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EXPLORING STORMWATER BEST MANAGEMENT PRACTICES FOR URBAN FLOOD REDUCTION IN KHULNA CITY OF BANGLADESH USING PCSWMM

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ABSTRACT

Khulna City Corporation (KCC), located in a low-lying area in southwestern Bangladesh, has been suffering from frequent water logging in the rainy season almost every year. This situation is intensified due to rapid urbanization and the impact of climate change, which have consequently created numerous problems in KCC related to stormwater management issues that require immediate consideration. Therefore, the current study aims to explore stormwater management problems in KCC and find possible countermeasures through different best management practices. Stormwater management must be incorporated into urban design and development, particularly in densely populated urban areas like KCC. In Ward No. 30 of KCC, controlling stormwater is a vital concern due to heavy rainfall, a lack of proper drainage infrastructure, unplanned growth, extensive land cover areas, etc. In the current study, the most widely used Personnel Computer Storm Water Management Model (PCSWMM) software was adopted to evaluate the city's current stormwater management practices and develop a long-term stormwater management strategy. A reconnaissance investigation of the existing states of the soil, drainage, and outlet infrastructures was conducted. The study area (KCC Ward No. 30) was then divided into many small catchments in the ArcGIS platform, and areas of each sub-catchment were identified. To determine the percentage of impervious area and the elevation of the study area, the land use and land cover (LULC) map and the digital elevation model (DEM) were generated using the ArcGIS software. All the aforementioned parameters were then entered into the PCSWMM software, and simulations were performed for various rainfall durations using different best management practices. The PCSWMM simulation provided the results of runoff, infiltration, peak runoff, floods, or surcharges at every drainage node or discharge point in the existing and altered drainage system of the study area due to the occurrence of extreme rainfall. The results indicate that various best management practices, increasing the slope, reducing the roughness of the drainage systems, reducing imperviousness, permitting more infiltrations, and promoting green infrastructure, are highly effective in controlling urban flooding or surcharges in the study area caused by the occurrence of extreme rainfall in the future. The findings of this study are expected to be supportive to policymakers, urban planners, and water managers in implementing and promoting sustainable and climate-resilient urban drainage infrastructures to tackle stormwater management problems in the KCC area.

Keywords: *Stormwater Management; PCSWMM; Urban Flood; Best Management Practices; ArcGIS.*

1. INTRODUCTION

Globally, extreme rainfall has been increasing due to the impact of climate change. In recent years, excessive run-off caused by extreme rainfall has been a matter of concern to researchers and water managers all over the world, as it results in urban flooding and thus imposes a serious burden on the drainage systems, particularly in urban areas. Stormwater management refers to the sustainable drainage of stormwater, which usually causes flooding and water logging. Water logging is caused by several reasons, including changes occurring in the hydrologic cycle, such as uneven precipitation distribution in time and space; land use changes, such as decreasing green areas and occupying water bodies for land development; and a lack of proper management, such as improper maintenance of storm water drainage systems and inadequate emergency response systems (Akter et al., 2017). Therefore, it is vital to develop appropriate management measures for the reduction of urban water logging and sustainable stormwater management in urban areas.

Waterlogging is a widespread issue, particularly in developing nations. The accumulation of water on the surface happens when the earth is saturated with water and can no longer absorb any more. High impervious surfaces in urban areas, poor drainage systems, and improper land-use planning are the main contributors to

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waterlogging (Islam et al., 2020). One of the largest cities in Bangladesh, Khulna, has a serious waterlogging issue during the rainy season. The city's infrastructure, residents' lives, and property all suffer substantial losses as a result of the waterlogging (Azad et al., 2022). Hence, it is crucial to comprehend the causes of the waterlogging and identify potential remedies to the issue. Natural drainage channels, canals, and man-made drainage facilities like culverts and pumps make up the majority of the drainage system in the city of Khulna. It is necessary to maintain drainage channels that are large enough for all the rainwater that collects in the area (Ermalizar and Junaidi, 2018). The surface runoff rate and volume are increased due to more impervious areas like rooftops, squares, and roads. Overland flow direction is also changed by man-made facilities such as drainage systems, roads, and buildings (Hsu et al., 2000). It has an impact on people's quality of life, particularly in places where agriculture is the main source of income (Jahan et al., 2018). Unfortunately, the drainage system is unable to handle the extra runoff caused by intense rainfall during the monsoon season due to inadequate drainage infrastructure caused by growing urbanization and unplanned growth in the city (Ahmed et al., 2017).

Khulna, being the third-largest city, is located in the southwest region of Bangladesh. A flat alluvial plain with an average height of 1-2 meters above sea level best describes this area. The Ganges-Brahmaputra Delta, the biggest delta in the world and one of the most densely inhabited regions on earth, dominates the area. The network of rivers and tributaries that pass through the Khulna area, including the Ganges, Brahmaputra, and Meghna rivers and countless smaller rivers and canals, has influenced its landscape. These rivers have produced an intricate network of linked streams, channels, and estuaries that provide a critical habitat for a wide variety of plants and wildlife. Drainage difficulties are one of the main concerns brought on by urbanization in Khulna city. As a consequence, flooding has been a common occurrence in the city, particularly during the monsoon season. (Islam et al., 2017). The upshot is that the city's streets, residences, and businesses regularly flood, resulting in substantial economic and social losses. The city has a monsoon-influenced tropical climate, with a dry season from November to March and a wet season from May to October. The annual average rainfall in Khulna is 1802 mm and the temperature in Khulna varies from 21.3°C to 31.1°C with a mean value of 26.2°C (Rana and Adhikary, 2023).

