Simulation-based modeling of urban waterlogging in Khulna City
Showmitra Kumar Sarkar, Md. Atikur Rahman, Md. Esraz-Ul-Zannat and Md. Feroz Islam

ABSTRACT
Khulna City is extremely vulnerable to the effects of climate change. The city experiences frequent waterlogging during extreme rainfall events. This research prepared a drainage simulation model considering climate change issues for investigating the extent of waterlogging in the city. Watershed and precipitation were analyzed to examine the existing scenario of the study area. Finally, a Mike Urban-based hydrological simulation model was formulated to investigate the severity of waterlogging. As found by precipitation analysis, 180 mm, 346 mm, and 396 mm rainfall might occur for the 5-year, 50-year, and 100-year return period, respectively. This research identified that volume of overland flow might be affected by climate change-induced rainfall. According to the simulation, 62.52% of the study area was waterlogged with different inundation depths. It was found that traffic movements were severely disrupted and structures were hampered due to waterlogging. 45% paved, 77% brick soling, and 65% unpaved roads were inundated by different inundation levels. On the other hand, 61.1% of structures of the study area were affected by waterlogging. The findings of the research might help the concerned authority in decision-making, especially for the drainage and water-related issues, to solve the waterlogging.

Key words | coastal city, drainage density, GIS analysis, Mike Urban, simulation modeling, urban hydrology

ABBREVIATIONS
| BD | Bangladesh |
| BMD | Bangladesh Meteorological Department |
| BWDB | Bangladesh Water Development Board |
| DEM | Digital elevation model |
| FGDs | Focus group discussions |
| GIS | Geographic information system |
| KCC | Khulna City Corporation |
| KDA | Khulna Development Authority |
| KIs | Key informant interviews |

INTRODUCTION
Bangladesh (BD) is considered the world's most climate vulnerable country due to its setting as a vast low-lying land (Karim & Mimura 2008; The Asian Development Bank 2010; The World Bank 2011; USAID 2018). The adverse impacts of climate change are expected to be severe in BD and may lead to substantial economic loss (Mirza 2003). Major climate change phenomena (i.e., extreme rainfall and the delayed discharge caused by sea level rise) are chiefly responsible for frequent waterlogging in urban areas of BD (Alam & Rabbani 2007; Cazenave et al. 2014). The impacts of waterlogging result in traffic congestion and damage to urban infrastructures (i.e., buildings, roads...
Khulna City is one of the major coastal cities in Bangladesh and extremely vulnerable to climate change due to the influence of the tides of the Bay of Bengal (Ahmed & Ghosh 2010). It is also the third largest city as well as the industrial center of Bangladesh (World Bank 2000). According to the 2011 census, Khulna City Corporation (KCC) has an area of 50.61 square kilometers with a population of 663,342 and the density is 13,107 per square kilometer (Bangladesh Bureau of Statistics 2014). The city’s inhabitants face frequent waterlogging during the rainy season and extreme precipitation events make the situation worse (The Asian Development Bank 2010). In the past decades, Khulna City’s rain water used to drain out through the canals, and sometimes ponds were used to function as retention catchments for additional storm water. However, in recent years, waterlogging has become a severe problem for the city, especially during late monsoon, because of the unabated encroachment of perennial waterbodies and filling up of ponds for built-up areas due to rapid urbanization. In the southern part of KCC, more than 90% of households are affected by waterlogging and 38% of inhabitants experience short-term waterlogging frequently (Murtaza 2001). Annually, 1,808.5 mm (nearly 80% during the monsoon) rainfall is experienced by the city (Weatherbase 2018). The city dwellers are more vulnerable to waterlogging which results from a number of issues (i.e., unpredictable and intense rainfall, storm water stagnation, poor drainage capacity, and river water overflow). The KCC has spent USD 20 million over the last five years on the re-excavation of rivers and canals to improve the drainage system of KCC (The Daily Star 2017). However, waterlogging has remained a serious problem for the residents of the city. The methods of identifying affected areas and selecting priority projects by KCC have not yet been clarified, so it is not obvious which areas are actually affected by waterlogging. Spatial modeling of the drainage system has also not been studied and the impacts of waterlogging are not properly identified. As a result, KCC is spending huge amounts of government funds on implementing random projects but the condition of waterlogging remains the same.

