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HOW FAR RAIN BARREL CAN REDUCE URBAN FLOODING: AN ANALYSIS OF URBAN WATER RUNOFF USING SWMM

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ABSTRACT

Waterlogging constitutes a significant challenge encountered within the urban landscape of Dhaka. Moderate to intense rainfall, particularly during the monsoon season, results in severe inundation in the prime locations of the city. This study aims to simulate surface runoff using IDF curves for different return periods within the existing drainage systems at Begum Rokeya Sarani, Mirpur 10, Dhaka. The study also assessed to what extent Low Impact Development practices (LIDPs), specifically rain barrels, could reduce flooding in that area. ArcHydro tools were utilized for the construction of a hydrological model within the study area, which was subsequently integrated into the EPA SWMM software for further analysis encompassing hydrological and hydraulic aspects. The results indicate that the maximum runoff volume can range from 11,064 m3 to 15,024 m3 for return periods of up to 25 years within the current drainage system. When rain barrels are employed as Low Impact Development Practices (LIDPs), the maximum runoff volume can be reduced to a range of 8,874 m3 to 11,823 m3. Furthermore, the study suggests that the use of rain barrels can decrease the duration of maximum flooding by up to 35 minutes, demonstrating its efficiency as a Low Impact Development technique.

Keywords: *SWMM, Storm water, Urban runoff, LID*

1. INTRODUCTION

Stormwater is the water that forms on the ground surface as a result of precipitation or melting ice and snow. Despite its propensity to induce flooding, stormwater plays a pivotal role in the urban hydrological equilibrium. The augmentation of impervious surfaces within urban landscapes, such as concrete and asphalt, correlates with elevated stormwater runoff and peak flow rates, concurrently attenuating other hydrological cycle components, notably infiltration and evapotranspiration. Moreover, stormwater acts as a conduit for transporting contaminants from urbanized areas to downstream aquatic environments (Scalenghe & Marsan, 2009). Stormwater runoff was determined to be the fourth most significant factor contributing to the decline in water quality in rivers, and the third most considerable cause of water pollution in lakes (Novotny, 1994; USEPA, 1990). The resultant environmental ramifications are profound, manifesting in a demonstrable loss of biodiversity in urban streams globally.

The process of urbanization, characterized by an increase in impervious structures (e.g., rooftops, roadways), soil compaction, and alterations in vegetative cover, is intrinsically linked to hydrological and ecological perturbations. Such anthropogenic modifications engender exacerbated flood flows, intensify stream erosion, and potentially reduce baseflow in aquatic systems. For instance, During the period from 2008 to 2010, excessive rainfall resulted in flooding of 62% of metropolitan areas in China (Jianyun et al., 2016). This complex interplay of urban development and hydrological dynamics necessitates a nuanced understanding and strategic management to mitigate adverse environmental impacts.

Low-Impact Development (LID) controls embody an array of practices designed to mitigate stormwater runoff through mechanisms such as detention, infiltration, and evapotranspiration, thereby functioning akin to natural hydrological entities like aquifers and snowpacks (Rossman, 2016). These controls are integral to specific sub catchment areas and are effectively modelled by the Storm Water Management Model (SWMM) in eight distinct categories: Bio-retention Cells, Rain Gardens, Green Roofs, Infiltration Trenches, Continuous Permeable Pavement, Rain Barrels (or Cisterns), Rooftop Disconnection, and Vegetative Swales. A notable challenge in the maintenance of such systems is the potential for clogging, particularly in infiltration trenches and permeable pavement systems, which can lead to a reduction in hydraulic conductivity over time. This aspect underscores the importance of considering both the efficacy and longevity of LID controls in urban water management strategies.

