Modeling Urban Floods and Drainage of Ranchi Municipal Area using EPA-SWMM

Utkarsh Upadhyaya, Birendra Bharti, Ajai Singh, Kumar Nischal

Abstract: Rapid urbanization has led to the expansion of impervious areas and has slowed down the infiltration rate resulting in increased surface runoff, which is over the top for storm water drains in the cities. Flooding in urban areas has become a severe problem, especially in unplanned cities. It affects the life and economic conditions of the inhabitants of the city. Many wards of the city of Ranchi also suffers from the problem of waterlogging and inundation in low lying areas which occurred frequently after heavy downpour during monsoon season and created problem for the people living in the area. In view of the seriousness of the problems caused by urban flood, a need to develop measures that minimize its occurrence and devastations caused by it occurred. Modeling and control analysis of urban storm water using analytical models becomes altogether important to understand and in turn solve the problem.

The suitable deliberation of spatial variability of urban watershed play vital role in the effective management of urban storm water. Physically based urban watershed model, Storm Water Management Model (SWMM) was used for urban storm water modeling of wards 40, 41, 50, 51, and 52 in the study area. As per slope criteria and existing drainage pattern, the study area has been divided into several subcatchments. Time series was generated on the basis of 3-hour rainfall intensity for the modeling of drainage network. The simulation results imparted that the existing drainage system is inadequate to drain off the storm water and grey water from households.

Keywords: Urban Flood, Storm Water, Inundation, SWMM.

I. INTRODUCTION

Over flooded streets, ponding of water, traffic jam due to water inundation, economic damages are often observed during rainy season in urban areas. Huge losses have occurred in recent years in many Indian cities due to urban flooding. These situations led to the need of flood management and flood risk management in urban areas. Although new cities are being developed in conformity to flood risk management, older cities are witnessing the problem of water inundation. The main reason behind the havoc is urbanization of cities. Urbanization puts excessive pressure on urban streams that in turn cannot handle excess water entering into it and thus becomes overflowed. Generally, drainage systems are designed separately for storm water and municipal sewage but construction of combined sewer systems in real field increase the problem of urban flooding. Accumulation of solid wastes in the sewer systems adds on to the already occurred situation. Urban flood is the inundation of water in low-lying areas that occur due to failure of drainage system to drain away the excessive rainwater entering into it. Urban flood susceptibility in urban environment is immensely influenced by human activities rather than natural factors [1]. Catchment development takes place due to urbanization increasing the flood peak by 1.8 to 8 times and flood volume up to 6 times (National Disaster Management Authority). Therefore, it has become a necessity to develop adequate drainage network to prohibit water inundation within the city.

SWMM was developed in 1971. It is being extensively used for detailed hydrological and hydraulic modeling of storm water. The software has the ability to simulate precipitation movement from ground surface by the means of channel or pipe network. SWMM can be sued for simulation of both single as well as long-term continuous event. Many studies have been conducted using SWMM for simulation of urban drainage network. [2] Developed Storm Water Management Model (SWMM) for analyzing drainage network for the campus of National Institute of Technology (NIT) Warangal. [3] Evaluated the appropriateness of Storm Water Management Model for ungauged urban land extent situated in the area of Matura Municipal Council. [4] Carried a study in which self-operating design on the basis of progressive hydrological and hydraulic counterfeit component in Storm Water Management Model (SWMM) was developed to assist the design of the layout of the area is provided.

SWMM can be used in calculation of water depth in manhole of main pipeline of urban surface drainage system and can be used for computation of peak flood discharge in sub-catchment [5]. Peak runoff, total quantity of runoff, runoff coefficient and recurrence interval for a specific precipitation event was computed using SWMM [6]. SWMM was used for evaluating the effect of model parameters on watershed responses in 4 peri-urban basins located in Southern Brazil. SWMM can also be used for several other purposes [7]. SWMM was used to derive parameters on the basis of properties of storm sewer conduits and sub-catchments [8]. Storm Water Management Model was applied for simulating scenario having distinct layout and also layout effect on control efficiency having distinctive precipitation was investigated [9].
Storm Water Management Model was used for simulation of civic storm measures in Fragrance Hill area of Beijing and analytical simulation was carried out to appraise the effect of Low Impact Development (LID) measures on urban runoff reduction [10]. Water Management Analysis Module (WBAM) was developed to acquire efficient physical requirements for design and planning of Low Impact Development (LID) with the help of Storm Water Management Model (SWMM) [11].

