SIMULATION OF WATER LOGGING SCENARIOS USING SWMM: A CASE STUDY ON KHULNA CITY IN BANGLADESH

Md. Golam Kibria*[1], Md. Sabbir Hossain[2], Faysal Kabir Fahim[3], Sajal Kumar Adhikary[4] and Hrithik Nath[5]

[1] *Department of Civil Engineering, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail: kibriace1701088b@gmail.com*
[2] *Department of Civil Engineering, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail: sabbirhossain112ce@gmail.com*
[3] *Department of Civil Engineering, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail: faysalfahim1614.ff@gmail.com*
[4] *Department of Civil Engineering, Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, e-mail: sajal@ce.kuet.ac.bd*
[5] *Department of Civil Engineering, University of Creative Technology Chittagong (UCTC), Chattogram, Bangladesh, e-mail: hrithiknath.ce@gmail.com*

***Corresponding Author**

ABSTRACT

Khulna city in Bangladesh, being highly vulnerable to the impact of climate change, has been experiencing frequent water logging in almost every rainy season. The occurrence of frequent extreme rainfall events due to climate change and drainage congestion caused by human interventions aggravates the water logging situation. Therefore, the objective of this study is to explore the water logging scenarios in Khulna, Bangladesh. Ward No. 21 of Khulna City Corporation (KCC) is selected to develop an urban drainage modeling framework to simulate water logging situations using the widely applied EPA SWMMv5.1 software. In the current study, ten years of hourly rainfall data from 2013 to 2022 are analyzed to determine the maximum intensity and depth of water logging in the study area, which are found to be 28.34 mm/hour and 7.26mm, respectively. Land use and land classification (LULC) in the study area are delineated, and the corresponding areas in each LULC category are obtained using the ArcGIS software. Furthermore, the simulation is performed for different rainfall durations, which indicates that the water logging increases with longer rainfall durations. The findings also demonstrate that the water logging in field conditions is found to be higher than the simulated value due to drainage infrastructure failure, blockage, poor maintenance, and inadequate design of drainage systems. This study additionally offers some insights about the causes of water logging in Ward No. 21 of KCC and creates a foundation for further investigation into urban water logging on a larger scale using the SWMM model. Based on the findings, the study recommends some improvement guidelines for existing drainage infrastructures to mitigate water logging, including better maintenance, frequent cleaning of drains, and implementing water-sensitive development options for sustainable drainage systems. It is expected that the results of the current study could be supportive to the KCC authority and relevant policymakers in implementing and promoting improved urban drainage infrastructures in order to minimize the impact of water logging in the KCC area.

Keywords: *Water logging, SWMM, Urban Drainage, Rainfall Intensity, ArcGIS.*

1. INTRODUCTION

Water logging 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. Urban areas' high impervious surface area, poor drainage systems, and improper land-use planning are the main contributors to water logging (Islam et al., 2020). One of the largest cities in Bangladesh, Khulna, has a serious water logging issue during the rainy season. The city's infrastructure, residents' lives, and property all suffer substantial losses as a result of the water logging (Azad et al., 2022). Hence, it is crucial to comprehend the causes of the water logging 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 has become unable to handle the extra water during the monsoon season as a result of growing urbanization and unplanned growth (Ahmed et al., 2017).

A popular hydrologic and hydraulic modeling program for examining urban drainage systems is EPA SWMM 5.1. It is used to model how wastewater and stormwater runoff behave in sewage systems. The software is built on a dynamic simulation methodology that takes into account the interplay between precipitation, runoff, infiltration, and the hydraulic components of the drainage system. The EPA SWMM 5.1 model simulates the flow and water quality in the drainage system using a set of equations and offers a graphical depiction of the system's behavior. There are 31 wards in Khulna City Corporation (KCC), and Ward No. 21 of KCC is selected as the study area for this study. The water logging issue can be simulated in Ward 21 using EPA SWMM version 5.1 and examined in various circumstances. The study will involve gathering the information needed to create a hydrological model of the study area, including topography, land use, rainfall, and soil properties. The objective of this study is to simulate the runoff and drainage systems in the 21 No. Ward of KCC and evaluate the performance of the drainage systems under various rainfall scenarios using the widely applied EPA SWMM software.