Personnel Computer Storm Water Management Model (PCSWMM) is a widely adopted stormwater management simulation software that was employed to assess the effectiveness of a low-impact development (LID) strategy for stormwater management in a residential area (Lee et al., 2015). They discovered that the method was successful in lowering peak flow rates and stormwater discharge. In a separate study, PCSWMM was used to plan and assess a stormwater management system for the campus of a Chinese institution (Wang et al., 2016). They discovered that the technique was successful in lowering the danger of floods and raising the quality of the water. A complete examination of the current stormwater infrastructure is required to conduct the stormwater management project in the ward no. 30 of Khulan City Corporation (KCC). The efficacy of current stormwater infrastructure may be assessed, and new stormwater management systems can be designed, utilizing PCSWMM for this study. The use of PCSWMM will also make it possible to locate probable flood zones and create effective stormwater management plans. So, the goal of this study is to study the existing drainage properties, soil condition, land use condition, and land elevation of the area and to develop a model using PCSWMM to calculate runoff, infiltration, peak runoff, etc. It will enable us to check whether any flooding occurs in the study area; if not, then some preventive measures would be proposed to reduce runoff and increase infiltration in the area. The objective of this study is to explore the potentiality of using best management practices in urban stormwater and flood management in the KCC of Bangladesh.

2. METHODOLOGY

In the current study, stormwater best management practices are explored as a means of urban flood reduction in Khulna city of Bangladesh. The widely used stormwater management simulation software named as the Personnel Computer Storm Water Management Model (PCSWMM) is used to assess the efficacy of low-impact development (LID) strategy for urban stormwater management and urban flood reduction. The Ward No. 30 of Khulna City Corporation (KCC) is selected as the study area to carry out the current study. The urban drainage model of the study area is developed in the PCSWMM software platform. A number of stormwatrer best management practices is simulated and their contributions in reducing urban flooding are quantified. This helps to identify efficient stormwater management techniques to deal with urban flood reduction in Khulna city of Bangladesh.

2.1 Study Area and Data Description

The current study is undertaken in Khulna City Corporation (KCC) of Bangladesh. The location of KCC along with its different wards are shown in Figure 1. The Ward No. 30 of KCC is selected as the study area, known as the catchment, which is also showin in Figure 1, and the methodology is demonstrated through this KCC ward. The study area covers approximately 1.23 km^2, which frequently experiences water logging like other areas of

KCC during heavy rainfall (Ahmed et al, 2017; Islam et al., 2020). The ward is mainly a residential region with a mixture of formal and informal settlements. It also consists of certain business and industrial developments. A system of roads and drains are intended to regulate stormwater runoff and minimize urban flooding during heavy rainfall events. It consists of a number of drainage channels and outlets as it is located beside Rupsha River. Urban flooding is a major issue in the study area, especially during the monsoon season with extreme rainfall.

