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Best management practices (BMPs) site selection for reducing urban surface runoff at target locations

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ABSTRACT

Urban development generally tends to reduce the permeability of urban surfaces resulting in significant increase of stormwater volume and discharge. The volume and peak surface runoff may be effectively controlled in urban areas by using Best Management Practices (BMPs), the selection of which and its spatial arrangement is a challenging task. In this regard, Tehran metropolitan is trying to assess the effect of BMPs in reducing total runoff in developing zones. In this paper, the effectiveness of biological and structural BMPs exposed to different design rainfalls is investigated under several scenarios via Storm Water Management Model (SWMM). According to the results, the amount of reduction in the surface runoff volume closely depends on the type, area coverage and location of BMPs. Proper selection of BMPs in 2, 5 and 10 years return periods results in reduction of runoff volume by 68%, 60% and 51%, respectively. Furthermore, by reducing the surface areas of implemented BMPs for 50% and 25%, the total runoff volumes decrease up to 33% and 45%, respectively. A ranking index is also proposed for sub-watersheds in relation to their contribution in the total runoff reduction. Such index is quite effective in determining the appropriate BMPs sites within the whole urban region.

Keywords: Urban surface runoff; Best management practices (BMPs); Storm water management model (SWMM); Site selection; Runoff volume; Tehran

1. Introduction

Development of urban areas via changing natural landscape into impervious lands leads to drastic reduction in rainwater infiltration opportunity. Urban development also causes increase in the rate and volume of runoff [1,2]. Thus, urban development requires adequate attention to runoff drainage systems [3]. Impervious surfaces with significant effects on the watershed hydrology [4] can reduce the permeability and increase the runoff volume [5].

Best Management Practices (BMPs) and Low Impact Development (LID) are useful approaches for controlling urban stormwater. BMPs can control the runoff [6] and reduce the pollution [7,8]. Use of LID/BMPs may reduce flood risks [9], and urban stormwater runoff can be controlled quantitatively and qualitatively [10] while mitigating the hydrologic consequences of urbanization [11].

Studies in Beijing showed that green spaces have the potential to reduce runoff depending on rainfall, soil conditions and urban morphology [12]. It is also reported that the performance of rain gardens was better than rain barrels in reducing the volume and peak of runoff [13]. Modeling of BMPs for urban areas showed that peak flow was reduced by about 10%, 21% and 13% corresponding to rainfall return periods of 2, 5 and 10 years, respectively [14]. The reduction in runoff was analyzed through BMPs modeling through different scenarios, considering different BMPs in the Beijing Olympic Village, China. Based on the obtained results, total runoff volume and peak flow rate decreased by about 27% and 21%, respectively, depending on the selected scenario [15]. LIDs scenario planning studied

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in Indiana, USA, indicated that among area coverages of 50% rain barrel, 50% porous surfaces and combined scenario of 25% rain barrel and 25% porous surfaces, the latter scenario was the best in urban runoff control [16]. The results obtained by the Storm Water Management Model (SWMM) [17] showed that using porous pavement resulted in reducing the maximum peak flow by 50.7% and this much was about 43% in higher return periods [18]. In another study, it was reported that the maximum effect of BMPs on reducing the runoff volume in the main manholes ranged from 22% to 70% [19].

Searching for the most effective BMP spatial pattern can be a challenging task. Unit Response Approach (URA) has been previously introduced to spatially prioritize flood source sub-areas via simulating the share of each sub-area in flood generation at the outlet of natural watersheds [20]. The objective of this paper is to lay out the URA application in urban areas through simulating possible scenarios in BMPs implementation in a developing zone in Tehran metropolitan area. The best BMPs' spatial pattern is presumed to correspond to maximum efficiency in runoff reduction. The outcome of this study provides a practical methodology for BMPs' site selection in the context of urban surface runoff management.

2. Methodology

The considered region has been modeled using the information obtained from topographical, user, DEM and surface runoff transmission network maps. The region has been divided into sub-watersheds based on the existing maps.

The path and direction of the surface runoff transmission network and their physical specifications in each sub-watersheds have been considered in the program for modeling. Rainfall conditions with different return periods have been considered for hydrological modeling of the region using the information of weather stations and available statistics.

After modeling the sub-watersheds, BMPs are selected and modeled for each of them. In this research, different scenarios are considered to investigate various conditions (different rainfall intensity and different areas for BMPs execution) for analysis and assessment of BMPs. In order to evaluate the potential of BMPs in the management of runoff, two important parameters, volume and peak of runoff have been calculated for each sub-watersheds using the output of the program. The sub-watersheds have different potentials in reducing the runoff volume, considering the conditions and execution areas of BMPs.

Eventually, BMPs site selection maps of each sub-watersheds have been provided for reducing the runoff volume of the whole urban region.

SWMM program has been utilized for modeling and investigating as well as evaluating the effects of BMPs on the reduction of surface runoff volume in the urban areas. Three main parts of SWMM program are: (i) Modeling sub-watersheds; (ii) Modeling BMPs; and (iii) Modeling surface runoff transmission network of the region.

