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Designing Stormwater Drainage Network for Urban Flood Mitigation using SWMM: A Case Study on Dhaka City of Bangladesh

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Abstract The drainage congestion problem is getting intensified in Dhaka city of Bangladesh over recent years due to rapid urbanization, inadequate drainage channels, and improper operation of the existing channels. The areas of Shantinagar, Rajarbag, Motijheel, Paltan, and T&T Colony serve as vital economic hubs in South Dhaka, yet they are highly prone to flooding during the rainy season. This study aims to address this problem by employing mathematical modeling to design a robust drainage network capable of effectively managing stormwater for existing and projected rainfall scenarios over 50 and 100 years. To achieve this, we utilize the frequency analysis method to estimate the design storm corresponding to 50 and 100 years return period for the study area. EPA SWMM 5.1 is employed to calculate the parameters of each sub-catchment, conduit network, junction node, and outlet for the drainage model setup. Through model simulation, we analyze the water level of each of the junctions to generate an inundation and hazard map of the study area. The accuracy of our SWMM model is validated in two ways: firstly, by comparing the inundation map produced from the model's water level outputs with the observed flood extent derived from Google Earth imagery, and secondly, by cross-checking the model's simulated runoff coefficient with manually estimated coefficients based on the land use map created from Google Earth. The total runoff volume from the model simulation is used to design the minimum cross-section of each of the conduits. By incrementally adjusting the conduit areas we analyzed the response of the flood hazard scenario of the study area. The findings of this analysis provide insights into the percentage increase in cross-section area required for drainage channels to effectively manage the runoff volume for a 50- and 100-year return period. With the developed model, we are equipped to design and size new components of the drainage system necessary for flood control during extreme scenarios. We anticipate that the outcomes of this study will prove valuable to relevant organizations and experts involved in addressing the drainage congestion issue in Dhaka City. The findings offer insights and recommendations for effectively managing and mitigating flooding through the design and implementation of improved drainage infrastructure.

Keywords: *urban flood, drainage network, runoff volume, SWMM, Dhaka City, Bangladesh*

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1. Introduction

Dhaka, the capital of Bangladesh, stands as one of South Asia's largest megacities [1,2]. However, this densely populated urban center faces numerous challenges, including poverty, traffic congestion, substandard living conditions, and the looming threat of flooding and drainage system congestion. Among these issues, the pressing problem of drainage congestion emerges because of rapid urbanization, which involves the removal of forests and agricultural lands, alongside haphazard settlement patterns [3]. Urbanization contributes to the expansion of impermeable surfaces, impeding the natural flow of water from rainfall or sewerage lines both above and below ground [4]. Consequently, excessive impervious cover leads to the incapacity of the drainage network to effectively manage stormwater, resulting in urban flooding. Situated on a natural depression with an average ground elevation ranging from 1m to 14m, Dhaka City has experienced significant urbanization in recent decades, leading to a drastic reduction in the number of drainage channels [5,6]. Consequently, the city finds itself increasingly vulnerable to drainage congestion and the subsequent risks of flooding.

Inadequate stormwater management exacerbates the issue of urban flooding [7], motivating numerous researchers to explore stormwater modeling in urban areas. Mohammed et al. [8] investigated the effects of climate change on frequently occurring sewer flooding and its relation to human health in the Al-Shuhada Quarter sewer system in Samawah City, Iraq. Sebastian et al. [9] examined the role of pluvial flooding in generating urban flooding, an aspect historically overlooked. Their research shed light on the advantages and disadvantages of employing 1D, 2D, and 3D urban flood inundation models. Jiang et al. [10] employed SWMM to simulate urban flooding in Dongguan City, China and concluded that while SWMM serves as a useful tool for analyzing urban flooding, it lacks the capability to directly generate inundation and hazard studies internally. Consequently, users often need to extract data from the model and process it using geospatial tools such as ArcGIS or QGIS for representation. Agarwal et al. [11] investigated the capacity of the existing stormwater networks and identified the flood-endangered zones in Vaddeswaram Village of Guntur district, Andhra Pradesh, India. Rangari et al. [12] assessed the adequacy of the existing drainage network of NIT (National Institute of Technology), Warangal, India, by generating intensity-duration-frequency curves and collecting data from DEM. Haris et al. [13] a brief overview of numerous urban stormwater management software, focusing on their functionality, accessibility, characteristics, and potential solution for green infrastructure. Basnet et al. [14] attributed urbanization as the primary cause of urban flooding supported by a historic land use land cover analysis of Lamachaur, Pokhara, Nepal. A sustainable drainage network was also designed for the study area using SWMM.

Urban flooding remains a critical concern in Southeast Asia, particularly in densely populated and underdeveloped countries like Bangladesh. Cities like Chittagong, Dhaka, and Sylhet face frequent urban flooding now and then. Akter et al. [15] used the SWMM model to identify the most vulnerable areas after zoning the hazardous zones of Chittagong City. The study found that Bakalia, Chawkbazar, Chittagong Port, Probortak, and North Central Halishahar are the most vulnerable zones according to the Kernel hazard density strategic scale. Sheonty et al. [16] assessed the stormwater runoff of Padma Bridge Link Road in the Southwest part of Dhaka and proposed minimum cross-sectional areas for every conduit. Hossain et al. [17] checked the adequacy of the Goranchatbari Pump Station using the SWMM model under changing climates. Only in a few cases, the pump station will fail, for which preclusive measures can be taken by increasing lakes and retention ponds inside Dhaka city. Notably, many of these studies highlighted a common limitation of the SWMM model: its inability to generate an inundation map or locate hazardous zones, which can be done in 2D and 3D models effortlessly This study differs from the previous ones as it aims at generating both flood inundation and hazard maps for specific extreme rainfall events using the simulation results. By employing the widely used SWMM model, this research endeavors to simulate urban flooding in the rapidly urbanized city of Dhaka, considering the urgency of addressing drainage congestion in the study area. Hazard and susceptibility emerge as critical factors in identifying the most at-risk regions [18]. Inundation depth is regarded as the flood hazard indicator in this instance, with urban land use characteristics serving as a measure of vulnerability.

1.1. Study Area

Figure 1. Drainage congestion at Shantinagar (Jagonews24.com May 2022)

Figure 2. Drainage congestion condition at Motijheel (Prothom Alo April 2018)

Cities in South/ South-East Asia are facing severe drainage problems on both small and large scales when a slight amount of rain occurs [19]. This is basically due to the insufficient capacity of the drainage as well as the sewerage system [20]. Dhaka, the capital city of Bangladesh, is no exception, as its drainage capacity is progressively diminishing. The Greater Dhaka, spanning from 23040' N to 23054' N latitude and 90020' E to 90031' E longitude, covers an expansive land area of 258.78 sq. km. Within this region, our study focuses on the MODS Zone-06 of the Dhaka Water Supply and Sewerage Authority (DWASA), which is characterized by frequent flooding and serves as a bustling economic center for the nation as shown in Figure 4. Specifically, the study area encompasses Shantinagar, Rajarbag, Motijheel, Naya Paltan, and T&T Colony. These areas were selected due to their propensity for drainage congestion and subsequent flooding events, as illustrated in Figure 1 and Figure 2. This area slopes from North to South with a natural depression in the southern part, which includes the Buriganga River serves as the main distributary to carry the drainage water to the Bay of Bengal. However, due to underground sewage blockages, drainage in this area is hindered, resulting in sluggish water flow. The existing sewerage system proves inadequate for effectively transporting rainfall to the Buriganga River without causing subsequent flooding. Consequently, there is a pressing need for a comprehensive understanding of the flooding situation and the critical dependence on the drainage network's capacity to develop an improved stormwater management plan. Through our study, we aim to shed light on the prevailing flooding conditions and establish a clear correlation between flooding incidents and the capacity of the drainage network. This research endeavors to provide valuable insights and contribute to the formulation of an effective stormwater management strategy for the study area.