Isolated sanitary drains were constructed for discharging storm water and wastewater in distinct drains. The three leading components of wastewater outflow in sanitary sewer structure are (1) base sanitary flow, (2) groundwater infiltration and (3) rainfall derived inflow and infiltration [12]. When the cost of transporting and treating the inflow surpass the cost required to remove it, then the inflow is termed as excessive inflow. Usually, this excessive inflow is collected through adulterous connections from house drains, roof leaders, sump pumps and defective manholes and pipes [13].

Rainfall derived inflow and infiltration (RDII) is a major factor that determines sewer overloading, sanitary sewer overflows (SSOs) and efficient devaluation of treatment measures [14], [15]. RDII value can reach upto 200% of true wastewater flow. To protect the public health and water environment from harmful effects of RDII, it is necessary to replace and rehabilitate the sewers. Therefore, it is necessary to estimate RDII appropriately so as to design and implement such strategies [16].

The commonly used assumptions for direct calculation of RDII from flow data is that the Wet Weather Flow (WWF) comprises of RDII, Foul Sewage (FS) and Basic Groundwater Infiltration (GWI). It is also found that Dry Weather Flow (DWF) is the sum of GWI and FS, which means the difference of WWF and DWF will give RDII [17], [18]. Minimum night flow was used to determine the GWI [19]. Filters were used for extracting time series of total influents and deciding the quantity of inflow and infiltration. However, the method was suitable for determining total amount of RDII and was not able to describe rainfall derived inflow (RDII) and rainfall induced infiltration (RII) independently [20]. Inflow and infiltration processes can also be simulated using complex models based on hydraulic and hydrological mechanisms. Surrounding hydrological processes and their synergy with the sewer system can be described using distributed hydrological models like runoff routing models (RORB), the MouseNAM model and the RTK method employed in storm water management model (SWMM). An efficient and rigorous three-step optimization technique to solve problems related to sewer overflows. The genetic algorithm was used to calibrate RTK parameters so as to match RDII flow with RDII time series that were produced by the decomposition of measured flow data [21].

II. MATERIALS AND METHODS

A. SWMM Computational Methods

(a) Surface runoff

The model of surface runoff is based on two equations. The first equation is the continuity equation which helps to compute the depth of water over the sub-catchment and also update it with time:

\[ \frac{dV}{dt} = \frac{d[A.d]}{dt} = A_i - Q \]  (1)

Where \( \frac{dV}{dt} \) = change in volume stored on watershed per unit time
\( A_i \) = rainfall excess of the sub-watershed
\( V \) = A.d volume of water on the sub-watershed (m³)
\( A \) = area of watershed (m²)
\( D \) = depth of water in sub-watershed (m)
\( T \) = time (s)
\( i \) = rainfall excess (m/s)
\( Q \) = runoff flow rate (m³/s)

The second equation i.e. Manning’s equation is applied to model the surface runoff

\[ Q = \frac{A_r R^{2/3} S_b^{1/2}}{n} \]  (2)

Where \( A_r \) = cross-sectional area of flow over the sub-catchment (m²)
\( R \) = hydraulic radius of flow over the sub-catchment (m)
\( n \) = Manning’s coefficient
\( S_b \) = slope of sub-catchment

(b) Flow routing

The equations used are the Saint-Venant equations which is given by

\[ \frac{1}{A_i} \frac{dQ}{dx} + \frac{1}{A_i} \frac{d}{dt} \left( \frac{Q^2}{A} \right) + g \frac{dV}{dx} - g (S_f - S_e) = 0 \]  (3)