In this study, we investigated the waterlogging scenario and identified the actual affected areas based on the Mike Urban simulation model. A simulation study showed the future scenario and found cost-effective solutions, discarding the necessity of implementing large-scale projects. This study also identified the possible impacts of waterlogging, which might help to set projects’ priorities. A raster-based drainage simulation model was formulated using climate change-induced rainfall events and existing physical conditions (i.e., land use, drainage network, road network, etc.). The model identified waterlogged areas and the gap in drainage capacity within KCC, which in turn helped identify the impacts of waterlogging on various infrastructures. The findings of the research will help KCC in effective decision-making for sites which require specific solutions. Incorporating the methods of this study with a drainage improvement plan for urban areas will add a new dimension and increase the efficiency of the plan. The objective of the study is to prepare a drainage simulation model for identifying waterlogged areas and to investigate the impacts of waterlogging considering existing drainage capacity.

DATA AND METHODS

Description of study area and materials

The south-west coastal region of Bangladesh (Figure 1) is vulnerable to the impacts of climate-induced disasters (i.e., intense rainfall, sea level rise, coastal inundation, erosion, cyclones, saline water intrusion, etc.) (Alam et al. 2016). The KCC is located in this zone (Ali et al. 2018) and is highly vulnerable to a number of disasters. Four wards (i.e., ward-27, ward-29, ward-30, and ward-31) under the KCC were selected and finalized, based on several field visits and reconnaissance survey. Most of the households in these four wards regularly experience waterlogging leading to economic loss and environmental degradation (Rahman et al. 2009).

Primary and secondary data from relevant organizations, including physical features (i.e., boundary, roads, structures, rivers, etc.) from KCC, spot height of ground elevation from Khulna Development Authority (KDA), rainfall and temperature data from Bangladesh Meteorological Department (BMD), major flood events from Bangladesh
Water Development Board (BWDB), and satellite images from Google Earth were collected. The results of the model were validated through ground truth and key informant interviews (KII) (i.e., nine key persons of KCC, KDA, BMD, and ward councillors). Twelve focus group discussions (FGDs) (three with only females, three with only males, and six with both males and females) were also conducted to investigate the previous and existing condition of waterlogging.

Digital elevation model (DEM) and watershed analysis

A DEM of Khulna City was prepared through spot height, existing natural barriers (i.e., rivers and canals) and field observations. The DEM was then used as a main input for watershed analysis (Rivas & Koleva-Lizama 2008). The Arc Hydro tool was used to describe natural drainage patterns of the catchments (Abdullah 2011). On the other hand, raster analysis is simpler, a faster process, quicker, and suitable for analyzing attributes of large areas (Ratti & Richens 2004).

Precipitation analysis and catchment-wise volume of overland flow estimation

Historical daily precipitation data in the region from the last 69 years (1 January 1948–31 December 2017) were used. Return periods of extreme events were used to generate accurate models of extreme events (Alam et al. 2018). Various methods (e.g., Hazen, Weibull, Cunnane, Gringorten, etc.) were used to show the relationship among precipitation events, return period, and probabilities (Maidment 1993). Among all methods, Hazen plotting position determines the return period of rainfall events from probability of occurrence in a simplified way (Urias et al. 2007). This research applied the Hazen plotting position method to estimate precipitation amount in different return periods that helped to calculate catchment-wise volume of overland flow. To
determine the return period, yearly maximum precipitation data were ranked from highest to lowest. This research used yearly maximum precipitation instead of yearly total precipitation to identify waterlogged areas developed from extreme precipitation events. The probability of occurrence was calculated using Equation (1) according to Ward & Trimble (2014):

$$F_a = \frac{100 (2n - 1)}{2y}$$

where, $F_a$ = probability of occurrence (%), $n$ = rank of each event, $y$ = total number of events, and return period ($P_o$) = $100/F_a$.

Return periods, probabilities of occurrences (as independent variables), and log yearly maximum precipitation (in millimeters as dependent variable) were plotted on log-probability graph paper. A regression line was drawn to derive a model. Finally, three scenarios (i.e., for 5 year, 50 year, 100 year) were developed to understand the extent of extreme precipitation events. Catchment-wise volume of overland flow was calculated using the following concept according to Subramanya (1994):

$$Volume\ of\ overland\ flow = \left(\frac{\text{precipitation \ for \ return \ period \ + \ area \ of \ catchment}}{\text{loss \ due \ to \ natural \ process \ + \ existing \ drainage \ volume}}\right)$$

This research assumed the volume of overland flow losses due to some natural processes (i.e., percolation, evaporation, evapotranspiration, infiltration, etc.). Finally, mapping was done to determine the spatial variation of overland flow volume in each catchment in three return periods.

**Simulation of drainage system**

This research formulated a mathematical simulation model of the drainage system of KCC using Mike Urban 11.

