becomes polluted as it mixes with solid waste, clinical waste, silt, contaminants, and domestic wastes and turns into a health hazard. The stagnant stormwater leads to the increase of waterborne diseases (e.g. diarrhea, malaria, dengue), respiratory problems, and eye and skin diseases by creating the breeding sites for disease vectors (Mowla & Islam 2013). For example, in 2019, the city struggled with the worst outbreak of dengue fever, a mosquito-borne viral infection, affecting nearly 60,000 people (Mone et al. 2019).

The cities problems with water logging and urban flooding problem are created as the existing storm sewers are not fully operational owing to the occurrence of natural siltation, blockage by leaves and wastes including household and non-perishable plastic wastes and lack of proper maintenance (Alom & Khan 2014). In addition, the internal and peripheral canals of Dhaka, an important part of the overall drainage system of the city, are being illegally encroached (Ishtiaque et al. 2015). Thus, assessment of the capacity of the existing drainage system of Dhaka, especially the Hatirjheel-Begunbari (HB) canal drainage system – the largest stormwater drainage system - has become imperative for better understanding and improving the drainage capacity of the city. However, few studies have been conducted so far to assess the capacity of different components of the HB system (the HB system is described in detail in the method section). For example, Malik & Matin 2016 investigated the adequacy of the Storm Diversion System (SDS) of Hatirjheel lake, while Matin et al. 2016 assessed the capacity of Hatirjheel lake only to carry the storm runoff for different storm events without considering its after-effect on Begunbari canal. In contrast, Matin et al. (2010) and BRTC (2013) assessed the adequacy of Begunbari canal along with all canals connecting to Balu river without considering Hatirjheel. A recent study (Ahmad et al. 2018) modeled the catchment of Begunbari canal using GeoSWMM and suggested the establishment of an embankment along the Balu river with a pump regulation at the canal outlet to prevent backwater flow from Balu River to Begunbari canal. To our knowledge, no study assessed the capacity of Begunbari canal considering the contribution of the Hatirjheel lake flow to it. In addition, none of the studies considered future stormwater runoff due to climate and land-use change.

Changing landscape is one of the anthropogenic stressors for the variation in the future stormwater runoff of a city (Basnayaka 2012; Huong & Pathirana 2013; Zhou et al.
The landscape of Dhaka has been changing rapidly over time due to progressive and unplanned urbanization associated with high population growth and inward migration from rural areas (Dewan & Corner 2014). Several studies have estimated the overall change in land covers in Dhaka city and peripheral areas (Dewan & Yamaguchi 2009; Ahmed & Bramley 2015; Hassan & Southworth 2017). Using the Random Forest image classification approach, Hassan & Southworth (2017) estimated a 980% increase in built-up area from 1972 to 2015. This rapid urbanization ultimately leads to canal encroachment by unauthorized landfilling, illegal construction and expansion of slums over canals, and solid waste dumping (Ishtiaque et al. 2015). As a result, the amount of wetland and water body is reducing day by day. The total area of wetland and water bodies in Dhaka Metropolitan (DMP) area decreased significantly by 59 and 65% respectively between 1978 and 2009 (Mahmud et al. 2011). A similar study by Sultana et al. (2009) reported a 50% reduction in wetland from 1968 to 2001, while Das & Islam (2010) reported a 45% reduction in wetland in the west part of the city from 1989 to 2007. Around 34% area of 13 natural canals in and around Dhaka had already been encroached upon by land developers, private individuals and others (Das & Islam 2010). According to a report of the World Bank project on climate and disaster resilience (World Bank 2015), 17 out of 43 natural canals of the city no longer exist. This decrease of wetlands and water bodies and the expansion of built-up area are collapsing natural drainage systems of the city by reducing the pervious land (Sultana et al. 2009; Mahmud et al. 2011; Ishtiaque et al. 2015). The amount of impervious land is expected to increase in future years (Islam & Ahmed 2011), which might cause an increase in surface runoff in the future years. To our knowledge, no study has considered the effect of land cover change on future stormwater flow while assessing the capacity of the drainage system of Dhaka.