The first part includes the presentation of physical situation, application types, hydrological condition, and rainfall statuses of the sub-watersheds in the program. Physical situation and application types of each sub-watersheds are calculated for modeling based on the available maps of the region, and rainfall statuses upon the information of adjacent weather station and existing statistics.

The second part, modeling of BMPs in SWMM program, is to select the types and locations of BMPs. Considering the physical, hydrological and economic conditions of the region, six types of BMPs (bioretention, rain garden, vegetative swale, infiltration trench, permeable pavement and rain barrels) have been selected for the sub-watersheds.

The locations of BMPs are selected based on different applications of each sub-watersheds; and the types of BMPs are chosen appropriate to their certain applications.

The third part is related to the modeling of surface runoff transmission network for sub-watersheds. It has three main sections, including physical conditions, hydrological statuses and the locations of executing surface runoff transmission network. Physical conditions are the apparent specifications of the network such as shape, depth, length, slope and roughness. Hydrological conditions include the initial flow parameters, maximum flow and loss coefficients of the network. The location and components of the surface runoff transmission network are determined with respect to the available maps of the region and used in SWMM program for modeling.

In this research, three main parts of SWMM program have been used for modeling including the sub-watersheds modeling, BMPs modeling and surface runoff transmission network modeling. Each modeling has its own main sections with important parameters which should be considered in SWMM program. Fig. 1 presents the main parts of modeling in SWMM program along with their relevant parameters and the steps of analysis and assessment.

2.1. Case study

The case study watershed is located in northwest of Tehran, Iran, with about 613.2 ha in area, average slope of 8.5%, and average elevation of 1324 m. The watershed was divided into 30 sub-watersheds as shown in Fig. 2. Different land uses of the watershed are distinguished by different colors in the map shown in Fig. 3. The residential area occupies most of the area. The density of residential buildings is higher in central region and lower in north and northwest. Green and less developed areas are more expanded in the north and west. The density of commercial land use is higher in the southern region. Most types of BMPs may be implemented as a practical solution for managing surface runoff.

Mehrabad station, located in the southwest of the study area, is the closest weather station. The following intensity-duration-frequency (IDF) curves were used [21]:

$$\begin{aligned} T &= 2\ Year \rightarrow I = 134D^{-0.645} \\ T &= 5\ Year \rightarrow I = 171D^{-0.645} \\ T &= 10\ Year \rightarrow I = 199D^{-0.645} \end{aligned} \tag{1}$$

where I is rainfall intensity (mM/h); and D is rainfall duration (min).

