Building Tomorrow's Society

Bâtir la Société de Demain

Fredericton, Canada

June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

IMPROVING RESILIENCE OF URBAN DRAINAGE SYSTEM IN ADAPTATION TO CLIMATE CHANGE (CASE STUDY: NORTHERN TEHRAN, IRAN)

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Abstract: Given the adverse impacts of climate change on urban water infrastructures' resilience, using adaptive strategies is of great importance. For urban drainage systems (UDSs), despite considerable progress in sustainable management of such infrastructures all over the world, they are still exposed to uncertain drivers of future changes. Quantifying the resilience is an important step for long-term increase in resilience of UDSs. In current paper, the resilience of UDS against flooding is conducted through combining hydraulic performance of storm water drainage network with the system performance function. To do this, baseline and future extreme rainfall time series for different return periods were calculated for West Flood-Diversion (WFD) catchment in Tehran, Iran, and then related IDF curves were obtained. Afterwards, hydraulic and hydrodynamic simulation of storm water drainage system was performed for future time under two scenarios: with and without BMPs. This methodology was applied on one flooded node in the network where the amount of system performance and resilience were estimated under extreme rainfall with different return periods. The results showed that adding a vegetative swale to the drainage system would decrease nodal flooding duration and flood volume up to 30% and 35%, respectively. Moreover, resilience against flooding can increase up to 9.12%. Therefore, the existence of low-impact development measures along with traditional urban drainage can be efficient for increasing system sustainability.

Keywords: Adaptive strategies, climate change, performance function, resilience, urban drainage system (UDS).

1 INTRODUCTION

Recent changes in global climatic conditions, has been followed by increase in extreme rainfall events. This phenomenon along with malfunction of Urban Drainage Systems (UDSs) and lack of capacity due to sedimentation, accumulation of garbage in minor drainage network, entrance of swage in separated drainage networks, etc., is the source of urban flooding and inundation problems (Lee and Kim 2017). Therefore, in recent years, building resilience of UDSs has been taken into consideration as an important approach in reducing floods and their consequences under uncertain future changes (Blockley et al. 2012, Butler and Davies 2011, Djordjević et al. 2011, Gersonius et al. 2013). According to Todini (2000), resilience is referred to the ability of a system to return to the normal level of service, so that it could meet the pre-defined goals of the system after the failure occurs. In other words, resilience is the ability of the system to restore function following the system failure. Therefore, resilience index is determined based on system failure duration (Nazif 2010). In current paper, resilince is defined as: the ability of the UDS for minimising the volume and duration of flooding caused by extreme rainfall events (Mugume et al. 2014). Herein, flooding means the excess runoff volume which overflows from the UDS to the surrounding urban area.

In recent decades, considerable progress have been achieved in context of resilience concept and its quantification in different urban water systems (Jung et al. 2013, Lansey, 2012). However, few studies have been conducted on developing appropriate methods for evaluation and quantification of resilience in storm water drainage infrastructures. Though, the subject is getting more and more interesting for researchers, so that the number of such studies is increasing in recent years. De Bruijn (2004) proposed some indicators aiming at defining resilience of flood risk management systems. The indicators cover three aspects of resilience concept including amplitude, graduality- trend of increasing reaction by increase in severity of flood waves-, and recovery rate. After applying the proposed indicators on simple hypothetical systems, she came to the conclusion that a combination of these indicators can be effective in achieving an overall view of resilience of flood risk management systems. A study performed by Mugume et al. (2014) represents that by increasing rainfall return period, flood duration increases in residential areas of England, and consequently, much reduction occurs in performance of urban stormwater drainage infrastructure. They also showed that urban-drainage performance reduction curve did not change for high return periods (50 and 100 years) and coincided each other. Tahmasebi Birgani (2014) introduced a tool box for quantifying resilience concept in urban-drainage risk management systems (UDRMS). Zhang et al. (2017) compared the vulnerability of tree vs. loop drainage systems under different rainfalls and investigated structural failure due to pipe blockage in such networks. They introduced an index for measuring vulnerability of drainage system before and after applying adaptive measures. The obtained results represented that tree networks possesses higher percent of pipes with critical hydraulic condition compared to loop systems. Therefore, vulnerability of tree systems is significantly greater than loop networks. They also concluded that vulnerability index of tree systems decreases after changing them into loop systems and using adaptive measures.

