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Application of SWMM for Urban Storm Water Management: A Case Study of Hyderabad City

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Abstract

Urban stormwater management involves strategies to mitigate the adverse effects of urban runoff. These strategies aim to reduce flood risk and enhance the environmental values and sustainability of urban water systems. But the effective urban stormwater management is highly dependent on the factors such as spatial variability of urban watershed characteristics as well as the scale of the area under consideration. This insight has prompted increasing utilization of physically based urban watershed models such as the Environmental Protection Agency (EPA) Stormwater Management Model (SWMM). Thus, in this study we utilized SWMM for modeling the dynamic runoff response in a stormwater zone of Hyderabad, India. The study results are validated for a particular observed 48-hour storm event occurred on 3rd and 4th of October 2015. Five years (2010-2014) of hourly rainfall data have been used to estimate the design storms with 2, 5, 10, and 25 years return periods using Gumbel distribution. The results indicate that the existing drainage system is insufficient to withstand the generated runoff by the design storm of 2-year return period and causes notable flooding. The water elevation profile generated from the initial node, representing the beginning of the drainage system, to the outfall indicates that the flooding occurred at the outfall during the peak precipitation event. Also, the hydrographs which were developed through SWMM at different links and outfalls are crucial in designing the sumps or ponds and determining pump capacities, aiding in effective stormwater management practices.

Keywords: Urban stormwater management, EPA-SWMM, GHMC, Water elevation profile, Runoff response.

1. INTRODUCTION

Managing the quantity and quality of stormwater runoff presents a complex challenge that is becoming more critical for urban environments due to rapid urbanization. Recognizing the impacts of urban drainage systems, combined with socioeconomic considerations, underscores the importance for researchers to gather data on how these systems react to different weather conditions. Ideally, stormwater systems should be designed and assessed using catchment modeling tools that fully replicate the key processes involved in stormwater generation and transmission (Choi et al., 2002). The use of spatially distributed and physically based models increases the capability to simulate the dynamic response of urbanizing catchments. The Storm Water Management Model (SWMM), a modeling tool utilized since the 1970s, exemplifies such an approach (Huber et al., 1983). Historically, stormwater drainage systems in India were designed for rainfall intensities of 12-20 mm/hr (Londhe et al., 2022), specifically tailored for urban flood scenarios. However, at the present scenario, a dramatic increase in urban surface runoff has been observed due to increase in impervious surfaces and decrease in infiltration and evaporation associated with urbanization (Wang et al., 2022). Consequently, drainage systems must now be redesigned with sufficient capacity to manage larger volumes of surface water and implement mitigation measures to reduce peak flow rates to pre-urbanization levels. As for the design of these drainage systems, the estimation of the peak rainfall events occurred in the near past and the associated surface runoff generated due to these events becomes necessary (Aronica et al., 2000). In the past few years, significant attention has been directed towards the creation of digital simulation models aimed at assisting in the design, assessment, and administration of urban drainage systems (Rangari et al., 2018). This study presents an application of such a model, the Storm Water Management Model (SWMM), which integrates information from GIS databases in ERDAS and ArcView environments. The primary objectives of this study are (i) to develop outfall hydrographs and water elevation profiles along the drains, (ii) evaluate the runoff volume and the water level depths during flooding for a 2-year return period storm, and (iii) assess the feasibility of integrating the existing drainage networks with the interflow to reduce the impact of urban flooding.