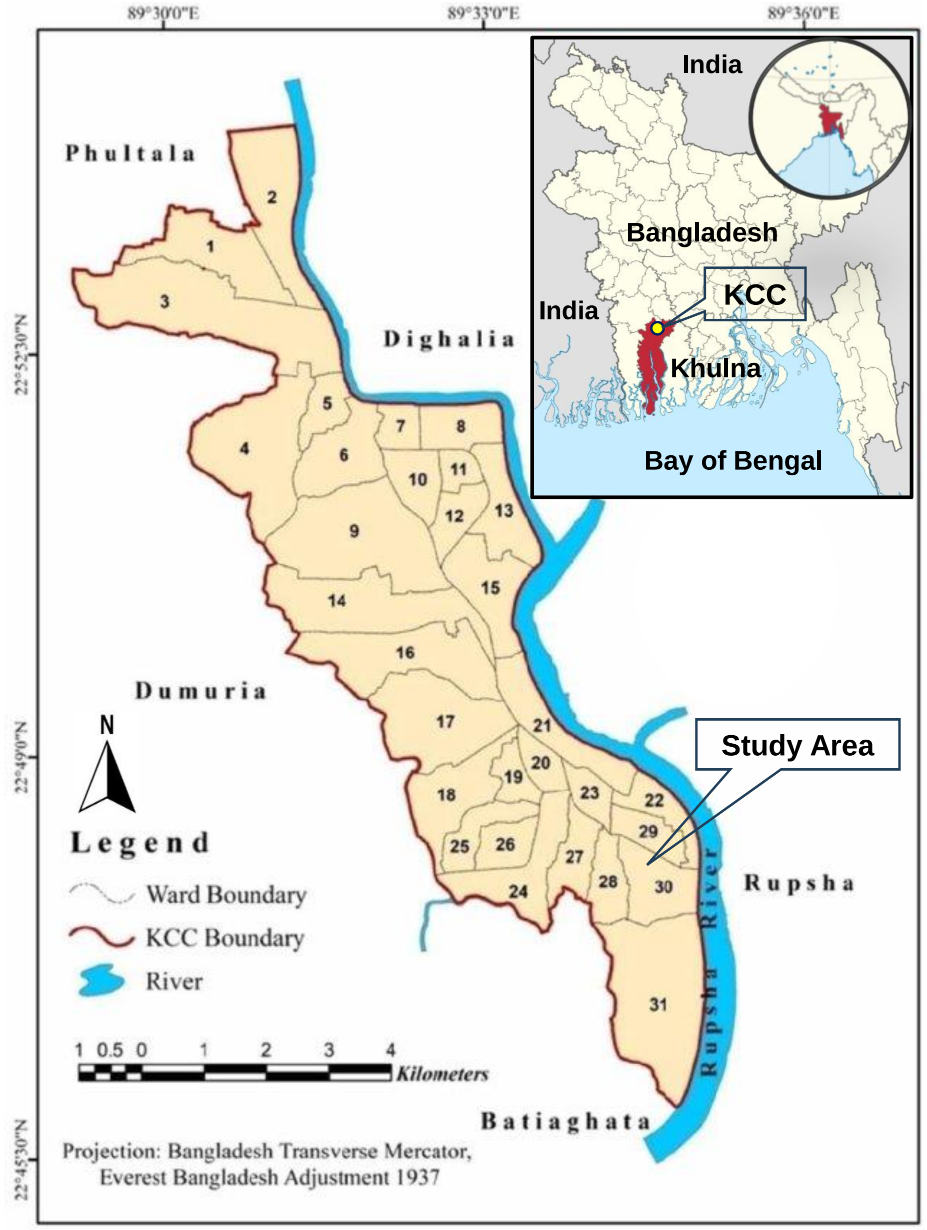


Figure 1: Location of the study area (Ward No. 30) in Khulna City Corporation

In order to carry out the analysis and model development, the study catchment is divided into twenty-six (26) sub-catchments using the digital elevation model (DEM) in the ArcGIS software platform. Figure 2 shows the outline of several sub-catchments that flow water into a common junction/node. The area of each sub-catchment is calculated using ArcGIS area calculation tool. The shape file is created by using the Google Earth Pro and ArcGIS softwares. First, .kml file of each sub-catchment is generated from the Google Earth Pro and the .kml file is then used to produce the desired shape file of the sub-catchment. The width of the sub-catchments is calculated by dividing the area with the longest flow path. Width and area are measured for each sub-catchments. The area is measured in m^2 and it is then converted into hectare for simulation purposes using the PCSWMM software. The study area is surveyed to collected the information about the drainage dimensions, outlet dimensions, drain types, materials used for drain constuction, and soil types present in the study area. The existing drainage map of the KCC ward no. 30 is collected from KCC. The areas of sub-catchment, percent imperviousness of land use, and percent slope have been calculated using ArcGIS software. The flow direction map is also collected from the KCC drainage master plan report and validated during the field survey.

Figure 2: The study catchment (KCC Ward No. 30) with its delineated sub-catchments

2.2 Model Development and Simulation Setup

The existing drainage model is developed in PCSWMM after collecting all the data. After that, a simulation was done for a particular Ten-Year Rainfall Data from 2011 to 2020 which was taken from a website of NASA called Data Access Viewer. Horton's Infiltration parameters have been used for necessary calculations. Figure 3 shows the PCSWMM model for the existing condition of the study area with nodes, outfalls, sub-catchments, and conduits. Stormwater modeling using PCSWMM requires short duration rainfall to generate intensity-duration-frequency (IDF) chart, which varies from minutes to hours. However, short duration rainfall data less than 3 hours are not available in the Bangladesh Meteorological Department (BMD). Therefore, hourly rainfall data are collected from the Data Access Viewer-NASA Power (https://power.larc.nasa.gov/data-access-viewer/), which is freely available to download and use. In the current study, the duration of hourly rainfall data adopted is taken as for 2013-2022 period that are collected in the form of an Excel CSV file.

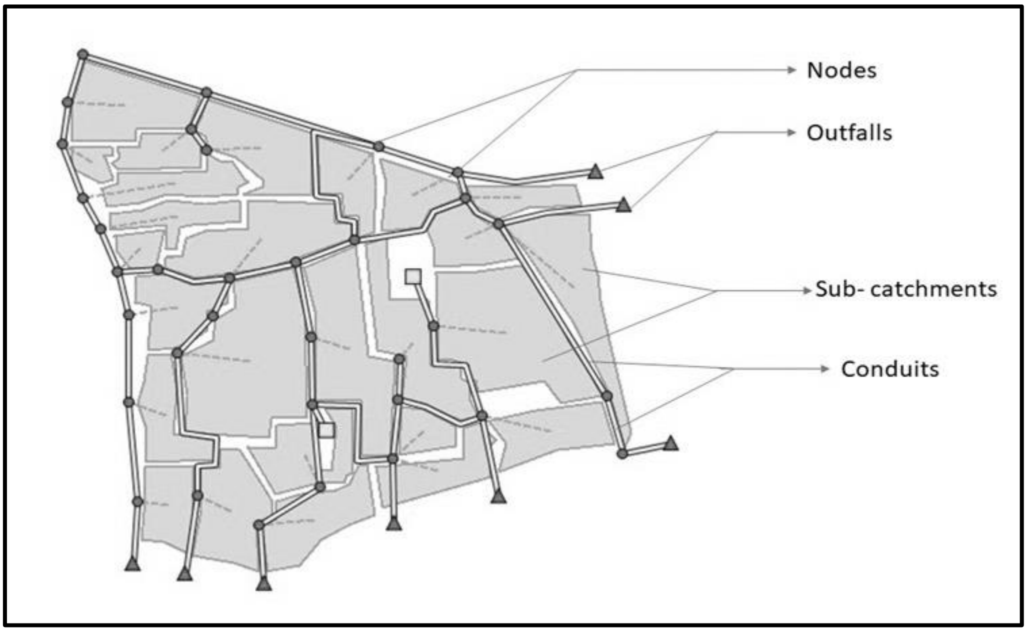


Figure 3: The Model Developed in PCSWMM for the study area with their designations