The continuity equation is:

\[ \frac{1}{A_i} \frac{dQ}{dx} + \frac{A_i}{t} = 0 \]  (4)

Where \( y \) = flow depth (m)
\( x \) = distance along conduit (m)
\( t \) = time (s)
\( g \) = (acceleration due to gravity (9.8 m/s²))
\( S_f \) = friction slope (m/m)
\( S_e \) = bed slope (m/m)
\( Q \) = flow rate (m³/s)

Routing of the flow is described as a function of time and space making, the Kinematic and the Dynamic Wave routing models as distributed models [22]

- Kinematic wave routing

In addition to the pressure terms, the local & convective acceleration is oversighted in Kinematic method in the momentum equation [22]. According to [23], it is thus represented by:

\[ g(S_o - S_f) = 0 \]  (5)

- Dynamic wave routing

Generating the most authentic results, Dynamic wave routing solves the complete Saint-Venant equations. Dynamic wave routing can account for entrance/exit losses, backwater effects, channel storage, pressurized flow, and flow reversal (ibid). However, the computation time is longer as compared to other methods.
(c) Infiltration model
In SWMM infiltration is modeled using Curve Number Method and Horton’s equation. The Horton model has been used long before in dynamic simulation whereas on the other hand Curve Number method a derivative of SCS Curve Number method is applied for simulation of simplified runoff models.

- Horton’s equation
  The Horton’s equation depends upon the factual observations and states that when rainfall intensity surpasses the infiltration capacity the initial maximum rate of infiltration decreases exponentially to minimum rate during long rainfall event for the soil having infiltration capacities (mm/h). The equation is given by the relation:

  \[ f_t = f_e + (f_i - f_e)e^{kt} \]  

  Where \( f_t \) = infiltration rate at time \( t \)  
  \( f_e \) = minimum infiltration rate  
  \( f_i \) = initial infiltration rate  
  \( k \) = decay coefficient

- Curve number method
  The U.S. Department of Agriculture (USDA), also known as Soil Conservation Service (SCS) developed the curve number method. It is based on the fact that soil’s Curve Number (CN) can be used to compute the total infiltration capacity of a soil. The equation is:

  \[ F = \frac{Q}{P - I_o} \]  

  Where \( I_o \) = all losses before runoff begins, including water retained in surface depression, intercepted by vegetation, evaporation and infiltration  
  \( F \) = loss of additional rainfall in the form of infiltration after runoff has begun  
  \( S \) = potential maximum retention reached with increasing rainfall

(d) SWMM sub-catchments parameters
In order to solve the various equations discussed above various parameters like area, imperviousness, width, depression storage, slope, Manning’s coefficient and infiltration coefficients needs to be encoded into the model. Different value for each parameter was calculated to assess the impact of these factors on the modeling for adjustment.

- Area
  The resolutions of the Watershed output and number of pixels contained in each sub-catchment concludes the area of watershed.

- Width of overland flow
  The width, physically, has no real meaning and it only represents the width over which surface runoff takes place. It is considered as a calibration parameter to adjust a good match. [24] Computed the width in different way. First a skew factor \( \gamma \) and is defined as

  \[ \gamma = \frac{A_2 - A_3}{A} \]  

  Where \( A_2 \) and \( A_3 \) are the area of two sides of the main channel and \( A \) is the total area of the sub-catchment (\( A = A_1 + A_2 \)). The width is then defined as:

  \[ W = (2 - \gamma)kL \]  

  Where \( L \) is the length of the main drainage channel.

- Slope
  The slope related to every single sub-catchment is the slope of land surface over which the flow of runoff occurs. It can be calculated from the DEM using the slope function.

- Percentage of impervious area
  This component is one of the sensitive parameter in hydrologic characterization and is denoted by the percentage of impervious land area. The average imperviousness percentage can be computed from the imperviousness coefficients for different land use class.

(e) Manning’s coefficient
The Manning’s roughness coefficients denote the amount of resistance offered by the sub-catchment surface to the overland flow. SWMM use Manning’s equation widely to define flow in the channel.

