Technical Report

Performance assessment of urban drainage system
(Case Study: District 10 of Tehran Municipality)

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Abstract. A drainage system degrades by multiple factors and its performance reduces in
time. Since such infrastructure play a key role in preventing urban floods, their
performance should be monitored and quantified. The present research is aimed at
simulation of urban drainage network of district 10 of Tehran Municipality in Iran, and
focuses on hydraulic assessment of drainage system’s level of service. Indicators of
reliability, resiliency, and vulnerability are used to evaluate the system’s performance.
Inundation spots were determined in the study area, and three performance indices were
calculated for all conduits and the whole system. The results indicate that some conduits
in the urban drainage network are in critical condition and should be rehabilitated, while
the others represent an acceptable performance in conveying the urban runoff and do a
nice job in preventing urban flooding in the region. Reliability of the system is acceptable,
and vulnerability is relatively low, and system represent a relatively high percent of
resiliency; however, applying sustainable drainage approaches are still required
considering climate change and continuous urban development.

Keywords: urban drainage; runoff; reliability; resiliency; vulnerability

1. Introduction

Flood is a hydrologic phenomenon that is characterized by both precipitation and soil-
water contributions (Simonovic et al., 2001). Flooding in urbanized areas has become a
very important issue around the world (Barreto Cordero, 2012). Cities are growing fast
and large amounts of impervious surfaces replace the natural landscape as a result of
urban development. Impervious surfaces can have an effect on local streams and flooding
characteristics.

Storm water drain networks in cities are usually designed to effectively collect and
convey excess surface runoff in order to avert urban flooding (Gouri and Srinivas, 2015).
But, often most of them face reduction of functionality and capacity for transferring the
runoff flow, and their level of service reduces due to degradation in time, improper
maintenance, inappropriate design, aging, sedimentation and siltation, increase in
materials’ roughness, and structural deterioration. In addition, urban development and
climate change exacerbate the situation (Torres, 2006; Barreto Cordero, 2012). Because
such phenomena are followed by increase in runoff volume and peak flow rates. This
means that even when there is a drainage system with acceptable functionality, the
design capacity of the system are inadequate for extreme events and flood occurrence.

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Hydrological and hydrodynamic modeling plays a key role for the hydraulic, structural and environmental assessment. Sustainable approaches, oriented to the control of runoff volumes from the beginning of the rainfall are preferable than methodologies based on conveyance. These sustainable approaches are also oriented to keep environment, social and economic values in balance. (Barreto Cordero, 2012).

Since such infrastructure play a key role in preventing urban floods, their performance should be assessed after being quantified. A number of studies have been conducted in this context by several researchers. Simonovic et al. (2001) identified statistical indices of the Red River flood protection system performance (reliability, resilience and vulnerability) under different climate change scenarios. The study results showed that flood protection capacity of the Red River infrastructure is sufficient under low reliability criteria but may not be sufficient under high reliability criteria. Barreto Cordero (2012) focuses on several aspects such as the improvement of the performance of the multicriteria optimization through the inclusion of new features in the algorithms and the proper selection of performance criteria. Gouri and Srinivas (2016) investigated performance of an existing storm water drain network in Bangalore, India, through reliability analysis by Advance First Order Second Moment (AFOSM) method. The results of this study represented that the reliability values are low under the considered failure modes, indicating a need to redesign several of the conduits to improve their reliability.

The main objective of this study is to investigate the ability of the existing urban drainage network in district 10 of Tehran municipality in operating satisfactorily in collecting and conveying runoff from typical rainfall, without inundation. The appropriate performance of urban drainage systems (UDS) play a key role in preventing urban flooding. In order to this goal, following a review of the state-of-the-art in performance assessment of water resources, the study region was simulated through SWMM model after sensitivity analysis and model calibration. Then, the performance of the drainage network was assessed by means of three indicators including reliability, resiliency, and vulnerability. At the end, the total performance of the model- also known as sustainability index- was gained by combining these three indices.