In addition to land use, climate change is another influential challenge for present and future stormwater management strategies (Willems 2013; Skougaard Kaspersen et al. 2017; Wu et al. 2017; Arnone et al. 2018; Zhou et al. 2019). Climate change is likely to affect the storm runoff and pose threats to the drainage system of a city by changing the patterns of precipitation extremes (Karamouz et al. 2011; Yazdanfar & Sharma 2015; Mahmoud & Gan 2018). According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), Bangladesh will experience a likely 5–6% increase in rainfall causing frequent massive and prolonged floods by 2030 (IPCC 2007). The average annual precipitation of Bangladesh from 1985 to 2004 was 4.26% higher compared to the average from 1953 to 1972 (Rajib et al. 2011). The Intensity-duration-frequency (IDF) relationship of Dhaka city developed using historical and projected precipitation variability (Afrin et al. 2015) also indicates a likely increase in maximum rainfall intensity in future years. Similar to land-use impact, the effect of climate-exerted changes on future runoff has not been considered in the drainage capacity assessment studies of Dhaka mentioned above. In this context, assessment of stormwater flow under different land-use and climatic scenarios, and check the adequacy of existing drainage system has become an urgent area of research to help reduce present and future waterlogging and flooding.

In this paper, we estimate the future stormwater runoff of the combined Hatirjheel Begunbari drainage system considering future land-use scenarios, and future precipitation variability due to climate change in addition to the 2013 runoff of the system. We then check the adequacy of the existing geometry of the Begunbari canal to carry the future and 2013 stormwater runoff for different operating conditions of Hatirjheel Lake. A basic diagram showing the workflow of this paper is presented in Figure S1 in Supplementary Materials.

**METHODS**

**Hatirjheel-Begunbari (HB) canal drainage system**

HB drainage system is the largest and most important stormwater drainage system of Dhaka. This system drains stormwater from both the eastern and western side (central Dhaka) of a flood control embankment constructed along ‘Pragati Sarani’ (Figure 1 and Figure S2a). As a part of the HB drainage system, Hatirjheel (the largest surface water body within Dhaka) serves very important hydrologic functions of draining and detaining stormwater from a large area of central Dhaka where stormwater flow is predominantly governed by previously established roadside
storm sewer network (Figure 1). Two regulatory gates (Figure S2) along with a pumped system located at the connection between Hatirjheel and Begunbari canal regulate the flow from Hatirjheel to Begunbari, and also prevent the back-water flow from Begunbari canal. Although this system is expected to carry stormwater runoff only during monsoon, it carries sewage flow in the dry period, usually known as dry weather flow, due to illegal connection of sewage lines to the storm sewer network of Hatirjheel. This dry weather flow is diverted through eleven special sewage diversion structures (SSDSs) constructed at major storm sewer outfall locations around Hatirjheel. All SSDSs except 6 and 11 are connected to a peripheral ‘diversion sewer’ network, which discharges into Hatirjheel. SSDS 6 and 11 discharge directly downstream of Hatirjheel gate into the Begunbari canal. Thus, Hatirjheel plays an important role in the flow of Begunbari canal in both dry and rainy season. In addition to the contribution from Hatirjheel, Begunbari canal carries storm runoff from the eastern side of Progati Sarani and finally discharges to the Balu River (Figure 1). Moreover, three tributary canals – ‘Sutivola’ and ‘Gozaria’ from the north and ‘Nasirabad-Nandipara’ from the south – discharge runoff into Begunbari canal.

Data collection and processing

A drainage map of Dhaka city and information regarding the existing storm sewer network (Figure 1) along with the direction of flow and outlets were collected from Dhaka Water Supply and Sewerage Authority (DWASA). Data on the existing stream network and the most updated land-use map (2013) of the city were collected from Rajdhani Unnayan Kartipakkha (RAJUK). For historical land-use maps, Landsat satellite images for the years 1989, 1999, and 2009 were downloaded from the official website of the United States Geological Survey (USGS). The study area is located in the Landsat path 137 and row 44. The pixel size of the images are 30 x 30 m. The Universal Transverse Mercator (UTM) projection (within Zone 46 North) and the World Geodetic System (WGS)-1984 datum were applied to process the images. For the catchment delineation of the HB drainage system, we retrieved the 30 m resolution Digital Elevation Model (DEM) of Dhaka (Figure 2(a)) from the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) instrument of the Terra satellite. For the estimation of runoff, we used runoff coefficient data for different land covers from Lindeburg (1994). Finally, to assess the existing capacity of the system, geometric data of Begunbari canal and SSDSs were collected from a topographic survey conducted by the BRTC-BUET Team (BRTC 2015).