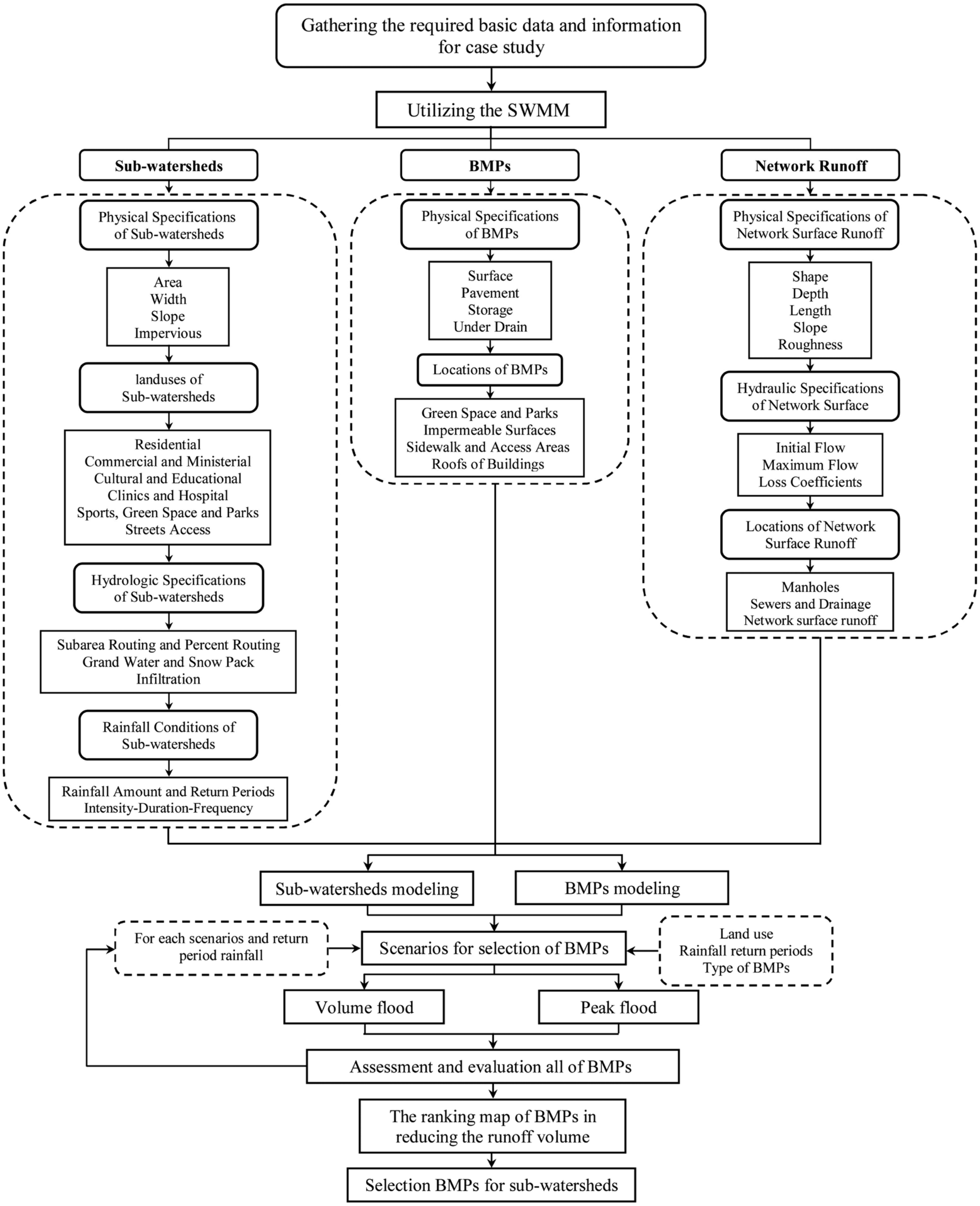

Fig. 1. Methodology flowchart.

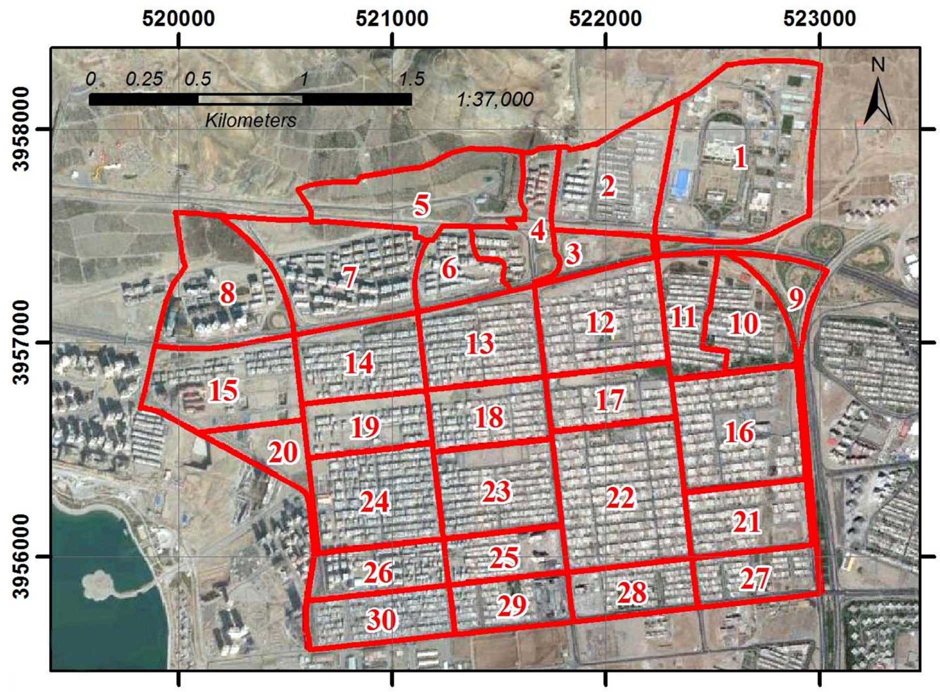

Fig. 2. Study watershed area and sub-watersheds (laied on Google Earth.).

2.2. Simulation of BMPs in SWMM

The BMPs are generally categorized into biological and structural. The BMPs that have plant, lawn and organics are called biological BMPs and include vegetable swale, rain garden and bioretention. Structural BMPs have saving barrels or porous and permeable surfaces. Such BMPs are rain barrel, permeable pavement and infiltration trench. Available space, land use, public perceptions, funding and intended functions are important factors generally considered in selection of type of BMPs [22]. In this research, the feasible types of BMPs are adopted according to the specifications of studied area as follows:

a) **Rain barrels** are storage tanks in which the rainwater collected from the roofs, which is stored for use in the future. Harvesting rainwater from the roofs of the buildings is an alternative water resource [23–29] which can reduce the runoff volume [30–35] and reduce the use of potable water for non-potable purposes [36]. The important parameters in designing rainwater harvesting systems are weather conditions, the surface area of the roofs and tank volume [37–39].
b) **Permeable pavements** are surfaces with the capability of absorbing and infiltrating the runoff. They can be used on sidewalk, access areas, streets and open spaces such as parking areas. Permeable pavements are effective in stormwater managing and can improve the permeability in the development site [40–46].
c) **Infiltration trenches** are narrow trenches with gravel that increase the permeability of the surface. They can be effectively used for reducing/controlling the surface runoff in the urban areas [47–49].
d) **Bioretentions** are surfaces with vegetation, porous and permeable bed. They can reduce and control the runoff [50–52] and even the runoff pollution [53–55].
e) **Rain gardens** are BMPs with vegetation or more broadly with shrubs but without porosity and permeability beds. They can reduce and control runoff and also decrease the runoff pollution [56–60].
f) **Vegetative swales** are channels with the sloping sides covered by lawn and other suitable vegetation. Swales are designed shallow with side slopes. The presence of grass on the surface of channel causes the reduction in the velocity and consequently the volume of crossing runoff. The green cover of channels will influence the stormwater runoff as well [61]. The swale is effective in reduction of runoff and also decreases the runoff pollution [62,63].

All the sub-watersheds were simulated by SWMM based on topographic conditions and land use. The details utilized in SWMM to model the sub-watersheds are sub-watersheds area, and types and percentages of different land uses in the sub-watersheds, porosity and impermeable percentages of the land, slope and physical characteristics of the sub-watersheds. The climatological parameters used in the simulation are depth and duration of design rainfall. Channels, surface runoff ducts, and manholes constitute the hydraulic network of the study watershed. The manholes are mostly located in the southwest of the watershed The surface runoff transmission channels are placed in the northeast to southwest direction. The outlet of the watershed lies within sub-watershed 30. The channels are rectangular concrete channels. The hydraulic parameters of the channels such as length, depth, shape, roughness and

Fig. 3. Land use map of the study area.

slope were input to SWMM. Fig. 4 presents the schematics of SWMM modeling procedure.

V'_{Sc_i} represents the total watershed runoff volume after sub-watershed i is removed:

$$V'_{Sc_i} = \left(\frac{V_T - V_{Sc_i}}{V_T}\right)100 \quad (2)$$

where V_T is total runoff volume; and V_{Sci} is total runoff volume without sub-watershed i. The impact of total output runoff volume of the region on the surface areas of each sub-watersheds (W'_{Sc_i}) is calculated as follows:

$$W'_{Sc_i} = \frac{V'_{Sc_i}}{A_i} \quad (3)$$

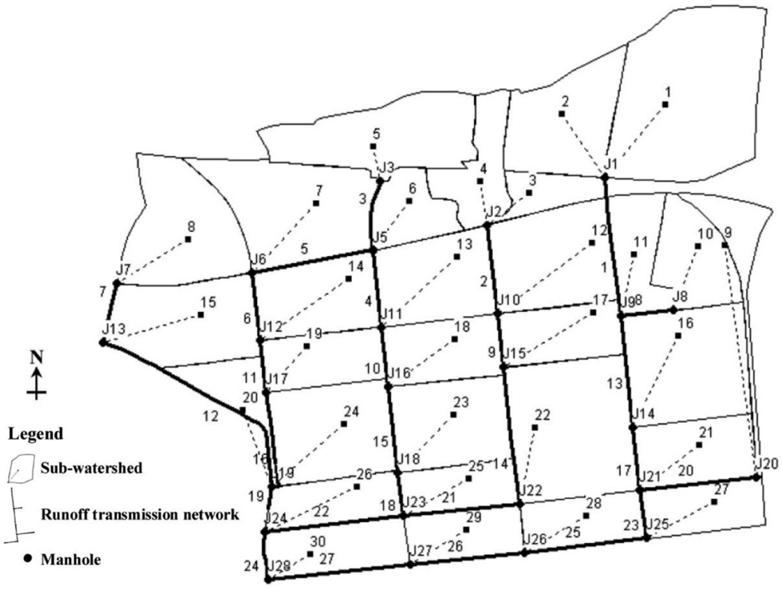

Fig. 4. Topology of sub-watersheds in SWMM.

where A_i is the surface area of sub-watershed *i*. V'_{Sc_i} should be determined for each sub-watershed in order to determine the suitable location and the performance of installed BMPs in reducing the total runoff volume. The ranking map of BMPs in reducing the runoff volume may be presented based on W'_{Sc_i} indicator.

Three scenarios (SC1, SC2 and SC3) were considered for analyzing different types of BMPs. The scenarios were defined as follow:

Scenario 1 (SC1): only biological BMPs are used in all sub-watersheds.
Scenario 2 (SC2): only structural BMPs are used in all sub-watersheds.
Scenario 3 (SC3): the combination of biological and structural BMPs are used in all sub-watersheds.

Table 1 presents the details of feasible scenarios. The base case represents the current condition without any BMPs, hereafter labeled as Business As Usual (BAU) scenario. The results of the three scenarios are compared with those of the BAU. The area of BMPs for the studied scenarios are assumed as the maximum possible area for each sub-watershed.