![Tehran Map](source: google maps)
2. Study Area

The study area is a part of district 10 of Tehran municipality located in southwest of the city. This area meets Azadi Street in north, Shahidan and Hormozan Streets in west, Qazvin Street in south, and Shahid Navvab Safavi highway in the east (Fig. 1). The region has an area of approximately 870 ha, which is the smallest among all Tehran municipality’s districts. The general slope in the region extends from north to south (around 1.2%) and from east to west (less than 1%). The dominant land use in the area is residential (37%); while 25% of the region is allocated to pathways and access routes. The rest of the area (around 18%) is earmarked for other types of land uses including green spaces, small industries, etc (Behrouzi et al., 2015).

3. Materials and Methods

As was mentioned earlier, the main objective of this study is to evaluate the performance of existing urban drainage system in the study area in conveying rainfall-induced runoff, and measure sustainability of the system based on performance indices. The proposed algorithm for such a goal has been presented in Figure 2.

![Diagram](attachment:image.png)

Fig. 2. The algorithm for performance assessment of urban drainage system

SWMM version 5 was used as a tool to simulate hydraulic and hydrological processes in rainfall-runoff modelling. This software is a dynamic rainfall-runoff simulation model which is used for single event or long-term (continuous) simulation of runoff (quantity and quality) in urban areas. It tracks the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period made up of multiple time steps (Rossman and Huber, 2016).
Meteorological data (1951-2005) from Mehrabad airport synoptic weather station were used in the model since this weather station is the closest one to the study area, and is nearly in the same altitude as the region (1127-1207 m).

Rainfall data was derived from IDF curves and relations available for Mehrabad weather station in Tehran (MGCB and Poyry, 2011). Rainfall return period and duration were considered 5 years (which is common for urban areas) and 6 hours, respectively. The model time step for rainfall data was chosen as 15 minutes. In addition, in simulating infiltration parameters, Horton equation was applied. This method is based on empirical observations that control how infiltration of rainfall into the upper soil zone of sub-basins is modelled (Rossman and Huber, 2016). Dynamic wave was used as routing method which accounts for channel storage, the effects of backwater, and flow reversal.

In addition, data gathered for a study conducted by Zistab consulting engineering company (2012) were used to model Firouzabadi channel as the main drainage conduit of the region. The channels' walls and the floor are of concrete and the dimensions are 1.75m by 2.6m in the form of brick arc. The detail characteristics of Firouzabadi channel are presented in table 1.

Table 1. Characteristics of Firouzabadi channel in the study area

<table>
<thead>
<tr>
<th>Conduit's cross section</th>
<th>Dimensions (height*length)</th>
<th>Conduit material</th>
<th>Slope (m/Km)</th>
<th>Conduit length (m)</th>
<th>Manning’s roughness Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>closed rectangular</td>
<td>2.6*1.75</td>
<td>concrete</td>
<td>8/8</td>
<td>2643</td>
<td>0.014</td>
</tr>
</tbody>
</table>

4. Sensitivity Analysis, Model Calibration, and Rainfall-Runoff Simulation

Sensitivity analysis done for parameters of the model indicated that the output by SWMM model is sensitive to roughness coefficient for impervious areas (N-Imperv) the most. Table 2 shows the parameters used for sensitivity analysis and their allowable range of change proposed by Li et al. (2014).

Table 2. Some key parameters used for sensitivity analysis in this study and their allowed range of change (Li et al., 2014)

<table>
<thead>
<tr>
<th>parameter</th>
<th>description</th>
<th>allowed range of change</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-Imperv</td>
<td>Manning's roughness coefficient for impervious areas</td>
<td>0.005-0.05</td>
</tr>
<tr>
<td>N-Perv</td>
<td>Manning's roughness coefficient for pervious areas</td>
<td>0.05-0.5</td>
</tr>
<tr>
<td>Dstore-Imperv</td>
<td>Depth of surface storage in impervious areas (mm)</td>
<td>1.3-2.5</td>
</tr>
<tr>
<td>Dstore-Perv</td>
<td>Depth of surface storage in pervious areas (mm)</td>
<td>2.5-7.6</td>
</tr>
<tr>
<td>Zero-Imperv</td>
<td>Impervious areas without surface storage (%)</td>
<td>50-80</td>
</tr>
</tbody>
</table>

It should be mentioned that different allowed ranges for above parameters has offered by several researchers; however the current study mostly used the values represented in table 2.
In the next stage, model was calibrated for the most sensitive parameters (i.e. the parameters to which the model is most sensitive) until the results by the model matches the observed data (discharge from the outlet of the study area). Observed runoff data used for calibration, was gathered by Dayyarian (2014) in a 2.5 hour time period.