Watershed delineation

For the watershed delineation, we used the Arc Hydro Terrain Preprocessing tool, which requires DEM of the area as the input vector. However, a comparison between the DEM (Figure 2(a)) and existing water bodies (Figure 1) indicates that the 30 m resolution DEM of the study area was not fine enough to reflect water body, an important feature within the flood plain affecting hydrology. To incorporate this topographic feature, we reconditioned (Cubanski 2012) the existing DEM to adjust the elevation data based on stream network assuming that the stream network data are more reliable than the DEM data. In addition, we incorporated the embankment along Progati Sarani and the built-in storm sewer network in our DEM reconditioning analysis since stormwater flow in the western catchments is influenced by the existing storm sewer network, embankment,
and topography. Using this new conditioned DEM (Figure 2(b)) and considering the endpoint of the Begunbari canal before reaching Balu River as the outlet, we performed terrain analysis to generate data on flow direction, longest flow path (the path within a catchment through which water travels from the farthest point to the outlet), watershed boundaries and catchment areas. The resulting subcatchments from the terrain analysis are further grouped into seven major catchments based on the stream network and labeled by the name of the contributing stream.

Calculation of time of concentration

Time of concentration (Tc) for each catchment of the drainage system was calculated employing the Natural Resources Conservation Service (NRCS) velocity method (NRCS 1972; Fang et al. 2007). This method assumes that time of concentration is the sum of travel times for the various consecutive flow segments along the hydraulically most distant flow path including an initial time (Ti), overland flow time (To), travel time through storm sewer (Tn), and travel time through open channel (Tv). The longest flow path (L) used in this approach was derived from the watershed delineation. For each segment of the flow path, travel time was calculated as the ratio of flow length to flow velocity. Flow velocities were different depending on types of flow. In this study, we assumed an overland flow velocity of 0.3 m/s and velocity through canal of 0.8 m/s following previous studies (Matin et al. 2010; BRTC 2013). To determine the velocity through storm sewers, we used Manning’s equation of pipe flow considering the pipe is full with a diameter of 6.1 feet as per data collected from DWASA, roughness coefficient of 0.022 (Chow 1959) and longitudinal slope of 0.0004 ft/ft.

Land-use analysis and runoff coefficient calculation

For land-use analysis, we used the historical satellite images (1989, 1999, and 2009) with respect to their spectral and spatial profiles. We used a chosen color composite (RGB = 432) to digitize polygons around each training site for similar land cover. Then a unique identifier was assigned to each known land cover type followed by statistical characterizations of each land cover class. This analysis employs a maximum likelihood classification method, which calculates the probability of the cell belonging to that class given its attribute values for each class. The classified land cover images were then generalized and reclassified into three broad land cover types based on Anderson et al. (1976): (a) built-up area, (b) open and cultivable land, and (c) water body and wetland. For the 2013 land use map, we also used the above three land cover types for consistency in analysis. In addition, we generated the future land-use scenario of 2025 and 2040 by analyzing the trend of the generalized land-use maps of 1989, 1999, 2009 and 2013. We considered the runoff coefficient of 0.6, 0.25 and 1 for built-up areas, open and cultivable land, and wetland and water body respectively as suggested by Matin et al. (2010). Finally, using the summary of land area and associated runoff coefficient for each land cover type, we estimated the area-weighted runoff coefficient for the 2013 and proposed (2025 and 2040) land-use scenarios.