Numerous research has been undertaken to investigate the characteristics of runoff in urban environments and to assess the impact of Low Impact Development (LID) techniques on runoff responses. Li et al. (2019) developed a hydrological model specifically for green roofs, aimed at evaluating the integrated impacts on runoff reduction and the enhancement of actual evapotranspiration (AET). Trajkovic et al. (2020) found that LID approaches yielded the most favorable outcomes in terms of reducing pollutants and the volume of drained atmospheric water. The findings from another study suggest that implementing bioretention basins or infiltration trenches on 0.5% of the sub watershed or enriching 20% of the open space with soil composts would effectively decrease the runoff quantity (Hekl & Dymond, 2016). Yeon et al. (2014) showed varying degrees of runoff reduction, ranging from 3.42% to 17.94% attributable to different Low Impact Development (LID) techniques.

Despite the extensive global research on the effectiveness of Low Impact Development (LID) techniques, there has been a notable lack of focus on their application in mega-cities situated in developing countries, which often face extreme challenges related to population density and pollution. In this study, a section of Dhaka city, exemplifying a densely populated megacity with a developing economy, was used as a prototype. The city, even with minimal rainfall, experiences significant stagnation during the monsoon. The consequences of such urban flooding include extensive infrastructure damage, such as property and road deterioration, decreased income opportunities with halted commercial activities and financial losses for daily wage earners, contamination of water sources leading to waterborne diseases, destruction of vegetation affecting the ecosystem, and severe disturbances to daily life including educational disruptions and business closures (Subrina & Chowdhury, 2018).

The primary objective of this research is to ascertain the magnitude of waterlogging in the Mirpur region, with the overarching goal of enhancing the drainage system to alleviate this issue. The specific aims of the study are as follows: firstly, to evaluate the impact of urban water runoff on drainage networks using simulations in the Storm Water Management Model (SWMM); secondly, to establish boundary conditions for the catchments and delineate the sewer network; thirdly, to develop a dynamic rainfall-runoff model for analyzing runoff volume; and lastly, to employ rain barrel as a Low Impact Development (LID) technique to examine its effects on the stormwater drainage system.

2. METHODOLOGY

2.1 Study Area

In this research, the focus area is Begum Rokeya Sarani in Kazipara, Mirpur, Dhaka. The area covers approximately 0.5 square kilometres in the north-east of Dhaka. Mirpur, a well-known neighborhood in Dhaka established in 1962, is particularly vulnerable to waterlogging, even with minimal rainfall. For instance, on June 13, 2017, just 28 mm of rain caused significant inundation in many areas of the city, including Mirpur-10, leading to substantial disruptions. The primary drainage systems of the area, particularly the canals, are often overwhelmed during heavy rainfall, exacerbating the flooding issues in regions like Kazi para and Shewra para. The climatic conditions of Dhaka, including Kazipara, play a crucial role in this scenario. The city experiences a tropical wet and dry climate with a distinct monsoonal season from June to September, marked by heavy rainfall and flash floods that are common almost every year. The average precipitation in Dhaka amounts to 2085 millimeters (82.1 inches) per year, with the monsoon months of June through September receiving the highest rainfall, often exceeding 300 mm (about 12 inches) per month. This heavy rainfall contributes significantly to the urban waterlogging issues in areas like Mirpur.