Then the rainfall-runoff simulation for the given case study was conducted using the calibrated model. Applying the relations mentioned in “materials and method” section, the amount of precipitation for a 6-hour 5 years rainfall regarding the altitude of the study area was derived as 20.81 mm. This value applied to the model as cumulative rainfall in order to obtain the output runoff from the studied basin. The simulation was done for 23 hours which contains 276 time steps (The number of simulating time steps are required for performance calculations in the next stage). The results showed that inundation occurs in the nodes J1 and J11 as shown in figure 3. In addition, some conduits including C4, C6, C7, C8, C9, and C10 are in critical conditions, indicating the highest instability indexes among all links, respectively. The mentioned conduits can be observed in red color in figure 3.

Fig. 3. The figure shows regionalization of the study area as well as flooded nodes (in blue) and critical conduits (in red)
5. Performance Assessment

Indices of reliability, resiliency, and vulnerability are used to assess the performance of urban drainage network of the study area. First time, Hashimoto et al. (1982) formulated these three criteria for evaluating the possible performance of water resource systems. Following that, some other researchers used these criteria after adapting them with the type of water resource or infrastructure whose performance was to be evaluated. Reliability is representative of the likelihood of system being in a satisfactory state, resiliency measures how quickly the system recovers after a failure occurs, and vulnerability represents the severity of the failure. In current study, these three criteria were adapted and modified for the performance assessment of urban drainage system.

5.1. Reliability

As noted before, in general, the reliability can be expressed as the ratio of the number of satisfactory states to the total number of system activities. In Case of UDS, reliability can be defined as: total number of time intervals in which system can convey the runoff flow without surcharging, to the total simulated time steps, i.e.:

\[
\operatorname{Rel} = \frac{1}{T} \sum_{t=1}^{T} Z_t
\]

With

\[
Z_t = \begin{cases} 
1 & \forall X_t \in S \\
0 & \forall X_t \in F
\end{cases}
\]

Where \( Z_t \) is the state of the drainage system in the time interval \( t \), \( X_t \) is the value of investigatory parameter in the time interval \( t \), \( S \) is the satisfactory state, \( F \) is the failure state, and \( T \) is the duration of operating period. Failure states in this study are considered to be time intervals during which flow exceeds the channel capacity (flow depth exceeds the channel's height) in the whole system.

5.2. Resiliency

Resiliency can be calculated through different formulas presented by several researches. Among all, the two following relations seem to be appropriate for the goal of the current research:

1) Resilience defined as the inverse of the maximum duration of failure time that UDS can experience over a specified planning horizon (or total simulating time steps for single-event simulation):

\[
\operatorname{Resilience}_1 = \frac{1}{\operatorname{Max}T_f}
\]

Where \( T_f \) is the length of time (i.e. a number of consecutive time steps) during which flooding occurs. Flooding refers to any volume of water more than conduit capacity at any time step.

2) Resilience defined as the inverse of the expected value of failure over a specified planning horizon, as expressed in equation (5). Hashimoto et al. (1982) showed that this is equivalent to the ratio of the probability of a satisfactory state following an unsatisfactory state (i.e. \( X_t \in F \) and \( X_{t+1} \in S \)) to the probability that a system is in an unsatisfactory state \( (X_t \in F) \) as Eq. (5):

\[
\operatorname{Resilience}_2 = \frac{1}{E(T_f)} = \frac{\operatorname{Prob}[X_t \in F \text{ and } X_{t+1} \in S]}{\operatorname{Prob}[X_t \in F]} \times 100
\]
Where $X_t$ and $X_{t+1}$ are system outputs at times $t$ and $t+1$ respectively, $F$ and $S$ are set of all unsatisfactory and satisfactory outputs, respectively.

Given that the planning horizon is definite, the second resilience definition can be expressed as the ratio of the number of times a satisfactory state follows an unsatisfactory state to the number of times an unsatisfactory state occurs (Behzadian et al., 2014). In current paper, the second relation for resiliency was used to estimate rate of recovery of the conduits.

