Urban Flood Estimation in Bhubaneswar city using Storm Water Management Model (SWMM)

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ABSTRACT

Flood risk analysis is often subject to severe uncertainties, which can potentially undermine flood management decisions. Hence analysis of flood frequency and flood inundation models is always a topic of concern. Finding the urban drainage system's ability to convey water requires estimating the peak first and then the volume of urban runoff. Understanding the issues of drainage system and determining the degree of a flood or surcharge can be done by simulating urban floods. The primary aim of this study was to estimate urban flooding in Bhubaneswar city of Odisha using Storm Water Management Model (SWMM) by simulating urban watershed runoff. The land use map and topographic map were used to identify the study's urban drainage system. This study uses DEM obtained from Shuttle Radar Topography Mission (SRTM), Drainage map and LULC map (Landsat 08). The precipitation data was obtained from NASA Power. The main canals of the urban drainage system are predicted to be designed optimally using the runoff results of this study. Additionally, ideal locations for runoff storage will be found, and flood damage will be avoided.

Keywords: Urban flood, Urban drainage system, Watershed, SWMM

1. Introduction

India is extremely susceptible to flooding. Floods are a frequent occurrence that result in significant human casualties as well as damage to property, infrastructure, and public services. Numerous factors, such as a sharp rise in population, fast urbanisation, an increase in economic and development activity in flood plains, and global warming, might be blamed for this. Floods have also happened in places that weren't previously thought to be prone to flooding. We still need to create an effective response to floods, as evidenced by the ongoing and widespread loss of life and harm to public and private property caused by flooding. Therefore, the fact that flood-related damages are on the rise and constantly demand attention is cause for concern.

Three worldwide trends—urbanization, population increase, and climate change—have an ever-increasing impact on urban storm-water models. The first two trends cause cities to grow quickly, making storm-water management more difficult while also causing a rise in the number of people who are affected due to storm-water's negative effects on the environment. Due to climate change and its increased frequency of severe weather events, these consequences are anticipated to be intensified in many locations in the future.

Storm-water is interesting in terms of the urban water balance despite flooding. The increase in impervious land cover suggests higher peak and volumetric storm-water runoff, which affects other hydrologic cycle elements like infiltration and evapotranspiration. In addition, storm-water immediately introduces toxic elements from urban surfaces into water systems further downstream, lowering the quality of the water.

1.1 Literature Review

Ali Moafi Rabori and Reza Ghazavi (2018) used Storm Water Management Model (SWMM) to predict urban flooding in a semi-arid region (Iran). Investigations were also conducted into the effectiveness of an urban drainage network in the given study region. The DEM, digital map, and underground pipeline network were used to set up SWMM. From there, parameters were created with respect to the characteristics of the storm sewer conduits and the sub-catchment. **Zuxin Xu et al. (2019)**

assessed two common forms of urban green spaces—lawns and shrubs—that can be converted into LID (Low Impact Development) areas and examined the sensitivity of the runoff factors. They looked at the vegetation biomass, slope, and coverage. For this study, typical rainfall occurrences were chosen based on rainfall characteristics. The sensitivity of the total runoff and peak flow parameters of the two green land types was examined for light and heavy rainfall events using SWMM and the observed data, and the runoff parameters were subsequently calibrated and confirmed. **Toth et al. (2000)** used time-series analysis techniques to examine the accuracy of short-term rainfall forecasts by employing past rainfall depths as the only input data. Artificial neural networks (ANN), linear stochastic auto-regressive moving average (ARMA) models, and the non-parametric nearest-neighbours method are the strategies which are suggested. **Ad P. J. de Roo et al (2003)** used a European Flood Forecasting System (EFFS) in order to assess the level of skill that may be attained in flood forecasting for meteorological events, specific basins and prediction products. In order to drive high-resolution scale water balance and rainfall-runoff models, the rainfall estimates from regional Numerical Weather Prediction models are first downscaled to spatial scales appropriate for hydrological forecasting. **Marina Campolo et al (2003)** suggested a flood forecasting model that can forecast the evolution of the water level using real-time information for a basin (rainfall data, hydrometric data, and information on dam operation). This model was constructed using artificial neural networks that have been productively applied in the past to forecast floods in uncontrolled basins and the evolution of water levels in the Arno basin during periods of minimal flow. **Pao-Shan Yu et al (2006)** used the support vector machine, a cutting-edge artificial intelligence-based technique created by using statistical learning theory, to create a real-time stage prediction model using the mean annual precipitation, hourly water stage data, and hourly rainfall data as input. **Rupal K. Waghwala and P.G. Agnihotri (2019)** analyzed the effects of urbanisation on the flood occurrences that occurred in Surat and the surrounding area (Gujarat, India), which is the lowest portion of the Tapi river basin. Using and a remote sensing satellite image and topographic maps, the growth of urban areas between 1968 and 2006 has been assessed. Along with the land-use pattern, the flood risk assessment for two distinct years has also been determined. **Dhrubajyoti Sen et al. (2013)** proposed an instrumentation network that uses a variety of automatic rain gauges to attempt to collect the scattered rainfall data over the city in real time. Real-time data on the water level is provided by digital water level sensors that keep track of the elevations of the drainage canals. **Mukesh K.Tiwari and Chandranath Chatterjee (2010**) created an accurate and reliable ANN model for hourly flood forecasting using a hybrid wavelet-bootstrap-ANN (WBANN) model to investigate the potential of wavelet and bootstrapping approaches.