2. METHODOLOGY

According to the methodology, potential mitigation strategies are assessed based on the outcomes of simulations and their efficacy is evaluated (Kumari et al., 2021). This method enables the discovery of efficient management techniques to deal with water logging in the study area.

2.1 Study Area Selection

Any hydrological study must begin with the selection of the study region. When water logging occurs, the choice of the study region should take into account a number of variables, including its frequency, severity, and effects on the local population and environment. These criteria, together with the study region's position within Khulna, a city that is vulnerable to flooding during the monsoon season, were taken into consideration while choosing the study area in the case of Khulna 21 no ward.

Figure 1 shows Ward No. 21, which is a neighbourhood in Khulna City's north that is bordered to the east, west, north, and south by Ward No. 20, Ward No. 22, Ward No. 23, and Ward No. 16. The ward has a population of about 31,000 people and a land area of roughly 2.63 square kilometres. With a mix of formal and informal settlements, as well as certain business and industrial districts, the ward is largely a residential region. A system of roads and drains that are intended to regulate stormwater runoff and minimize water logging during heavy rain events services the ward. Water logging is a major issue in the region, especially during the monsoon season, due to increased development and inadequate drainage infrastructure.

Figure 1: Location of the Ward No 21 (study area) in Khulna City Corporation

2.2 Data Collection

2.2.1 Field Survey

In order to model and simulate the water logging situation in Khulna 21 No Ward accurately, it is necessary to gather data on the dimensions of the drainage system and the soil characteristics in the area. Figure 2 and 3 shows the measurement of drain and an outlet called Bat Tala Ghat. In the field survey drainage dimensions (length, width, depth) and soil characteristics of the sub catchment were measured. Invert elevation of the drains was collected from the KCC office and was validated by field measurement.

Figure 2: Measurement of Drain

Figure 3: Bat Tala Ghat Outlet

The Horton's infiltration equation is a mathematical model used to describe the rate at which water infiltrates into the soil surface. It is expressed in units of inches per hour (in/hour) and is widely used in hydrology and soil science. The equation can be expressed by Eq. (1), which assumes that the infiltration rate decreases exponentially with time, as the soil becomes saturated and can no longer absorb water at the same rate:

$$f(t) = f_c + (f_o - f_c) e^{-kt} \quad (1)$$

Where, f_o is the initial infiltration rate at which water infiltrates into the soil at the beginning of the process when the soil is dry, f_c refers to the final infiltration rate, which is the limiting value that the infiltration rate approaches as the soil becomes completely saturated. Soil characteristics are important to calculate infiltration values. The soil of Khulna city is predominantly clay. Based on the soil characteristics, f_c was taken 1.27 mm/hour and f_o was taken 25.4 mm/hour. Manning's roughness coefficient was taken as 0.015.

2.2.2 Satellite Data

Stormwater modeling using SWMM requires short duration rainfall, 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 were collected from the Data Access Viewer-NASA Power (https://power.larc.nasa.gov/data-access-viewer/), which is freely available to download and use. The duration of hourly rainfall data adopted in the current study was taken as for 2013-2022 period that were collected in the form of an Excel CSV file.

2.3 Delineation of Sub Catchments and Land Use Land Cover Analysis

2.3.1 Area Calculation of Sub Catchments

The study area was divided into several sub catchments using the digital elevation model (DEM) in the ArcGIS platform. The study area was divided into 17 sub catchments, which is shown in Figure 4. Area of each sub catchment was measured by using ARCGIS. Shape file was created by the use of google earth pro. First, .kml file of each sub catchment was generated from the Google Earth Pro and the .kml file was then used to generate the desired shape file of the sub catchment. Width of the sub catchments is calculated by dividing the area with the longest flow path. Width and area were measured for each sub catchments. Area was measured from attribute table by creating of new field. The area was measured in m^2 and then it was converted to hectare for simulation purposes using SWMM software.