2. Materials and Methods

The research methodology encompassed several steps, which are outlined in the flow chart depicted in Figure 3. The initial phase involved collecting the necessary data from relevant sources, which were subsequently preprocessed using ArcGIS to ensure their suitability for utilization in the Storm Water Management Model (SWMM). The SWMM model was then employed, and calibration was conducted to achieve a minimum accuracy threshold of 90%. Once the model was prepared, future predictions were made for rainfall events with both 50 and 100 years return periods, facilitating the proposal of a revised drainage network capable of withstanding future conditions. The specific steps undertaken are elaborated in the following sub-sections.

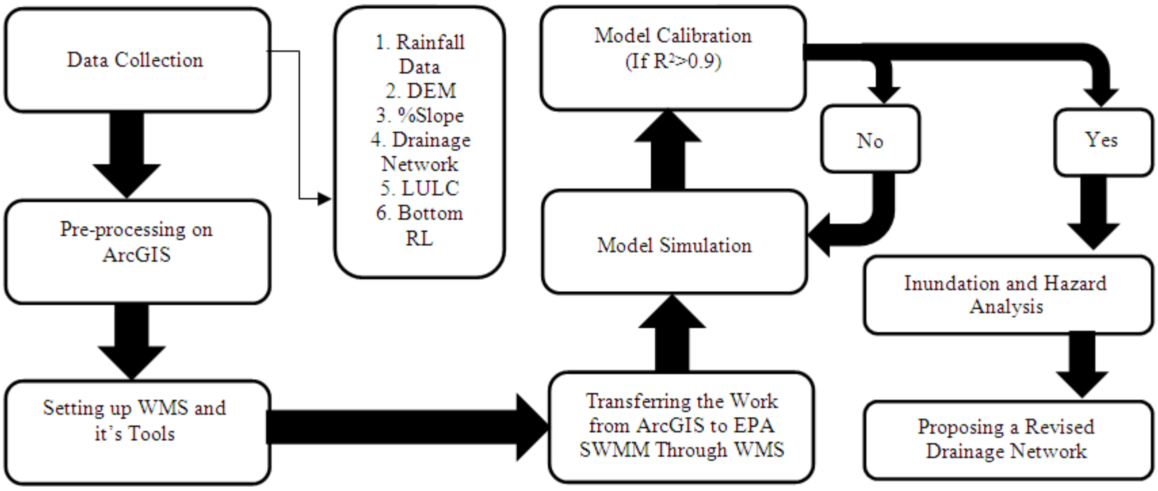

Figure 3. Methodology Flow Chart

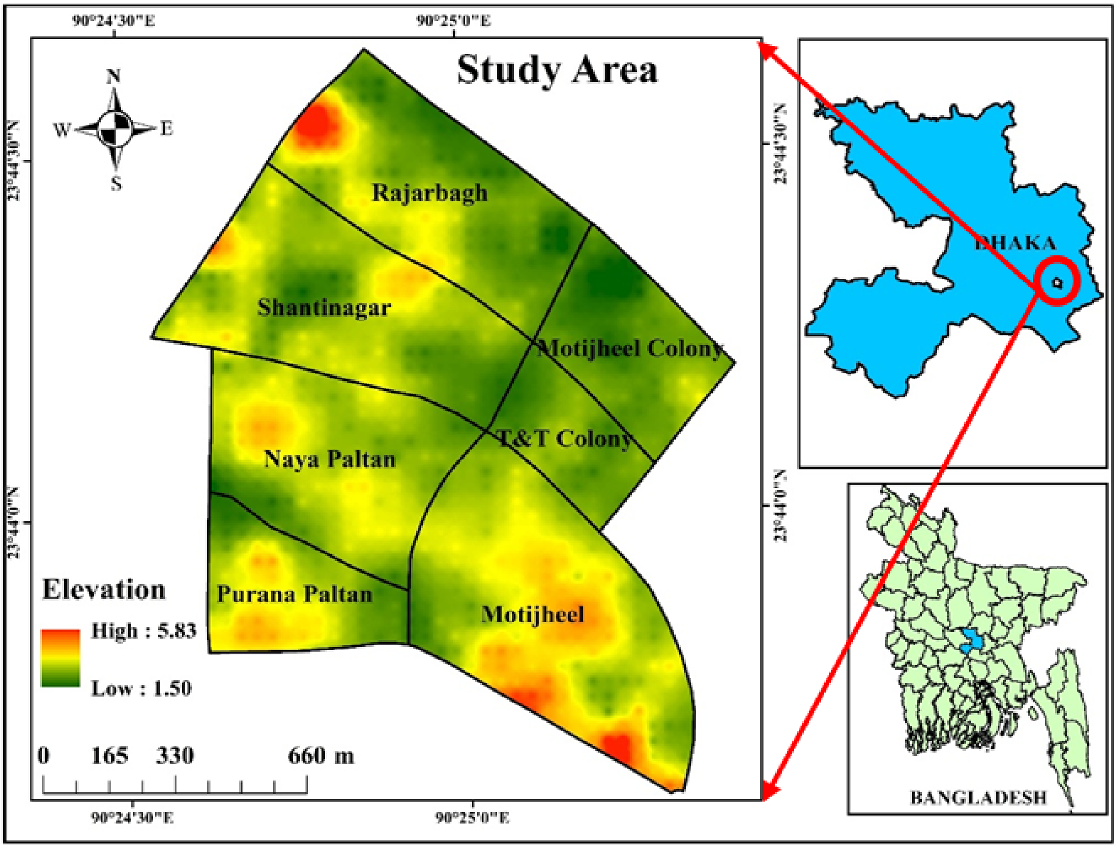

Figure 4. Map of the Study Area Map with Ground Elevation above Mean Sea Level

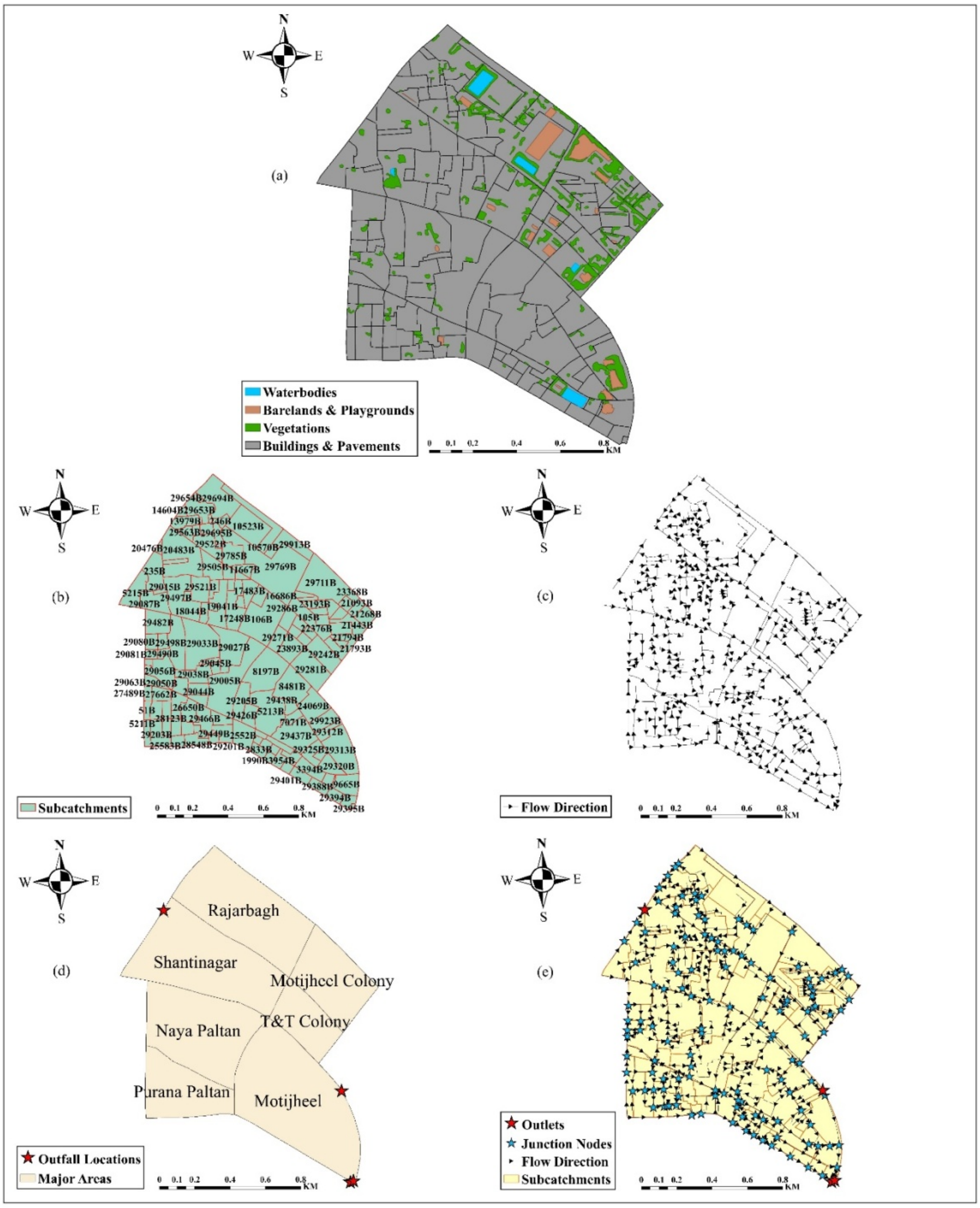

Figure 5. Key Model Inputs (a) LULC Map Generated from Satellite Image and Google Earth Pro, (b) sub-catchment Division of the Study Area, (c) Flow Direction Inside the Conduits, (d) Location of the 4 Outfalls, (e) Entire Drainage Network

Figure 6. Map of the Parts of Dhaka City with Boundary Selected for Study Area

2.1. Data Collection

Addressing the long-term drainage challenges in Dhaka city presents a significant task. However, a scientifically rigorous analysis focusing on mitigating this issue can prove instrumental. This study aimed to analyze the drainage conditions in the study area under rainfall events with 50 and 100 years return periods. The analysis involved conducting a zonal hazard study and generating an inundation map for the current scenario [21]. To facilitate proper drainage modeling, a comprehensive collection of data was imperative. The data utilized in this study are enumerated in Table 1. Daily rainfall data for the study area from 1965 to 2020 were acquired from the Bangladesh Meteorological Department (BMD) and subsequently processed for frequency analysis to serve as time-series data in the SWMM model. A 3-band satellite image, obtained from Global Mapper, enabled the generation of a land use and land cover (LULC) map, with a satellite image of the study area extracted from Dhaka city depicted in Figure 6. Additionally, the digital elevation model (DEM) collected from the Shuttle Radar Topography Mission (SRTM) by the United States Geological Survey (USGS) was utilized to calculate junction invert elevations and generate various inundation maps, as demonstrated in Figure 4. The average altitude of the study area ranged from 1.5 to 5.83 meters above mean sea level. Furthermore, the existing basic drainage network data for the study area was obtained from the Dhaka Water Supply and Sewerage Authority (DWASA).

Table 1. List of Data Used in This Study

Data Type	Data Source
Rainfall data (1965-2020)	Bangladesh Meteorological Department (BMD)
3 Band RGB satellite image	Global Mapper
Digital elevation model (DEM)	SRTM
Drainage network data	DWASA
Land use map	Google Earth Pro and ArcGIS
Slope map	ArcGIS
Width of every sub-catchment	ArcGIS

2.2. Data Pre-processing

The pre-processing of data for stormwater management modeling (SWMM) posed a complex task. Several raw data sources required processing before they could be effectively employed. In this study, the pre-processing phase was executed in ArcGIS and involved multiple steps. Firstly, the road network was digitized using Google Earth Pro and subsequently used as the foundation for creating sub-catchments. Secondly, the drainage and sewerage network data for Dhaka city, obtained from DWASA, was accurately digitized, aligning with the boundaries of the sub-catchments. Junctions or nodes were then inputted into the model at appropriate locations as point shapefiles. Outfalls were placed at four distinct locations. The SRTM DEM of the study area was processed by adding 0.46m to the existing elevation to adjust to Public Works Department (PWD) level [22], [23]. This modified DEM was utilized to calculate the percentage of slope per sub-catchment, a crucial input for the model. Finally, the LULC map was created using a combination of Google Earth Pro and ArcGIS, classifying the land use into four major categories: water bodies, bare lands and playgrounds, vegetation, and buildings and pavements. The final processed version of these datasets is visualized in Figure 5.