One of the most solutions that, nowadays, is popular for increasing resilience of UDSs, includes using BMPs for controlling runoff quantity and quality (Jia et al. 2012). Many researchers have considered BMPs in some case studies in order to see the effect on reducing stormwater volume and peak discharge (Åstebøl et al. 2004, Villarreal et al. 2004, Chang and Liou 2010, Stovin 2010, Pyke et al. 2011, Jia et al. 2012). The results are often representative of significant effect of using such management practices.

Despite a large number of studies of which some of them were mentioned, only few studies have examined the performance and resilience of UDS in facing extreme rainfalls. Since urban drainage systems are designed for rainfalls with specific return periods, would be subject to reduced performance in case of extreme rainfall occurrence and in facing phenomenon such as climate change and urban development. Therefore it is necessary that quantifying resilience of such systems in face of extreme events. As mentioned in the literature review above, a study have been conducted by Mugume et al. (2014) in which resilience of an UDS system in England has been examined under higher return periods. In current study it is intended to go further and see the impact of future climatic conditions on a drainage network for a basin in Iran. The effect of using management practices in adapting to climate change will be also investigated. In the proposed methodology, performance of UDS is measured based on hydrologic and hydrodynamic simulations, using flood depth-damage curve and performance function of drainage infrastructure, in two states: with and without using BMPs. At the end, resilience of the system against flooding is quantified.

2 MATERIALS AND METHODS

In figure 1, the methodology and steps for quantifying resilience of UDS is presented. In the following sections, the details of each stage are explained and then, the case study is introduced.

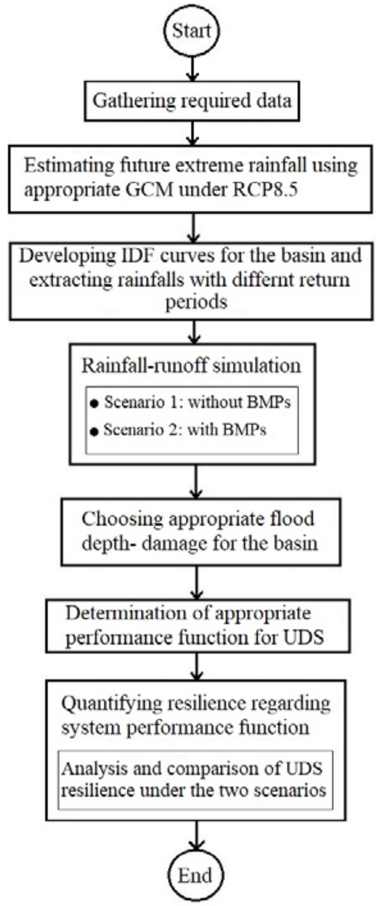


Figure 1: The flowchart of quantifying resilience of urban drainage network

2.1 Input Data to the Model

As mentioned earlier, the goal of current research is to estimate the performance and resilience of UDS under future conditions. According to the literature, climate change impacts mainly emerges as increase in extreme precipitation by increase in rainfall frequency and intensity. Therefore, in current research, in order to consider the impacts of climatic changes on increase of extreme rainfall intensity, future extreme rainfall time series were obtained using the output of General Circulation Models (GCMs), downscaled through Change Factor (CF) method. The reason why downscaling was performed through CF method is its simplicity and ease of use. However, since in current study we deal with extreme precipitation for estimating system flood resilience, an advance version of CF method- in which the changes in extremes, and not just in mean values, are taken into account- was considered (Ruiter, 2012).

After examining different models of 5th Assessment Report (AR5), MRI-CGCM3 was chosen as the best climatic model for simulating future rainfall in the study area (Binesh et al. 2016). Historical data of precipitation as the base of calculations were extracted from two stations: Mehrabad synoptic station in the south and Darakeh hydrometer station in the north, to be able to cover the climatic condition of the whole catchment. The other reason why these two stations were chosen is that they are the only active ones in the basin which included enough data for the purpose of this study. Average precipitation of the area was calculated based on the elevation of each station and daily rainfall recorded in the two mentioned stations, and considering the average elevation of the whole catchment. The characteristics of these two stations has been presented in table 1 according to information obtained from Iranian Water Resources Company and Iranian Meteorological Organization.