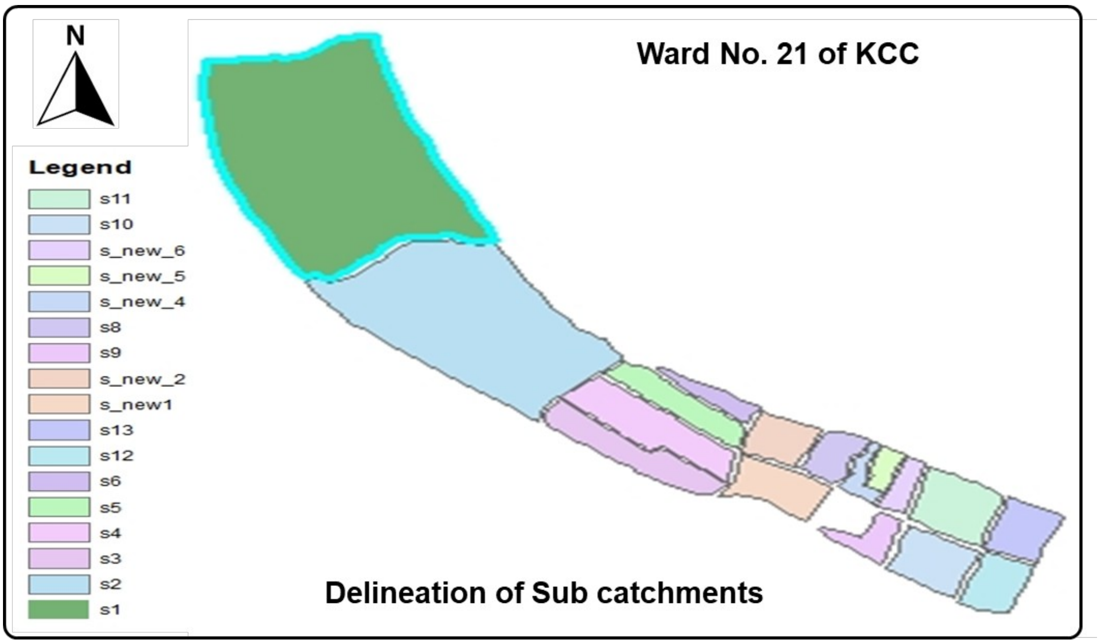

Figure 4: Delineated map of the sub catchments for Ward No. 21 of KCC

2.3.2 Determination of Land Use

Land use land classification (LULC) of the study area was obtained by using the ArcGIS software. At first, data was collected from the USGS Earth Explorer (https://earthexplorer.usgs.gov/) open accessible database. After that the shape file of the study area was used. Based on the LULC analysis of the study area, three major land use categories were identified, namely agriculture (22%), vegetation cover (16%) and covered urbanized area (62%). Hence, it can be concluded that imperviousness of the study area is 62%. This higher value of imperviousness is important for model simulation and significant for causing water logging in the study area by reducing infiltration. Figure 5 shows the land use land classification map of the study area.