(f) SWMM conduits and junctions parameters
The length, shape, width, Manning’s coefficient and depth for each conduit needs to be determined

- Length and slope
  The elevation of upstream and downstream side of every single conduit must be incorporated in the model to define the slope of each designed drain. DEM is used to define the elevation and the length between elevation points is also measured..

- Manning’s coefficient
  Manning’s coefficient is needed to be assumed as per the land use class to be applied in Manning’s equation for computation of overland flow.

- Cross-sectional geometry, width and depth
  The width, depth and shape of conduits needs to be determined and the values are encoded in the model manually.

- Junction invert elevation
  The invert elevation of the junction is encoded using DEM which is related to the upstream and downstream elevation of conduits

B. RTK Method
Base Sanitary Flow (BSF), Groundwater Infiltration (GWI) and RDII are main parameters of wet weather wastewater flow which occurs in a sanitary sewer system. RTK method is a method that can be used to produce hydrograph on the basis of precipitation data. The three components of flow that are used to generate the hydrograph are (1) rapid flow, (2) moderate infiltration and (3) slow infiltration. The RTK hydrograph is believed to be most flexible and commonly used RDII methods.
The RTK hydrograph represents the reaction of sewershed to a precipitation event with the help of series of up to three triangular hydrographs that can be used for any storm events for producing resulting time history of RDII flow rates. The summation of ordinates of volume adjusted hydrographs at various points will result in overall response of the storm. Also the product of contributing area and ordinates of composite hydrograph will provide the volumetric RDII inflow entering into the conveyance system. This process is termed as convolution which is mathematically expressed as:

\[ Q_t = \sum_{i=1}^{n} u_{t-i} \cdot P_j \]  

(10)

Where,

- \( Q_t \) = RDII flow per unit area during time period \( t \)
- \( U_t \) = ordinate of hydrograph for time period \( t \)
- \( P_j \) = depth of rainfall for time period \( t \)

III. RESULTS AND DISCUSSIONS

A detailed study for urban storm water drainage design for Ward 41 of Ranchi Municipal area was done. Design storm intensity derived from Intensity-Duration-Frequency plot was used to estimate peak runoff from each sub-catchment. This peak runoff was used as an input parameter in simulation of runoff in SWMM. This chapter includes results and their significance for the current study.

Arc GIS 10.1 was used for spatial data analysis of study area. The study area lies in Survey of India toposheet no. 73 E/7 which was obtained from soinakshe.uk.gov.in. The stream map was developed with the Cartosat 30 m DEM obtained from Bhuvan. Arc GIS was used to mark the existing main drainage stream present in the wards 40, 41, 42, 50, 51.

A. Storm Water Analysis

Storm water management model (SWMM) version 5.1 was used for plotting storm water drains in the study area. On the basis of physical validation of the area, it was divided into different sub-catchments according to the slope, population and prospected outfall locations.

B. Output

On running the simulation the outputs obtained are as follows:

<table>
<thead>
<tr>
<th>Table- I: Total runoff and storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff quantity continuity</td>
</tr>
<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Total precipitation</td>
</tr>
<tr>
<td>Evaporation loss</td>
</tr>
<tr>
<td>Infiltration loss</td>
</tr>
<tr>
<td>Surface runoff</td>
</tr>
<tr>
<td>Final storage</td>
</tr>
</tbody>
</table>