2. STUDY AREA & DATA USED

2.1. Study Area

The city of Hyderabad was established by Mohammed Quli Qutub Shah in 1591, located on the southern bank of the Musi River. Positioned on the Deccan plateau at an altitude of 536 meters above sea level, it sits between 17.59°N & 17.18°N latitudes and 78.69°E & 78.12°E longitudes. In terms of its geographical area, Hyderabad became the fourth largest city of India with a spread of 650 km^2. The Greater Hyderabad Municipal Corporation (GHMC) divides the city into different stormwater zones, with each being the sub basins of the catchment area itself. The zone considered for this study, is shown in Figure 1 (a), has an area of approximately 173.68 km^2 and consists of 15 delineated sub-catchments. Records from the Indian Meteorological Department (IMD) indicate that the months of July, August, and September typically experience heavy rainfall, contributing more to Hyderabad's annual average rainfall value, which is approximately 847 mm. The city's unique topography, characterized by its undulating terrain, often leads rainwater to flow into low-lying areas, resulting in rapid inundation. With a population of around 11 million , Hyderabad experiences localized flooding mainly in built-up and low-lying areas, as well as in the vicinity of the water tanks. The process of urbanization in Hyderabad has led to an enhancement in impervious surfaces, intensifying runoff rates and overwhelming the designed capacity of the drainage system.

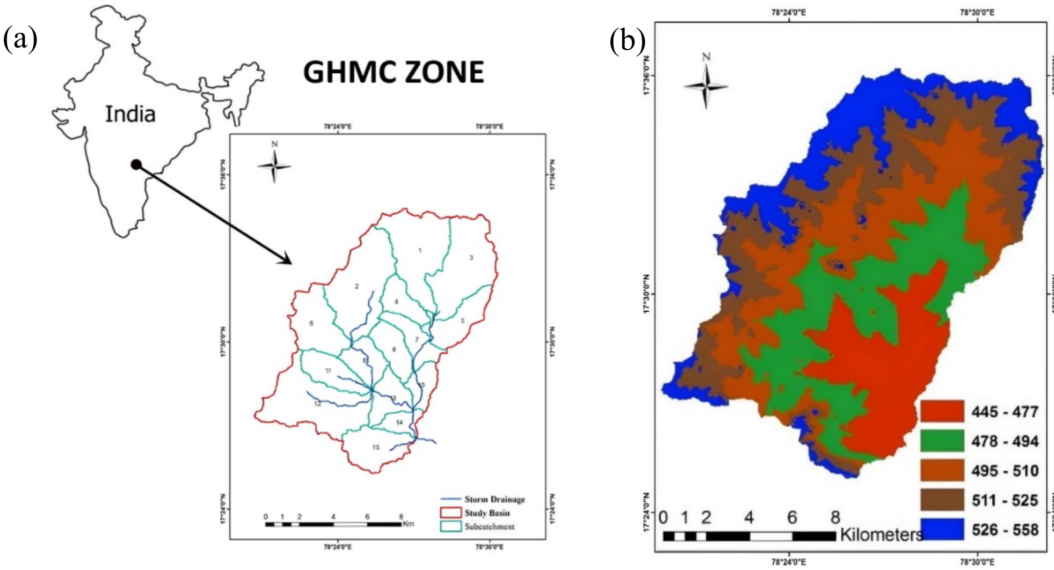

Figure 1. (a) Delineated Map and (b) Digital Elevation Model of GHMC Stormwater Zone

Consequently, frequent flooding in Hyderabad is primarily attributed to human factors rather than meteorological or hydrological factors. Datasets used for this study includes the Digital Elevation Model (DEM), which was obtained from Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 m. The elevation of this area varies from 445 m to 558 m as shown in Figure 1(b). By using the DEM data, the percentage slope map was prepared, and colour coded according to the steepness of the terrain. The land use land cover map was prepared using the images acquired through Landsat 8 Operational Land Imager/Thermal Infrared Sensor captured on twenty-first of May, 2015. Identification of various land covers in the study area was based on the digital image downloaded from Earth Explorer as reference. Maximum likelihood classification method was used to process the raw data into different classes of land use and the final map was prepared as shown in Figure 2(a). Soil map for the study area (Figure 2(b)) was obtained from National Bureau of Soil Survey and Land Use Planning (NBSS).

