Sustainable Management of Stormwater to Prevent Urban Flooding Using SWMM

Anurag Swarnkar, Samir Bajpai, and Mani Kant Verma

Abstract Stormwater is an essential component of the urban water cycle, and its improved management is beneficial in managing water requirements of cities and improving urban life in environmental, economic, and social aspects. Increasing industrial and anthropogenic activities have significantly raised the necessity of discharging the runoff safely. In most of the cities, the existing stormwater drains are in the dilapidated stage, resulting in clogged drains, which causes frequent urban flooding. This paper elucidates the present status of management of the stormwater drainage system in Raipur City, capital of Chhattisgarh State, India. The estimation of the stormwater runoff and identification of the urban flooding hotspots are the principal objectives of this work. To develop an integrated approach for examining the effects of urban growth on surface runoff at the local level, the stormwater management model (SWMM) is employed. From the results, the drainage network of the city is found to be incapable of accommodating the inflow runoff, which results in the nodes getting flooded frequently. Therefore, the improper drainage system is the root cause of urban flooding at most of the hotspots. It is also found that the stormwater obtained from the rooftops is comparatively less contaminated as compared to the roadside drains and thus can be diverted and stored for further uses. This study will certainly help to develop effective stormwater management strategies, especially over the Raipur City.

Keywords Stormwater · Runoff · SWMM · Raipur City · Drainage

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Y. A. Mehta et al. (eds.), *Advances in Water Resources and Transportation Engineering*, Lecture Notes in Civil Engineering 149,
https://doi.org/10.1007/978-981-16-1303-6_7

1 Introduction

The world has witnessed rapid urbanization over the last few decades. One of the many complex problems resulting from increased urbanization is related to the management of stormwater, producing significant problems such as regular flooding, erosion, sedimentation, drainage problems [1–4]. The point and non-point source release of various pollutants is also adversely affecting the stormwater quality. Improper management of stormwater may lead to economic losses [5]. Stormwater management is the process of managing the quantity and quality of stormwater by using both structural or engineered control devices and systems. Stormwater runoff occurs when the rain falls over the land surface, such as roads, parking lots, rooftops, and other impervious surfaces that prevent water from soaking into the ground to the landscape. This increases the quantity of stormwater runoff generated during the monsoon season. Estimation of such runoff reaching the storm sewers, therefore, is dependent on the intensity, duration of precipitation, characteristics of the tributary area, and the time required for such flow to reach the sewer [6–10]. The intense rainfall events occur frequently over the urban regions, especially due to climate change, which further deteriorates the problems [11–18]. In this regard, proper stormwater management is pivotal.

Sustainable stormwater management practices tend to reduce the volume and remove the pollutants from runoff generated on their development sites lowering the impact of stormwater runoff [19–21]. Therefore, it is essential to develop a low-impact development for managing stormwater along the roadways, parking lots and on the nalas and river banks.

Stormwater modeling has a major role in preventing issues such as flash floods and urban water-quality problems. However, in-detail modeling of large urban areas is time-consuming. However, modeling of large urban is time-consuming as detailed input data is required for model calibration. Stormwater models with low spatial resolution may be cherished if the results provided by the model are satisfactory.

Despite the defects in the input data, the process adopted in this study for catchment delineation and subdivision is relatively fast and accurate. Developing a low-resolution sub-catchment for Storm Water Management Model (SWMM) is a complex task. However, SWMM provides acceptable results for such cases too [22]. Thus, SWMM is applied in this study.

2 Study Area and Data Used

Raipur is the capital of Chhattisgarh State, India, and expanses from 21.20° to 21.32° latitude and 81.58° to 81.68° longitude [22, 23]. The surface runoff from the drainage system in Raipur City embraces of a hierarchical system of natural and man-made drains, water bodies that ultimately discharge into River Kharun flowing through the west side of the city [20]. The current stormwater collection network seems to be unplanned as well as inadequate, with coverage of a mere 6.48% of total area with a total length of drainage network being 63.58 km, resulting in frequent overflows. The low carrying capacity and poor conditions of the stormwater drain in some areas have resulted in constant inundation of the majority of areas in the city, especially the low-lying areas. Due to the lack of the data availability, it was difficult to carry out the modeling for the whole Raipur City. Since Raipur City is categorized into different wards, a small drainage area of a particular ward was taken for detailed analysis. The selected area is the V.V. Vihar colony (ward no. 27, zone no. 2), presented in Fig. 1.