Peak runoff estimation

We estimated the maximum rainfall intensity for different return periods by employing the estimated time of concentration (Tc) into the IDF curves developed by Afrin et al. (2015). For each return period, we determined two sets of rainfall intensity: 2013 and future. For the 2013 scenario, we used the IDF curve (Afrin et al. 2015) developed based on the historical data; whereas for the future, we applied the IDF curve from the same study but developed using PRECIS model projected future precipitation data up to 2040 from Rajib et al. (2011). Finally, we estimated both
2013 and future peak runoff of each catchment of the HB system using the rational method (Kuichling 1889), the most commonly used method of determining peak runoff. The Rational Formula is expressed as 
\[ Q = C 	imes I 	imes A \]
where \( Q \) is peak runoff, \( C \) is runoff coefficient, \( I \) is rainfall intensity, and \( A \) is catchment area. Note that estimated \( C \) is different for three different time scenarios (2013, 2025 and 2040), however, calculated \( I \) is different between 2013 and future (2025/2040) case scenarios. The rational method performs well for the natural drainage system and is traditionally used to design storm sewers, channels, and other stormwater structures (Needhidasan & Nallanathel 2013). As the flow through the HB drainage system is governed by both storm sewer and natural drainage, we used the rational model rather than conventional hydrologic models. Malik & Matin (2016) and Matin et al. (2016) also found the rational formula effective for the calculation of peak discharge of stormwater drainage system of Dhaka.

**Drainage capacity assessment under different scenarios**

To assess the capacity of the HB system to carry the peak flow, we conducted hydraulic analysis using the HEC-RAS model considering uniform flow. The model input consists of runoff at various canal sections and diversion points, geometry of canal sections (cross-sections), and estimates of canal roughness. We employed the collected geometry information of 19 stations of Begunbari canal along with stations where the three eastern tributaries (Sutivola, Nasiranad-Nandipara and Gozaria canals) merge into the canal. The flow entered at the upstream end of a reach was assumed to be constant until another flow was encountered with the same reach. Since Hatirjheel works as a regulatory structure and the two regulator gates (Figure S2) maintained the flow from Hatirjheel to Begunbari canal, we considered two extreme scenarios based on the operational conditions of these gates: (a) both gates were open and (b) both gates were closed. The details of these two scenarios along with the contributing catchments to the inflow of Begunbari canal are summarized in Table S1. For both operating scenarios, we modeled water depths at each of the 19 stations of Begunbari canal for both 2013 and future stormwater runoff using HEC-RAS. By comparing model predicted water depth for the 2013 scenario with the observed water depth at Begunbari canal, we validated our overall modeled results. The observed water depth was reported by Ahammad et al. (2018) and was measured at the upstream section of Begunbari canal in 2016 by the Institute of Water Modeling (IWM) as part of a project by the Bangladesh Water Development Board. Finally, based on the predicted 2013 and future water depths, we assessed the adequacy of the existing canal sections to carry the 2013 and future flow.

**RESULTS AND DISCUSSION**

**Catchment area (A)**

Figure 2 shows the DEM of Dhaka. In general, elevation of the eastern part of Dhaka is lower compared to that of the western part. Figure 2(b) represents the reconditioned DEM of the city after adjusting it for the elevation of the stream network, storm sewer network, and flood protection structure along Pragati Sarani. The reconditioned DEM seems to reflect the topographic features of the study area better than the unconditioned DEM (Figure 2(a)), which allows us to delineate a more representative watershed boundary for the drainage system. The resulting watershed boundary and the grouped catchments of the HB drainage systems are shown in Figure 3. This drainage system is carrying stormwater from a 70.5 km² area, which is around one-fourth of the entire Dhaka city. The individual area and relative percentage of each catchment are also reported in Figure 3. Hatirjheel lake has the largest catchment area (19 km²) of the western catchments, whereas, on the eastern side, Nasirabad-Nandipara canal’s catchment area is the highest (22 km²). Eastern catchments of HB systems (e.g. ‘Sutivola’, ‘Gozaria’, and ‘Nasirabad-Nandipara’) directly contribute to Begunbari canal flow; in contrast, western catchments (e.g. ‘Hatirjheel’ and ‘Gulshan-Banani’) primarily contribute to Hatirjheel flow, except for SSDS 6 and SSDS 11 catchments. The flow from SSDS 6 and SSDS11 discharges directly into Begunbari canal beyond Hatirjheel gate. Hence, for the ease of calculating the inflow to Begunbari canal, we treat the catchments of SSDS 6 and SSDS 11 separately from the ‘Hatirjheel’ and ‘Gulshan-Banani’ lake.
catchments and present them as separate groups (Figure 3).
Overall, nearly 61% of the total HB watershed directly contributes to the inflow of Begunbari canal and stormwater from the rest of the watershed routes towards Hatirjheel lake. The calculated catchment area of Begunbari canal (summation of eastern catchments, and SSDS 6 and 11) is 43.2 km² which is comparable to the catchment area of 47.67 km² found in a previous study (Ahammad et al. 2018), where a hydrologic model was applied for catchment delineation.