3. Results and discussion

Table 2 presents the effects of installed BMPs on reducing total runoff volume and peak discharge in three different scenarios under three design rainfalls. The total runoff volume was reduced by about 40%, 28% and 65%, respectively, and peak runoff volumes by about 42%, 22% and 68%, respectively, compared to BAU. Furthermore, total runoff volumes were reduced by about 29%, 24% and 56%, respectively, and the peak discharge by about 22%, 6% and 51%, respectively, compared to BAU. The lowest and highest impacts of BMPs on decreasing total volume and peak discharge corresponded to SC2 and SC3, respectively.

By increasing the rainfall return period, the efficiency of BMPs in reducing total volume and peak runoff reduced more in SC2 in comparison to those of other scenarios. Total runoff volumes of the whole urban region are less reduced in SC2, comparing to those of SC1 and SC3, about 8% and 35%, respectively in average, and peak runoff volumes about 19% and 47%, respectively. The best performance of BMPs were achieved in SC3. The percentages of the peak runoff and total volume reduced in the whole watershed in SC3 were more than 50% for rainfall return periods of 2–10 years. In this scenario under higher rainfall return period, BMPs were more efficient in reducing the runoff.

Table 3 presents the effects of different BMPs surface areas on the peak and total runoff volumes. According to the obtained results, total and peak runoff volumes increase with the decrease of about 50% in the areas of implemented BMPs in sub-watersheds. Accordingly, the percentages of total runoff volumes are about 14–19%, 8–10% and 31–34% in SC1, SC2 and SC3, respectively, and those of peak runoff volumes 16–20%, 4–9% and 34–42%, respectively, for the entire area. In SC3 all types of BMPs have been considered for the sub-watersheds. In this case, the effects of reducing in the surface area of BMPs significantly increase on the runoff volume; such effect is lower in SC2 (structural BMPs). In the sub-watersheds, by reducing the implemented area of BMPs for about 25%, the highest and lowest increase of the total runoff volume are observed in SC3 and SC2, respectively. In the second scenario, by reducing the implemented area of BMPs about 25%, the runoff volume in the entire area in averagely increases about 25%.

Table 1
Scenarios for implementation and development of sub-watersheds

Scenario ID	Classification of BMPs	Select of BMPs
BAU	With out BMPs	–
SC1	Biological BMPs	Bioretention, Rain garden and Vegetative swale
SC2	Structural BMPs	Infiltration trench, Permeable pavement and Rain barrel
SC3	Combination of biological and structural BMPs	Bioretention, Rain garden, Vegetative swale, Infiltration trench, Permeable pavement and Rain barrel

Table 2
The effects of BMPs on reducing surface runoff and peak flow volumes in different scenarios

Return period (year)	Runoff volume (m^3)				Runoff peak (m^3/sec)			
	BAU	SC1	SC2	SC3	BAU	SC1	SC2	SC3
2	85097	51022	61043	29580	13.57	7.81	10.65	4.32
5	105368	69422	78263	41309	14.98	10.24	13.07	5.97
10	118866	84553	90462	52355	15.29	11.88	14.34	7.46

Table 3
The impacts of reduced BMPs areas (50% and 25%) in reducing total and peak runoff volumes

Return period (year)	Area of BMPs (%)	Runoff volume (m^3)			Runoff peak (m^3/sec)		
		SC1	SC2	SC3	SC1	SC2	SC3
2	50% of BMPs	62784	67486	44343	9.32	11.65	6.57
5		83887	85677	62530	13.03	13.88	10.46
10		98756	98475	75941	14.83	14.87	12.76
2	25% of BMPs	71844	71204	57368	12.25	12.25	10.35
5		92832	89771	76454	14.69	14.22	13.22
10		107116	102734	90176	15.20	14.94	14.71

According to the outflow hydrograph in the region, Fig. 5, by reducing the area of BMPs for about 50%, the peak of hydrograph is nearly the business as usual (BAU) state in the first scenario concerning the rainfall with high return period (10 years). If the area of BMP coverage is reduced by 25%, the peak of the 10 yr return period hydrograph