Table 1: Characteristics of two stations used in this study

Station Name	Type of the station	Latitude	Longitude	Height (MASL)
Haft-Howz (Darakeh)	Hydrometric	35 ˚48' N	51˚23' E	1700
Mehrabad	Synoptic	35 ˚41' N	51˚19' E	1190.8

Baseline period- according to available data and statistical years the two stations had in common- was considered from 1990 to 2006, and future climate was investigated during the distant future (2084-2100) under RCP8.5 (Representative Concentration Pathway 8.5). In order to have a better view on the system performance under critical future conditions, it is necessary to examine the UDS efficiency in face of more intensified rainfalls with higher return periods. To do this, Intensity-Duration-Frequency (IDF) curves for the catchment were obtained for the distant future (figure 2) using daily extreme rainfall events and relationships proposed by Ghahreman and Sepaskhah (1980) and Ghahreman (1996) who represented equations appropriate for the condition of Iran based on relationships presented by Bell (1969).

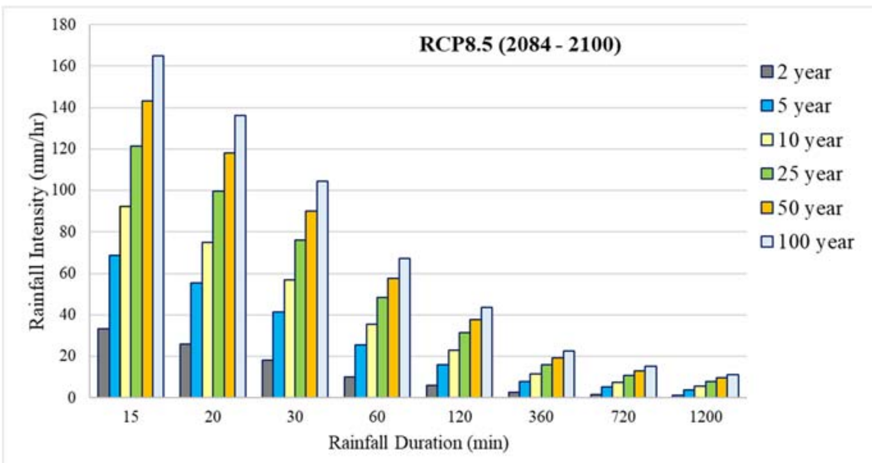


Figure 2: Future IDF curves based on observed data for WFD catchment

2.2 Rainfall-Runoff Simulation

Storm Water Management Model (SWMM) version 5 is used to model UDS. SWMM is a physical model for hydrologic and hydrodynamic simulation, with discrete time step, that can be used for single-event and continuous simulation of storm water quality and quantity in urban areas. In current study, simulating the runoff quantity is considered in a network composed of both open-channels and covered channels, with rectangular and horseshoe-shaped cross-sections, with the width from 1.4 m to 30 m and height of 1.4 meters to 6 meters. System configuration in SWMM software include 73 nodes (apart from the outlet), and 74 links as drainage channels (figure 5). The length of drainage channels and height of the nodes were extracted from DEM of the study area, prepared by Yekom Consulting Engineers (2009). Since curve numbers (CN) of sub-basins were known based on previous studies, infiltration process was simulated through CN method. Flow routing was done through dynamic wave (solving the full Saint-Venant equations), because dynamic wave flow routing is able to consider different types of flow regimes such as backwaters, overflow from the system (i.e. surcharging), reverse flow, and surface ponding (Vanrolleghem et al. 2009). It should be noted that model calibration and sensitivity analysis were done for runoff velocity and depth at the end of the catchment, using data gathered by Mo'afi Rabari (2012).

Since rainfalls in northern Tehran usually last for 6 to 7 hours (Nazif 2010), in current study 6-hour rainfall distribution pattern was used (Mahab-e-Ghods Consulting Engineers 2011) to simulate rainfall-induced runoff in the catchment. In this study, it is assumed that temporal characteristics of extreme rainfall events remains unchanged (Mugume et al. 2013). Rainfall time step was considered 30 min and for output runoff, the time step was considered as 1 hour. Rainfall-runoff modelling was done for a time duration of 3 days.

Simulation was performed under future climatic conditions for two scenarios: 1) for current situation of the system (assuming the system layout and characteristics remain unchanged), and 2) after adding a BMP to the system. In order to investigate the effect of using BMPs on control of nodal flooding, a "Vegetative Swale" of which 50 percent of surface is vegetated was applied as a BMP in all sub-basins. The longitudinal slope is around 1 m, the side slope is 3 m, and the roughness coefficient equals to 0.1. The presence of vegetation in "Vegetated Swale" improves the infiltration of rainwater into the soil. It is also effective in increasing the resilience of the drainage system. The type of herbs used in the swale is mainly adapted to the vegetation of the given area. According to researchers from the University of San Diego, using indigenous plants in this type of BMP rather than a using grass (in Grass Swales) increases the efficiency in terms of reducing runoff rate, as well as removing contaminants and improving runoff quality.