1.2 Objectives and Scope of This Study

The major aim of this analysis was to estimate urban flooding using Strom Water Management Model (SWMM). This is achieved by a catchment delineation and parameterization methodology that would enable the widespread application of the SWMM (Storm Water Management Model) to an urban area (Rossman, 2010). Successful large-scale SWMM implementations would be a valuable tool for resolving storm-water challenges. Additionally, the generated data will be applied to other ongoing hydrological and water quality investigations in the same region.

1.3 Critical Appraisal of Reviewed Literature

- Decisions about flood management are important, as the existence of significant uncertainty in analyses of flood risk is frequent. Hence analysis of flood frequency and flood inundation models is always a topic of concern.
- Heavy rainstorm events that over-run the restricted capacity of drainage systems usually result in flooding. As a result, flow from sewers to the urban surface is exchanged through manholes. So, it is important to assess the performance of drainage systems periodically and examine the flood-related damages.

2. Methodology

2.1. Method for choosing design storm

Utilizing intensity-duration-frequency (IDF) curve, the calculated rainfall intensity was determined. Rainfall duration (D), Rainfall Intensity (I) and Return Period (P) are mathematically related by the IDF curve (T) (Eq.2.1.a). It provides the anticipated intensity of the rain for a storm with the specified frequency of occurrence over the course of a specific time period. Rainfall data from the past that spans both long and short time periods is needed for this, which was obtained from "NASA Power". As a result, rainfall intensities for various durations — 5 min, 10 min, 15 min, 30 min, 1 hour, 2 hours, 12 hours, and 24 hours—have been calculated using the empirical reduction formula from the past 15 years of hourly data (2000–2021) (Rathnam et al. 2001).

$$P_t = P_{24}\left(\sqrt[3]{\frac{t}{24}}\right)$$

(Eq.2.1.a)

Where, P_t = Rainfall depth needed for time period t-hour (mm); P_{24} = Daily rainfall (mm); and t = the length of time needed for a certain depth of rainfall (hour). Due to its adaptability for modelling maximum rainfall events, Gumbel's Extreme Value distribution approach is adopted in the current work for IDF analysis. Design Storm was thereafter chosen from the IDF curve.

2.2. Hydrological model by using GIS

The majority of urban storm water models use distributed rainfall-runoff models (such as SWMM, HEC-HMS, etc.), that separate entire catchment or watershed into sub-catchments. To avoid affecting the accuracy of the simulated findings, the sub-catchment should be divided appropriately based on the characteristics of a watershed. A strong spatial analysis feature of a geographic information system (GIS) can be used to build a hydrological model (Dongquan et al. 2009). As a result, GIS is employed to prepare majority of the hydrological data. Firstly, the entire catchment area was separated into certain number of sub-catchments based on slope and area. By modifying the area's threshold, one can create small sub-catchments. A threshold is a minimal water collection area that draws water from the nearby stream or river and was created using a DEM. For the subdivision of catchment areas, DEM, LULC maps, and soil maps were used. Additionally, the GIS layer output (such as slope, sub-catchment size, percent of impervious land, etc.) can be used as an input data in SWMM for model simulation.