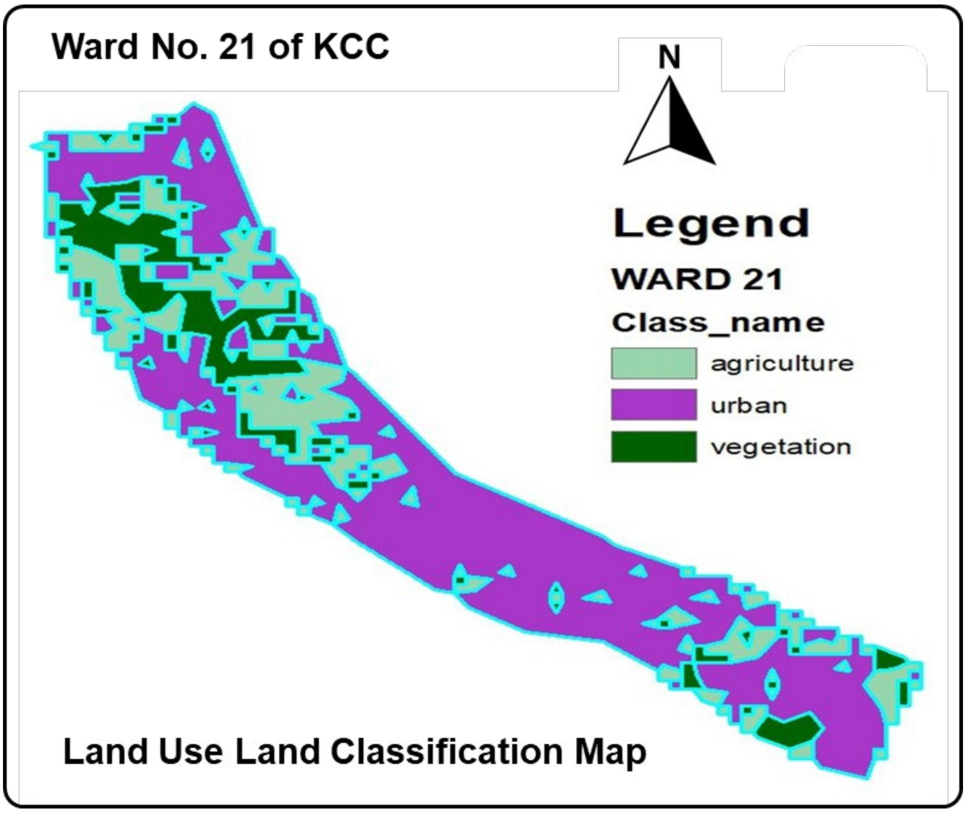

Figure 5: Land use land classification map for Ward No. 21 of KCC

2.4 Model Formulation

The hydrologic model in SWMM determines the volume and flow rates of runoff as well as the time and amount of rainfall that becomes runoff. It is made up of a number of parts that includes the following:

- **Rainfall**: To enter rainfall data into the model, either local weather stations or a rainfall generator can be used.
- **Infiltration**: To calculate how much rainfall seeps into the soil, the model employs the Horton infiltration method.
- **Runoff**: The model uses the Rational method to determine the quantity of runoff.
- SWMM's hydraulic model is used to simulate how water moves through the drainage system. It is made up of a number of parts, such as:
- **Nodes**: Nodes are places in the drainage system where water can enter, escape, or be diverted.
- **Links**: They stand in for the pipes, channels, or other water-flowing conduits.
- Storage units: These are the structures that temporarily store or permeate stormwater runoff, such as detention basins, wet ponds, and infiltration basins.
- **Outfall**: Outfalls are the locations where water exits the drainage system, such as when it is discharged into a river or another natural body of water.

In order to create a model in SWMM, 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. For the hourly rainfall data of 2013-2022, From these data maximum intensity of water logging was found. Using the maximum intensity, model was run for different rainfall duration. The model setup for water logging simulation in the study area is shown in Figure 6.

Figure 6: Model setup for water logging simulation in the study area in EPA SWMMv5.1 software

3. RESULTS AND DISCUSSION

3.1 Summary Results

The model was run for the time period of 2013-2022 hourly rainfall data. After that various simulation results were formed.

Table 2: Calculated runoff from different sub-catchments in the study area

Sub catchment	Total rainfall (mm)	Total infiltration (mm)	Total imp runoff (mm)	Total per runoff (mm)	Total runoff (mm)	Total runoff ($x10^6$ liters)	Peak runoff (m^3/s)
S1	20555.22	6164.27	12744.7	1646.85	14391.56	6328	3.38
S10	20555.22	6065.72	12744.99	1745.48	14490.48	557.89	0.3
S11	20555.22	6061.96	12745.01	1749.26	14494.27	678.34	0.36
S12	20555.22	6079.9	12744.93	1731.28	14476.22	723.82	0.39
S13	20555.22	6041.84	12745.13	1769.4	14514.53	458.66	0.24
S2	20555.22	6197.71	12744.65	1613.39	14358.04	4242.82	2.26
S3	20555.22	6106.05	12744.84	1705.11	14449.95	732.62	0.39
S4	20555.22	6102.71	12744.85	1708.46	14453.31	900.45	0.48
S5	20555.22	6099.99	12744.86	1711.18	14456.04	531.99	0.28
S6	20555.22	6100.81	12744.86	1710.35	14455.21	212.49	0.11
S8	20555.22	6012.03	12745.37	1799.28	14544.66	311.26	0.17
S9	20555.22	6074.15	12744.96	1737.05	14482	262.13	0.14
snew1	20555.22	6031.89	12745.2	1779.38	14524.57	537.41	0.29
Snew2	20555.22	6018.31	12745.31	1792.99	14538.3	404.17	0.22
snew4	20555.22	3634.97	15828.55	1092.95	16921.5	181.06	0.08
snew5	20555.22	6009.55	12745.4	1801.78	14547.18	144.02	0.08
snew6	20555.22	6029.12	12745.22	1782.16	14527.37	199.03	0.11