In order to create a model in PCSWMM, input data must be included, including information on rainfall, land use, and the physical attributes of the drainage system, such as the pipe network and storage facilities. By altering input factors like the amount of rainfall, the size of storage facilities, and the slope of the channels, the user can then simulate various situations. The model's outputs, which may be used to evaluate the drainage system's performance and spot potential improvement areas, include flow rates, volumes, and water levels at different points in the drainage system. Water level fluctuation or tidal effect is not considered in the study. Water level fluctuations, influenced by tides, impact drainage systems by altering flow patterns and causing backflow. Elevated water levels can impede drainage, leading to increased flooding risks. Effective design and management strategies are crucial to mitigate these tidal effects on urban drainage systems and prevent inundation. From the climatology section of the software, evaporation was considered as the default value but transpiration was not considered. evapotranspiration reduces surface runoff by absorbing and releasing water through plant transpiration and soil evaporation. This natural process helps regulate water flow, mitigating the risk of flooding, and influencing the overall hydrological balance within a watershed or catchment area. For the study area considering all parameters model was run for different scenarios.

2.3 Scenario Analysis for Different Best Management Practices

A reconnaissance investigation of the existing states of the soil, drainage, and outlet infrastructures was conducted. The study catchment (KCC Ward No. 30) is then divided into many small catchments in the ArcGIS platform, and areas of each sub-catchment are identified. In order to calculate the percentage of impervious area and the elevation of the study area, the land use and land cover (LULC) map and the digital elevation model (DEM) are generated using the ArcGIS software. Land use land classification (LULC) of the study area is obtained by using the ArcGIS software. At first, LULC data is collected from the USGS Earth Explorer (https://earthexplorer.usgs.gov/) open accessible database. After that the shape file of the study area is used. Based on the LULC analysis of the study area, three major land use categories are identified, namely agriculture (18%), vegetation cover (12%) and covered urbanized area (70%). It is important to note that the covered urbanized area is regarded as the area of imperviousness in the current study. This higher value of imperviousness is important for model simulation and significant for causing water logging in the study area by reducing infiltration. All the aforementioned parameters are then entered into the PCSWMM software, and simulations are performed for various rainfall durations using different best management practices with different combination of infiltation, percent of imperviousness and slopes. The PCSWMM simulation provided the results of runoff, infiltration, peak runoff, floods, or surcharges at every drainage node or discharge point in the existing and altered drainage system of the study area due to the occurrence of extreme rainfall.

3. RESULTS AND DISCUSSION

Table 1 represents the sub-catchment runoff and infiltration for 10-year rainfall with existing imperviousness which shows total precipitation, total infiltration, impervious runoff, pervious runoff, total runoff, peak runoff, and runoff of each sub-catchment of the study area.

Table 1: Summary of sub-catchment runoff and infiltration for 10-year rainfall with existing imperviousness

Sub-catchment	Total precipitation (mm)	Total infiltration (mm)	Impervious runoff (mm)	Previous runoff (mm)	Total runoff (mm)	Total runoff ($\times10^6$ L)	Peak runoff (m^3/s)	Runoff coefficient
S4		4923.0	14812.3	1424.9	16237.1	396.2	0.19	0.767
S5		4965.5	14811.9	1382.4	16194.2	510.1	0.24	0.765
S8		4914.0	14812.4	1434.0	16246.3	495.5	0.24	0.768
S9		4960.7	14811.9	1387.2	16199.0	349.9	0.17	0.766
S10		4957.5	14811.9	1390.4	16202.2	275.4	0.13	0.766
S11		4918.6	14812.3	1429.3	16241.6	495.4	0.24	0.768
S12		4957.8	14811.9	1390.0	16201.9	431.0	0.21	0.766
S13	21158.8	4947.2	14812.0	1400.7	16212.6	405.3	0.19	0.766
S22		12354.0	5290.5	3515.7	8806.2	440.3	0.38	0.416
S24		4958.7	14811.9	1389.1	16201.0	1344.6	0.64	0.766
S23		4920.8	14812.3	1427.1	16239.3	446.6	0.21	0.768
S25		4932.7	14812.1	1415.2	16227.3	308.3	0.15	0.767
S19		4985.2	14811.8	1362.6	16174.4	769.9	0.37	0.764
S26		4969.5	14811.9	1378.4	16190.2	971.4	0.47	0.765
S1		4946.8	14812.0	1401.0	16213.0	1085.7	0.52	0.766

Sub-catchment	Total precipitation (mm)	Total infiltration (mm)	Impervious runoff (mm)	Previous runoff (mm)	Total runoff (mm)	Total runoff (×10^6 L)	Peak runoff (m^3/s)	Runoff coefficient
S2		4952.9	14812.0	1394.9	16206.9	836.3	0.40	0.766
S3		4915.5	14812.4	1432.5	16244.8	175.8	0.08	0.768
S7		4945.1	14812.0	1402.7	16214.7	405.4	0.19	0.766
S6		4880.6	14813.4	1467.6	16280.9	182.4	0.09	0.769
S16		4943.9	14812.0	1403.9	16215.9	489.7	0.23	0.766
S17		4918.2	14812.3	1429.7	16242.0	438.5	0.21	0.768
S15		4989.8	14811.8	1358.0	16169.7	1109.2	0.53	0.764
S14		4969.0	14811.9	1378.8	16190.6	1586.6	0.76	0.765
S18		4962.8	14811.9	1385.0	16196.8	1023.7	0.49	0.765
S20		4939.8	14812.1	1408.1	16220.1	220.6	0.11	0.767
S21		4949.1	14812.0	1398.8	16210.8	376.1	0.18	0.766

Table 2 shows the simulated outfall discharge obtained for 10-years of rainfall with existing imperviousness of the area. As can be seen from the Table 2, there are a total of 8 outlets, 2 directly discharge to Rupsha River, and the other 6 outfalls are at Khal par area, which are indirectly connected to the Rupsha River. Here, from the table, the percent flow frequency, average flow, maximum flow, and total volume of discharge have been found. The total discharge volume for the existing condition is 15570.2×10^6 liters.