2.3. SWMM Model Description

The focus of this study was to analyze the current flooding scenario and propose a new drainage network for the study area. Noteworthy steps in data pre-processing included frequency analysis, transitioning from GIS to the Environmental Protection Agency's (EPA) SWMM, and setting appropriate model parameters. EPA SWMM is a 1D stormwater management model developed to simulate the hydrological and hydraulic parameters of a catchment, including the sewer network [24]. The fundamental hydrodynamic aspect of this model relies on solving the 1D Saint Venant equations (Equations 1 and 2) for gradually varied, unsteady flow. Manning's equation is utilized for calculating hydraulic parameters within conduits. These elements are part of the dynamic wave analysis, with most of the functionality available in the EXTRAN model [25].

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (1)$$

Equation 1 is the continuity equation where x is referred to as distance, t is time, A is the flow cross-sectional area, and Q is the flow rate.

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x}+gA\frac{\partial H}{\partial x}+gAS_f=0 \qquad (2)$$

It is the 1D Saint Venant momentum equation. Here, H is the hydraulic head of water in the conduit which is the summation of invert elevation and water depth, and Sf is the friction slope. Manning’s equation is used to determine the flow inside the conduits where Manning’s coefficient represents the roughness parameter, as shown in Equation 3. Here, Q is the flow in the conduit, A is the cross-sectional area of the conduit, R is the hydraulic radius, and S is the slope of the ends of the conduits. The roughness coefficient, n is used as a calibration parameter, and a value of 0.015 is used.

$$Q=\frac{1.49}{n}AR^{\frac{2}{3}}S^{\frac{1}{2}} \qquad (3)$$

2.4. Frequency Analysis

In order to analyze the extreme case scenario, the frequency analysis was conducted using the Gumbel Distribution Method [26]. This method was chosen as it provides a suitable approach for capturing extreme events. The objective of the frequency analysis was to calculate the total precipitation for rainfall events with both 50 and 100 years return periods. To facilitate this analysis, daily rainfall data spanning from 1965 to 2020 was obtained from the Bangladesh Meteorological Department (BMD). The yearly maximum precipitation values were compiled, and the frequency analysis was performed using these data [27]. The Gumbel Distribution equation utilized for the frequency analysis is as follows:

$$X_T = \overline{X} + K\sigma_X \qquad (4)$$

Here, XT is the total daily precipitation for n years return period,

$\overline{X}$ is the average of the maximum daily precipitation per year,

K is the frequency factor which can be expressed as $\frac{Y_T - \overline{Y_n}}{S_n}$ where Y_T is reduced variate, $\overline{Y_n}$ and S_n are constant values that depend on the number of samples,

σ_X is the standard deviation of the sample size.

After calculating the X_T, this total precipitation was divided according to JICA reports [28], [29]. In Figure 7, the hydrographs which have been used in modeling are displayed. For 50 years return period, the precipitation reached its peak of 133.72 mm while in the case of 100 years return period, this value was 149.28 mm.

2.5. Modelling in SWMM and Calibration of the Developed Model

This study employed WMS (Watershed Modeling System) software for the seamless transfer of files from GIS to EPA SWMM [30]. Since EPA SWMM only accepts delineated watersheds, junctions, and conduits in INP format, WMS was utilized to carry out sub-catchment delineation and junction inputting. The GIS files were loaded into WMS, enabling the creation of a reverse drainage network. The GIS Module tool was employed to input the junction nodes and compute the basin data. Following the successful transfer of the work from GIS to EPA SWMM, several parameters were established prior to conducting the simulation. Table 2 outlines the four major components of the model.