### 5.3. Vulnerability

Vulnerability which measures the severity of the failure, can be expressed as the maximum difference between allowed and calculated value of a certain variable (i.e. runoff depth). In the case of UDS, it is calculated as Eq. (6):

$$V_{ul} = \begin{cases} 0 & \text{if } D_i \leq D_f \\ \text{Max}[D_i - D_f] & \text{else} \end{cases}$$

(6)

Where $D_i$ is the notation of reference level of runoff depth which the system can convey without being surcharged (equals to channel depth), and $D_f$ is the calculated value of runoff depth. Finally the mean vulnerability ($V_m$) obtains from Eq. (7):

$$V_m = \frac{\sum_{i=1}^{NF} V_{ul}}{NF}$$

(7)

In which $f$ is the counter of failure states, and $NF$ is the total number of failure states during the operating period.

### 5.4. Sustainability Index

The whole system’s total performance which is known as sustainability index of the system, can be calculated using Eq. (8):

$$\text{Sustainability} = \frac{\text{Rel} \times \text{Res}}{V_{ul}}$$

(8)

The above relation represents that sustainability of a system has a direct relationship with reliability and resiliency, and an inverse relationship with vulnerability of the system.

### 6. Results

Table 3 represents the values of reliability, resiliency, and vulnerability for drainage system’s conduits and the whole drainage system in the study area. As can be seen in the table, conduits C4, C6, C7, and C10 are the least reliable and the most vulnerable ones, while conduits C3, C5, and C9 are completely reliable, and their vulnerability index equals to zero. Other conduits represent good performance and act effectively in conveying the produced runoff. The results show that nearly all conduit of UDS in the study area can be considered as resilient which means the system’s ability to bounce back to its primary function after a failure occurs, is acceptable.
Table 3. Calculated performance indices for all conduits and the whole drainage network

<table>
<thead>
<tr>
<th>Conduit</th>
<th>Reliability</th>
<th>Resiliency</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>96.46</td>
<td>97.68</td>
<td>16.78</td>
</tr>
<tr>
<td>C2</td>
<td>93.5</td>
<td>99.23</td>
<td>4.65</td>
</tr>
<tr>
<td>C3</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>C4</td>
<td>69.2</td>
<td>74</td>
<td>46.64</td>
</tr>
<tr>
<td>C5</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>C6</td>
<td>60.45</td>
<td>74.5</td>
<td>50.32</td>
</tr>
<tr>
<td>C7</td>
<td>72.54</td>
<td>85.98</td>
<td>16.66</td>
</tr>
<tr>
<td>C8</td>
<td>97.36</td>
<td>98.34</td>
<td>10.51</td>
</tr>
<tr>
<td>C9</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>C10</td>
<td>66.96</td>
<td>71.67</td>
<td>68.7</td>
</tr>
<tr>
<td>The whole system</td>
<td>86.75</td>
<td>90.14</td>
<td>23.42</td>
</tr>
</tbody>
</table>

Given the whole systems reliability, resiliency, and vulnerability, sustainability index for drainage system in the study area is 3.34.

7. Conclusion

In this paper, performance of urban drainage system in district 10 of Tehran municipality was investigated. Rainfall-runoff processes in the region and sub-basins was simulated and three performance indices were calculated and combined to give the sustainability index for the whole UDS system. The results showed that system resilience is high and its vulnerability is low. The drainage network reliability is also acceptable, though should be improved through rehabilitation. The calculated performance indicators for each channel in the system indicated that rehabilitation is required at some conduits of the system. Inundation occurs at some parts of the study area which should be improved through some rehabilitation measures. Applying the performance indicators in rehabilitation process is helpful to understand how much of a measure is required for improving the condition of each part of the system, and to give a sight to decision makers about the appropriate costs of each measure and budgets for rehabilitation.

Using best management practices can be effective for the purpose of improving the drainage system’s performance as such measures reduce the volume and peak of runoff flow, and decrease the flooding risk. It is particularly important because the demand of the system is not constant and is dynamically changing over time due to factors such as urbanization and climate change. In this research, the performance of a UDS was only investigated for current situation, which means the system’s functionality can be less than calculated for the future, and therefore, applying sustainable drainage approaches seems to be of great importance in the studied region.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References


Dayyarian, M. A. (2014). Developing an optimized model for quantity and quality of urban runoff regarding optimized layout of BMPs and economic considerations (Iran, Tehran University Master Degree Thesis).