Parameters for each catchment (i.e., unique ID, area, coordinates of centroids, percentages of imperviousness, and time of concentration using the Kirpich method) were first defined. The main sources of impervious surfaces in city scale are structures and roads (Roy & Shuster 2009). The percentage of imperviousness for each catchment was calculated by structures and roads’ coverage identified from satellite images. The concept of imperviousness (Figure 2) was used for estimating the percentage of imperviousness in each catchment using the following equation according to Deguchi & Sugio (1994):

$$\text{Percentage of imperviousness} = \frac{\text{Area covered by roads and structures in a catchment}}{\text{Total area of the catchment}} \times 100$$

There are numerous methods for calculating time of concentration ($t_c$) (Green & Nelson 2002; Davis 2008). The watershed method, Morgali and Linsley method, Kirpich method, Kerby-Hathaway method and velocity method are widely used in hydrological research. The watershed method, Morgali and Linsley method, Kirpich method, Kerby-Hathaway method and velocity method are widely used in hydrological research.
method uses complex retardance factor, the Morgali and Linsley method depends on rainfall intensity, the Kerby-Hathaway method uses a roughness parameter for different surfaces, and the velocity method calculates different time for sheet flow, shallow overland flow, and channel flow which is too complicated for a system of a large number of catchments (Thompson 2006; Gericke & Smithers 2014). The Kirpich method is suitable for small catchments with channels (McCuen et al. 1984). For simulation of the drainage system of KCC, drainage areas were divided into smaller ones in such a way that each inlet has a single catchment. This resulted in a large number of catchments with open channels and culverts covered by concrete slabs. For this drainage system, the Kirpich method was best suited to calculating the time of concentration. According to Kirpich (1940):

\[ t_c = 0.0078(L^3/h)^{0.385} \tag{4} \]

where, \( t_c \) = time of concentration (minutes), \( L \) = length of main channel (ft), \( h \) = relief along main channel (ft).

To generate the hydrological model, nodes were defined in the intersection and end points of a drainage system. This work used some parameters for each node such as unique name, ground levels, coordinates, diameters of drain, and invert level. Ground levels for nodes were extracted from DEM and diameters for each node were assumed as the width of connecting drains. The invert level of the upper stream was assumed as 2 meters below the ground level (according to KCC drainage design) and additional nodes of the network were calculated using slope, and distance between nodes along the drainage network. The invert level for downstream was calculated using the following formula according to Gupta et al. (1983):

\[ I_{Ds} = I_{Us}(1 - nL) \tag{5} \]

where, \( I_{Ds} \) = invert level of downstream (meters), \( I_{Us} \) = invert level of upstream (meters), \( n \) = slope, \( L \) = distance between upstream and downstream (meters).

Links (i.e., connection of nodes through the drainage network) were defined through the center line of the drainage network. Lengths (i.e., calculated from existing drainage network) and widths were represented by drainage network in the model. Connected nodes for each link (i.e., from node in the upstream to node at the downstream) were also identified that relate links with connected nodes in the model.

A simulation model that supports the estimation of the drainage capacity of each catchment was formulated using Mike Urban 11. A sensitivity analysis was carried out for the parameters of MOUSE time-area (TA) method to understand the effect of these parameters on runoff. The hydrological parameters considered were imperviousness, reduction factor, initial loss, time of concentration, and time-area curve. Hydrological runoff reduction factor was used to address water losses caused by evapotranspiration, imperfect imperviousness, etc. on the catchment area. Initial loss defined the precipitation depth required to start the surface runoff considering the wetting and filling of catchment depressions. On the other hand, a time-area curve was used for the shape of the catchment layout. The sensitivity analysis indicates that imperviousness and reduction factor directly influence peak runoff whereas time-area curve and time of concentration dictate the shape of the runoff hydrograph, and initial loss effects the time of initial peak flow. Local parameter values were used for the model (i.e., time-area coefficient, type of time-area curve, reduction factor, etc.). Outlets for all networks were defined and rainfall data were also imported through boundary items. Finally, simulations were run for 2-day rainfall scenarios and output of the model was the volume of overland flow discharged in each outlet. Using the maximum discharge value and digital elevation model (DEM), inundation maps were prepared. This work identified waterlogged areas using inundation maps. The model was validated through field observations. A drainage density map was also prepared to analyze the drainage capacity of waterlogged areas. Finally, this research identified some site-specific impacts of waterlogging on infrastructure and roads by GIS analysis, field observations, and interviewing major stakeholders. Ninety residential structures and 60 commercial and mixed-use structures were surveyed to generate the relation between economic loss and inundation depth.

**RESULTS AND DISCUSSION**

This work analyzed the different physical components of the study area associated with climate change and waterlogging.
Figure 3(a) shows the 3D representation of existing topographical condition of the study area. According to the FGDs, waterlogging had little impact on KCC because of the natural waterbodies. Overlay of two components (i.e., elevation and natural waterbodies) might justify the source of waterlogging in the KCC area.