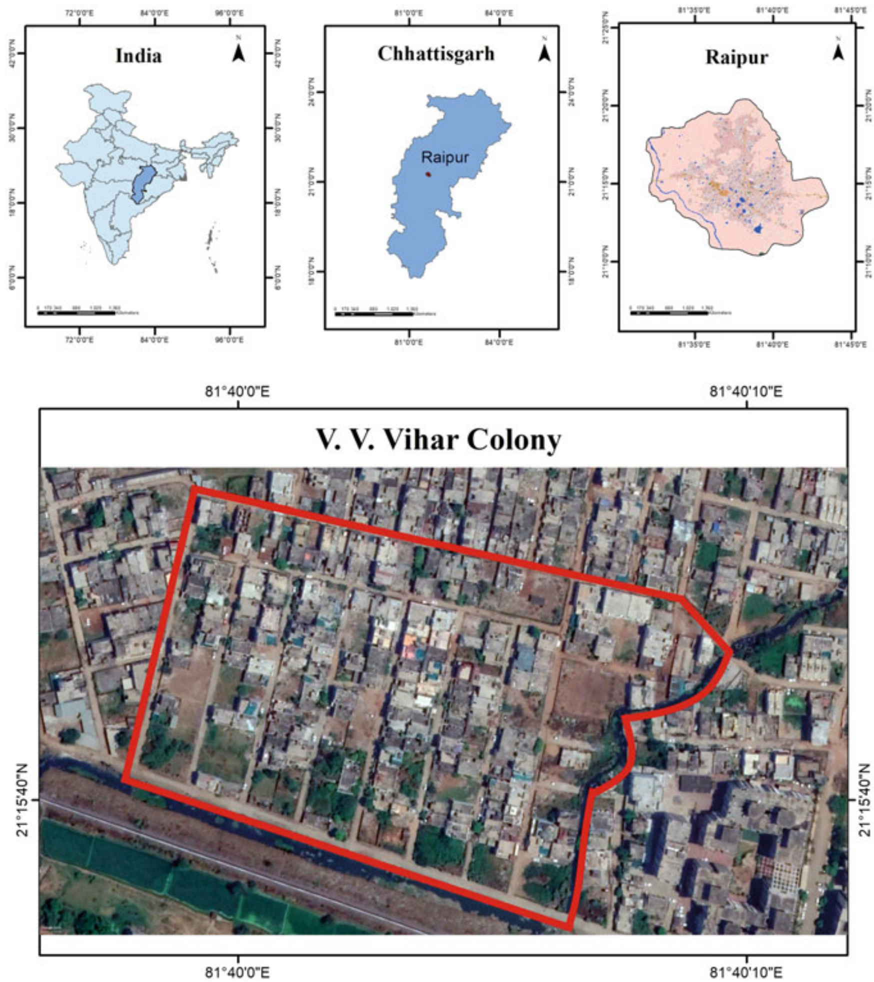

Fig. 1 Location of V.V. Vihar colony from ward no. 27, zone no. 2, Raipur District, Chhattisgarh

3 Methodology

As the study deals with the urban stormwater management, it is necessary to find the boundary of Raipur urban City. This was done in ArcGIS 10.1, wherein a map downloaded from the Bhuvan website was imported. Thereafter, the map was georeferenced, taking four points within the map, coordinates of which were already known. For georeferencing, it is necessary to take at least three points within the map; the coordinates of the fourth point is then taken automatically. This georeferenced map was exported and was used as the base map for drawing the boundary of the Raipur City. A high-resolution map was also downloaded from Google Map Downloader. Although the map downloaded was a picture without any properties, it helped explore various locations of the city. A DEM is taken as the input file for plotting the contours and the slope map. The contour map and slope map helps us to define the direction of the flow, identification of the low lying areas, etc. Both the maps were prepared in ArcGIS 10.1. The slope of the study area was calculated by the percent rise method using the Arc-Hydro tools. The highest slope of the Raipur City calculated using ArcGIS 10.1 was 113.27%, whereas, for the flat surface, it was 0%. To prepare the contour, we have to process the DEM using the tool 'focal statistics' so that all the tiles in the DEM are converted into circles from the square.