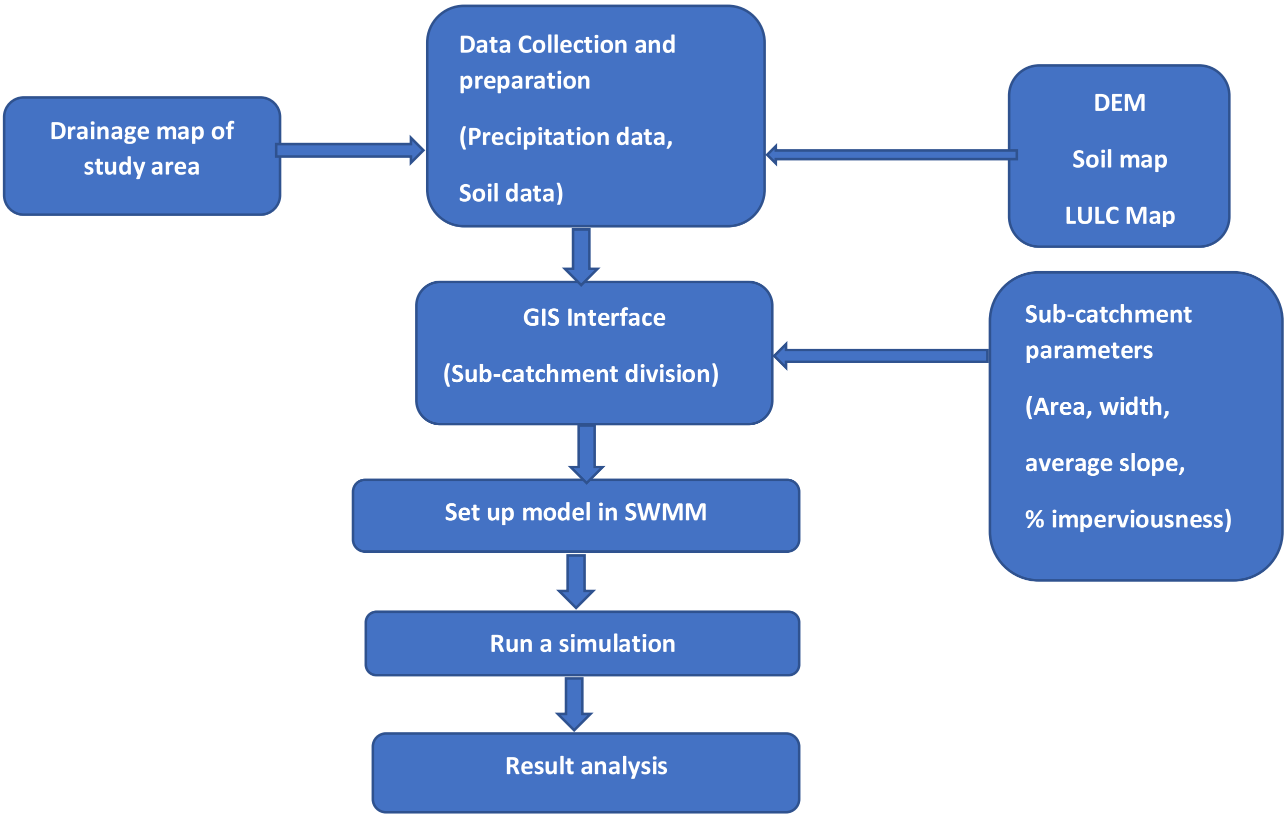


Fig.1.Flowchart showing the Methodology

2.3. Storm water management model (SWMM)

EPA's Storm Water Management Model (SWMM) was utilised in this study to analyse the flood. The United States Environmental Protection Agency created SWMM in 1971. It is a dynamic rainfall-runoff simulation model that is applied to estimate the quality and quantity of runoff from urban and semi-urban catchments for either a single event (design storm) or long-term (continuous) simulation (Rossman 2015). It is a distributed model that divides an entire catchment into smaller sub-catchments so as to capture the catchment's hydrologic response to runoff generation with spatial variability (such as land cover, topography, soil type, etc.). The non-linear reservoir model, which couples Manning's equation with a spatially lumped continuity equation, is used by SWMM to estimate runoff from rainfall (Huber 2003). Kinematic wave routing is used for flow routing in the simulations of the present study because it solves the one-dimensional Saint Venant flow equation producing theoretically more accurate findings (Rossman 2015). The Green-Ampt infiltration model approach has been used out of all models available in SWMM for computing infiltration.