Table- II: Sub-catchment runoff
### Table III: Node depth

<table>
<thead>
<tr>
<th>Node</th>
<th>Type</th>
<th>Average depth (m)</th>
<th>Maximum depth (m)</th>
<th>Maximum HGL (m)</th>
<th>Hours of maximum depth</th>
<th>Maximum reported depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>Junction</td>
<td>0.30</td>
<td>0.63</td>
<td>0.63</td>
<td>00:59</td>
<td>0.59</td>
</tr>
<tr>
<td>J2</td>
<td>Junction</td>
<td>0.37</td>
<td>0.56</td>
<td>0.56</td>
<td>00:50</td>
<td>0.55</td>
</tr>
<tr>
<td>J4</td>
<td>Junction</td>
<td>0.26</td>
<td>0.36</td>
<td>28.36</td>
<td>00:50</td>
<td>0.36</td>
</tr>
<tr>
<td>J5</td>
<td>Junction</td>
<td>0.29</td>
<td>0.42</td>
<td>26.42</td>
<td>00:50</td>
<td>0.42</td>
</tr>
<tr>
<td>J6</td>
<td>Junction</td>
<td>0.32</td>
<td>0.48</td>
<td>24.48</td>
<td>00:50</td>
<td>0.47</td>
</tr>
<tr>
<td>J7</td>
<td>Junction</td>
<td>0.37</td>
<td>0.56</td>
<td>22.56</td>
<td>00:51</td>
<td>0.55</td>
</tr>
<tr>
<td>J3</td>
<td>Junction</td>
<td>0.48</td>
<td>0.80</td>
<td>0.80</td>
<td>00:51</td>
<td>0.79</td>
</tr>
<tr>
<td>O1</td>
<td>Outfall</td>
<td>0.19</td>
<td>0.42</td>
<td>0.42</td>
<td>00:59</td>
<td>0.39</td>
</tr>
<tr>
<td>O2</td>
<td>Outfall</td>
<td>0.25</td>
<td>0.39</td>
<td>0.39</td>
<td>00:50</td>
<td>0.38</td>
</tr>
<tr>
<td>O4</td>
<td>Outfall</td>
<td>0.00</td>
<td>0.00</td>
<td>20.00</td>
<td>00:00</td>
<td>0.00</td>
</tr>
<tr>
<td>O3</td>
<td>Outfall</td>
<td>0.28</td>
<td>0.48</td>
<td>0.48</td>
<td>00:51</td>
<td>0.47</td>
</tr>
</tbody>
</table>

### Table IV: Node inflow

<table>
<thead>
<tr>
<th>Node</th>
<th>Type</th>
<th>Maximum later inflow (CMS)</th>
<th>Maximum total inflow (CMS)</th>
<th>Hour of maximum inflow</th>
<th>Lateral inflow volume $10^6$ liters</th>
<th>Total inflow volume $10^6$ liters</th>
<th>Flow balance error percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>Junction</td>
<td>0.558</td>
<td>0.558</td>
<td>00:59</td>
<td>0.647</td>
<td>0.647</td>
<td>5.298</td>
</tr>
<tr>
<td>J2</td>
<td>Junction</td>
<td>0.479</td>
<td>0.479</td>
<td>00:50</td>
<td>0.891</td>
<td>0.891</td>
<td>2.053</td>
</tr>
<tr>
<td>J4</td>
<td>Junction</td>
<td>0.649</td>
<td>0.649</td>
<td>00:50</td>
<td>1.17</td>
<td>1.17</td>
<td>1.506</td>
</tr>
<tr>
<td>J5</td>
<td>Junction</td>
<td>0.424</td>
<td>1.067</td>
<td>00:50</td>
<td>0.76</td>
<td>1.91</td>
<td>1.802</td>
</tr>
<tr>
<td>J6</td>
<td>Junction</td>
<td>0.932</td>
<td>1.988</td>
<td>00:50</td>
<td>1.62</td>
<td>3.5</td>
<td>0.914</td>
</tr>
<tr>
<td>J7</td>
<td>Junction</td>
<td>0.226</td>
<td>2.183</td>
<td>00:50</td>
<td>0.297</td>
<td>3.76</td>
<td>2.096</td>
</tr>
<tr>
<td>J3</td>
<td>Junction</td>
<td>0.718</td>
<td>0.718</td>
<td>00:50</td>
<td>1.26</td>
<td>1.26</td>
<td>6.438</td>
</tr>
<tr>
<td>O1</td>
<td>Outfall</td>
<td>0.000</td>
<td>0.549</td>
<td>00:59</td>
<td>0</td>
<td>0.615</td>
<td>0.000</td>
</tr>
<tr>
<td>O2</td>
<td>Outfall</td>
<td>0.000</td>
<td>0.476</td>
<td>00:50</td>
<td>0</td>
<td>0.873</td>
<td>0.000</td>
</tr>
<tr>
<td>O4</td>
<td>Outfall</td>
<td>0.000</td>
<td>2.180</td>
<td>00:51</td>
<td>0</td>
<td>3.69</td>
<td>0.000</td>
</tr>
<tr>
<td>O3</td>
<td>Outfall</td>
<td>0.000</td>
<td>0.708</td>
<td>00:51</td>
<td>0</td>
<td>1.18</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Table V: Outfall loading