2.2 Datasets for Model Development

In the study, precipitation data spanning from 2010 to 2019 was obtained from the Bangladesh Meteorological Department. This dataset comprises a decade worth of tri-hourly daily rainfall measurements. Nodes, junctions, and sub catchments were delineated using ArcGIS software based on an analog map derived from a Google Earth screenshot of the study area. The process involved drawing nodes and junctions as per the map details, making this dataset a primary source. The slope data, crucial for understanding terrain dynamics, was extracted using the slope function on the actual DEM. Average slope of each catchment was then integrated as an attribute in the sub catchment shapefile. Similarly, average imperviousness for each sub catchment was calculated using an imperviousness raster, also sourced from ArcGIS software. Sewer network data, essential for understanding urban drainage, was collected from the Water and Sewerage Authority (WASA) and pertains to the year 2013. This comprehensive dataset includes details about the entire sewage network of the area, such as conduit lengths, manhole positions, slope data, and outfall locations. Lastly, specific control data for rain barrel technique were sourced directly from the tables in the Storm Water Management Model (SWMM) manual. Containers known as rain barrels, often called sterns, are used to catch roof runoff during storms and have the ability to release or reuse the collected rainfall during dry spells. With the water that has been conserved, it is possible in many places to use it for several weeks of landscape irrigation while minimizing the amount of runoff that occurs during rainy seasons. The rate of flow through a drain is determined by the drain coefficient C and exponent n in relation to the height of water stored above the offset of the drain. From the equation, $q=Ch^n$, where the flow Coefficient for the study was found to be 58.5 and flow exponent to be 0.5 where the drain acts like an orifice. Where h is the height of saturated media over the drain (inches or mm), and q is the outflow (in/hr or mm/hr). Drain offset height is the distance the drain line rises above a rain barrel or storage layer's bottom. The drain offset is 0. The amount of dry weather hours required before opening a rain barrel's drain line (which is presumed to be closed after precipitation starts) is known as the "drain delay." The drain delay is 6 hours. The drain's "open level" is its storage layer height, which opens automatically when the water level rises above it, and its "closed level" is its storage layer height, which causes the drain to automatically close when the water level drops below it. Both open level and close level are 0. The barrel height is 48 inches.

2.3 Storm Design

The study utilized tri-hourly precipitation data to develop an Intensity-Duration-Frequency (IDF) curve, employing Gumbel's Distribution method to estimate rainfall for return periods of 5, 10, 25, 50, and 100 years. Frequency Analysis was employed to correlate the magnitude of natural events, such as rainfall, with their probability of occurrence within a specific time frame or their recurrence interval. The aim is to deduce from historical data the likelihood of different event magnitudes being exceeded. This technique hinges on distributional assumptions about the mean, variance, and sometimes a distribution coefficient of the event series. The magnitude of a hydrologic event (X) is represented as the sum of the mean ($\bar{X}$) and the deviation from the mean ($K_T\ \sigma$), where σ represents the standard deviation, K is the frequency factor defined by the specific distribution, and T is the return period. For Gumbel Distribution, frequency factor K can be expressed as follows:

$$K = -0.78(\, 0.577 + ln\, ln\, (ln\, ln\, \frac{T}{T-1}))$$

The developed IDF curve (*Figure 1*) was then incorporated into the Storm Water Management Model (SWMM) to ascertain the intensity of rainfall over time. As observed, intensity decreases with increasing duration, a typical characteristic of IDF curves. Across all return periods, the curves converge, suggesting a consistent pattern of diminishing intensity over time. Notably, the 100-year return period consistently exhibits the highest intensity (34.9 mm/hour for 3-hour precipitation) across all durations, indicating that more severe storms are statistically less frequent. Conversely, the 5-year return period curve demonstrates the lowest intensity (24.2 mm/hour for 3-hour precipitation), reflecting more common, less severe rainfall events.