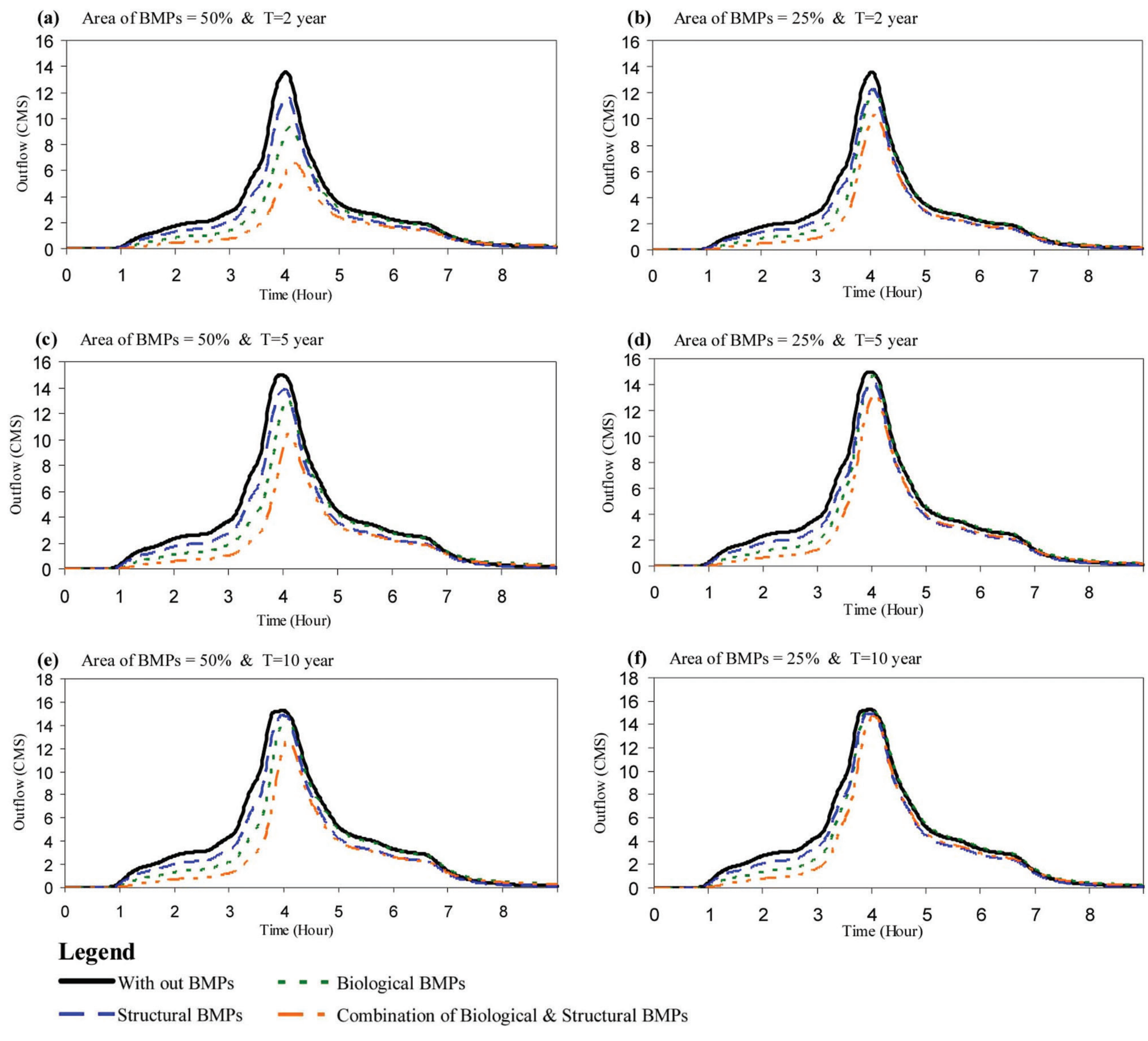

Fig. 5. Flood hydrographs at the outlet in all scenarios.

changes negligibly in all scenarios compared to the BAU scenario. Therefore, it can be said that BMPs have no significant effects on the reduction of hydrographic peak of output runoff of the region.

Fig. 6 presents the ratio of reduction percentages of total volume runoff to the total area of BMPs implemented in the entire region for each scenarios. According to the figure, the potential of runoff reduction to the BMPs implemented area is higher in the biological BMPs (SC1), comparing to that of other scenarios. Moreover, biological BMPs show better performances in the rainfalls with lower return periods. Considering the limitations of required areas, the implementation of biological BMPs show greater efficiencies in reducing runoff volumes, compared to that of structural ones. Biological BMPs present the maximum efficiencies and best performances in controlling the surface runoff and base in the implemented area. However, structural BMPs (SC2) show the least potential in decreasing the runoff volume. Better performances and higher efficiencies are met by combining biological and structural BMPs, in comparison to implementing separately.

Fig. 7 presents the decrease percentage ratio of total peak runoff to the total area of BMPs implemented in the region for each scenarios. The minimum potential in reducing peak runoff is corresponded to the structural BMPs implemented for the rainfalls with higher return periods (10 years). Biological BMPs are more efficient in

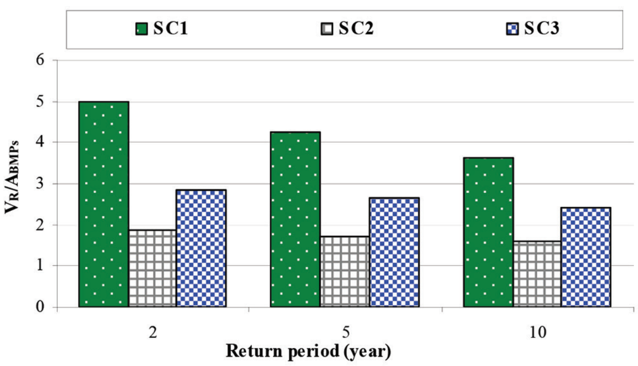

Fig 6. Ratio of reduction of total volume runoff to the total area of implemented BMPs.