Table 2: Outfall discharges for 10-year rainfall with existing imperviousness of the study area

Outfall Node	Flow frequency (%)	Average flow (m^3/s)	Maximum flow (m^3/s)	Total volume (×10^6 L)
O6	59.71	0.010	0.997	1952.4
O3	55.46	0.008	0.734	1303.5
O1	60.14	0.022	1.521	4188.2
O2	58.27	0.013	1.135	2457.9
O4	58.63	0.013	1.143	2467.2
O5	54.19	0.008	0.790	1328.6
O8	54.36	0.004	0.400	646.0
O7	53.15	0.007	0.900	1226.4
			Total =	15570.2

Table 3 shows the node depth for existing imperviousness and drainage condition. As can be seem from the table, the maximum reported water logging depth is less than the drainage depth for the existing condition of the study area, no node or junction is flooded. Thus, it is obvious from these findings that there is no flooding in the study catchment through model simulation.

Table 3: Node depth for existing imperviousness and drainage

Node	Type	Average depth (m)	Maximum depth (m)	Maximum HGL (m)	Day of maximum depth	Hour of maximum Depth	Maximum depth (m)
J1		0.02	0.48	8.83	2485		0.48
J2		0.01	0.39	8.69	2485		0.39
J3		0.01	0.87	8.67	2485		0.87
J6		0.03	1.01	8.56	2485		1.01
J7		0.03	0.93	8.43	2485		0.93
J8		0.03	0.65	8.10	2485		0.65
J12		0.02	0.60	8.55	2485		0.60
J4		0.02	0.95	8.65	2485		0.95
J13		0.01	0.42	8.32	2485		0.42
J41		0.01	0.39	8.24	2485		0.39
J40		0.01	0.41	8.33	2485		0.41
J37		0.01	0.54	8.52	2485		0.54
J23		0.00	0.53	8.53	2485		0.53
J16		0.01	0.80	8.60	2485		0.80
J5		0.03	1.00	8.60	2485		1.00
J15		0.01	0.65	8.60	2485		0.65
J18		0.02	0.71	8.59	2485		0.71

Node	Type	Average depth (m)	Maximum depth (m)	Maximum HGL (m)	Day of maximum depth	Hour of maximum Depth	Maximum depth (m)
J22	Junction	0.02	0.51	8.11	2485	12:00	0.51
J17		0.01	0.70	8.60	2485		0.70
J45		0.01	0.40	7.90	2485		0.40
J46		0.01	0.24	7.72	2485		0.24
J24		0.01	0.62	8.52	2485		0.62
J26		0.01	0.46	8.21	2485		0.46
J27		0.01	0.36	8.01	2485		0.36
J32		0.01	0.49	8.24	2485		0.49
J31		0.02	0.48	8.18	2485		0.48
J30		0.01	0.46	8.11	2485		0.46
J25		0.01	0.46	8.26	2485		0.46
J33		0.02	0.56	8.46	2485		0.56
J35		0.01	0.43	8.18	2485		0.43
J10		0.02	0.61	8.89	2485		0.61
J11		0.01	0.58	8.83	2485		0.58
J9		0.01	0.60	8.90	2485		0.60
-	Inlet	0.00	0.33	8.83	2485		0.33
O6		0.01	0.38	7.73	2485		0.38
O3		0.01	0.31	7.81	2485		0.31
O1		0.01	0.50	7.90	2485		0.50
O2		0.01	0.41	7.86	2485		0.41
O4	Outfall	0.01	0.41	7.86	2485		0.41
O5		0.01	0.38	7.83	2485		0.38
O8		0.00	0.21	7.56	2485		0.21
O7		0.01	0.35	7.75	2485		0.35

Table 4 represents the sub-catchment runoff and infiltration obtained for 10-year rainfall with 60% improved imperviousness and a 1.5% increase in slope. It can be seen that the total runoff decreases from 396.2×10^6 L to 356.1×10^6 L if we take sub-catchment 4 into consideration and the runoff coefficient decreases from 0.767 to 0.690. For other sub-catchments, similar results are also found. This indicates the fact that best management practices including improved imperviousness and increase in slope reduce the flooding runoff volume.

Table 4: Summary of sub-catchment runoff and infiltration for 10-year rainfall with 60% improved imperviousness and 1.5% increase in slope

Sub-catchment	Total precipitation (mm)	Total infiltration (mm)	Impervious runoff (mm)	Previous runoff (mm)	Total runoff (mm)	Total runoff (×10^6 L)	Peak runoff (m^3/s)	Runoff coefficient
S4		6568.1	12696.4	1895.8	14592.2	356.1	0.19	0.690
S5		6616.7	12696.1	1847.0	14543.1	458.1	0.24	0.687
S8		6559.5	12696.5	1904.4	14600.9	445.3	0.24	0.690
S9		6610.5	12696.1	1853.3	14549.4	314.3	0.17	0.688
S10		6578.7	12696.3	1885.2	14581.5	247.9	0.13	0.689
S11		6566.3	12696.4	1897.6	14594.0	445.1	0.24	0.690
S12		6596.3	12696.2	1867.5	14563.7	387.4	0.21	0.688
S13		6601.6	12696.2	1862.2	14558.4	364.0	0.19	0.688
S22		12342.9	5290.6	3526.8	8817.3	440.9	0.38	0.417
S24		6614.0	12696.1	1849.7	14545.8	1207.3	0.64	0.687
S23		4915.3	14812.4	1432.6	16245.0	446.7	0.21	0.768
S25	21158.8	6582.0	12696.3	1881.9	14578.2	277.0	0.15	0.689
S19		6647.7	12696.0	1816.0	14512.0	690.8	0.37	0.686
S26		6637.8	12696.0	1825.9	14521.9	871.3	0.46	0.686
S1		6600.0	12696.2	1863.8	14560.0	975.1	0.52	0.688
S2		6605.4	12696.1	1858.4	14554.6	751.0	0.40	0.688
S3		6545.3	12696.7	1918.7	14615.4	158.1	0.08	0.691
S7		6598.2	12696.2	1865.6	14561.8	364.1	0.19	0.688
S6		6499.1	12697.7	1965.4	14663.0	164.2	0.09	0.693