<table>
<thead>
<tr>
<th>Outfall node</th>
<th>Flow frequency percentage</th>
<th>Average flow (CMS)</th>
<th>Maximum flow (CMS)</th>
<th>Total volume $10^6$ liters</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>85.37</td>
<td>0.208</td>
<td>0.549</td>
<td>0.615</td>
</tr>
<tr>
<td>O2</td>
<td>90.24</td>
<td>0.273</td>
<td>0.476</td>
<td>0.873</td>
</tr>
<tr>
<td>O4</td>
<td>88.35</td>
<td>1.184</td>
<td>2.180</td>
<td>3.686</td>
</tr>
<tr>
<td>O3</td>
<td>89.43</td>
<td>0.375</td>
<td>0.708</td>
<td>1.180</td>
</tr>
</tbody>
</table>
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### Table VI: Link flow

<table>
<thead>
<tr>
<th>Link</th>
<th>Type</th>
<th>Maximum flow (CMS)</th>
<th>Hour of maximum flow</th>
<th>Maximum velocity (m/s)</th>
<th>Maximum/ full flow</th>
<th>Maximum/ fill depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Conduit</td>
<td>0.549</td>
<td>00:59</td>
<td>1.32</td>
<td>11.62</td>
<td>0.52</td>
</tr>
<tr>
<td>C2</td>
<td>Conduit</td>
<td>0.476</td>
<td>00:50</td>
<td>1.30</td>
<td>8.55</td>
<td>0.47</td>
</tr>
<tr>
<td>C3</td>
<td>Conduit</td>
<td>0.708</td>
<td>00:51</td>
<td>1.34</td>
<td>20.26</td>
<td>0.64</td>
</tr>
<tr>
<td>C4</td>
<td>Conduit</td>
<td>0.645</td>
<td>00:50</td>
<td>2.65</td>
<td>0.07</td>
<td>0.20</td>
</tr>
<tr>
<td>C5</td>
<td>Conduit</td>
<td>1.064</td>
<td>00:50</td>
<td>3.41</td>
<td>0.10</td>
<td>0.23</td>
</tr>
<tr>
<td>C6</td>
<td>Conduit</td>
<td>1.988</td>
<td>00:50</td>
<td>4.95</td>
<td>0.14</td>
<td>0.28</td>
</tr>
<tr>
<td>C7</td>
<td>Conduit</td>
<td>2.180</td>
<td>00:51</td>
<td>4.73</td>
<td>0.20</td>
<td>0.31</td>
</tr>
</tbody>
</table>

On the basis of input parameters water elevation profile was obtained for different nodes and outfall locations which are as follow:

![Water Elevation Profile for J4-O4.](image)

**Fig. 2: Water Elevation Profile for J4-O4.**

The water elevation profile obtained for various nodes and outfall signifies that no water logging takes place between any node and outfall indicating that the simulation carried out was appropriate for the study area.

### IV. CONCLUSION

The present study was done to analyze the existing drainage system of the study area. Simulation of existing drainage system by SWMM and physical validation of the study area suggests that current drainage system is not sufficient to capture the storm water runoff. Sewerage system overflows (SSOs) are common phenomenon at regular nodes. Apart from rapid urbanization, combined drainage systems for storm water & sewerage, and disposal of solid wastes in a haphazard manner are primary sources of drainage system failure in the area. A new drainage system with separate sewers for storm water and sewerage was designed for peak rainfall intensity and forecasted population growth which can be used in the city development master plan.

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