The above table describes runoff for each sub catchment. For sub catchment S1 the peak runoff is higher than other sub catchments. The model also shows the simulation results for node flooding, conduit surcharge, and outfall loading also.

Table 3: Summary of Conduit Surcharge

Conduit	Both ends full (hour)	Upstream full (hour)	Downstream full (hour)	Above normal flow (hour)
C22'	0.01	0.01	78459.93	0.01
C29'	0.01	0.01	79553.65	0.01
C42'	0.01	0.01	78459.93	0.01
C43	0.01	0.01	79553.65	0.01

3.2 Estimation of Wate Logging

Water logging over the study area was calculated as runoff for the elapsed time from the time series table by using Eq. (2) as follows:

$$Runoff\ Depth(mm) = (Q/A) \times time \quad (2)$$

Where, Q is the surface runoff (m^3/s), A is the area of the sub catchment, and time is 15 minutes. From each sub catchment runoff depth was measured. It is water logging depth of the sub catchment. From the water logging depth of each sub catchment average water logging depth was found. Figure 7 shows the part of simulation results when maximum water logging occurred. It was found that maximum average water logging depth was 7.26 mm.

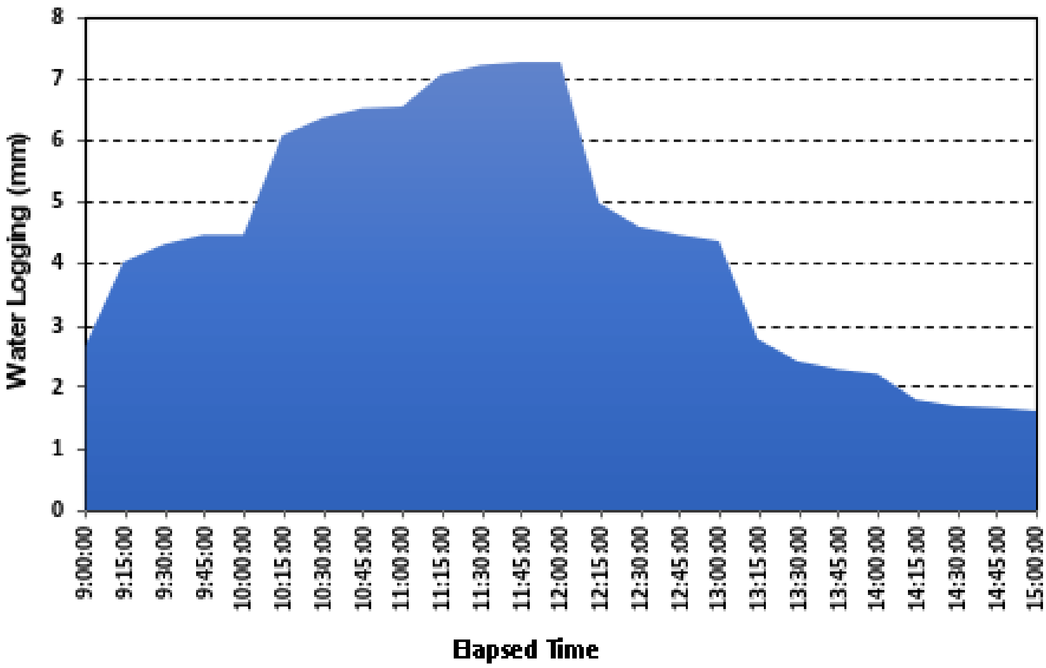

Figure 7: Water Logging depth in the study area over the elapsed time

Maximum water logging happens at 1754th day. It was 21 October, 2017. The maximum intensity which caused highest water logging is 28.34 mm/hr.