Sub-catchment	Total precipitation (mm)	Total infiltration (mm)	Impervious runoff (mm)	Previous runoff (mm)	Total runoff (mm)	Total runoff (×10^6 L)	Peak runoff (m^3/s)	Runoff coefficient
S16		6594.0	12696.2	1869.8	14566.0	439.9	0.23	0.688
S17		6562.2	12696.5	1901.7	14598.2	394.2	0.21	0.690
S15		6648.5	12696.0	1815.2	14511.2	995.5	0.53	0.686
S14		6626.1	12696.0	1837.6	14533.7	1424.3	0.76	0.687
S18		6630.0	12696.0	1833.8	14529.8	918.3	0.49	0.687
S20		6560.0	12696.5	1903.9	14600.4	198.6	0.11	0.690
S21		6601.0	12696.2	1862.8	14559.0	337.8	0.18	0.688

Table 5 shows the simulated outfall discharges obtained for 10-year rainfall with improved 60% imperviousness and a 1.5% increase in slope. The total discharge for the existing condition is found be 14073.1×10^6 liters.

Table 5: Outfall discharges for 10-year rainfall with improved 60% imperviousness and 1.5% increase in slope

Outfall Node	Flow frequency (%)	Average flow (m^3/s)	Maximum flow (m^3/s)	Total volume (×10^6 L)
O6	59.10	0.010	0.992	1762.2
O3	54.41	0.007	0.730	1170.5
O1	59.11	0.020	1.515	3759.1
O2	56.86	0.012	1.129	2206.1
O4	57.46	0.012	1.138	2228.3
O5	53.13	0.007	0.787	1225.2
O8	53.63	0.004	0.398	594.8
O7	52.25	0.007	0.896	1126.9
			Total =	14073.1

Table 6 presents the sub-catchment runoff and infiltration for 10-year rainfall with improved 50% imperviousness and 2.5% increase in slope. It is seen from the table that the total runoff decreases from 396.2×10^6 L to 315.8×10^6 L and the runoff coefficient decreases from 0.767 to 0.612 when the sub-catchment 4 is taken into consideration. Accordingly, similar findings are obtained for the study catchment.

Table 6: Summary of sub-catchment runoff and infiltration for 10-year rainfall with improved 50% imperviousness and 2.5% increase in slope

Sub catchment	Total rainfall (mm)	Total infiltration (mm)	Impervious runoff (mm)	Pervious runoff (mm)	Total runoff (mm)	Total runoff (×10^6 L)	Peak runoff (m^3/s)	Runoff coefficient
S4		8219.5	10580.5	2360.3	12940.8	315.8	0.19	0.612
S5		8280.4	10580.2	2299.2	12879.4	405.7	0.24	0.609
S8		8210.2	10580.6	2369.6	12950.2	395.0	0.23	0.612
S9		8272.3	10580.2	2307.4	12887.6	278.4	0.17	0.609
S10		8225.1	10580.5	2354.7	12935.2	219.9	0.13	0.611
S11		8219.4	10580.5	2360.4	12940.9	394.7	0.23	0.612
S12		8250.9	10580.3	2328.8	12909.1	343.4	0.20	0.610
S13		8264.2	10580.3	2315.5	12895.7	322.4	0.19	0.609
S22		12317.4	5290.6	3552.3	8842.9	442.2	0.38	0.418
S24		8279.3	10580.2	2300.4	12880.6	1069.1	0.64	0.609
S23		8226.0	10580.5	2353.8	12934.3	355.7	0.21	0.611
S25	21158.8	8238.3	10580.4	2341.5	12921.9	245.5	0.15	0.611
S19		8322.8	10580.1	2256.8	12836.9	611.0	0.37	0.607
S26		8315.0	10580.1	2264.6	12844.7	770.7	0.46	0.607
S1		8261.6	10580.3	2318.1	12898.4	863.8	0.51	0.610
S2		8267.5	10580.3	2312.2	12892.4	665.3	0.40	0.609
S3		8184.9	10580.8	2395.0	12975.8	140.4	0.08	0.613
S7		8259.5	10580.3	2320.2	12900.5	322.5	0.19	0.610
S6		8124.3	10581.5	2456.2	13037.7	146.0	0.09	0.616
S16		8252.8	10580.3	2326.9	12907.2	389.8	0.23	0.610
S17		8211.9	10580.6	2367.9	12948.5	349.6	0.21	0.612
S15		8321.9	10580.1	2257.8	12837.8	880.7	0.53	0.607
S14		8294.5	10580.2	2285.2	12865.3	1260.8	0.75	0.608

Sub catchment	Total rainfall (mm)	Total infiltration (mm)	Impervious runoff (mm)	Pervious runoff (mm)	Total runoff (mm)	Total runoff (×10^6 L)	Peak runoff (m^3/s)	Runoff coefficient
S18		8305.5	10580.1	2274.2	12854.3	812.4	0.49	0.608
S20		8201.5	10580.6	2378.4	12959.0	176.2	0.10	0.612
S21		8262.1	10580.3	2317.6	12897.9	299.2	0.18	0.610

Table 7 shows the simulated outfall discharge volumes for 10-year rainfall with the improved imperviousness of 50% and an increase in slope by 2.5%. The total discharge volume for this scenario is found to be 12476.2×10^6 liters.