According to the FGDs, the vast number of natural waterbodies cannot protect the area from persistent waterlogging during extreme rainfall events. Elevation of the study area is one of the key factors for waterlogging. The DEM in Figure 3(a) shows the topographic elevation in the study area from mean sea level. The study area is relatively more low-lying than other parts of KCC and mostly vulnerable to sea level rise and rainfall-induced waterlogging. On one hand, the shipyard road alone with the Rupsha River protects the city from the backwater effect of the Rupsha River, but on the other hand, during heavy rainfall, it might be a barrier to draining out logged water from the city to the Rupsha River.

Historically, run-off of ward-27 drained into the Dhonai Ali Khal, ward-28 and ward-30 into the Motia Khali Khal, and ward-31 into the Khetra Khali Khal. Previously, those canals collected run-off through artificial and natural drains and drained out to the Rupsha River at Alutola Sluice Gate point, 3 kilometers away from the city boundary. The FGDs identified that this process is hampered due to encroachment of the canals, unplanned development, narrow artificial drains, and conversion of natural drains to built-up surface. Having low-lying areas in the southern parts of ward-27 and ward-28, Toot Para and Dorga Para area of ward-30 and Molla para and Dokshin Laban Chora area of ward-31 might be inundated due to the excess water from elevated ground.

The KCC authority constructed three sluice gates at the connecting points of the Motia Khali Khal, Ghora Khal, and Lobon Chhora Sluice Gate Khal to directly drain out run-off into the Rupsha River. According to field visits, those sluice gates were not functioning well. As stated by the FGDs, intense rainfall during high tides inundates the area severely. According to KIIs of the KCC authority, the bed of the Rupsha River has increased by several meters in the last ten years due to siltation, and this...
draining of run-off might not be possible using those sluice gates without pumping.

The analysis of watersheds and stream links shown in Figure 3(b) also clarifies the existing physical condition. Stream links are natural drainage paths and carry water from higher to lower land. In the study area, stream links are connected to canals and might discharge into the canal. However, the actual scenario is different because of unplanned and haphazard development. The vast number of structures built on the stream link shown in Figure 3(b) might affect natural flows and inundate the area. Watershed analysis shown in Figure 3(b) also illustrates that the southern part of the study area, especially ward-31, might contain more water from the northern part.

**Precipitation analysis**

The hydrological analysis estimated the precipitation amount for different return periods to investigate waterlogging scenarios in KCC. According to descriptive statistics, annual maximum precipitation sample distribution is approximately normal with arithmetic mean of 134.67 mm (13.47 cm), median of 115 mm (11.5 cm), skewness of 1.05, and p value equal to 0.077, as found from the Anderson–Darling normality test.

Figure 4 illustrates the relationship between annual maximum rainfall and return period. The plotted data are fitted with a logarithmic trend line and interpolation or extrapolation calculates the desired precipitation amount corresponding to the return period. Three scenarios (i.e., for 5-year, 50-year, and 100-year return periods) assisted in investigating the extent of extreme precipitation events in the study area. Table 1 shows computed precipitation amount corresponding to the scenarios’ return periods. Based on the data, around 396 mm rainfall might occur during the 100-year return period (i.e., probability of occurrence 1%). Interpolation result using the regression line shows 346 mm and 180 mm rainfall might occur for the return period of 50-year and 5-year, respectively. According to historical data, maximum precipitation in a day occurred in 1986 and calculation shows the precipitation amount was 430 mm with a return period of 122 years (i.e., probability of occurrence 0.82%). As stated in the KIIs of Bangladesh Meteorological Department (BMD), 100 mm to 120 mm maximum daily precipitation might occur once within every two years in the Khulna region.

**Volume of overland flow estimation considering climate change**

This research identifies different inundation zones in the study area for extreme precipitation events. The model calculates catchment-wise water depths based on precipitation amount, different natural processes (i.e., percolation, evaporation, infiltration, etc.), and existing manmade drainage volume. Figure 5 illustrates the spatial variation of

![Figure 4](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2020.256/688523/jwc2020256.pdf)

**Figure 4** | Relation between annual maximum rainfall and return period.
volume of overland flow in each catchment for three different scenarios (i.e., for 5-year, 50-year, and 100-year return periods).