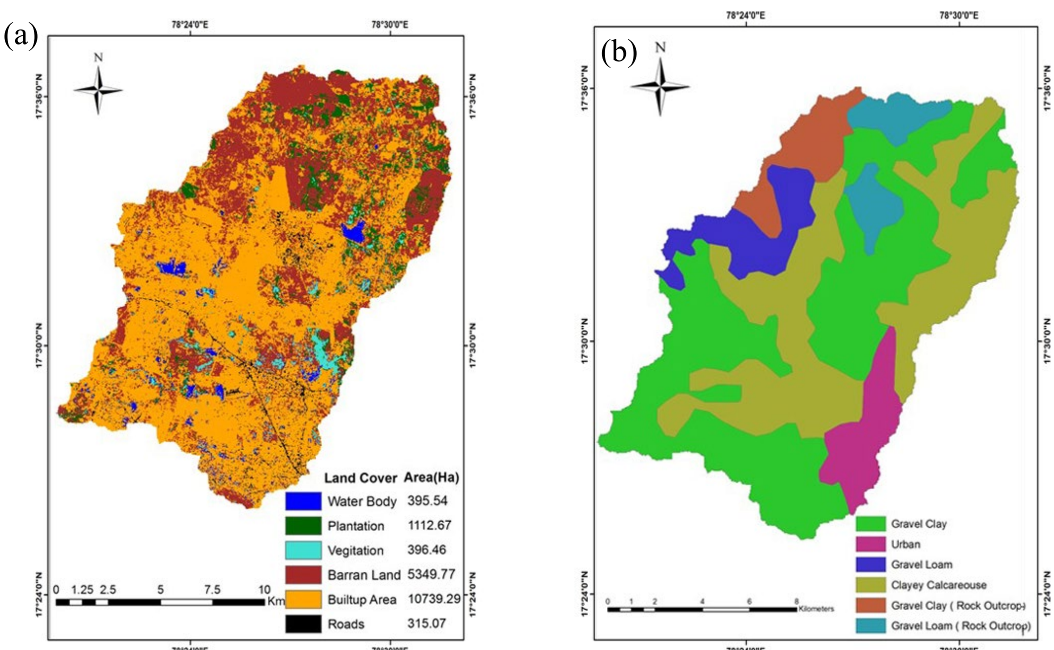

Figure 2. (a) Land Use Land Cover Map and (b) Soil map of GHMC Stormwater Zone

3. METHODOLOGY

In this study, a systematic approach was undertaken to address the management of stormwater runoff. Initially, the study area was delineated using base maps, focusing on key features such as drainage networks, pumping houses, and outfalls. Subsequently, land use classification was performed to distinguish between pervious and impervious areas, while considering surface roughness characteristics to assess the storm runoff. The process of estimating sub-catchment parameters, such as Manning's coefficient and depth of depression storage, has been tiresome in the traditional calibration processes, which typically involve a time-consuming and laborious search for precise values of numerous model parameters. Catchment data was compiled using ERDAS image processing software/ArcView database, and transformations were carried out to produce the required input information for operating the EPA-SWMM model to simulate the surface runoff. The contour map of the study area was digitized, and the DEM was used to generate a slope map for identifying flow directions. Five years of hourly rainfall data was utilized to estimate design storms for various return periods, including 2, 5, 10, and 25 years. Evaluation of existing drain cross sections was done to determine the adequacy of stormwater runoff conveyance. With the help of mathematical modeling, water elevation profiles along the channels and outfall hydrographs were developed for design storms for a 2-year return period. Finally, strategies were devised to mitigate the impacts of anticipated short-term rainfall events attributed to climate change. EPA-SWMM model utilizes the mass-momentum conservation equation that governs the unsteady flow through drainage network of the channels and pipes, in order to model the catchment hydrology. In hydrology and fluid mechanics, "kinematic" and "dynamic" methods refer to different approaches for routing water flow through a channel or a network of channels. The kinematic wave method of routing is unable to deal with processes such as back water effects, pressurized flow, flow reversal, and non-dendritic layouts. EPA-SWMM involves a dynamic wave routing for a conduit, combinedly solving the continuity (Equation 1) and momentum (Equation 2) equations known as Saint Venant equation (Saint-Venant, 1871) which is presented as:

$$\frac{\partial Q}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \tag{2}$$

where, 'x' represents the distance along the conduit, 't' denotes time, 'A' stands for cross-sectional area, 'Q' represents flow rate, 'H' indicates the hydraulic head of water in the conduit (comprising elevation head and any potential pressure head), 'S_f' signifies the friction slope (head loss per unit length), 'h_L' denotes the local energy loss per unit length of conduit, and 'g' represents the acceleration due to gravity. This study utilizes the St. Venant's equation for the routing of collected runoff from the sub-catchments through the entire drainage network. This comprehensive methodology offers a framework for effective stormwater management in the study area, providing insights for sustainable urban development.