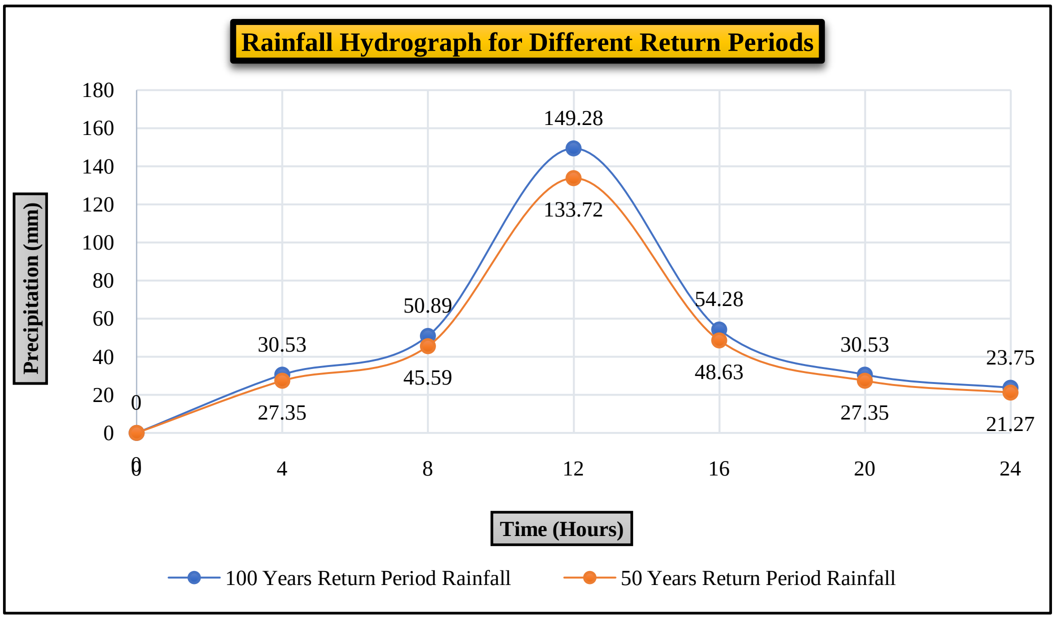

Figure 7. Time Series Hydrographs Obtained from Flood Frequency Analysis for 50 and 100 Years Return Period

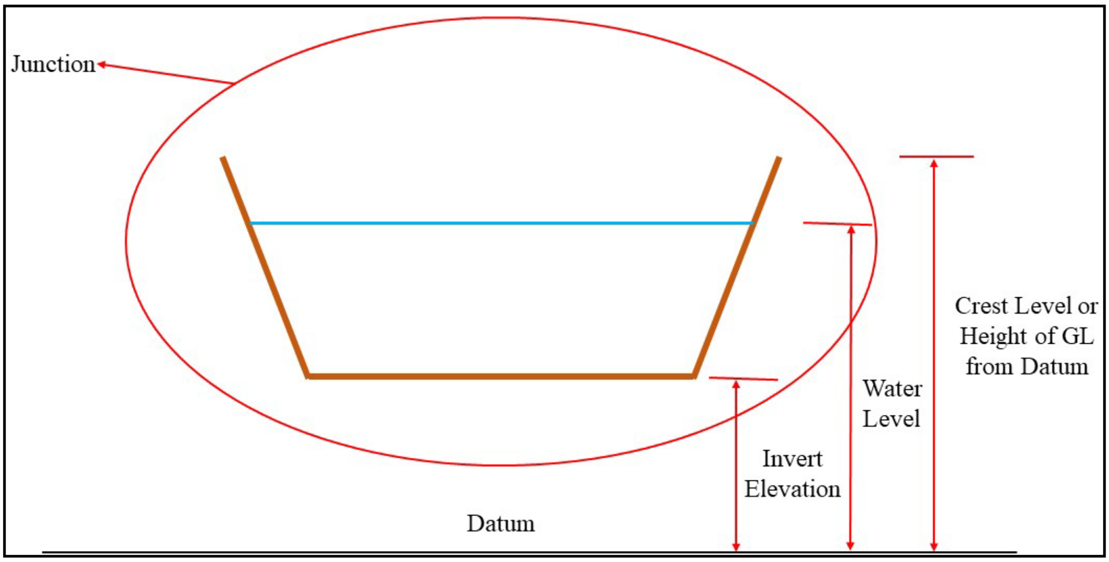

Figure 8. Figure Showing How to Calculate the Invert Elevation

Table 2. Component Details

Name of the Component	Numbers
Sub-catchments	141
Conduits	678
Junctions	665
Outfalls	4

The width of each sub-catchment was calculated using ArcGIS. The land use map played a crucial role in this study, serving both as a model input and a means to validate parameters. Initially generated in ArcGIS using a satellite image, manual generation was subsequently employed to address the limitations of the image's accuracy. This refined land use map was considered a vital input for the model. Another significant input was the invert elevation, representing the bottom reduced level (RL) of the junctions. Its calculation was based on the methodology presented in Figure 8.

Horton's model was selected to simulate rainfall infiltration, while the dynamic routing model was utilized for flood routing. The model was simulated over a period of 48 hours. Internal terms within the Saint Venant momentum equation were handled using the Dampen option, which reduces these terms when the flow approaches critical and disregards them when the flow becomes supercritical. The minimum nodal surface area was set to 1.167 m2. After carefully configuring these options, the model was simulated for both 50 and 100 years return periods, representing extreme precipitation events. The flow routing error was -0.6% and the continuity error was 0.73%, indicating excellent performance within acceptable limits [31].

The calibration of the model in this study was performed using the runoff coefficient as a key parameter. The calibration process involved a comparison between the model's simulated runoff coefficients and manually calculated runoff coefficients. The runoff coefficient for each catchment was determined based on the land use characteristics, utilizing the following equation 5. This approach allowed for a precise assessment of the model's performance by evaluating the agreement between the simulated and calculated runoff coefficients. By iteratively adjusting the model parameters, the calibration process aimed to optimize the accuracy of the model in representing the hydrological behavior of the catchments.

$$Runoff\ Coefficient\ = \left\{\begin{array}{l}(Percentage\ of\ \ PR\ \times\ 0.9)\\ +(Percentage\ of\ \ CB\ \times\ 0.85)\\ +\ (Percentage\ of\ \ V\ \times\ 0.3)\\ +(Percentage\ of\ \ BL\ \times\ 0.2)\\ +\ (Percentage\ of\ \ WB\ \times\ 0)\end{array}\right\} \div\ 100 \qquad (5)$$

Here, PR= Pavement and Roofs, RB= Residential Buildups, CB= City Business Areas, V= Vegetation, BL= Barren Lands, WB= Water Bodies. It was done by following the Ohio Department of Transportation Hydraulics Manual [32]. In consideration of Dhaka's urban nature, a flat surface assumption was adopted for the study, as indicated in Table 3. Within the SWMM model, the runoff coefficient value is determined by three fundamental parameters: percent imperviousness, percent slope, and depth of storage, all falling under the sub-catchment component. These parameters, once appropriately configured, consistently yield the same runoff coefficient value regardless of the rainfall scenario. Conversely, in real-life situations, the runoff coefficient can be calculated using the following equation:

$$Runoff\ Coefficient = \frac{Total\ Volume\ of\ \ Runoff}{Total\ Volume\ of\ \ Precipitation} \qquad (6)$$