Table 7: Outfall discharge for 10-year rainfall with improved 50% imperviousness and 1.5% increase in slope

Outfall Node	Flow frequency (%)	Average flow (m3/s)	Maximum flow (m^3/s)	Total volume (×10^6 L)
O6	58.57	0.009	0.986	1568.4
O3	53.57	0.006	0.725	1036.8
O1	58.31	0.018	1.508	3328.4
O2	55.86	0.011	1.123	1952.0
O4	56.51	0.011	1.131	1962.0
O5	52.11	0.007	0.782	1056.1
O8	52.96	0.003	0.396	544.0
O7	51.49	0.006	0.892	1028.5
			Total =	12476.2

Figure 4 shows the comparison of the outlet flood discharge volume reduction with improving measures undertaken. As can be seen from the figure, for 70% imperviousness with a normal slope, the outlet discharge is less than 15570.2×10^6 litres. The outlet discharge reduces to about 14073.1×10^6 litres for 60% imperviousness with a 1.5% increased slope. Furthermore, it becomes almost 12476.2×10^6 litres for 50% imperviousness with a 2.5 % increased slope. The current study also shows that the outfall flood discharge volumes decrease with decreasing imperviousness and increasing slopes. It is also seen from the simulated findings shown in Figure 4 that the outfall flood discharge volume is reduced when the imperviousness is decreased and the slope is increased.

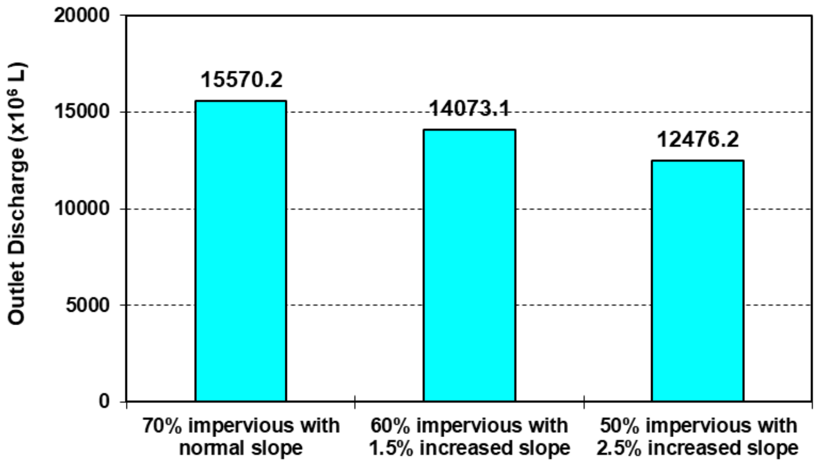
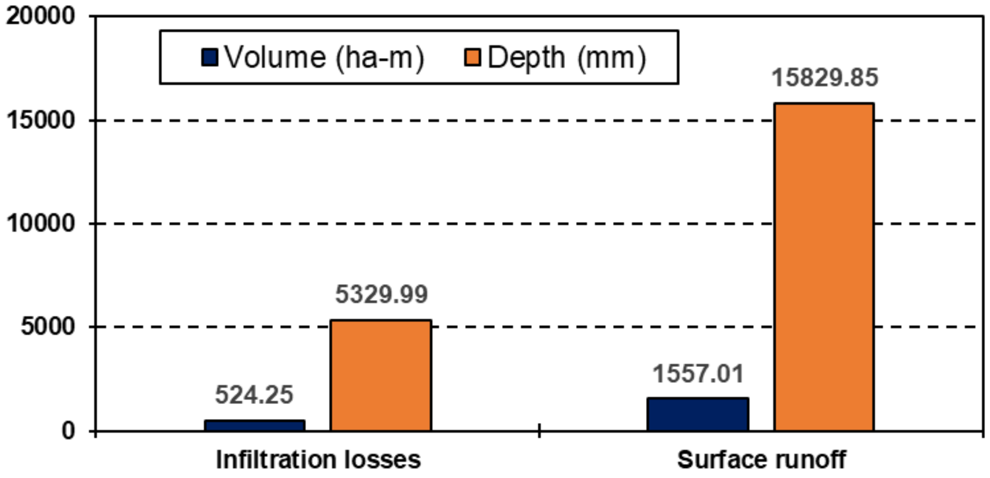
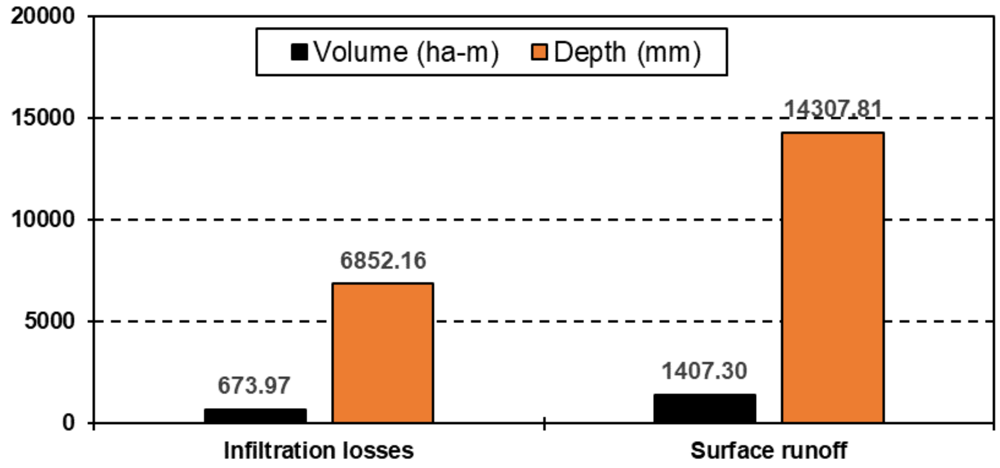