2.3 Flood Depth-Damage and UDS Performance Functions

Due to the lack of recorded flood damage data for different inundation depths in the study area, a depth-damage curve developed by Tajrishi and Malek Mohammadi (2009) for residential areas of Iran (single-storey buildings with and without basement) was used. By linear fitting to the points recorded in this curve (assuming that the variations are linear), the equation for damage versus inundation depth was obtained as follows:

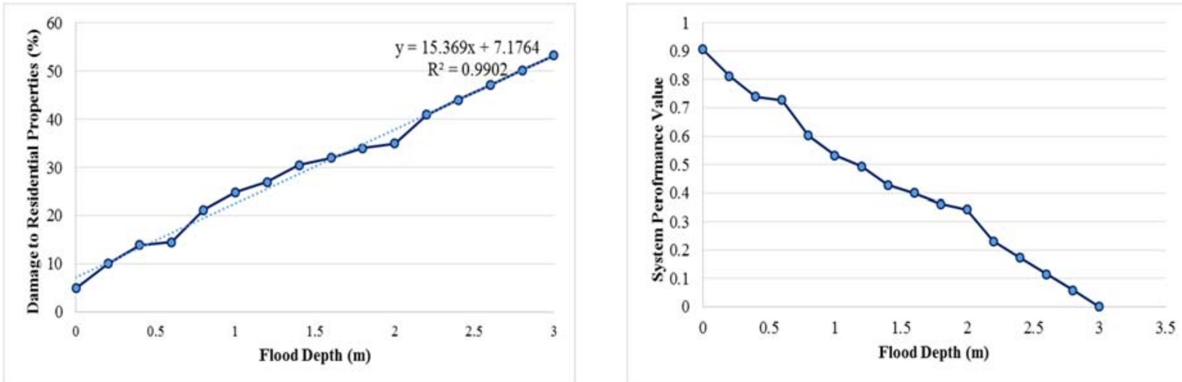
[1] $D_x = 15.369x + 7.1764$

In which *x* is inundation depth (m) and D_x is the percent of flood damage for the depth equal to *x*. It should be noted that in Eq. [1], the amount of damage for zero depth is related to the buildings with basement and storeys below the ground floor.

Performance function of the system against flooding is considered as Eq. 2 (Mugume et al. 2014). Performance functions of UDS relate total performance of the system to flood depth. In fact, such functions are mathematical models that relate a given characteristic to a number in range of 0 to 1. The number 1 is representative of perfect performance and zero is related to the least level of system performance (Cardoso et al. 2004, Gharaibeh et al. 2006).

[2] $u(x) = 1 - \frac{D_x}{D_{max}}$

In which is the maximum flood damage that occurs for the maximum inundation depth (considered as 3 m based on previous studies). According to this function, the best system performance happens when inundation depth equals to zero (*x=0*). In such a condition, the value of UDS performance is considered as 1 (*u(x)=1*). The least level of system performance is for the flood depth equals or more than 3 m (Mugume et al. 2014) where UDS performance is considered zero. Figure 3-a shows flood depth-damage curve used for residential areas of Iran, and the figure 3-b is representative of UDS performance function based on the given depth-damage curve and Eq. 2. According to the figure, it is understood that UDS performance has a negative correlation with increase of flood depth. Such that flooding with a depth of more than 60 cm causes the system performance to decrease more than 30 percent.



(a) (b)

Figure 3: a) Depth-damage curve for residential areas of Iran and the best-fitting line, b) System performance function values for different depths of urban flooding

2.4 Quantifying the Resilience of UDS

According to figure 4, the concept of resilience could be explained as the following: a system disruption due to an extreme event at the time t_0, causes a reduction in system performance up to ("100" minus "system robustness"). By starting the system recovery, the performance is slowly restored so that returns to the normal level of performance at the time t_r. The upper area of the curve that is formed in such a process for the considered time period, indicates the level of non-resilience of the system (Bocchini et al. 2013). The smaller this area is, the more is the resilience of the system. Vice versa, the area below the performance curve represents the level of resilience of the system. Therefore, after estimating UDS performance function at each time step for different flood depths (x_t), system resilience (Res) can be quantified through equation 3 (Mugume et al. 2014):

[3] $Res = \frac{1}{t_n}\int_{t_0}^{t_n} u(t)dt$

In which t_0 is the start time of simulation, and t_n is the total time past at the end of simulation process. *u(t)* is the value of UDS performance function in time steps with 1-hour intervals.