The data obtained from Municipal Corporation Raipur was imported in ArcGIS 10.1. The spatial reference of the data obtained was different from that used to adopt while working in ArcGIS. The spatial reference given to all the data is WGS_1984. The data was exported in Google Earth by creating KML file using the tool conversion tool 'layer to kml.' All the data were visualized in Google Earth to get the real scenario of the study area, such as the number of buildings, roadways, drainage networks, and open space. After importing all the datasets, attributes were prepared and calculated as per the new spatial reference. To calculate the attributes, the spatial reference of the map layer has to be set as WGS_1984 UTM Zone 44 N. The spatial reference for the map layer is WGS_1984 UTM Zone 44 N, whereas the data which are included in that map layer has WGS_1984 as their spatial reference. Low lying areas were identified and located using all the prepared datasets. The dark tiles in the DEM show the location having low elevation. The DEM was overlapped with the high-resolution city map, adjusting the transparency of the DEM layer; the low lying areas were marked. Out of the marked location, V.V. Vihar Colony was selected for the analysis.

Many other low lying locations were also obtained from other sources such as news reports, local government reports, and survey other than the analysis done in ArcGIS 10.1. Some of the low lying areas were V.V. Vihar Colony, Jalvihar colony, forest colony, RDA colony, Anupam Nagar, Indravati colony, Khadan Nagar, Mahavir Nagar, Krishna Nagar, Choubey Colony, Panchsheel Nagar. A customer survey was also done in some of the above areas to get information about the current scenario. It was found that some of the areas have recovered from poor drainage systems resulting in a lack of floods. The people residing in respective areas told that after

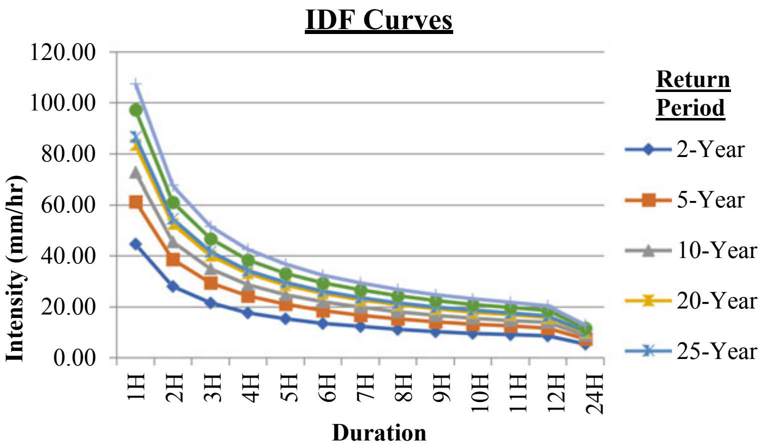

Fig. 2 IDF curves over the study area

retrofitting of drains, the stagnation time of the stormwater has reduced compared to earlier situations.

SWMM 5.1 is used to manage the drainage system of the study area. Since the data prepared in ArcGIS 10.1 cannot be exported/imported in SWMM 5.1, we have to use the image file of the study area as the backdrop image and draw all the objects by tracing the backdrop image. To run the model in SWMM, it is necessary to feed the rainfall time series data in an hourly format. Computation of hourly data from daily data was done using the Indian Meteorological Department IMD 1/3rd rule [24]. IDF curves were generated to determine the intensity of the rainfall event at various time durations for different return periods (Fig. 2). Before preparing the curve, goodness of fit test was done for the available rainfall data. This test was carried out for Gumbel's distribution, Poisson's distribution, and normal distribution. It was found out that the rainfall data follows Gumbel's extreme Value Type-1 distribution. The model was also simulated for the forecasted rainfall for 10 years from 2015 to 2025. Based on the model and improved conduit dimensions, there was no flooding identified in the study area. It was observed that no nodes were flooded with the proposed dimensions. The nodes (denoted by J) and conduits (denoted by C) are presented in Fig. 3.