Longest flow path (L) and time of concentration (Tc)

Another important outcome of watershed delineation is the longest flow path (L). The flow path of the HB drainage system consists of different types of flow including overland flow, open channel flow, and flow through storm sewer. The length of these flows for each catchment is summarized in Table S2. Hatirjheel lake and Nasirabad-Nandipara canal have all three types of flow in their flow-path. Although the catchment area of Hatirjheel is smaller than Nasirabad-Nandipara, Hatirjheel has the largest flow path of 9.7 km owing to its having the longest storm sewer path. According to this table, the flow path of Hatirjheel lake includes around 1.5 km of overland flow, 3.89 km of storm sewer flow coming through SSDS 1, and 4.32 km of open channel flow. In contrast, the catchment of SSDS 11 has the shortest flow path. Using these flow paths, time of concentrations for different catchments was calculated (Table S3). An initial time of 20 min is considered for all catchments. Time of concentration of different catchments varies from 1 hour to 5.2 hours. Like flow path length, time of concentration is highest for Hatirjheel and lowest for SSDS 11.

Runoff coefficient (C) for 2013 and future land-use scenario

As shown in Figure 4, satellite images of 1989, 1999, 2009 and the land-use map of 2013 are digitized and classified into the three broad land-use categories: water body and wetland, open and cultivated, and built-up area. This figure demonstrates that built-up area is gradually increasing over the decades, whereas wet-land and water bodies, and open

Figure 3 | Watershed of Hatirjheel-Begunbari canal drainage system showing the total area and relative percentage of the grouped catchments. The longest flow paths through canals and storm sewer network for each of these catchments are also shown. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2020.369.
and cultivated land are decreasing. More specifically, built-up area increased by 96% from 1989 to 2009 within the HB watershed boundary. For water body and wetlands, a considerable decrease (60% in last 20 years) is observed as this land-use class acted as the donor to both built-up areas, and open and cultivated land. Compared to the change of the other two land-use classes, decrease in open and cultivated land (29%) is not substantial, possibly due to the fact that their conversion into built-up area was balanced by their growth from the encroachment of water body and wetlands.

We further plot the percentage of area under each land use category against the corresponding year (Figure 5). According to this figure, change in built-up area over time follows a linear trend. The best-fit equation gives a correlation coefficient of 1 with an 8.8 km² linear increase of built-up area per 10 years. Using this linear relationship, we estimate the built-up area for 2025 and 2040 as 71.6% and 90.4% of the entire HB watershed respectively. Water body and wetlands seem to follow an exponentially decreasing trend from 1989 to 2013 (Figure 5). We calculate the percentage of their area in 2025 and 2040 following this exponential relationship. Finally, we estimate the percentage of open and cultivated land by subtracting the percentages of the other two land-use classes in 2025 and 2040 from 100. For instance, in 2040 the estimated percentage area of water body and wetland, open and cultivated, and built-up area are 3.6%, 6%, and 90.4% respectively. Using the percentages of the three land-use categories and their respective runoff coefficients, the area-weighted runoff coefficient of the study area for the years 2013, 2025 and 2040 are calculated as 0.53, 0.55 and 0.59 accordingly.