Figure 5(a) shows the waterlogging areas for the 5-year return period (i.e., 180 mm precipitation in a day). Accordingly, most parts of the study area might be inundated during these scenarios and maximum inundation depth can be around 14.37 cm. The FGDs identified ward-31 as the least developed and physically most low-lying area under the KCC and maximum inundation depth was found in this ward through the simulation model. A few artificial surface drains and narrow natural canals are the main causes of inundation in this ward. Dokshin Laban Chora area in this ward is home to low-income residents and waterlogging might easily affect their income and livelihood. Royal Mor in the northern part of ward-27 is one of the busiest places of Khulna City and frequently used by residents as well as foreign visitors. The result showed 10–15 cm inundation in this area and field visits suggest that this slight inundation might hamper the local traffic system. According to KIIs, compact development, huge paved area, and narrow surface drains are the main causes of waterlogging here during intense rainfall. The cause of waterlogging in Toot Para and Darga Para in ward-30 are similar to Royal Mor, but sometimes, surface drain water overflows due to additional inundation and degrades environmental quality. According to field observation and FGDs, ward-27 has a better drainage connection with Motia Khali Khal and runoff water during rainfall can easily drain out in this part. A few inundation-free zones are indicated in ward-27 and ward-28 of the study area for the 5-year return period.

Figure 5(b) shows the inundation depth for the 50-year return period (i.e., 346 mm precipitation in a day) with maximum inundation depth of 28.09 cm. According to the model, the entire study area may be inundated. The inundation depths are higher than the previous scenario (i.e., 5-year return period) due to increasing precipitation level associated with climate change. Ward-31 might have an inundation

| Return period (year) | Probability of occurrence % | Annual maximum precipitation (mm) |
|----------------------|-------------------------------|----------------------------------|
| 2                    | 50                            | 114                              |
| 5                    | 20                            | 180                              |
| 10                   | 10                            | 230                              |
| 25                   | 4                             | 296                              |
| 50                   | 2                             | 346                              |
| 75                   | 1.33                          | 375                              |
| 100                  | 1                             | 396                              |
| 122                  | 0.82                          | 412                              |

Table 1 | Probability of occurrence for different return periods and corresponding rainfall at Khulna City

Figure 5 | Inundation map for (a) 5-, (b) 50-, and (c) 100-year return period of wards 27, 28, 30, and 31.
depth of $>30$ cm. This higher inundation depth might cause economic loss and degrade the environmental condition of the study area. In this scenario, the inundation-free zones of the 5-year return period scenario might also be inundated with slight inundation depth. Most parts of ward-27, ward-28, and ward-30 might be inundated with 20–25 cm inundation depth due to extreme precipitation events.

Figure 5(c) illustrates inundation depth for the 100-year return period (i.e., 596 mm precipitation in a day); most of the area would be severely inundated. According to the result, the highest and lowest inundation depths were 32.22 cm and 5.95 cm, respectively. The inundation depths are very high for most parts of the study area due to the high amount (396 mm) of precipitation. As stated in the FGDs, residents of the Laban Chora area of ward-31 might be the worst sufferers of such high inundation.

This research summarizes that inundation depths are increasing gradually with the increase of rainfall. The increase of precipitation events due to climate change may severely affect infrastructure and daily life for the city dwellers.

Simulation-based inundation level and drainage capacity analysis

Based on the simulation model, 37.48% of areas were inundation-free and 29.94% areas had inundation depth of 1–90 cm. In addition, 25.13% of areas had inundation depth of $>150$ cm. Comparison between model-based results and existing drainage density clarifies the impact of drainage capacity on waterlogging in KCC. Figure 6(a) illustrates the result of the 1D hydrological simulation model with spatial variation of inundation level. The inundation map presents the extent of waterlogging within the study area, where ward-31 seems to be highly vulnerable to climate change-induced waterlogging. Laban Chora area in the southern part of ward-31 might experience a maximum inundation level of $>150$ cm. According to field observations and FGDs, low elevation, lack of drainage network, and tidal flow of the Rupsha River might be responsible for such a high inundation level in this area. In relation to KIIs of KCC, intense rainfall during high tide causes a devastating waterlogging scenario leading to

Figure 6 | (a) Inundation map and (b) drainage density map of wards 27, 28, 30, and 31.
a huge amount of economic loss. Royal Mor in the northern part of ward-27, and Toot Para and Dorga Para in the northern part of ward-30 might experience a moderately high inundation with a depth of 30–60 cm. According to field observations and FGDs, the dense development and inadequate drainage networks are responsible for waterlogging in this part. The drainage network in most parts of ward-27 and ward-28 collects surface runoff and drains into the Dhonia Ali Khal and Motia Khali Khal. According to FGDs, this part of the study area is slightly affected by urban waterlogging, but in future, those parts might be affected more severely due to the destruction of natural canals and breakneck development.