Figure 4: Reduction in the outlet flood discharge by adopting different stormwater best management practices

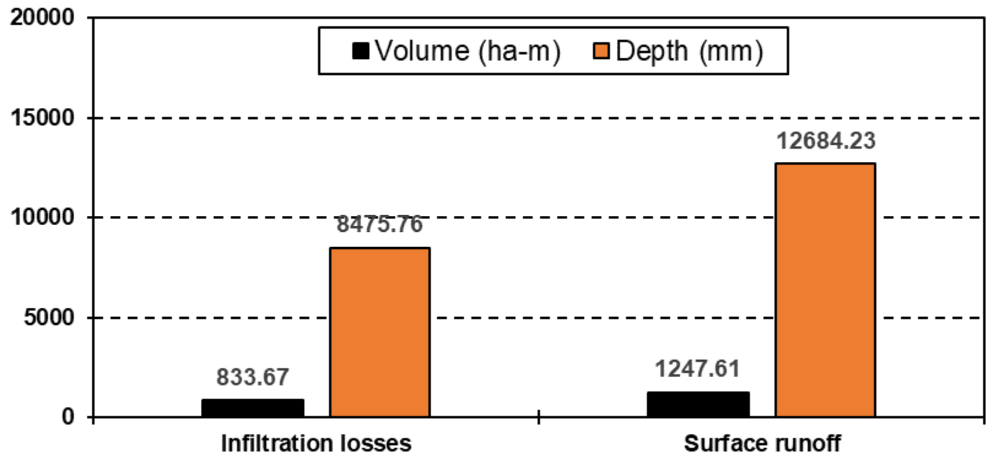
Figure 5 shows the variation in runoff and infiltration for 10-year rainfall with three different scenarios of imperviousness and slopes. The infiltration loss and surface runoff are about 539 hectare-m in volume, 5400 mm in depth, and almost 1600 hectare-m, in volume and 15800 mm in depth respectively. For 60 % imperviousness and a 1.5% increase in slope, it reduces a little. Finally, for 50% imperviousness and a 2.5 % increase in slope, infiltration loss became about 833 hectare-m in volume and less than 8500 mm in depth. On the other hand, surface runoff became a little less than 1250 hectare-m in volume and almost 12600 mm in depth. As can be seen from the figure, the infiltration losses increase with the decrease of imperviousness and increase of slopes. At the same time, the surface runoff decreases with the reduction in imperviousness and increase of slopes. This implies that the implementation of the best management practices or nature-based solutions are highly effective to reduce water logging and helps in the effective stormwater management in the urban areas.



(a) 10-year rainfall with 70% imperviousness and existing slope



(b) 10-year rainfall with 60% imperviousness and 1.5% increase in slope



(c) 10-year rainfall with 50% imperviousness and 2.5% increase in slope

Figure 5: Variation in runoff and infiltration for 10-year rainfall with three different scenarios of stormwater best management practices adopted in the study area

4. CONCLUSIONS

The current study focuses on the assessment of different stormwater best management practices for urban flood reduction in Khulna City of Bangladesh. In order the carry out the analysis, the Ward No. 30 of KCC is taken as the case study area and the methodology is demonstrated through this ward. The stormwater management model is developed using the widely adopted stormwater management simulation software, PCSWMM to explore the effectiveness of the low-impact development (LID) strategy for stormwater management and urban flood reduction in Khulna city. Based on the findings of the current study, the following conclusions can be drawn:

- It is found that with a reduction in imperviousness of 60% and an increase in slope of 1.5%, the outlet flood discharge is reduced by about 1.497×10^6 m^3. It is also found that with a reduction in the imperviousness by 50% and an increase of slope by 2.5%, the outlet flood discharge volume is decreased by almost 3.094×10^6 m^3. This is occurred due to the increased infiltration in the study area as a result of the reduction in the imperviousness. This reveals the fact that the best management practices, such as increasing infiltration and reduction of imperviousness, are highly effective as a nature-based solution to reduce stormwater induced flooding in urban areas for achieving sustainable urban stormwater management.
- The average infiltration loss for the existing or base condition is found to be 5329.99 mm, whereas for the proposed reduction of imperviousness in the study area, this loss is found to be 6852.16 mm. Hence, it can be concluded that as the imperviousness is decreased by 10%, the average infiltration is increased by about 1522.17 mm (in depth) and 1.497×10^6 m^3 (in volume), and the runoff is decreased with the same values as infiltration.
- According the aforementioned findings, the study thus conclusively demonstrates the usefulness and efficacy of stormwater best management practices, including increasing slopes, reducing imperviousness, reducing the roughness of the drainage systems, and permitting more infiltrations, in controlling urban stormwater induced flooding or surcharges in urban areas caused by the occurrence of extreme rainfall.

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