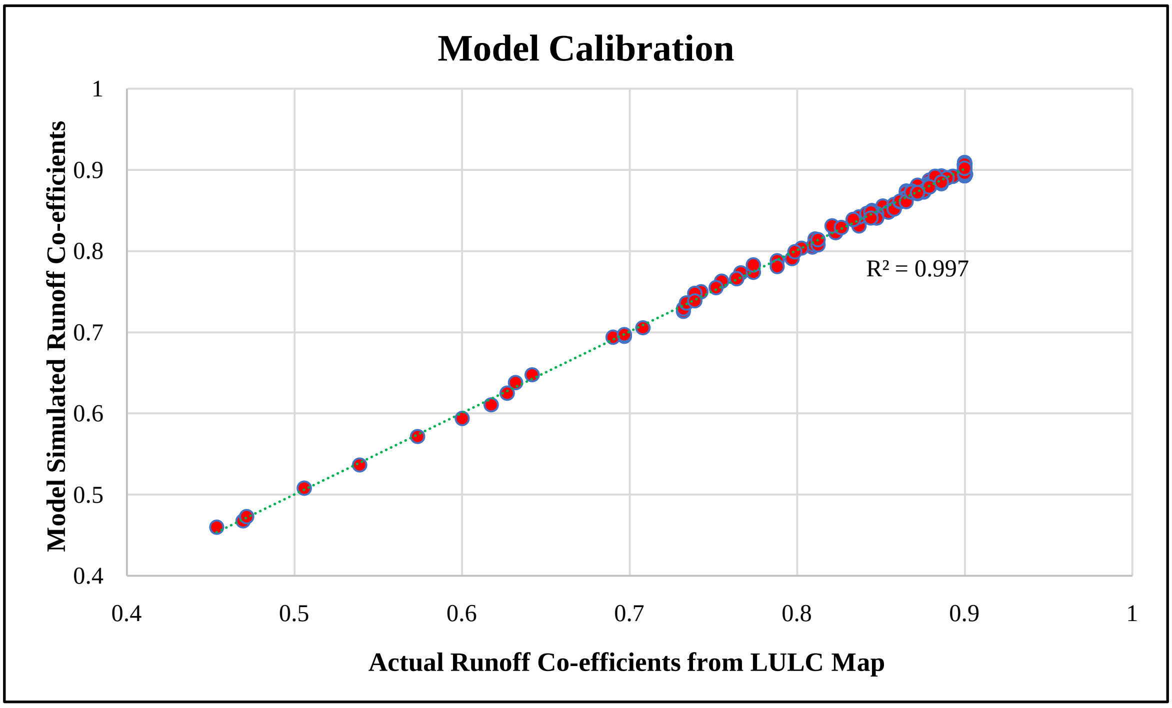

Figure 9. Correlation Between Model and Actual Value

Once the model is correctly established, the coefficient remains constant for the scenarios. The cross-validation of the model was assessed through the calculation of the RMSE (Root Mean Square Error), which yielded a remarkably low value of 0.0048. This negligible value provides substantial evidence for the high level of accuracy achieved in this research endeavor. Notably, the crucial role played by the Land Use Land Cover (LULC) map in this analysis cannot be understated [33]. The correlation coefficient (R^2) between the actual and model-simulated runoff coefficients was determined to be 0.9978, affirming the model's calibration efficacy. A graphical representation of the model calibration process is depicted in Figure 9.

Table 3. Runoff Coefficient Provided by Ohio Department of Transportation Hydraulics Manual

Runoff Coefficients for Rational Method			
	FLAT	**ROLLING**	**HILLY**
Pavement & Roofs	**0.90**	**0.90**	**0.90**
Earth Shoulders	0.50	0.50	0.50
Drivers & Walks	0.75	0.80	0.85
Gravel Pavement	**0.85**	**0.85**	**0.85**
City Business Areas	**0.80**	**0.85**	**0.85**
Apartment Dwelling Areas	0.50	0.60	0.70
Light Residential: 1 to 3 units/acre	0.35	0.40	0.45
Normal Residential: 3 to 6 units/acre	0.50	0.55	0.60
Dense Residential: 6 to 15 units/acre	0.70	0.75	0.80
Lawns	0.17	0.22	0.35
Grass Shoulders	0.25	0.25	0.25
Side Slopes, Earth	0.60	0.60	0.60
Side Slopes, Turf	0.30	0.30	0.30
Median Areas, Turf	0.25	0.30	0.30
Cultivated Land, Clay & Loam	0.50	0.55	0.60
Cultivated Land, Sand & Gravel	0.25	0.30	0.35
Industrial Areas, Light	0.50	0.70	0.80
Industrial Areas, Heavy	0.60	0.80	**0.90**
Parks & Cemeteries	0.10	0.15	0.25
Playgrounds	0.20	0.25	0.30
Woodland & Forests	0.10	0.15	0.20
Meadows & Pasture Land	0.25	0.30	0.35
Unimproved Areas	0.10	0.20	0.30

Impervious surfaces in bold
Rolling = ground slope between 2% to 10%
Hilly = ground slope greater than 10%

2.6. Flood Inundation and Hazard Estimation

One of the notable limitations of SWMM is its inability to internally analyze flood inundation or hazards, posing a challenge in visual representation. To address this, the maximum depths at junctions were extracted from the SWMM model. As previously mentioned, a total of 665 junctions across 141 sub-catchments provided information on water depth. This data was exported and used to generate a point shapefile in ArcGIS, representing the maximum depth. By leveraging the IDW (Inverse Distance Weighting) algorithm, these points were interpolated into a raster, resulting in an inundation scenario map for the study area [34].

Subsequently, the inundation map was utilized to create a hazard map and identify vulnerable zones, with the primary indicator being inundation depth. This classification was performed in GIS by reclassifying the inundation map into five levels, based on the water level at junctions: very low, low, medium, high, and very high hazard levels. To gain a comprehensive understanding of the results, the zonal statistics tool in ArcGIS was employed to calculate the mean inundation level across the seven zones within the study area.

2.7. Proposing an Adequate Capacity-Based Drainage Network

Upon assessing the current scenario, a revised drainage network was proposed, primarily focusing on increasing the cross-sectional area of stormwater pipes along main roads to accommodate runoff associated with the 100-year return period precipitation. The objective was to determine the necessary increments in the drainage network's capacity, ensuring it can effectively handle water flow during extreme events without node surcharge or flooding. By designing a drainage network capable of accommodating the yearly seasonal flows and potential extreme flood events, this proposed solution aimed to mitigate the existing flooding issues within the study area. Multiple iterations were conducted to determine the appropriate dimensions for the drainage channels, striking a balance where inundation conditions were minimized, and the drainage system operated optimally. It is important to note that this proposed design is hypothetical, tailored specifically to address the flooding challenges in the study area.

3. Results and Discussions

3.1. Prediction of Flood with Existing Drainage Network

The flood predictions were conducted for the 50-year and 100-year return periods of precipitation using the existing drainage network in the selected study area. The results exported from SWMM provided valuable insights into the extent of inundation and flood hazards, as depicted in Figure 10. It is evident that the flooding scenario poses a significant threat to the socio-economic aspects of the study site, particularly in the Shantinagar and Rajarbagh areas, which are prone to urban flooding resulting from extreme precipitation events.

The flood inundation levels varied considerably for the 50-year and 100-year return periods. For the 50-year return period, the maximum overland inundation depths ranged from 0.01 m to 0.22 m, whereas for the 100-year return period, the range expanded to 0.02 m to 0.31 m. The zonal analysis revealed an average increase of 40.91% in the maximum inundation depth across the seven primary regions within the study area. The maximum change was observed to be 68.42% in the Purana Paltan area (maximum inundation depth was around 0.16 m for a 100-year return period, whereas it was around 0.10 m for a 50-year return period). On the contrary, a minimum change of 43.48% was observed for the inundation depth in the Rajarbagh area. Even though numerically Rajarbagh and Shantinagar showed the minimum amount of change in maximum inundation depth both of the areas are predicted to have the maximum inundation depths for both cases. From Figure 11 it can be observed that these two areas will have an inundation depth of 0.22 m and 0.31 m for 50 years and 100 years return periods respectively. However, considering from a geographic point of view, areas like T&T Colony and Motijheel Colony possess the lowest ground elevation (2.32 mMSL and 2.18 mMSL respectively) which also holds some sign in the model results. For 50 years return period 99% and for 100 years return period, 100% area gets inundated in these two areas. This is very threatening considering the fact that both of the areas are basically government residential zones. Even from the inundation and hazard analysis, we see that Motijheel Colony might face severe flooding under extreme flood scenarios. From Figure 11 it can be seen that the entire study area is situated on a very low ground elevation zone having an average elevation of only 2.66 mMSL which is very poor considering the fact that Dhaka is situated high above the shoreline of Bangladesh. This scenario has been historically hitting hard in this area while dealing with urban flooding. It has been found that for 50 years return period, apart from Motijheel and Shantinagar, 99% area of all other major spots will be inundated and the percentage rises up to 100% in the case of 100 years return period. Shantinagar holds the least amount of inundated area having 82% for 50 years return period and 83% for 100 years return period even having the maximum inundation depth for both cases. The flood extent and inundation water depth for this region have been the complete opposite in this study. But from an overall view, the flood extent of the study area has been found to be catastrophic. Poor stormwater management and unplanned policy-making are the two vital causes behind this utter failure of the drainage system in these areas.