**Determination of maximum flow (Q)**

The 2013 and future maximum rainfall intensities of the seven major catchments of HB drainage system are estimated for different return periods. Rainfall intensities considering a 5-year return period suggest that maximum rainfall intensity would be around three times higher in future years than that of 2013 for all the catchments (Table S4), which is due to the likelihood of frequent occurrence of extreme rainfall events by climate change (Rajib et al. 2011). We then determine the 2013 as well as future peak stormwater runoff for the seven major catchments of the HB drainage system considering a constant catchment area (Table S4). Overall, ‘Nasirabad-Nandipara’ catchment has the largest contribution to the inflow of Begunbari canal followed by Hatirjheel lake and Sutivola canal. We observe higher contributions from eastern catchments (Sutivola, Nasiranad-Nandipara, and Gozaria) relative to western catchments to Begunbari canal flow.
For example, total peak runoff from the eastern catchments is 57% higher than the western catchments for the 2013 scenario. Note that the contribution of western catchments (except SSDS 6 and 11) to Begunbari flow depends on the operating condition of Hatirjheel (see Table S1). Among the two future runoff scenarios, the discharge in 2040 is higher for all catchments due to the higher runoff coefficient in 2040.

The longitudinal profile of the Begunbari canal along with the location of 19 stations with cross-sectional data are shown in Figure 6(a). Station 1 (6,363.855 m upstream from the outlet) is the most upstream, and station 19 (241.2447 m upstream from the outlet) represents the most downstream station. Additionally, stations 5, 16 and 17 are the immediate downstream stations where the ‘Sutivola’, ‘Nasirabad-Nandipara’ and ‘Gazaria’ canals merge into the Begunbari canal respectively (see Table S5). The peak 2013 and future storm runoffs for each of these 19 stations are then calculated from the estimated maximum runoff of the contributing catchments for both operating conditions of Hatirjheel (Table S5). The discharge data of Table S5 depict that Begunbari needs to carry successively higher runoff as it flows towards the Balu river due to the merging of eastern catchments. We also see a considerably high flow in Begunbari after station 16 even when both operating gates of Hatirjheel are closed (Scenario 1) due to the significant contribution of eastern catchments.

**Validation of modeled water depth and capacity assessment of Begunbari canal**

Using the cross-sections of 19 stations and associated modeled runoffs as inputs to HEC-RAS, we modeled the water depths at Begunbari canal for both operating scenarios of Hatirjheel lake. Since runoff data are not available at any segment of the Begunbari canal, in this study we validated our results by comparing the modeled water level with the measured water depth at Begunbari canal. At the upstream portion of Begunbari canal, the average modeled water depth, considering the 2013 estimate of a 5-year return period runoff, is 4.6 m, which is in between the range of measured water depths (1.77–4.77 m) (Ahammad et al. 2018). The model’s performance in capturing the 2013 condition highlights the model’s applicability in predicting future scenarios. The modeled water levels for the 2013 scenario with 5-year return period at some stations of Begunbari canal are shown in Figure 6(b). Station 1 (the most upstream cross-section) and station 17 seem to accommodate the 2013 peak flow; however, other cross-sections presented in this figure do not seem to be adequate to retain the 5-year return period peak runoff of 2013. The adequacy of Begunbari canal at each of 19 cross-sections against a 5-year return period storm event is summarized in Table 1. Even under the 2013 flow scenario with no contribution from Hatirjheel lake (gates are closed), 42% of...
the cross-sections seem to be flooded at least at one side of the reach. Most of these inadequate sections are located downstream of station 5 (4,789 m upstream) where Sutivola canal discharges into the Begunbari canal. None of the cross-sections seems adequate if the contribution of Hatirjheel runoff is added to the Begunbari canal even for the 2013 stormwater flow. These findings are in line with the usual scenario of Begunbari canal and adjacent areas during monsoon (May to September). The condition will be more critical for the higher runoff in future scenarios (Table 1) and will create the risk for frequent flooding in both banks of Begunbari canal in future years.