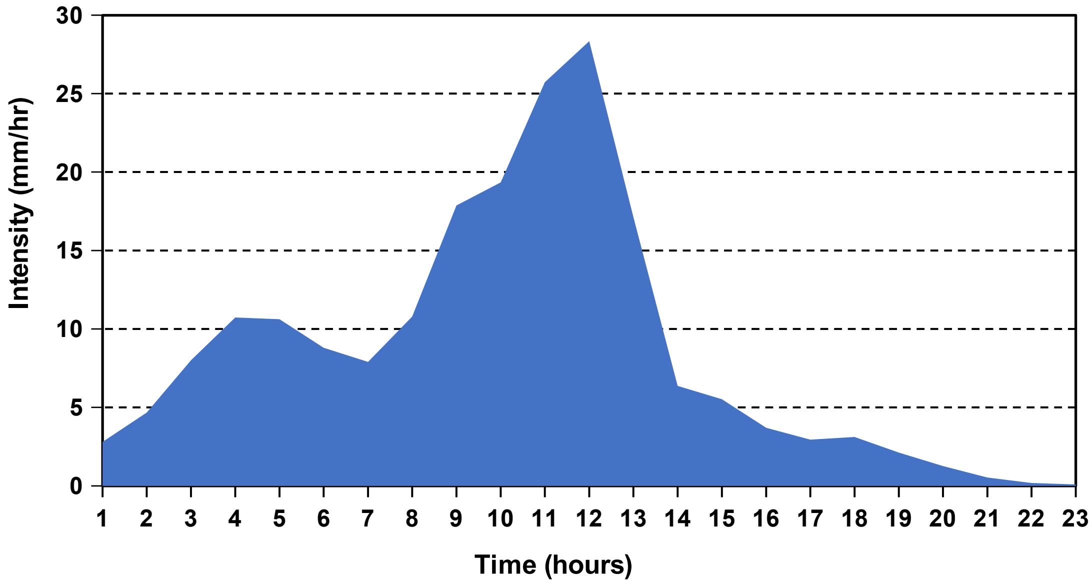

Figure 8: intensity vs time graph for maximum water logging

Figure 8 is the maximum intensity vs time graph and by taking the maximum intensity of 28.34 mm/hour, for different time duration the model was run. The model was run for 3 hours, 4 hours, 5 hours and 6 hours. Then, the average water logging depth was calculated in the Microsoft Excel spreadsheet application. Different scenarios of water logging over the study area for different durations of rainfall were generated. For demonstration purpose in the current study, water logging depths were generated for four rainfall durations, namely 3-, 4-, 5-, and 6-hours rainfall durations. which are presented in Figures 9-12.