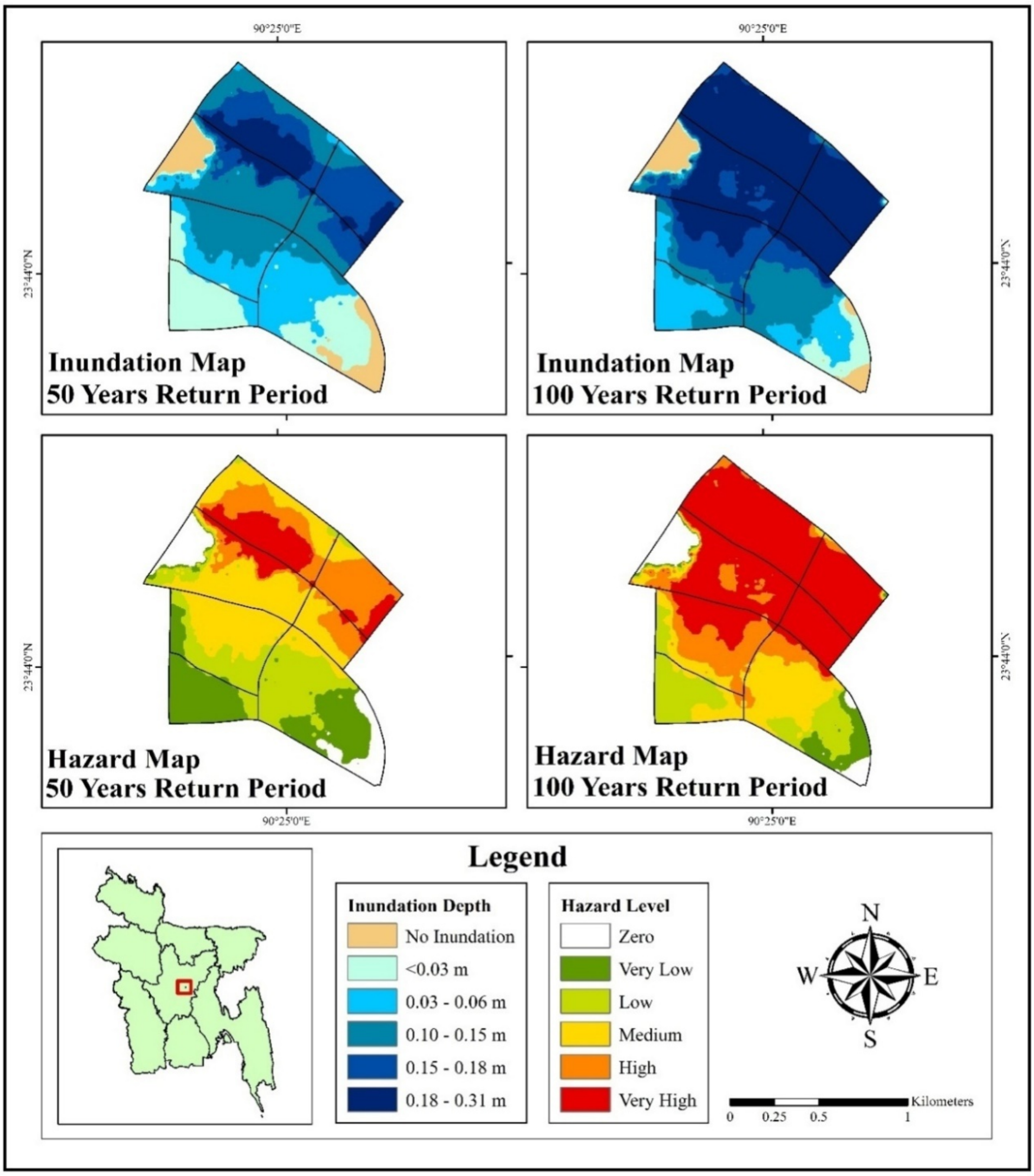

Figure 10. Model Results for Different Cases

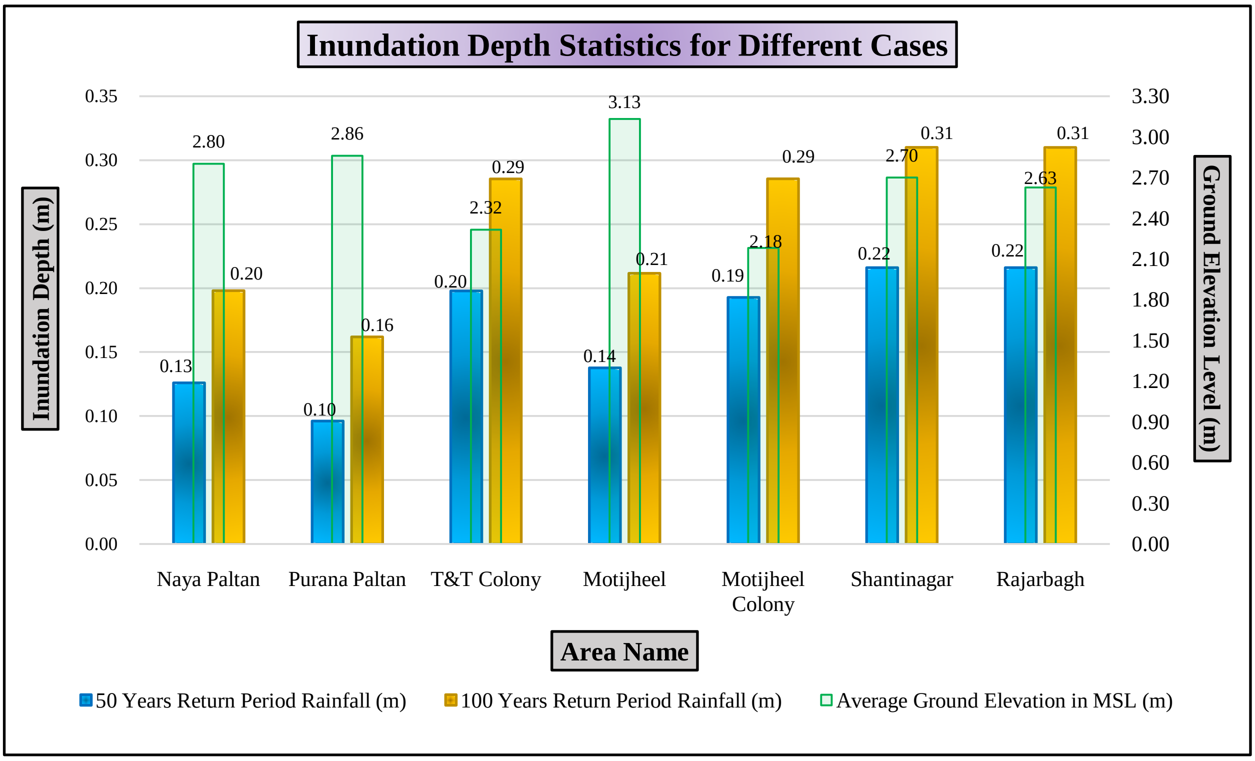

Figure 11. Zonal Inundation Depth

In Figure 10, the water depth at every junction is projected. The junction depths were first exported from EPA SWMM, and then it was converted into an inundation map or water depth map in GIS, showing that areas of Shantinagar, Rajarbagh, Motijheel Colony, and T&T Colony are facing a serious amount of trouble. The water depth in those places is higher than average. Figure 11 shows that the maximum inundation depth at the Rajarbagh and Shantinagar was the maximum. Flooding extent and water level at Motijheel Colony and T&T Colony are also threatening. This may be caused because these areas lay on natural depression. In contrast, areas like Motijheel, Purana Paltan, and Naya Paltan are situated on higher ground elevations. This could be the reason why these areas face less flooding. Even though, as mentioned earlier, all of the areas are predicted to have severe flooding extent. Among all areas, Shantinagar, Rajarbagh, T&T Colony, and Motijheel Colony face severe flooding, which is also the case in this study. In these areas, floodwater reaches around 0.3 m in depth for 100 years return period [35]. While in this study, the water depth reached up to 0.31 m for the 100-year return period rainfall simulation. To assess the hazard levels, the inundation map was reclassified, resulting in a hazard map for both return periods. As depicted in Figure 10, these maps highlight the high-hazard zones within the study area, with Shantinagar, Rajarbagh, T&T Colony, and Motijheel Colony classified as very high-hazard areas.