Figure 6(b) shows the existing drainage density of the study area. In the Laban Chora area, located in the southern part of ward-31, drainage density is low and the inundation level is severe. It can be said that poor drainage capacity is one of the major reasons for waterlogging in this part. Some parts of ward-27, ward-28, and ward-30 also have low drainage density and those areas might be affected by moderate inundation during extreme rainfall. According to Figure 6(a) and 6(b), the areas having higher drainage density as well as drainage capacity and have low levels of inundation. As stated in field observations and discussion with residents, roads in the study area are frequently inundated during heavy rainfall and the daily life of people is hampered due to waterlogging.

One of the previous extreme rainfall events happened on 21 August 2016 when the metrological office recorded 137 mm of rainfall in the city. The situation of that extreme event is shown in Figure 7. That scenario also supported the model result alone with the ground truth.

**Impacts of waterlogging on traffic movement and physical structures**

The research identified the major impacts of waterlogging based on the extreme rainfall for the study area. This section of the research covers the results and discussion of different impacts.

Waterlogging affects the natural traffic flow of the study area during extreme rainfall. Damage to road elements, traffic jams with higher delay times, and hampering of people’s daily routine were the results of the interruption. It was observed that waterlogging not only created problems for pedestrians but also affected the income opportunities of different groups (especially easy bike drivers, rickshaw pullers, and retail shopkeepers). In the study area, roads were classified into three categories, unpaved road (unpaved and made from mud), brick soling road, and paved. As shown in Figure 8, about 55% of paved roads were located in inundation-free zones, whereas only 23% and 35% of roads in this zone were brick soling roads and unpaved roads, respectively. The percentage of paved roads was slightly higher than the other two categories in the inundation zones, 1–30 cm and 30–60 cm. In the context of Khulna City, most of the paved roads have a bituminous surface and such inundation might damage the roads severely. On the other hand, unpaved roads might also be damaged by those inundation levels through top soil removal and become risky for pedestrian movement. 44% of unpaved roads and 34% of brick soling roads are located within the inundation level greater than 150 cm. Most of those roads are located in the Laban Chora area of ward-31. Historically, southern parts of the ward along with the KCC boundary are low-lying with...
paddy lands and operate as a container for the runoff of Khulna City. On the other hand, the Royal Mor (see Figure 7) area including the express bus stop of the city (for Khulna to Dhaka) in ward-27 is inundated frequently even due to light rainfall and this frequently hampers the bus schedule. According to field observations and FGDs, waterlogging hampers the traffic movement during extreme rainfall events and is responsible for accidents to small vehicles. In relation to KII of KCC, the durability of the roads has decreased due to waterlogging and people suffer much due to the deplorable condition of roads. Hence, it can be concluded that waterlogging hampers the traffic system and places an increased financial burden on the KCC to repair damaged roads.

The research classified the structural use into eight classes and identified the number of waterlogging affected structures according to different inundation levels. As shown in Table 2, 38.9% of the study area was located in inundation-free zones and 39.5% was affected by waterlogging with inundation levels of 1–30 cm, 30–60 cm, and 60–90 cm. It was observed that 16.7% structures were affected by an inundation level of more than 150 cm. The lower part of the structures might be damaged due to inundation. In the context of Khulna City, brick and concrete structures become weaker due to the corrosive effect of saline water. Temporary structures made from mud might be damaged severely and become vulnerable to waterlogging. In addition, reconstruction costs might increase for the maintenance of damaged structures. 88.4% of structures of the study area were residential buildings and only 33.7% of buildings were located in inundation-free zones. The residents of the affected buildings might experience disturbance as well as additional maintenance costs due to waterlogging. Among 5.3% of commercial buildings, 2.8% were affected by different inundation levels. Income opportunity might decrease in inundated commercial buildings during rainfall.

Table 2 | Impacts of waterlogging on structures in percentage of numbers of ward 27, 28, 30, and 31, for KCC