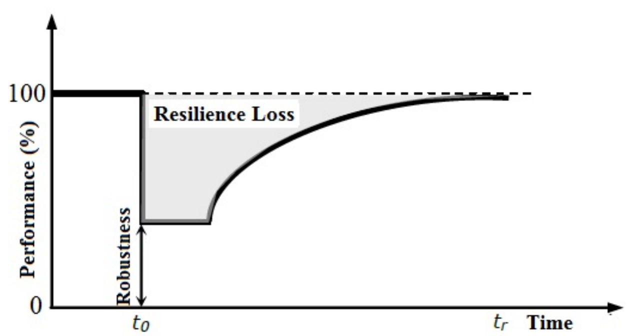


Figure: 4. Schematic of resilience concept (Valizadeh et al. 2016)

3 INTRODUCTION TO THE STUDY AREA

The above methodology was applied on UDS of West Flood-Diversion (WFD) catchment in northern Tehran, Iran, which covers an area of 142.63 km2. This catchment includes three sub-basins namely: Drakeh, Farahzad, and Hesarak (Vesk), and is located in the geographic coordination from 35-48-30 to 35-52-49 N latitude and 51-19-13 to 51-22-29 E longitude. WFD catchment consists of urban and non-urban (mountainous) parts. The storm water runoff from the mountainous areas also incorporates in the urban runoff entering the UDS. Therefore, both urban and sub-urban parts of the catchment were simulated in current study considering the capabilities of SWMM in modelling different types of natural and man-made channels. Figure 5 shows a perspective of urban and mountainous areas as well as the drainage system in SWMM environment.

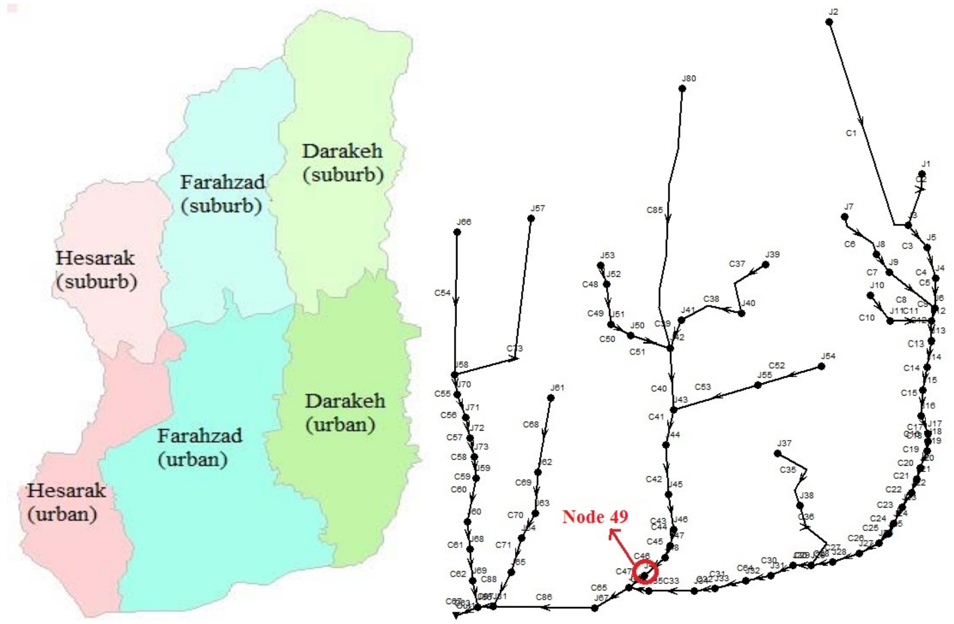


Figure 5: West Flood-Diversion catchment (scale: 1/200000) and modelled nodes and links in SWMM (Source: Authors)

4 RESULTS AND DISCUSSION

4.1 The Results for Hydrologic and Hydrodynamic Simulations

The results of future rainfall-runoff modelling represented that for the first scenario, for the return periods from 2 to 10 years, 11 nodes were inundated. While for 25, 50, and 100-year return periods, the number of flooded nodes were obtained as 16, 19, and 25, respectively. In order to analyse the simulation results in current study, the node number 49 was selected as a sample, whose situation has been shown in figure 5. The reason why we chose this node among the others in the system, is firstly the high volume of flooding, and also being flooded in simulations for all return periods.