3. Study Area and Data Collection

3.1. Study Area

In Odisha (India), Bhubaneshwar is the state capital and the largest city, Bhubaneswar is located in the Khordha district of Odisha. It is situated in the eastern coastal plains, all along the axis of the Eastern Ghats highlands. It is in the Mahanadi River delta, which marks the northern boundary of the Bhubaneswar metropolitan zone. The Daya River flows through the city on the south, while the Kuakhai River runs through the city on the east. In the city's western and northern parts, respectively, the Chandaka Nature Reserve and Nandankanan Zoo can be found. Bhubaneshwar City is situated at 20.2961 N, 85.8245° E. with an average elevation of 45m above sea level. The city has an area of around 186 square kilometres. The average annual rainfall in this city is 143.61cm, with a highest temperature of 37.2°C and a low temperature of 15.6°C. Saheed Nagar is the one of most flooded region of

Bhubaneswar city, SWMM model run over that part of the city. Total area of this region is 1.47 square km.

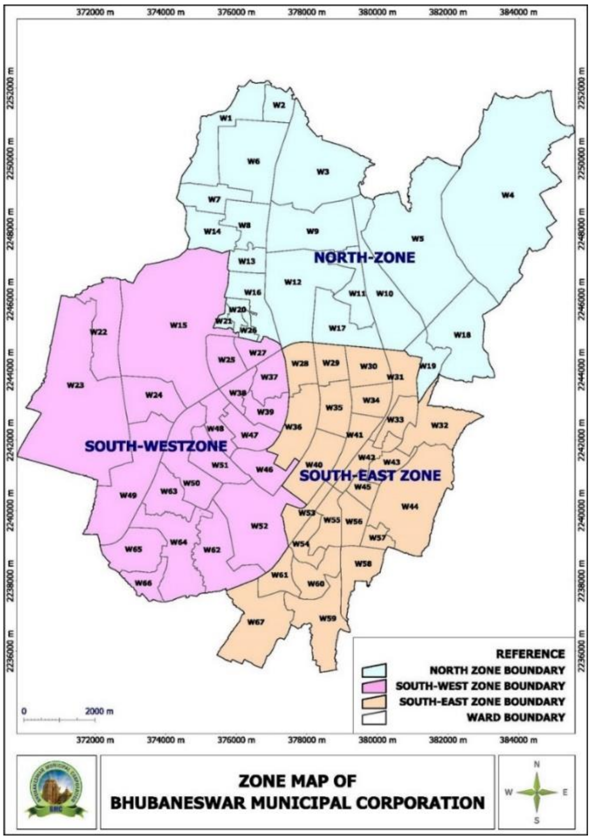


Fig.2.Ward Map of Bhubaneswar City

3. Data Collection

3.1. Rainfall Data and Drainage Data

NASA POWER was used to obtain the rainfall data. The National Aeronautics and Space Administration (NASA) has long financed satellite systems and research that would provide data for the research of climate and climatic phenomena through its Earth Science research programme. There are also time series figures for the base meteorological and solar data. In areas where there are few or no surface observations, these model and satellite based solutions have shown to be precise enough to provide correct information on solar and meteorological resources.

The data is worldwide and chronologically contiguous. The Applied Sciences Program of NASA's Earth Sciences Division promotes the production and publication of user-friendly data sets tailored to specific user populations, with data accessible via a user-friendly web-based mapping site to encourage the use of global solar and meteorological data.

3.2. Landsat Data

The Landsat series of Earth Observation has been collecting photographs of the Earth's land surface continuously since 1972, providing continuous data to enable land management and policy makers make informed decisions about environmental protection, for tracking and documenting land change due to climatic changes, drought, urbanisation, wildfires, biomass changes (carbon assessments), and a variety of other natural and human-induced changes. Landsat offers the finest ground resolution and spectral bands.

3.2.1. Land Use Land Cover (LULC) Map

The term "land use" refers to how humans have used the land. The land use, for example, may be recreational, yet the land cover could be plant or forest. Satellite photography alone cannot be used to identify land use. Land cover represents the natural surface that covers the ground, such as forest, water, ice, bare rock, and sand. For example, land cover defines the physical forms of land, such as forests and open water. Land cover may be determined using satellite imagery. Land use and land cover are not the similar thing. They are sometimes applied interchangeably, although both have multiple interpretations. Understanding both land use and land cover gives a complete picture of a location.