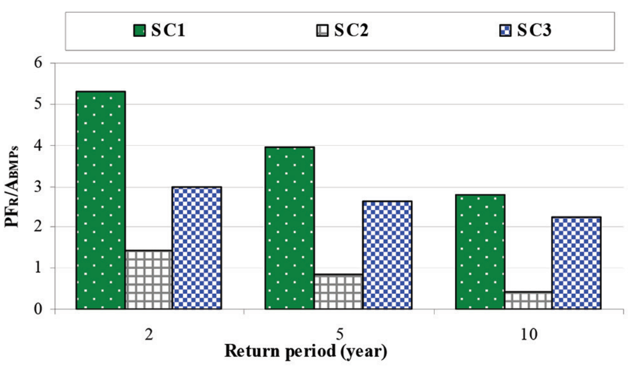

Fig 7. Ratio of reduction of total peak runoff to the total area of implemented BMPs.

reducing the peak base runoff in the implemented areas and show better performances. By combining biological and structural BMPs, their efficiencies will increase in reducing the base peak runoff in the implemented areas.

V'_{Sc_i} and W'_{Sc_i} parameters are determined for each sub-watersheds in order to rank the sub-basins with respect to their runoff reduction potentials.

In the sub-watersheds with low ranks, BMPs are more effective in reducing the runoff. Consequently, the corresponding sub-watershed is less effective in increasing the runoff volume in the entire region. In such sub-watersheds, BMPs show the appropriate performances and efficiencies. In the contrast, higher ranks are assigned to the sub-watersheds where the effects of BMPs are lower in reducing the runoff volume. That is the corresponding sub-watersheds will produce more runoff and will affect the total runoff volume of the area. For short, improper performances and efficiencies of BMPs are corresponded to the sub-watersheds with higher ranks, comparing to those with lower ranks.

Fig. 8 shows the ranking of sub-watersheds for implying BMPs. According to this figure, for scenario SC1 (Figs. 8a,b,c), several sub-watersheds have lower ranks based on the size and land uses. In such sub-watersheds, biological BMPs show appropriate performances in reducing and controlling the runoff. The land use in most of these sub-watersheds are often: green spaces, parks, refuges and the green area beside the streets. The sub-watersheds 8, 9, 10, 11, 14 and 15 have higher potential for implementing the biological BMPs such as bio-retention, rain garden and vegetative swale to reduce the runoff volume in the area.

In the scenario SC2 (Figs. 8d,e,f), the sub-watersheds with low ranks and better performance of structural BMPs in reducing the runoff, mostly contains the land uses such as outside parking, sidewalks, streets and open access area. The sub-watersheds 1, 6, 8, 10, 11 and 16 show higher and more appropriate potential for using the structural BMPs such as infiltration trench, permeable pavement, rain barrel to reduce the runoff in the area. Structural BMPs present better performances in reducing runoff volume in the mentioned sub-watershed, comparing to other sub-watersheds.

According to the ranking flood maps of BMPs presented for SC3 (Figs. 8g,h,i), that sub-watersheds with low ranks have lower building densities and various land uses appropriate for implementing all types of BMPs. BMPs show better performances in reducing and controlling the runoff in such sub-watersheds. However, the higher ranks are corresponded to the sub-watersheds with high building densities, such as those located in central zone. BMPs present improper performances in reducing and controlling the runoff in such sub-watersheds. The sub-watersheds 8, 10, 11, 12, 14 and 15 are more appropriate for implementing all BMPs (combination of biological and structural). That is they are suitable for combined biological and structural BMPs.

4. Conclusions

Selection of proper type and location of BMPs is one of the most important challenges in the implementation of BMPs in urban areas. Therefore, it is crucial to produce the ranking maps of flood generating areas as a guide to proper