**CONCLUSIONS**

This study discusses the drainage capacity of Hatirjheel-Begunbari canal drainage system, which is one of the most complex drainage systems of Dhaka as it collects stormwater from both western and eastern parts of the city and incorporates different types of flow path ranging from storm sewer to open channel in their routes. To our knowledge, this is the first-ever study to assess the capacity of this system by integrating different aspects including contributions from the western part of the city through Hatirjheel under certain operating conditions, and influence of land use and climate change on stormwater runoff. The
findings of the study suggest that future stormwater runoff is likely to increase significantly. The land-use trend investigation shows that built-up areas, within the HB watershed boundary, have been increasing linearly over the last three decades. Consequently, wetland and water body, and open and cultivated lands have been decreasing. Thus, overall land cover is changing and so is the runoff coefficient. Only the change in land use types shows an 11% increase in runoff in 2040 relative to 2013. When climate change impact is added, this study indicates around three times higher peak runoff in 2040 than that of the 2013 scenario, given that land use and precipitation will continue to follow the observed trend until 2040.

The adequacy analysis using 1D HEC-RAS model indicates that some of the downstream sections of the Begunbari canal are inadequate to carry a 5-year return period peak runoff for the 2013 precipitation scenario even without the contribution from the western catchments. These sections are mostly located after the eastern catchments (e.g. Sutivola and Nasirabad canal) merge

Table 1  | Capacity of different cross-sections of Begunbari canal for a rainfall event of 5-year return period
| Station distance from Downstream end (m) | 2013 Scenario 1 | Scenario 2 | 2025 Scenario 1 | Scenario 2 | 2040 Scenario 1 | Scenario 2 |
|------------------------------------------|----------------|------------|----------------|------------|----------------|-----------|
| 6364                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 5886                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 5348                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 4908                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 4789                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 4174                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 4096                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 4025                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 3961                                     | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 3911                                     | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 3205                                     | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 2832                                     | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 2767                                     | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 2653                                     | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 2273                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 2044                                     | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 1814                                     | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 941                                      | Overflow       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |
| 241                                      | Adequate       | Overflow   | Overflow       | Overflow   | Overflow       | Overflow   |

Note: Green color is used to highlight the adequate sections. Yellow color is for the sections with overflow at one of the banks, while pink color is for the stations with overflow at both banks.
into Begunbari canal. All the sections appear inadequate if we add Hatirjheel flow (including Gulshan-Banani catchment) to Begunbari flow (e.g. ‘gates are open’ scenario). Note that the monsoon backwater flow into the canal from Balu River was not considered in the model due to lack of bathymetric and discharge data of Balu river. However, the inadequacy of existing cross-sections of Begunbari even without considering backwater flow suggests that gravity drainage is not capable of draining water from Begunbari to Balu river without an overflow. Our results agree with the study by Ahammad et al. (2018), which emphasized the necessity of pump drainage to reduce backwater flow and consequent overflow in the bank of Begunbari canal. Unless we take any effective measures about this situation, the three times higher storm flow in future (2040) will probably result in significant overflow at both banks of the canal and cause frequent flooding in the adjacent areas.

The results from this study suggest that change in land-use and climate-induced change in extreme rainfall events might intensify the risk of severe waterlogging and flood vulnerability in future years in Dhaka. The goal of this paper was to assess whether the existing cross-section of Begunbari canal, an important part of the drainage system of the city, overflows under maximum stormwater runoff. The estimation of the magnitude of overflow at the banks caused by this overflow was out of the scope of this paper. Future study is recommended to determine the depth of overflowed water throughout the flood plain and develop flood inundation maps under the considered scenarios. Backwater flow effects can also be considered in future upon data availability. Overall, this study has made substantial attempts to enhance our understanding of how this HB system is working, and how important this system is in draining stormwater from a major part of the capital. Hence, the outcomes of this research will be useful for the policymakers to undertake development projects (e.g. pump drainage provision and excavation of specific segments of Begunbari) to enhance the performance of the HB system with the ultimate goal of improving the drainage situation of Dhaka city. In addition, this research will serve as a base for assessing the effectiveness of future development initiatives. This study also indicates the link of waterbody and marshy lands with stormwater drainage and management, and thus restates the importance of conserving water body and marshy lands. The results of this study can be helpful to the city planners while initiating appropriate plans to make Dhaka a more livable and planned city in the future. Thus, the current study makes several noteworthy contributions to the current literature by addressing various knowledge gaps and bridging several aspects of stormwater drainage of Dhaka aiming to reduce waterlogging problems faced by the city dwellers.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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