4. RESULTS AND DISCUSSION

4.1. Design Storm Selection and Model Validation

Hourly rainfall data for five years (2010-2014) was gathered from IMD for the gauge station located at Begumpet Airport in Hyderabad and was subsequently examined. The Gumble Extreme Value (EVI) distribution method was employed to determine the design rainfall corresponding to various return periods, using the annual maximum hourly peak values as the input data. To validate the SWMM model with measured field data, a 48-hour continuous storm event occurred on the 3rd and 4th of October, 2015, was chosen. Observed rainfall and water level data were used to estimate model performance at the junction of Kukatpalli nalla and chemical nalla within the basin. The water level data was recorded using an automated water level recorder installed at the Hyderabad Metropolitan Water Supply Office in

Balanagar (17.4622° N, 78.4463° E). Results showed a good agreement between the predicted and observed water levels, as seen in Figure 3 for a time period of 48 hours.

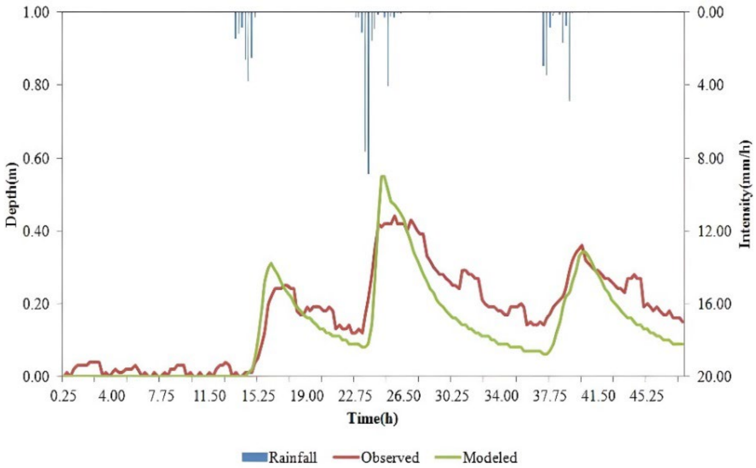

Figure 3. Model validation performed with observed and modeled water levels from 03rd and 04th of October 2015 (48hr)

4.2. Model Simulation and Calibration

The SWMM model is crafted to replicate the runoff of a drainage basin based on predetermined rainfall patterns. The entire watershed is divided into a finite number of smaller units or sub-catchments, each defined by its hydraulic or geometrical characteristics. Runoff from these sub-drainage areas converges into a single outlet, which connects to a junction or drainage node, then flows into the main drain, ultimately reaching the outfall. The model simulation results depict hydrographs for a 2-year return period at the outfall, as illustrated in Figure 4 (a). Flooding happens when the water level surpasses the designated maximum depth for the drains, resulting in the system experiencing water loss. From the model analysis, it was found out that the water level exceeded at the outfall and ultimately caused flooding.

SWMM can produce profile plots that illustrate the variation in water surface depth along a sequence of interconnected nodes and links. This plot is termed as Water Elevation Profile. The plot's X-axis represents the length measured from the start of the first selected conduit to the outfall, while the Y-axis shows ground level and conduit elevations. It also includes the link ID and node ID. This plot closely resembles the Hydraulic Grade Line (HGL) profile in both appearance and functionality. Figure 4 (b) illustrates the water elevation profile for the model, starting from Node-1 to the outfall. The elevation begins at 482.75 meters at Node-1 and gradually decreases to 444.20 meters over a distance of 12,800 meters at the outfall, showcasing the change in water level between these points. Key nodes such as 2, 3, 4, 11, and 13 are marked along the profile.