Land cover data includes wetlands, forests, impermeable surfaces, agricultural, and other land and water types. Land cover may be defined using satellite and aerial photos. Satellite and imagery cannot be used to assess land use. Land cover maps give information that managers may use to better comprehend the existing terrain. Maps can aid managers in assessing urban growth, modelling water quality issues, predicting and assessing flood and storm surge impacts, impacts due to rise in sea level, prioritising areas for conservation efforts, and comparing land cover changes with environmental impacts or socio-economic changes such as population increase.

3.3. Contour Map

Contour map (Fig.5) shows the imaginary line on the ground, joining the point of equal elevation. The contour map shown below, shows the elevation of the Bhubaneshwar city, which is mainly shown by five lines of five different colours: White, Blue, Green, Yellow and Brown. The white line indicates the elevation 0 -20 m, blue lines indicate the elevation 20-30 m, green lines indicate elevation 30-50m, yellow shows the elevation 50 70m and brown shows the elevation 70-110m from mean sea level. According to contour map the average elevation of the city is 45m from mean sea level.

3.4. Soil Map

For preparing soil map we downloaded the world soil map from the site of Food and Agriculture Organization (FAO) of the United State in shape file format. By using the Arc GIS, we extracted our study area from the world soil map data, shown in below (Fig.6). We found that the soil type of our study area is Ferric Luvisols whose code name is Lf. Luvisols are a type of soil that belong to one of the 32 Reference Soil Groups in the worldwide categorization system.

3.4.1. Soil properties

The soil characteristics in the ground slopes, drainage area, and ground cover all influence the rate of infiltration. Physically based parameters in the Green-Ampt equation to find infiltration can be determined using information about the soil. The soil characteristics employed in this process are saturated hydraulic conductivity, the initial moisture deficit (i.e., the difference of field capacity and porosity) and wetting front suction head. The soil classifications found in the sub-catchments are used to determine the parameter values.

3.4.2. Depression storage

Overland flow happens in the SWMM once the initial abstraction losses, which take the form of depression storage, are fulfilled. Due to penetration and evaporation losses, the depression storages are vulnerable to depletion. Evaporation phenomenon is not considered in the current study because it uses an event-based simulation. From the literature, typical depths of depression storage for impervious and pervious areas are to be taken (ASCE 1992). For ease, it was understood that the nature of depth of depression storage in each sub-catchment is uniform.

3.5. Sub-catchment Manning’s roughness

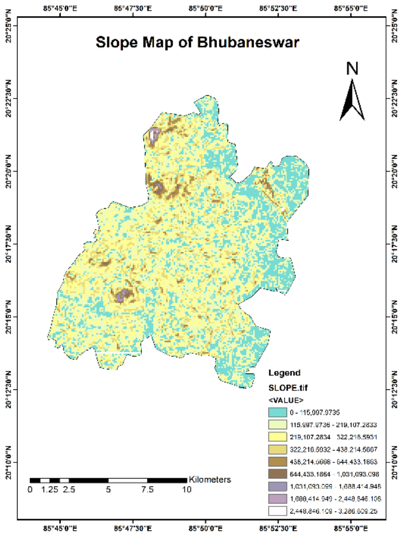
The literature serves as the source for Manning's roughness in case of overland flow for impermeable and pervious area (McCuen et al. 1996). For impervious and pervious areas, Manning's roughness is assigned a single value of 0.013 and 0.05, respectively, to avoid the difficulties inherent in determining it for different surfaces.

3.6. Conduit properties

Cross-sections of channel and Manning's coefficient are examples of conduit characteristics. Cross sections of channels were measured at various sites, and Manning's roughness values were gathered from the literature in order to give the conduit (drain) dimensions in the model setup (ASCE 1982).The drainage system is primarily made of earth with certain drains having cemented, concrete, or brick linings – so, this figure of 0.01 was chosen for simplicity.

3.7. Slope Map

The Slope tool makes it simple to convert a DEM into a slope map. Based on the elevation of each point, this map depicts the slope of each raster cell in degrees. DEMs are raster files that contain elevation data for each of the raster cells. DEMs are widely used for area computations, manipulations, and additional analysis, particularly analysis based on elevation. ArcGIS offers various built-in routines that will convert the DEM into a derivative map and are very simple to use. This fig.3 shows below a colourized representation of slope that was generated dynamically using the slope function. Light to dark colours represent the degree of slope steepness - dark green for level areas, light green for shallow slopes, light yellow for moderate slopes, and red for severe slopes. Slope values are calibrated to offer acceptable aesthetics at each map scale.