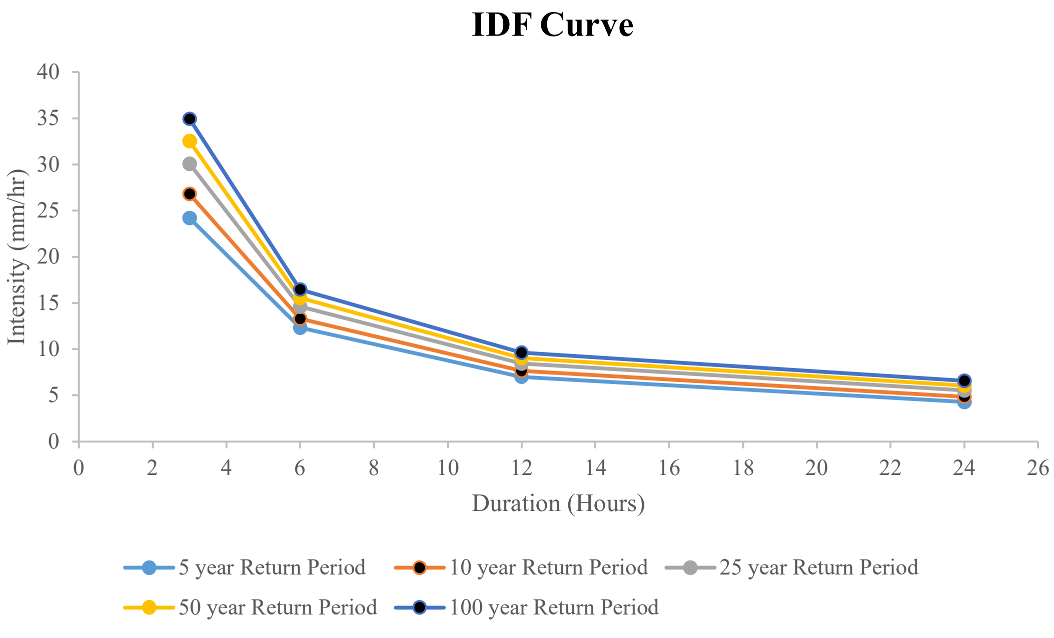

Figure 1: Intensity-Density-Frequency curve by Gumbel's Distribution for different return periods.

2.4 Model Development

The model for hydrological cycle simulation in this study was constructed using EPA SWMM 5.1 software, employing the Curve Number (CN) method. The Curve Number model was selected for its simplicity and ease of correlation with soil profiles. The model encapsulates a series of hydrological processes starting with evaporation from the outlet zone, where water transitions from a liquid to a gaseous state and ascends as water vapor. This vapor, upon condensation, returns to the earth's surface as precipitation. Precipitation is then subjected to various fates: interception by vegetation, infiltration into the soil, percolation, and eventual contribution to surface runoff and groundwater flow. Precipitation intercepted by the soil contributes to groundwater through percolation, at a rate considerably slower than surface runoff, and is subject to seepage into streams. The model also considers anthropogenic influence through the inclusion of a combined sewer system, which collects and conveys used water and sewage, with potential implications for groundwater quality in the event of leakage. A conceptual diagram of the hydrologic model is presented in *Figure 2*.

The model elements were methodically labeled in the SWMM platform to facilitate clarity in construction and analysis, with rain gauges, sub catchments, junctions, outfalls, and conduits identified by distinct labels and incremental identifiers. Parameters for sub catchments—area, slope percentage were derived from GIS data and satellite imagery. Manning's roughness coefficient of 0.013 was chosen for the conduits based on their construction material, which is concrete. For the infiltration component within sub catchment area, a Curve Number (CN) of 98 was predominantly utilized. This selection was based on the observation that the sub catchment primarily consisted of impervious surfaces, such as roofs and pavements, which align with a high CN indicative of low infiltration rates. Additionally, a standard drying time of seven days was applied as the default setting in the model. Lastly, the nodes and conduits are specified in detail, including ponded area settings, conduit geometry, roughness coefficients, flow units, and routing methods, ensuring a comprehensive representation of the hydrological dynamics within the study area.