4 Results and Discussion

For the system just evaluated, the report indicates satisfactory simulation results, with negligible mass balance continuity errors for both runoff and routing (− 0.28% and − 0.032), respectively, if all data were entered correctly. Also, of the 24.035 inches of rain (in terms of total volume, division by area gives rainfall depth) that fell

Fig. 3 Nodes and conduits depicted for the study area

on the study area, 1.75 in. infiltrated into the ground, and essentially the remainder became runoff.

It was found that the nodes J25, J27, J29 are flooded for 0.92, 1.03, 1.13 h, respectively. In SWMM, flooding will occur when the water surface at a node exceeds the maximum allocated depth. Similarly, the conduits C23, C25, C27 are surcharged for 0.90, 1.02, 1.12 h. The conduits were at full capacity and therefore appeared to be slightly undersized. The water elevation profile and time series plot of these conduits are shown in Fig. 4.

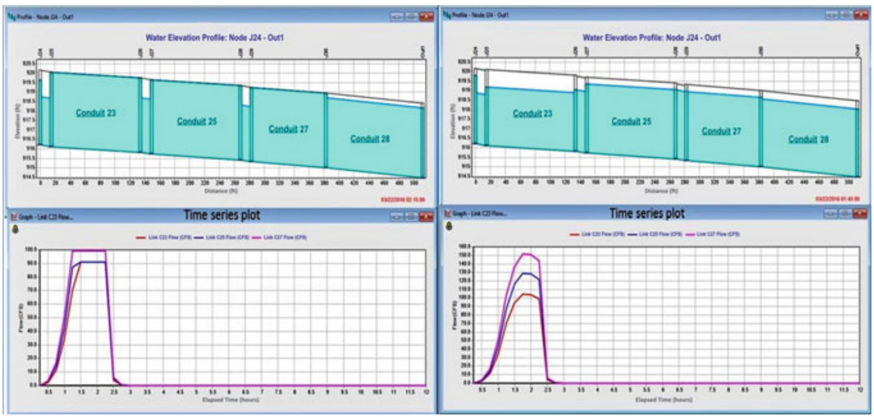

Fig. 4 Water elevation profile and time series plot of conduits C23, C25, and C27 for existing and proposed dimensions

The excess rainfall can be stored at a suitable location so that it may prevent flooding, provide groundwater recharge, and, when treated, can also act as a source to fulfill the domestic needs. Based on the contours of the area, two suitable sites are marked within the study area for the storage of stormwater (Fig. 5). The combined area of the reservoir was computed as 2012 m^2. The average depth of the reservoir is kept as 3 m, resulting in a joint capacity of 3036 m^3. The first pond may act as a settling tank or an oxidation pond, providing treatment to the incoming stormwater. The surplus water from the first pond will be fed to the second pond, and in this sequence, other suitable location or existing pond may be selected for storing the surplus stormwater.

Fig. 5 Location of the reservoirs within the study area

5 Conclusion

The rainfall and catchment characteristics have a strong influence on urban stormwater. Accurate assessments of stormwater will result in the effective design of urban stormwater management systems. Lack of availability finding the relevant available and derived hydrological data such as water flow in natural and man-made drains can be obtained by the designers/engineers by calibrating the model processes. The present work may be extended to provide sustainable stormwater management for the entire city. The network of stormwater drains of adequate capacity will provide effective drainage and prevent flooding of the area. The stormwater, which was creating a nuisance, can be converted into a valuable source. The storage of stormwater in small and big ponds will recuperate the existing ponds in the city as well as create new ponds. This will provide potential groundwater recharge and additional water sources.

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