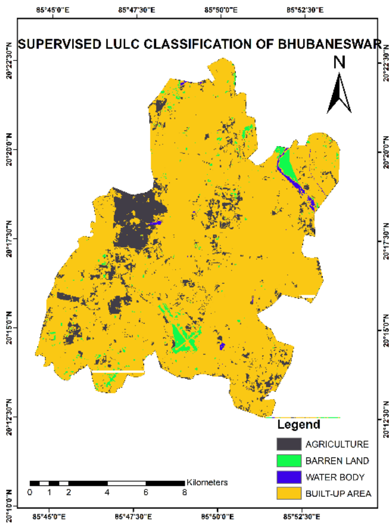


Fig.3.Slope Map of Bhubaneswar City; Fig.4.LULC Map of Bhubaneswar City

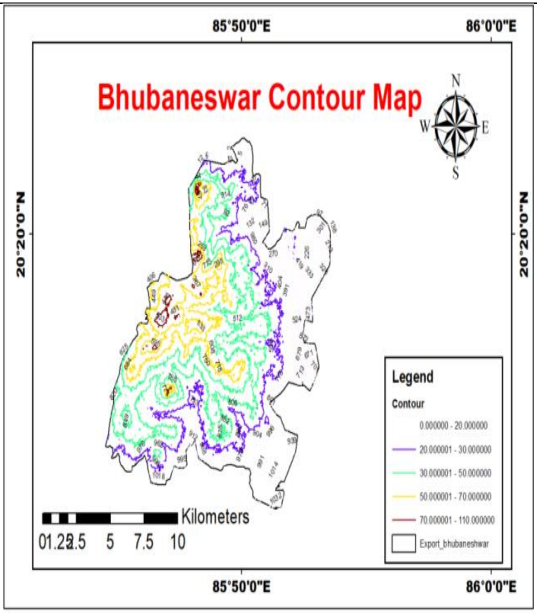


Fig.5.Contour Map of Bhubaneswar City

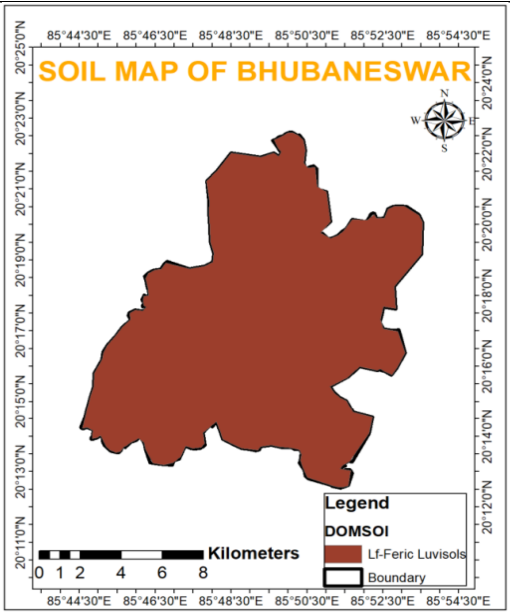


Fig.6.Soil Map of Bhubaneswar City

4. Results and Discussion

4.1. Sub-catchment Map

The Watersheds application creates water catchment areas using the Digital Elevation Model (DEM) shown in below fig.7. The DEM resolution utilised is determined by the analysis location and is reported in the Data Resolution field of the result layer. The input locations must be positioned on drainage lines for the result watersheds to be relevant. Our specific study area Saheed Nagar comes under a single sub-catchment area so the flow direction of all drainage line is same which is North to south direction.

According to slope and area, the entire study area may be divided into sub-catchments, junctions and storm water drains leading to an outlet, to build the drainage network.