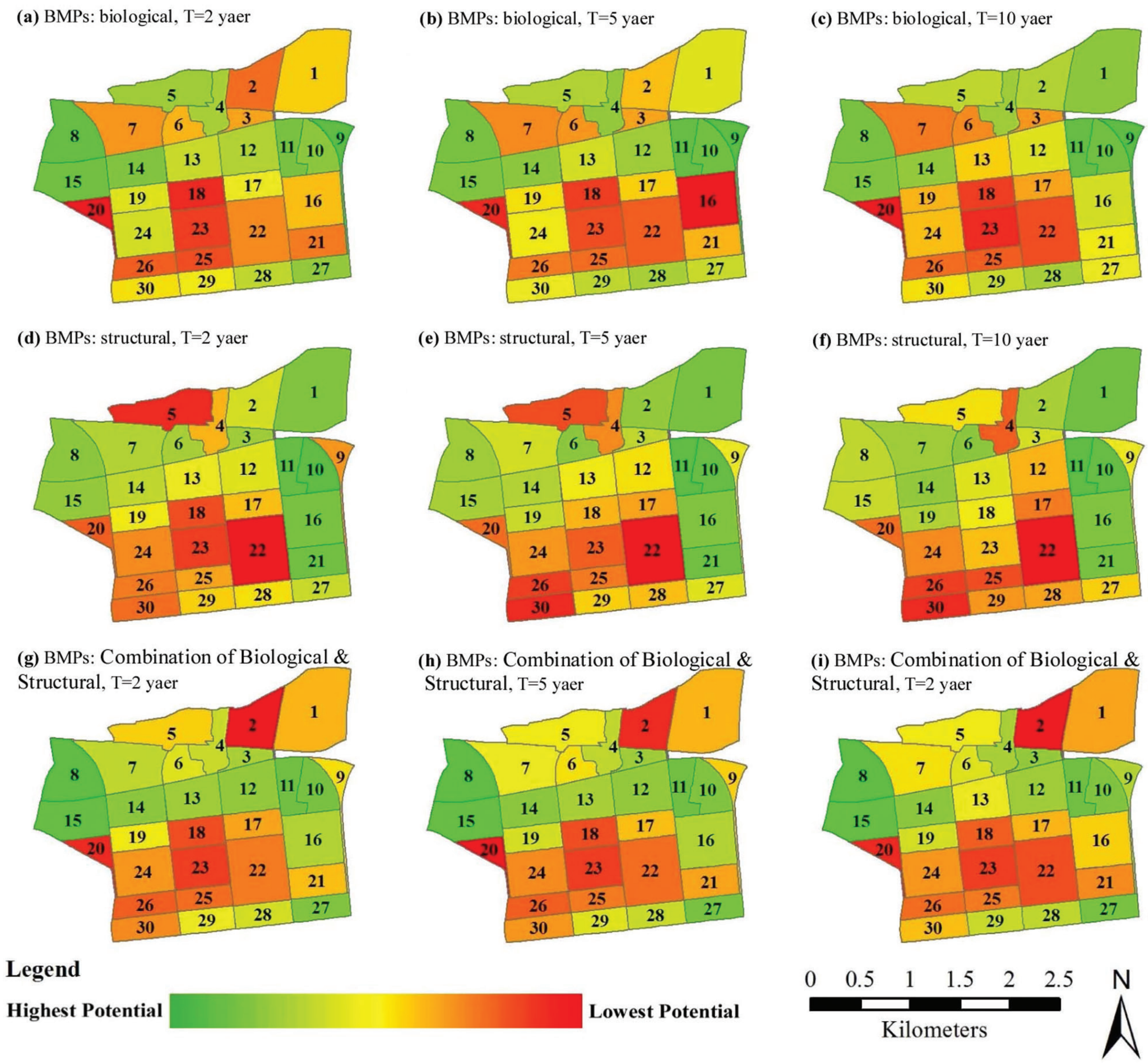

Fig. 8. Map of BMPs ranking in reducing urban surface runoff.

BMPs site selection. By using the ranking flood maps, BMPs efficiency and performance will improve in reducing urban runoff.

For this purpose, different design rainfall and BMPs scenarios were defined in case study urban watershed in Tehran, Iran. Six BMPs including three biological and three structural were considered in this study. The performance and potential of structural BMPs are low and therefore have not high efficiencies by themselves in reducing the runoff volume in the urban areas. Structural BMPs are recommended to be used in combination with biological BMPs in order to improve their potential in reducing runoff volume meet their maximum efficiencies and performances in the urban areas.

In order to meet the maximum volume of runoff reduction in the region, the appropriate location should be selected for implementing BMPs in the sub-watershed based on the land use of the sub-watersheds and land use types. The area can highly affect the potential of BMPs in reducing runoff in the region. Different types of BMPs have potential and performance in reducing the runoff volume in the sub-watershed. The proper location of BMPs can be determined by providing their ranking flood maps in reducing the total runoff. The results obtained from this research are briefly summarized as follows:

- The total reduced runoff volume and peak in the sub-watersheds of the region for rainfalls with the return periods of 2–10 years are:
  29–40% and 22–42%, respectively, in SC1;
  24–28% and 6–22%, respectively, in SC2;
  56–65% and 51–68%, respectively, in SC3.

- In general, biological BMPs have greater impacts on runoff volume reduction in comparison with structural BMPs;
- The performance of BMPs decreases with increasing in the return period of rain falls; this decrease is higher in the structural BMPs (SC2), comparing to that of biological ones (SC1);
- Combining biological and structural BMPs results in the increase of their performance in reducing total volume and peak runoff in the entire area;
- In the rainfalls with the return periods of 2–10 years, the runoff volume increases 17%, 9% and 33% for SC1, SC2 and SC3, respectively, by reducing the area of implemented BMPs about 50%, and 25%, 13%, and 45%, respectively, by decreasing 25% of the area;
- The effect of surface area of biological BMPs (SC1) on the runoff volume is more significant in comparison to that of structural BMPs (SC2);

The presented convenient and practical understanding of implementing BMPs on surface runoff management, especially in the developing regions, can be used and developed for other cities in the world as well. Developing other scenarios with other types of BMPs is suggested for further investigations.

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