3.2. Proposing a Revised Drainage Network for the Study Area

The findings of this study clearly indicate that the existing drainage network in the study area is ineffective in managing flood events. Consequently, there is a need to enhance the capacity of the conduits to accommodate a larger volume of runoff and reduce the severity of flooding. To achieve this, the conduit areas were selectively increased in the locations closest to city roadways, as these conduits play a critical role in carrying the water from the entire area. The conduit area increment is only done in those conduits that are closest to city roadways since these conduits drain out the entire flood water from the area. Rather than increasing all the drainage conduits of the network, only the conduit areas were increased, which has an area of 2 m^2 (1 m bottom width and 2 m depth) currently. By judging from the inundation map and zonal statistics, some of the conduits are increased to an area of 6 m^2 (3 m bottom width and 2 m depth) and others are to 4 m^2 (2 m bottom width and 2 m depth). So, the increment in conduit area is 4 m^2 and 2 m^2, respectively. This approach was adopted to ensure a cost-efficient design. The proposed drainage network, incorporating the incremented conduit areas, is presented in Figure 12.

Figure 13 illustrates the inundation map of the proposed drainage network, showing that no nodes experience any flooding or surcharge. The inundation depths would range from 0.02 m to 0.10 m after the increment of the conduits, a significant reduction compared to the current scenario, where depths ranged from 0.02 m to 0.31 m for a 100-year return period of rainfall. This marked change in the modeling results is noteworthy. It is important to note that apart from the conduit area modifications in the marked locations, no other model parameters or inputs were altered. Following the adjustment of conduit areas, the model was simulated again, revealing drastic changes in water level data. Average water level data for each sub-catchment has lessened to the extent that it can be considered negligible. The comparison can be seen in Figure 13 and Table 4. In the new design, no node faces flooding, while in the previous one, 55 junction nodes faced flooding among 665 nodes. The same thing happened in the case of conduits as well. In the previous condition, 143 conduits among 678 faced flooding. From Figure 14, we see that the water levels in the conduits have dropped to a great extent compared to the previous case. The maximum inundation depth has dropped in Naya Paltan at 89.06%, T&T Colony at 67.38%, Motijheel at 77.13%, Motijheel Colony at 68.12%, Shantinagar at 66.79%, and Rajarbagh 66.96%. Among all the areas, Purana Paltan becomes completely flood free. The existing flood is also negligible as the maximum inundation depth in the study area after the conduit area increment is a mere 0.10 m or 3.93 inches only. The flood extent also shows a drastic change in the proposed condition. Currently, when a 50-year return period rainfall occurs, it is predicted that around 93% area will get inundated while in the case of a 100-year return period, this percentage will rise up to 96%. However, in the proposed condition for 100-year return period rainfall, only a mere 34% area is predicted to face a minimum amount of inundation while in the previous case, it was severe inundation. From Table 4, it can be stated that, apart from T&T Colony and Motijheel Colony, the flood extent for 100 years return period in all the rest of the places is fairly negligible. Condition in Motijheel Colony and T&T Colony cannot be made better if not their average ground elevation is not increased. Due to their geographical location in a low-lying area, these two places are prone to flooding regardless of the conduit size improvement. This crucial finding highlights the diverse responses observed in different areas under the same revised drainage condition, which may be attributed to variations in imperviousness, slope, and storage depth.

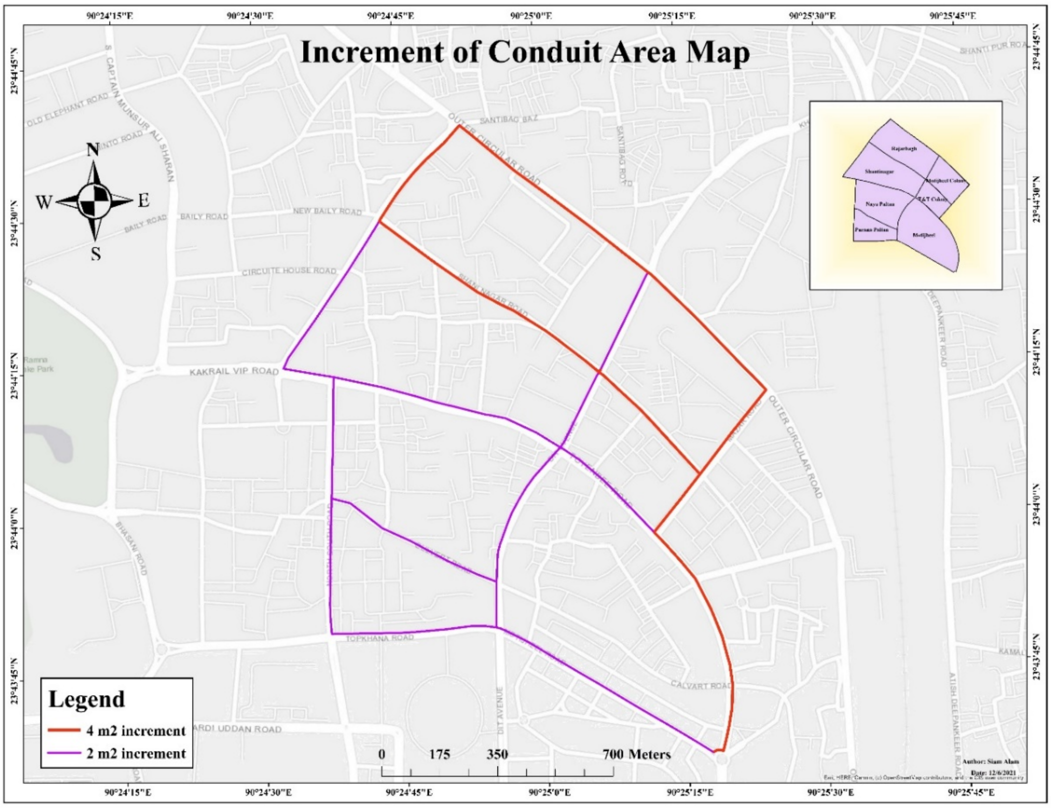

Figure 12. Proposed Revised Drainage Network

Table 4. Model Result Summary

Area Name	Inundated Area (Ha)			Maximum Depth of Inundation (m)		
	50-Year Return Period	100-Year Return Period	Proposed Condition (100-Year Return Period)	50-Year Return Period	100-Year Return Period	Proposed Condition (100-Year Return Period)
Naya Paltan	25.42	25.43	0.16	0.13	0.20	0.02
Purana Paltan	13.56	13.62	0	0.10	0.16	0
T&T Colony	9.46	9.48	8.48	0.20	0.29	0.09
Motijheel	31.03	35.05	3.14	0.14	0.21	0.05
Motijheel Colony	14.91	14.93	12.65	0.19	0.29	0.09
Shantinagar	24.96	25.37	10.42	0.22	0.31	0.10
Rajarbagh	27.33	27.33	19.80	0.22	0.31	0.10