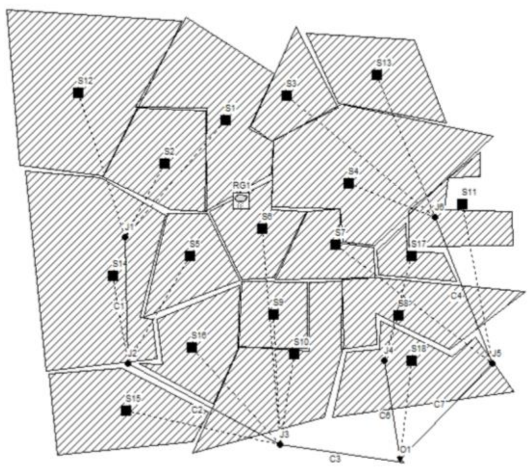


Fig.7. Sub-catchment division of Saheed Nagar Area

4.2. Intensity Duration Frequency (IDF) Curves

The Intensity-Duration-Frequency (IDF) curve represents the mathematical relationship between duration, intensity of rainfall, and frequency. Urban drainage system planning typically uses these curves in both hydrology and civil engineering. The design rainfall intensity has been calculated by using the IDF curve. It provides the anticipated intensity of the rain during a storm with the desired frequency of occurrence for a particular duration.

IDF Curves are produced from 20 years of data series (2000-2021) in order to acquire different I values (rainfall intensity) for different D (rainfall duration), return period (T), and for different data series lengths utilised in constructing IDF Curves (Fig.8).

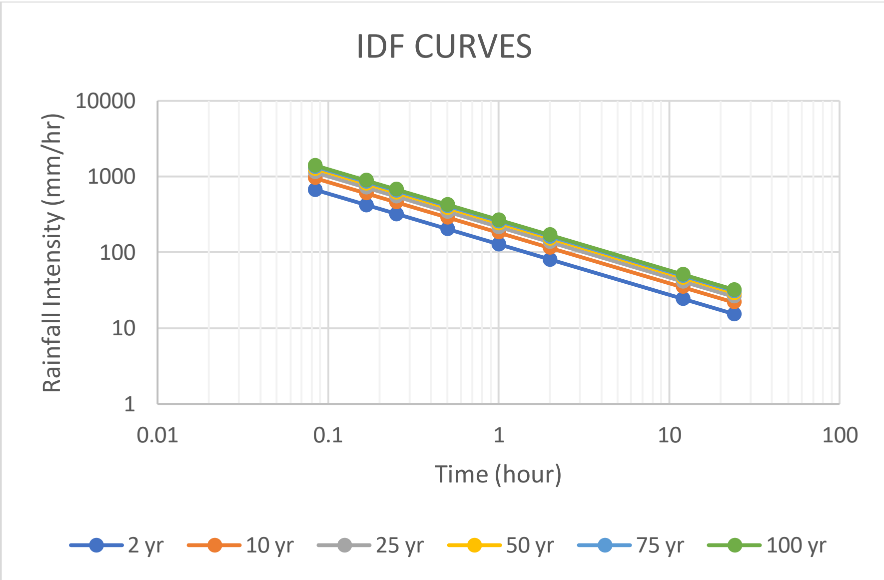
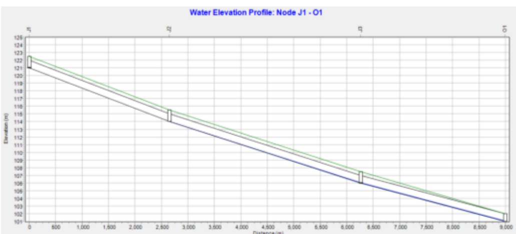


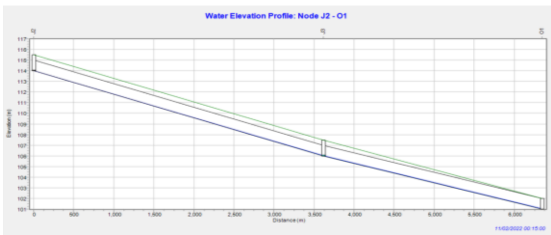
Fig.8.IDF Curves for various return periods (2 yr; 10 yr; 25 yr; 50 yr; 75 yr; 100 yr)

From IDF curves, it is clear that with the rise in return period, duration of storm also increases and vice-versa.

The non-linear reservoir model, which couples Manning's equation with a spatially lumped continuity equation, is used by SWMM to estimate runoff from rainfall. Among all the accessible models in SWMM- Horton's model, SCS Curve number technique, and others, Green-Ampt model has been used for computing the infiltration.

The water surface elevation profiles at some of the nodes is shown below (Fig.9). The total surface runoff generated accounted for 58.083 m3/sec having a depth of 2.842mm at the outfall-1.