| Use of structures | Inundation level (cm) | Free | 1–30 | 30–60 | 60–90 | 90–120 | 120–150 | >150 | Grand total |
|------------------|-----------------------|------|------|-------|-------|-------|--------|------|-------------|
| Agriculture      |                       | 0.1  | 0.0  | 0.1   | 0.1   | 0.0   | 0.0    | 0.3  | 0.6         |
| Commercial       |                       | 2.5  | 0.8  | 0.8   | 0.4   | 0.2   | 0.1    | 0.5  | 5.3         |
| Community service|                       | 0.3  | 0.1  | 0.1   | 0.0   | 0.0   | 0.0    | 0.1  | 0.7         |
| Educational      |                       | 0.3  | 0.1  | 0.1   | 0.1   | 0.0   | 0.0    | 0.1  | 0.7         |
| Industrial       |                       | 0.6  | 0.1  | 0.1   | 0.1   | 0.1   | 0.1    | 0.3  | 1.3         |
| Mixed use        |                       | 0.9  | 0.3  | 0.3   | 0.1   | 0.1   | 0.0    | 0.2  | 2.0         |
| Residential      |                       | 33.7 | 11.6 | 16.4  | 7.4   | 2.8   | 1.3    | 15.2 | 88.4        |
| Service facility |                       | 0.5  | 0.2  | 0.2   | 0.1   | 0.1   | 0.0    | 0.1  | 1.2         |
| Grand total      |                       | 38.9 | 13.3 | 18.0  | 8.2   | 3.3   | 1.5    | 16.7 | 100.0       |
events. Most of the shrimp processing industries in Khulna City are located in ward-31 along the Rupsa River and waterlogging might hamper the production of these industries. Waterlogging also might pose a danger to the longevity of educational, community, and service facility buildings. The relation between economic loss and inundation depth for major structures (i.e., residential, commercial, and mixed use) is shown in Figure 9. According to the findings, economic damage might increase with the increase in inundation depths.

**RECOMMENDATION**

The simulation model should be incorporated with the development plan. Policy-makers may then easily find the waterlogging affected areas as well as identify the site-specific solutions. Using the simulation model, future scenarios might be projected without construction, which will save both money and time.

According to the findings, drainage conditions, drainage facilities, and drainage system should be improved to tackle drainage problems to reduce the potential waterlogging risk. On the other hand, without any interventions in the drainage system in future, more waterlogging risk was expressed as the simulation was done based on existing scenarios.

**CONCLUSION**

Waterlogging in the study area is increasing due to the possible impact of climate change on precipitation. Inundated
areas in four wards of the KCC were identified in this work. It was found that physical structures on the stream links might affect natural flows and inundate the area. According to the precipitation analysis, 396 mm, 346 mm, and 180 mm rainfall might occur for return periods of 100 years, 50 years, and 5 years, respectively. This research identified that the volume of overland flow, considering climate change, was increasing gradually with the increase of return period. According to the 100-year return period, the inundation depths were between 5.95 cm and 32.22 cm. As found by the simulation model, 62.52% of areas (i.e., around 1,000 acres) are inundated with different inundation levels. According to the hydrological model, it was found that drainage areas were inadequate and drainage capacity low. It was observed that the impacts of waterlogging are severe with regard to traffic movement, structures, as well as the daily life of people. About 45% paved, 77% brick soling, and 65% unpaved roads were located in different inundation zones. Waterlogging affects the natural traffic flow and longevity of the inundated roads of the study area during extreme rainfall. It was observed that 39.5% of structures were affected by waterlogging with inundation depths of 1–30 cm, 30–60 cm, and 60–90 cm. The substructure of brick and concrete buildings became weaker and temporary structures made from mud might be damaged severely due to waterlogging. It was observed that ward-31 of KCC was more vulnerable to waterlogging.

According to this study, waterlogging areas are identified that can help to resolve this issue. The study would help the development authority in the decision-making process for proper and efficient implementation of water management, drainage plans, and other projects in the study area.

**REFERENCES**

Abdullah, M. N. 2011 *Catchment Area Delineation Using GIS Technique for Bekhma dam*. Spatial Information Processing II, paper, (5335). FIG Working Week 2011, Bridging the Gap Between Cultures, Marrakech, Morocco.

Ahmed, K. & Ghosh, P. K. 2010 *Analysis of Impact of Development Projects on Water Security of the Mayur River in Khulna*. Khulna University, Bangladesh.

Alam, M. & Rabbani, M. G. 2007 *Vulnerabilities and responses to climate change for Dhaka*. Environment and Urbanization 19 (1), 81–97.

Alam, S., Alam, A., Rahman, M., Rahman, S. & Rahman, N. 2016 *Building Climate Resilience to Noapara Town: A Coastal Urban Centre of Bangladesh*. Asian Cities Climate Resilience Working paper.

Ali, F. M., Ingirige, B. & Abidin, N. A. Z. 2018 *Assembling and (Re) assembling critical infrastructure resilience in Khulna City, Bangladesh*. Procedia Engineering 212, 852–839.

Bangladesh Bureau of Statistics 2014 *Bangladesh Population and Housing Census 2011*. Bangladesh Bureau of Statistics (BBS), Dhaka, Bangladesh.

Azam, A., Dieng, H. B., Meyssignac, B., Von Schuckmann, K., Decharme, B. & Berthier, E. 2014 *The rate of sea-level rise*. Nature Climate Change 4 (5), 358.