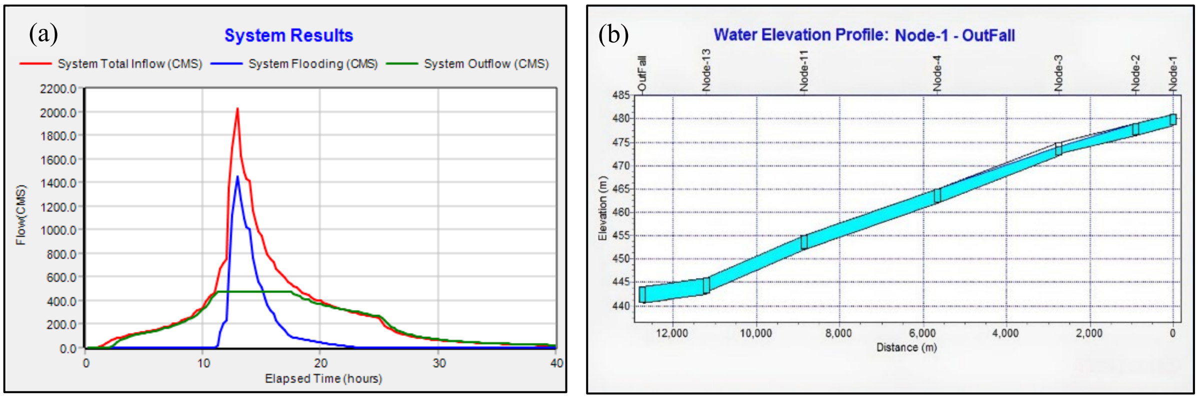

Figure 4. (a) Outfall Hydrograph (b) Water Elevation Profile generated along the drains for the design storm with 2-year return period

Analysis of the water elevation profile in the drains reveals their incapacity to handle the flow towards the outfall for a 2-year return period storm. As a result, excess water spills over and collects in lower areas, causing floods at different points or intersections. The average depth at each node point, the corresponding hydraulic grade line level and depth of water level at the time of flooding is shown in Table 1. It could be noted that the full drain depth capacity was reached at Node-13 and at the outfall during the flooding time. This analysis indicates that the existing drainage network of this stormwater zone is insufficient to manage runoff even from a 2-year return period rainfall.

Table 1. Details about the node depth and flooded water level

Node	Node Depth (m)	Flooded water level (m)
Node-1	2.25	2.23
Node-2	3.11	3.09
Node-3	3.01	2.99
Node-4	3.32	3.31
Node-11	3.83	3.81
Node-13	5.70	5.70
Outfall	5.70	5.70

5. CONCLUSIONS

- The drainage system for a stormwater zone of urban environment has been analyzed in the present study. EPA- SWMM model has been used to simulate the storm runoff for a period of two months and the same has been routed through the storm drains.
- Five years of hourly rainfall data has been used to estimate design storms for a recurrence interval of 2, 5, 10 and 25 years. The analysis indicated that the current drainage network in this stormwater zone cannot handle the runoff from a storm with a 2-year return period.
- As a consequence, this stormwater zone of Hyderabad experiences flooding and waterlogging on a yearly basis especially during the monsoon season.
- The elevation profile of the water surface along the drainage channels has been developed and we found that this storm runoff will lead to flooding at the areas where the depth of the drains was lesser than that of the flooded water levels.
- In summary, to reduce surface flooding, it's vital to regularly clean and maintain drains according to updated design standards. The obstruction caused by garbage and market waste highlights the importance of better waste management practices within communities. Structural modifications could also be made upon the drains as altering its geometric properties for better flood accumulation. By addressing these issues, we can mitigate the risk of flooding effectively.
- Application of water sensitive urban design techniques such as detention basin, rain garden,

green roof and infiltration basin can reduce the peak runoff, which should be implemented for the future development projects in the study area.

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