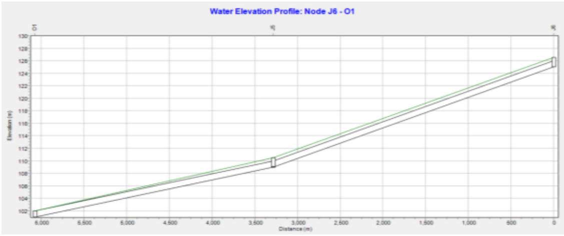


Fig.9.Water Elevation Profiles for various nodes

Outfall Node	Flow Freq. Pcnt.	Avg. Flow CMS	Max. Flow CMS	Total Volume 10^6 ltr
O1	99.72	2.558	5.067	55.026

Fig.10.a.Flow parameters at Outfall-1

Node	Type	Maximum Lateral Inflow CMS	Maximum Total Inflow CMS	Day of Maximum Inflow	Hour of Maximum Inflow	Lateral Inflow Volume 10^6 ltr	Total Inflow Volume 10^6 ltr	Flow Balance Error Percent
J1	JUNCTION	5.681	5.681	0	06:00	45	45	0.154
J2	JUNCTION	3.617	4.686	0	06:00	28.3	43	0.129
J3	JUNCTION	5.895	6.873	0	06:00	52.2	65.5	0.137
J4	JUNCTION	1.700	1.700	0	06:00	15.7	15.7	0.019
J5	JUNCTION	1.475	2.925	0	06:00	14.5	32.7	0.083
J6	JUNCTION	4.401	4.401	0	06:00	36.5	36.5	0.121
O1	OUTFALL	1.468	5.067	0	06:00	12.6	55	0.000

Fig.10.b.Node Inflow

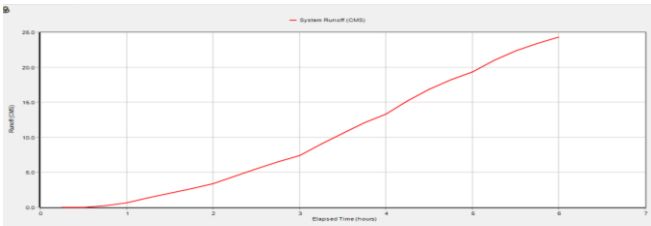


Fig.11. System Runoff vs Time plot

The above plot shows a relation between time vs depth of flow in outfall-1.

Also, from Table, total volume of flow accounts for $55.026*10^6$ litres with a flow frequency percentage of 99.72.

5. Conclusion

Engineers and urban planners in the modern world are in urgent need of creating an effective storm-water drainage system to prevent the inconvenience of frequent floods during the rainy season. In the current case study, the issue of storm-water management in an urban environment is addressed. This study sheds light on the value of the SWMM model in addressing site-specific flooding issues. Urbanization's main effects include the following: (1) more precipitation is converted to surface runoff; (2) the catchment's rainfall-runoff response is accelerated for a given rainfall event, resulting in a more steeper rising limb of flow hydrograph and a shorter time for the peak to occur ; (3) peak flow magnitude is increased for all but the most extreme events; The model input parameters and conditions are always critical for simulating urban storm-water drainage and management. Making the appropriate choice of precipitation depth is crucial when constructing any urban drainage system because rainfall has been cited as one of the most crucial inputs to developing the runoff response. To have a drainage design system that is technically practical and economically viable with the fewest risks to people's lives and property, it is necessary to develop acceptable estimates of tolerable frequencies. Otherwise, the system would be too expensive to build and run.

SWMM model was chosen because this model can be used for simulating flood extent or flood inundation depth. Any drainage system, regardless of its design, is supposed to flood when an extreme amount of rain falls in a short period of time. In our case, SWMM was used to estimate the flood magnitude in the study area due to design storms events which would help to find a solution flooding problem in further research works.

6. Future Scope of Research

Urban areas frequently experience water logging issues during the rainy season as a result of frequent flooding, which poses a number of health risks in addition to interfering with people's daily lives. To reduce flood-related losses, suitable flood management strategies must be offered in metropolitan areas. In order to handle the design storm safely throughout various return periods, this study has the potential to build an effective drainage system with the runoff results obtained here using SWMM.

There is no means in order to cope up with extreme rainfall events, even though we can construct a reliable drainage network system utilising SWMM to securely handle the design storm of varied return periods. By using a two-dimensional model, the proper design/modifications may be developed to deal with such unique instances.

The primary issues that require greater research include the integration of various urban flood management measures, community involvement, the net environmental effects of installed flood management structures, urban flood resilience, and hydraulic-hydrologic flood modelling methods.

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