Figure 6 shows the system failure time duration and surcharged runoff volume for the two scenarios (with and without BMPs). Based on this figure, it could be said that adding one vegetative swale to each sub-basin for the whole drainage system reduces the average time of nodal flooding between 17-30% and flood volume from 13% to 35%.

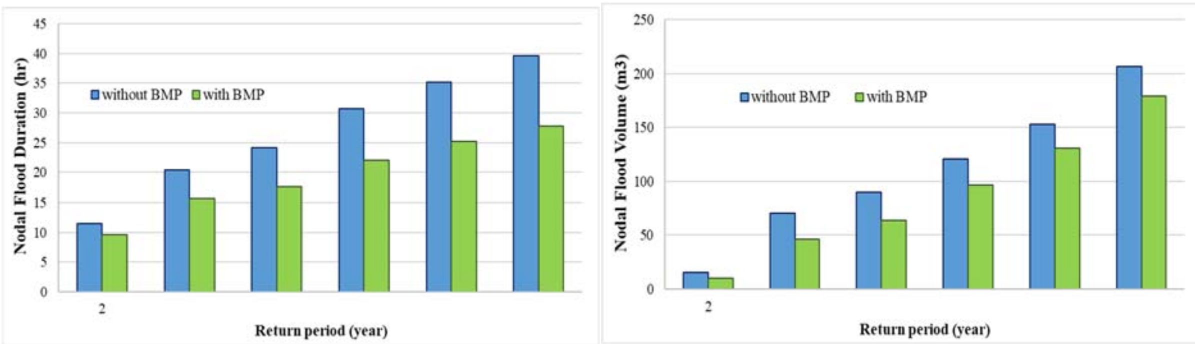
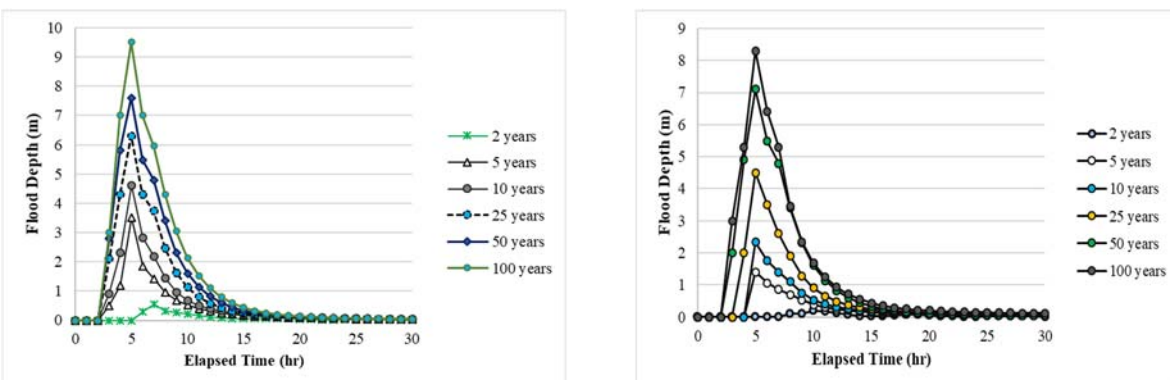


Figure 6: Flood duration and flood total volume for extreme events within different return periods for two conditions: with and without BMPs

Figure 7 represents the curves for the average future flood-depth versus time, for both scenarios: with and without “vegetative swale” alongside the drainage system. It is observed that maximum flood depth for all studied return periods occurs around 5 hours after the beginning of precipitation. The simulation results show that adding one “vegetative swale” to each sub-basin causes a significant reduction of inundation depth and delays the time to peak discharge to some extent.