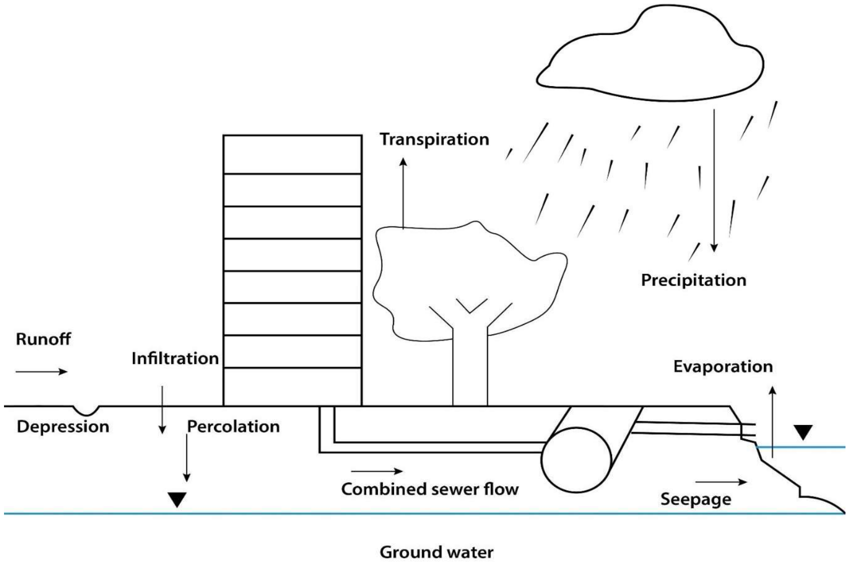

Figure 2: Conceptual diagram of the model

2.5 Model Calibration and Validation

For the calibration and validation of the hydrological model, the rainfall event on May 31, 2018, was selected as the benchmark, during which an intense 3-hour precipitation amounting to 82mm was recorded. This significant rainfall event led to flooding at junctions J2, J3, J6, and J7, a phenomenon reported by The Daily Star. Utilizing this information, the same rainfall input was incorporated into the model. Through an iterative process of calibration—modifying subbasin characteristics, Manning's n values for overland flow, infiltration and aquifer parameters, lateral groundwater flow coefficients, and channel roughness coefficients—the model parameters were fine-tuned to replicate the observed realworld flooding event. This approach ensured that the model would realistically simulate the hydrological response of the urban catchment to similar intense rainfall events.

3. RESULTS

3.1 Node Flooding

Table *1* and Table *2* compare the hydrological responses of the drainage network for 5 year return period under two different scenarios: without Low Impact Development (LID) controls and with LID controls implemented. Table *1* represents the scenario without LID measures, node J7 experiences the most prolonged flooding duration of 2.03 hours, a maximum flow rate of 2.6 CMS, and the largest volume of floodwater, reaching 11.1 million liters. Nodes J2 and J3 show a similar maximum rate of flooding at 0.134 and 0.205 CMS respectively, with J3 experiencing a higher total flood volume of 0.13 million liters compared to J2 (0.08 million liters).

Table *2* illustrates the system performance under the same conditions but with LID controls in place. Notably, there is a decrease in the total flood volume at each node, with J7's volume reducing to 8.9 million liters and J6's to 3.2 million liters, indicating a significant mitigation effect from the LID practices. Both J2 and J3 also see a decrease in their flood volumes to 0.026 and 0.052 million liters respectively.

Table 1:Node Flooding for 5 yr. return period without LID

Node	Hours Flooded	Maximum Rate (CMS)	Max Flooding (Days)	Max Flooding (Hours)	Total Flood Volume 10^6 ltr
J2	0.27	0.134	0	02:00	0.081
J3	0.27	0.205	0	02:00	0.133
J6	1.23	2.528	0	02:00	5.833
J7	2.03	2.589	0	02:00	11.064

Table 2: Node Flooding for 5 yr. return period with LID

Node	Hours Flooded	Maximum Rate (CMS)	Max Flooding (Days)	Max Flooding (Hours)	Total Flood Volume 10^6 ltr
J2	0.13	0.109	0	02:01	0.026
J3	0.14	0.168	0	02:04	0.052
J6	0.90	2.358	0	02:01	3.193
J7	1.72	2.681	0	01:46	8.874

Table *3* and Table *4* outline the baseline conditions without and with LID measures at various nodes (J2, J3, J6, J7), respectively. Similar to 5 year return period, J7 faced the most severe impact, with approximately 2.3 hours of flooding and a substantial volume of 12.8 million liters. After the application of LID measures, all nodes experienced reductions in both flooding duration and volume. For example, the flood duration at node J7 was reduced by about 21.5%, and the flood volume decreased by approximately 16%. The data also indicates an alteration in the timing of peak flooding for some nodes, suggesting that LID controls can delay the onset of peak flood conditions, thus providing additional time for drainage.