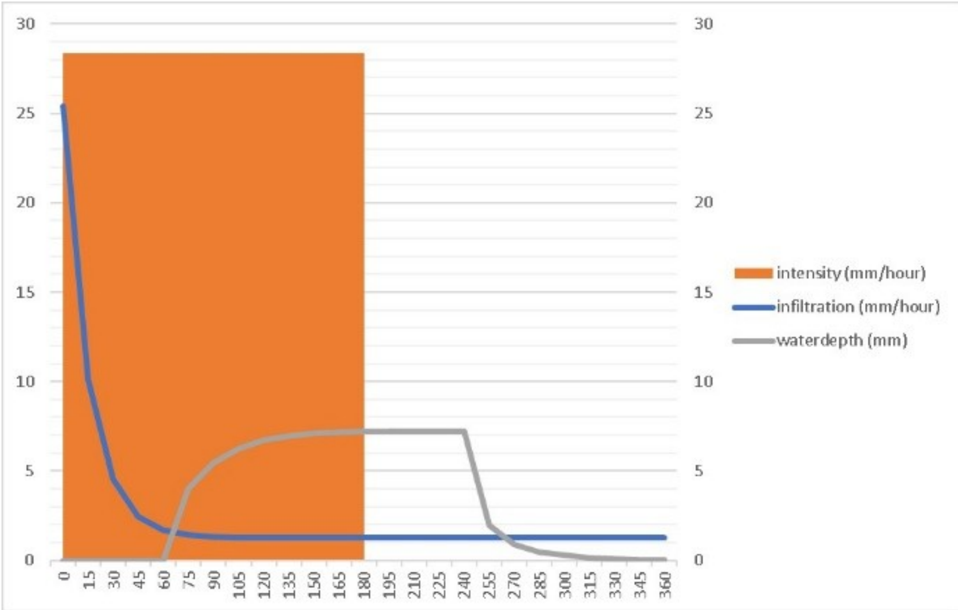

Figure 9: Water logging scenario over the study area for 3 hours of rainfall

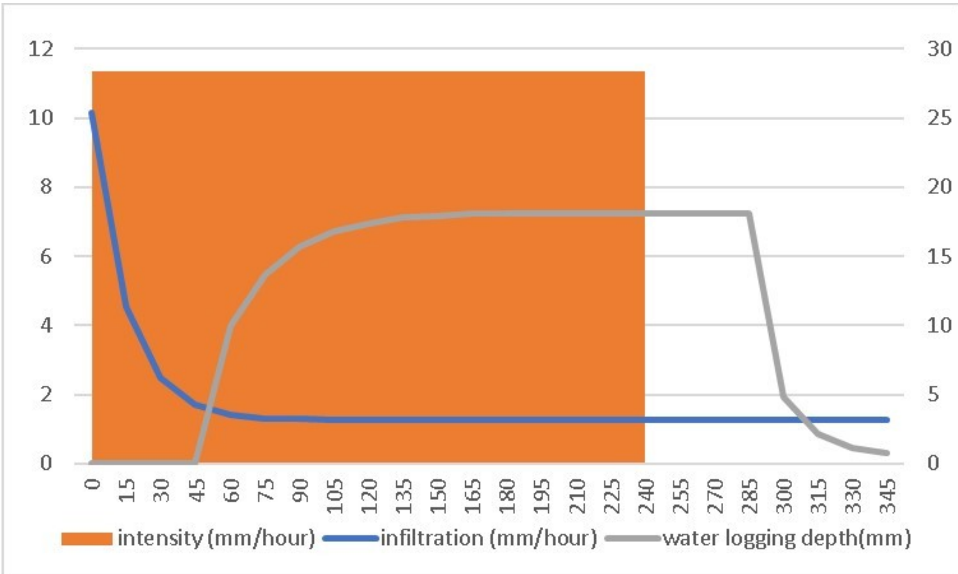

Figure 10: Water logging scenario over the study area for 4 hours of rainfall

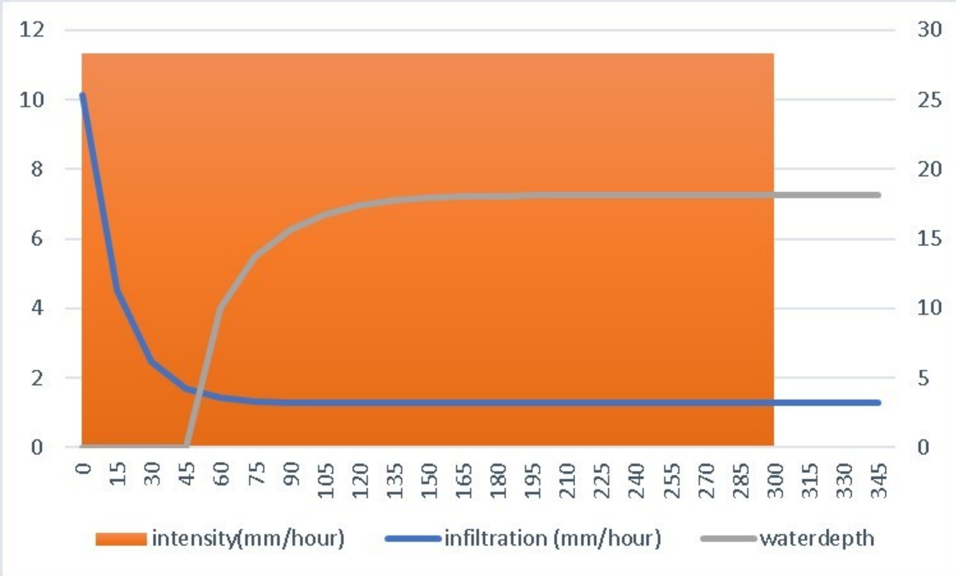

Figure 11: Water logging scenario over the study area for 5 hours of rainfall

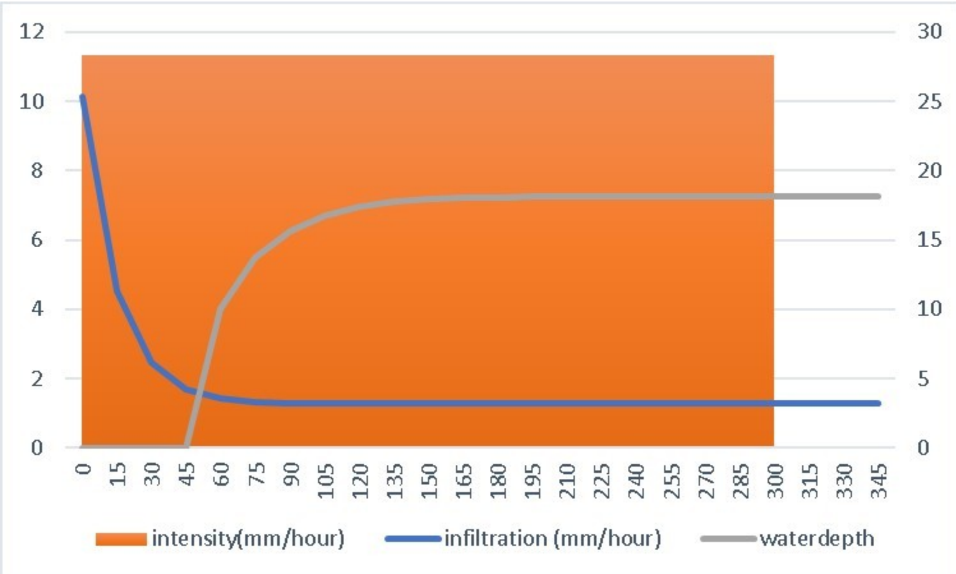

Figure 12: Water logging scenario over the study area for 6 hours of rainfall

As can be seen from Figures 9-12, the water logging depth exhibits significant variations for different rainfall durations. In these figures X axis is for rainfall duration and Y axis is for infiltration, intensity and water depth. The model was run for different rainfall durations and these are the outputs. Water logging depth are different for different rainfall duration but they are close values. If rainfall duration increases water logging depth increases. Water logging depth is not independent with rainfall duration. In simulation drains are considered as they have 100 percent capacity but real scenarios are different. Most of the drains are blocked. Defective drainage infrastructure, blockages, inadequate drainage design, and poor maintenance all contribute to water logging in the studied region. These are the main reasons why the simulated value is less than the practical value. It is recommended that the drainage system should be maintained regularly and sufficiently constructed to handle the current and future rainfall events in order to reduce water logging in the study area. In addition, appropriate planning for managing the drainage system should be developed to address the local water logging problems.

4. CONCLUSIONS

Based on the findings of the current study, the following conclusions can be drawn:

- The maximum rate of rainfall was 28.34 mm/hour and the maximum water logging depth was 7.26 mm after analyzing 2013-2022 hourly rainfall data.
- According to the simulation's findings, water logging gets worse as rainfall lasts longer.
- The difference between the observed and simulated levels of water logging is due to inadequate drainage infrastructure, blockages, poor maintenance, and improper drainage design.
- Thus, water logging in the study region can be successfully reduced by upgrading the drainage infrastructure, performing routine maintenance, and using the right drainage design.
- The study serves as a foundation for further investigation into urban water logging and the use of SWMM in hydrological modeling.
- The results of this study can aid urban planners and decision-makers in creating practical plans for dealing with water logging in the study area and other areas that are similar.

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