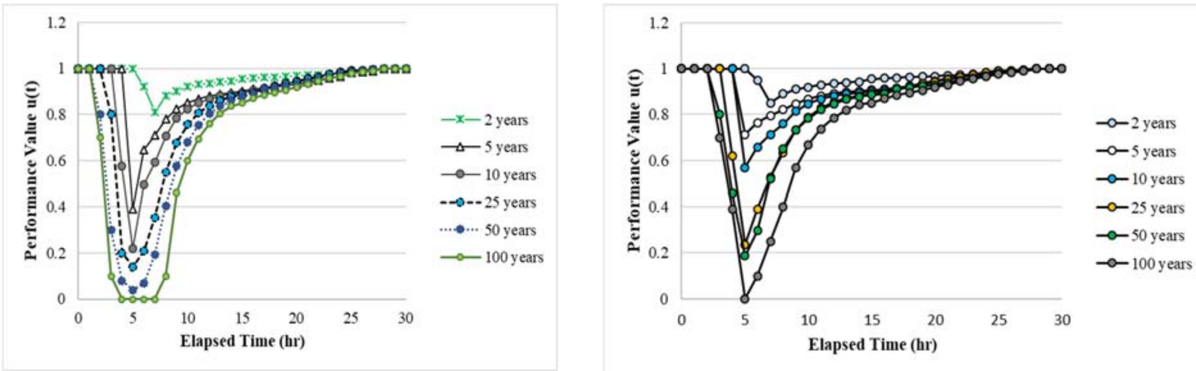


(a) (b)

Figure 7: Depth of nodal flooding for urban drainage system a) without BMP, and b) with BMP

4.2 Estimating the Performance and Resilience of UDS

The value of UDS performance ($u(t)$) in future time was obtained for the two scenarios based on Eq. 2 and inundated depth at each time step. The results are visible in figure 8. It is observed that existence of one BMP at each sub-basin along with the drainage network, has improved the system performance for all studied return periods and reduced the number of failed nodes in the drainage system.



(a) (b)

Figure 8. System performance curves for urban drainage system a) without BMP, and b) with BMP

Based on calculated performance for the drainage network, the amounts of system resilience in future time have been obtained and presented in table 2. According to this table, the range of resilience of UDS, for the without BMP scenario, changes from 96% (2-year return period) to 72.61% (100-year return period). Adding the “vegetated swale” to the system, causes the resilience to fall between 96.37% (2-year return period) and 78.50% (100-year return period). Therefore, the resilience of the system increases between 0.37% to 5.89%, and it could be said that existence of BMPs in sub-basins helps the hydraulic performance of the system return to its original (or acceptable) status in a smaller time duration. Such results agree with the findings by the other researchers (i.e. Mugume et al. 2014) on similar issues.

Table 2: System resilience at given node for different return periods during 2084-2100

Return period (year)	**2**	**5**	**10**	**25**	**50**	**100**
System resilience without BMP (%)	94	87.9	85.32	80.96	75.22	69.38
System resilience with BMP(%)	96.44	92.45	91.24	86.16	83.16	78.50
Improvement of system resilience(%)	2.44	4.55	5.92	5.2	7.94	9.12

5 CONCLUSION

Current research aimed at quantifying resilience of UDS in future time and investigating the impacts of BMP implication as an adaptive strategy on improving system resilience. To this end, flood depth-damage relationship for residential areas and drainage infrastructure performance function were used, and finally, resilience of the UDS was obtained through applying calculated performance values and based on simulation results in SWMM. The results represented that using BMPs along with surface-runoff drainage network can be effective in adapting to future climatic conditions of the basin and in improving the resilience of the system. Such an influence is quite obvious for high rainfall return periods. This means that with increase in extreme rainfall intensity, using management practices is so effective in flood volume reduction in urban areas. However, introducing BMPs to the model may not prevent nodal flooding thoroughly. The degree of flood prevention by such measures is dependent on the number and type of BMPs, their layout in the basin, drainage system configuration (Kim et al. 2013), and type of materials used for BMP construction, and other characteristics.

In order to achieve the best results in reducing runoff peak discharge, it is necessary that BMPs' numbers and layout are determined in an optimized way. As the current study indicated, installing appropriate BMPs in upstream suburban areas can also be effective in improving the system performance and resilience.

In current study, resilience of the system was measured only in one node. However, in order to estimate the resilience of the whole system, it is required to examine and analyze all flooded nodes in the whole system, which is recommended to be considered in future similar studies. In addition, since resilience concept encompasses several indicators such as robustness and recovery rate, it is recommended that ongoing similar researches concentrate on developing new indices for each of these indicators and sub-factors and evaluate the impact of different system failure states on resilience of UDS.

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