Cazenave, A., De Domenico, C., Meivogel, L. & Meyssignac, B. 2015 *Mathematical modeling and climate change projections for the management of coastal areas of Bangladesh*. Hydrological Sciences Journal 60 (8), 1431–1442.

Cox, P. M., Hà, T. & Williamson, D. T. 2014 *A dynamic global vegetation model with enhanced representation of hydrological processes*. Global Change Biology 20 (7), 2139–2155.

Decharme, B. & Berthier, E. 2014 *Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh*. Global Environmental Change 29 (5), 391–400.

Gericke, O. J. & Smithers, J. C. 2014 *Review of methods used to estimate catchment response time for the purpose of peak discharge estimation*. Hydrological Sciences Journal 59 (11), 1935–1971.

Green, J. I. & Nelson, E. J. 2002 *Calculation of time of concentration for hydrologic design and analysis using geographic information system vector objects*. Journal of Hydroinformatics 4 (2), 75–81.

Gupta, A., Mehndiratta, S. L. & Khanna, P. 1983 *Gravity wastewater collection systems optimization*. Journal of Environmental Engineering 109 (5), 1195–1209.

Karim, M. F. & Mimura, N. 2008 *Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh*. Global Environmental Change 18 (5), 490–500.

Kirpich, Z. P. 1940 *Time of concentration of small agricultural watersheds*. Civil Engineering 10 (6), 362.

Maidment, D. R. 1995 *Handbook of Hydrology*. McGraw-Hill, New York, USA.

Mccuen, R. H., Wong, S. L. & Rawls, W. J. 1984 *Estimating urban time of concentration*. Journal of Hydraulic Engineering 110 (7), 887–904.

Mirza, M. M. Q. 2005 *Climate change and extreme weather events: can developing countries adapt? Climate Policy* 3 (3), 233–248.

Murtaza, G. 2001 Environmental problems in Khulna city, Bangladesh: a spatio-household level study. *Global Built Environment Review* 1 (2), 32–37.

Rahman, M. M., Akteruzzaman, A. K. M., Khan, M. M. H., Jobber, A. & Rahman, M. M. 2009 *Analysis of water logging problem and its environmental effects using GIS approaches in Khulna City of Bangladesh*. Journal of Socioeconomic Research and Development 6 (2), 572–577.
Ratti, C. & Richens, P. 2004 Raster analysis of urban form. Environment and Planning B: Planning and Design 31 (2), 297–309.

Rivas, B. L. & Koleva-Lizama, I. 2008 GIS technology in watershed analysis. In Conference on Water Observation and Information for Decision Support, Ohrid, Macedonia, pp. 27–31.

Roy, A. H. & Shuster, W. D. 2009 Assessing impervious surface connectivity and applications for watershed management 1. JAWRA Journal of the American Water Resources Association 45 (1), 198–209.

Subramanya, K. 1994 Engineering Hydrology. Tata McGraw-Hill Education, New Delhi, India.

The Asian Development Bank 2010 Bangladesh: Strengthening the Resilience of the Water Sector in Khulna to Climate Change. Ministry of Local Government, Rural Development & Cooperatives, Dhaka, Bangladesh.

The Daily Star 2017 Waterlogging A Never-Ending Crisis in Khulna City: Thedailystar. Available from: https://www.thedailystar.net (accessed 8 August 2018).

The World Bank 2011 The Cost of Adapting to Extreme Weather Events in A Changing Climate. World Bank, Dhaka, Bangladesh.

Thompson, D. 2006 The Rational Method. Available from: http://drdbthompson.net/writings/rational.pdf.

Urías, H., Garcia, H. & Mendoza, J. 2007 Determination of the relationship between precipitation and return periods to assess flood risks in the city of Juarez, Mexico. In: UCOWR Conference Proceedings. Southern Illinois: OpenSIUC.

USAID 2018 Climate Risk in Bangladesh: Country Risk Profile. USAID, Dhaka, Bangladesh.

Ward, A. & Trimble, S. 2014 Environmental Hydrology, 2nd edn. Lewis Publishers, London, UK.

Weatherbase 2018 Khulna, Bangladesh: Weatherbase. Available from: http://www.weatherbase.com (accessed 8 August 2018).

World Bank 2000 Khulna: World Bank. Available from: http://info.worldbank.org (accessed 22 June 2016).

Wu, X., Yu, D., Chen, Z. & Wilby, R. L. 2012 An evaluation of the impacts of land surface modification, storm sewer development, and rainfall variation on waterlogging risk in Shanghai. Natural Hazards 63 (2), 305–323.

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