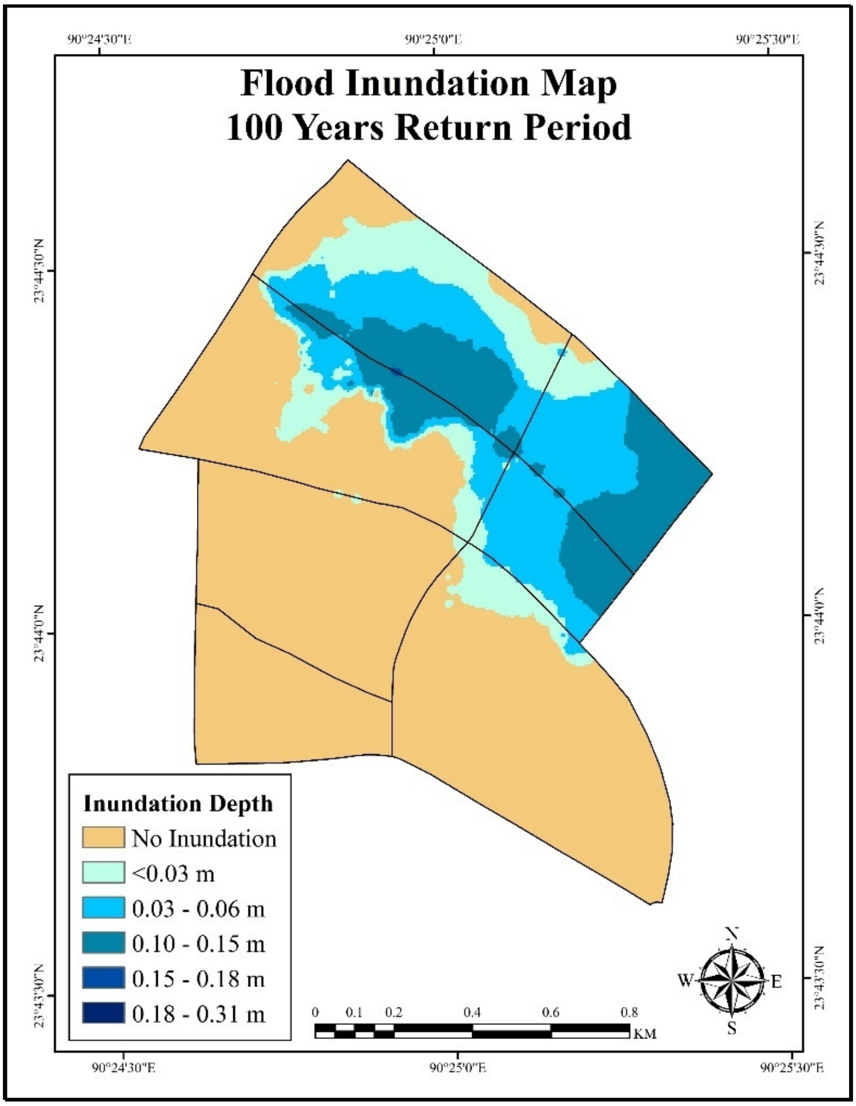

Figure 13. Flood Inundation Map for 100 Years Return Period Rainfall after Area Increment

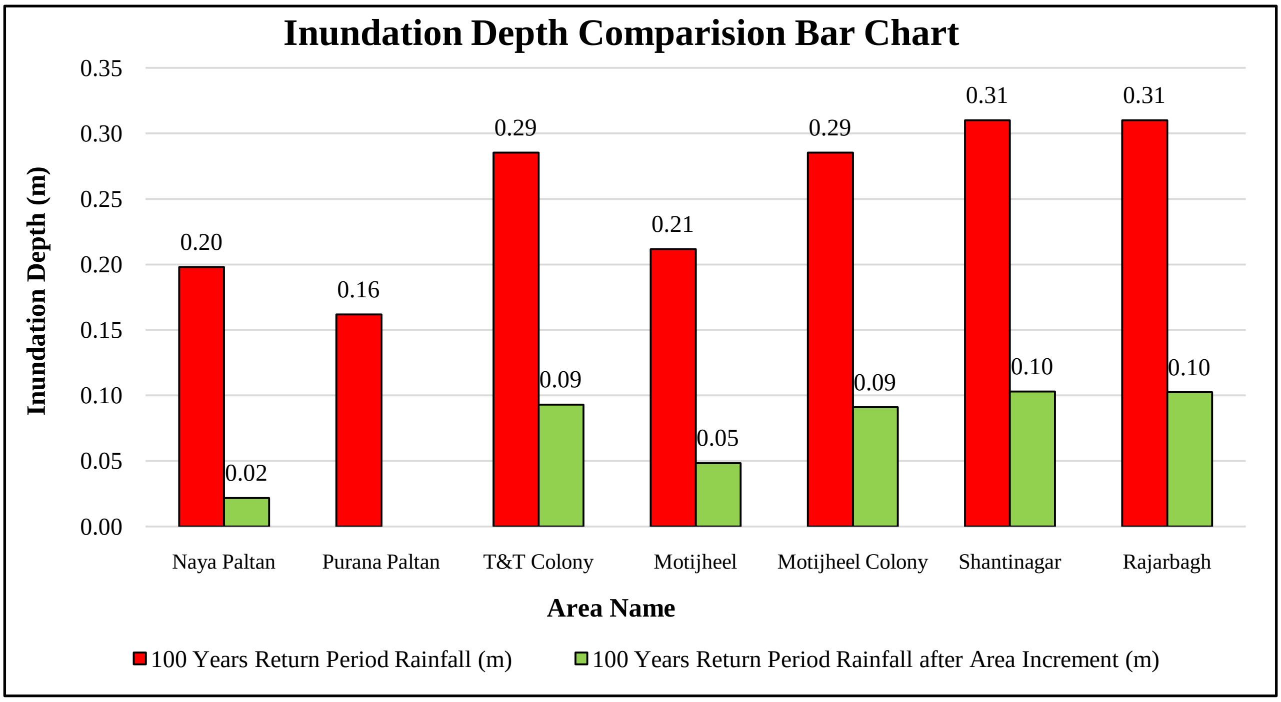

Figure 14. Comparison of Existing and Revised Drainage Network Zonal Average Water Depth in Junction

4. Conclusions

The escalating issue of urban flooding and drainage congestion, primarily driven by rapid urbanization, necessitates the implementation of more efficient flood management schemes in developing countries like Bangladesh. This study presents a comprehensive methodology for generating flood inundation and hazard maps in the study area, utilizing the 1-dimensional urban drainage model SWMM, considering both existing and extreme statistical scenarios. The findings reveal that certain areas, namely Shantinagar, Rajarbagh, T&T Colony, and Motijheel Colony, face severe threats from urban flooding. Despite substantial investments made to improve the drainage network, the situation remains unsatisfactory. The study demonstrates that the inundation depth can reach up to 0.61 meters during a 100-year return period precipitation event. Notably, low-lying areas are particularly vulnerable to flooding, which explains the heightened flood occurrences observed in Motijheel Colony and Rajarbagh compared to other sites across all simulation scenarios. The developed flood inundation and hazard maps provide crucial information for identifying flood-prone regions within the study area.

Addressing the challenges posed by urban flooding requires enlarging the capacity of drains to confine runoff within the drainage system, thereby reducing flooding and eliminating associated risks. Consequently, this study proposes a design for an optimized drainage network capable of effectively draining extreme flood flows. The findings clearly demonstrate the dependence of flood propagation on the carrying capacity of the drainage network and advocate for the necessary increment in drain size to control flooding in the selected urban area. The study highlights the effectiveness of increasing drain sizes in reducing the maximum depth of runoff within conduits to a level where no conduit or junction experiences flow surplus, which can lead to intense flooding. The proposed drainage network design serves as a valuable tool for flood forecasting and warning authorities, as well as policymakers, enabling them to prioritize flood-prone zones and implement appropriate measures to address the flood inundation problem in the Dhaka metropolitan area.

This study emphasizes the usefulness of the SWMM model as an effective tool for assessing urban floods. However, it is crucial to acknowledge that the accuracy of any drainage model depends on the reliability and availability of data. In this study, most of the dataset was collected from DWASA (Dhaka Water Supply and Sewerage Authority), but it is essential to recognize the limitations associated with these data sources. Furthermore, the study did not account for the dumping of waste and other materials in drains, which significantly contributes to urban flooding through blockages, along with the impact of non-disposable polymer products. Consideration of these factors would have enhanced the study's approximation of real-life flood scenarios.

In conclusion, this study highlights the severity of urban flooding and drainage congestion in the study area and underscores the importance of designing an effective drainage network. The developed flood inundation and hazard maps, along with the proposed drainage network design, provide valuable insights for flood management strategies and decision-making processes. Nonetheless, future studies should focus on improving data collection methods and encompass additional factors, such as waste dumping, to enhance the accuracy and applicability of findings, resulting in a more comprehensive understanding of the real-life scenario.

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