Table 3: Node Flooding for 10 yr. return period without LID

Node	Hours Flooded	Maximum Rate (CMS)	Max Flooding (Days)	Max Flooding (Hours)	Total Flood Volume 10^6 ltr
J2	0.42	0.303	0	02:00	0.244
J3	0.42	0.424	0	02:00	0.363
J6	1.40	2.989	0	01:59	6.893
J7	2.27	2.832	0	02:00	12.757

Table 4: Node Flooding for 10 yr. return period with LID

Node	Hours Flooded	Maximum Rate (CMS)	Max Flooding (Days)	Max Flooding (Hours)	Total Flood Volume 10^6 ltr
J2	0.25	0.303	0	02:00	0.164
J3	0.26	0.421	0	02:00	0.242
J6	1.09	2.886	0	02:00	4.464
J7	1.78	2.833	0	02:00	10.502

Table 5: Node Flooding for 25 yr. return period without LID

Node	Hours Flooded	Maximum Rate (CMS)	Max Flooding (Days)	Max Flooding (Hours)	Total Flood Volume 10^6 ltr
J2	0.49	0.280	0	01:45	0.307
J3	0.52	0.401	0	01:45	0.463
J6	1.68	2.960	0	01:45	8.358
J7	2.71	2.785	0	01:45	15.024

Table *5* and Table *6* detail the hydrological response of the drainage network to a 25-year return period rainfall event, without and with Low Impact Development (LID) controls, respectively. In Table *5*, representing the condition without LID, node J7 is most affected, enduring 2.71 hours of flooding with a peak flow rate of 2.785 CMS, culminating in a total flood volume of 15.024 million liters. Other nodes, such as J2 and J3, also experience significant flooding, with J2 accumulating a flood volume of 0.307 million liters and J3 reaching 0.463 million liters.

Table 6: Node Flooding for 25 yr. return period with LID

Node	Hours Flooded	Maximum Rate (CMS)	Max Flooding (Days)	Max Flooding (Hours)	Total Flood Volume 10^6 ltr
J2	0.31	0.280	0	01:45	0.188
J3	0.34	0.396	0	01:45	0.300
J6	1.22	2.850	0	01:45	5.805
J7	2.26	2.886	0	01:25	11.823

Upon the integration of LID measures, as depicted in Table *6*, the duration of flooding and volume of water at each node is reduced. Notably, node J7 witnesses a decrease in flooding time to 2.26 hours, which is a 16.5% reduction, and a lowered flood volume to 11.823 million liters, signifying a 21.5% decrease. Nodes J2 and J3 follow this trend, with J2's flood volume reduced to 0.188 million liters and J3's to 0.300 million liters.

4. CONCLUSIONS

The study, focusing on the densely populated area of Begum Rokeya Sarani in Dhaka, evaluates the efficacy of Low Impact Development (LID) practices, particularly rain barrels, in mitigating urban flooding. Employing the Storm Water Management Model (SWMM) and using the Curve Number method for infiltration, the study effectively simulated the surface runoff for various return periods. The results affirmatively indicated that the implementation of rain barrels can substantially reduce the volume of runoff and the duration of flooding up to 21.5% for return period of 25 years and 10 years, respectively. These findings reinforce the importance of incorporating LID techniques, particularly rain barrels, in urban planning and infrastructure design to enhance resilience against flooding in megacities with similar environmental and climatic challenges.

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