Using AHP-PROMOTHEE for selection of best Low-Impact Development designs for urban flood mitigation

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Abstract

In this study, in addition to studying the effects of several LID schemes on urban flood control, the Analytic Hierarchy Process-Preference Ranking Organization Method for Enrichment Evaluation (AHP-PROMETHEE) combination method has been used to select the best design. This paper investigates the drainage system in Golestan town of Semnan under a 5-year return period. The LID methods have been selected based on the region's conditions and available facilities. Then Rain Barrel (RB), Permeable Pavement (PP), and Infiltration Trench (IT) were considered as LID methods. Seven scenarios with the names RB, PP, IT, IT-PP, IT-RB, PP-RB, and IT-PP-RB have been considered to provide the best LID usage combination. Four analytical ranking criteria were selected for the ranking procedure, including implementation cost, hydraulic performance, environmental impact during implementation, and ease of implementation. Then the weight of these criteria was obtained using Analytic Hierarchy Process (AHP). Finally, after determining the weight criteria, the LID designs were ranked using the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) method. The results of hydraulic studies indicate the effectiveness of the PP-RB scenario with an average reduction of 90% of peak discharge and an average reduction of 80% of total flood volume. Also, the weakest performance is related to the IT scenario, with an average decrease of 60% of peak flow and 47% of total flow volume. AHP-PROMETHEE analysis showed that the simultaneous use of RB and IT with a coverage percentage of 5% and a cost of $ 57,710 reduced the total volume by 51.54% and the peak discharge by 48.8% compared to the results of the current system. According to AHP-PROMETHEE, IT-RB-5 is the best project proposed among the 70 projects studied. This study showed that the AHP-PROMETHEE method could be used as a practical method to choose from several LID schemes for flood control.

1) Introduction

Urban flood control studies are always looking for and improving ways to address flood control and mitigation problems or flood quality. In the introduction section, first, articles that pay attention to the issue of urban floods and Low-Impact Development methods, then articles that have used multi-criteria decision-making methods in studies related to urban floods have been discussed.

1-1) Stormwater management model (SWMM) and Low-Impact Development (LID) studies

Today, more than half of the world's population lives in urban areas (UN, 2012), and most of the world's population growth also occurs in cities (Flood, 1997). These changes have caused floods to have more severe effects on residential areas and urban infrastructure. These effects include drastic runoff quality and quantity changes due to storm rains (Jacobson, 2011; Shen et al., 2014; Huang et al., 2018). Numerous studies have shown that urban development increases surface runoff (Dietz and Clausen, 2008; Schoonover et al., 2006; Wang et al., 2005; Palla and Gnecco, 2015). In recent years, many urban designers facing the challenge of urban flooding (Bisht et al., 2016). However, proper Runoff management can benefit semi-arid and arid regions (Ghazavi et al., 2012; Huang et al., 2018).

Mathematical models can achieve the best possible design for urban runoff management (Faye et al., 2016). Rainfall-runoff models either act on the occurrence of an event or continuously perform simulation. Event-based models usually perform rainfall-runoff calculations based on a unique short-term event. These models typically simulate only part of the hydrological processes of the catchment. Most event-based models use fixed time steps for hydraulic and hydrological analysis. The SWMM model was first introduced by the U.S. Environmental Protection Agency (U.S.EPA) in 1971. Based on the environmental plan of the study area, SWMM simulates the rainfall-runoff of the basin and prepares the results of quantitative and qualitative analyzes related to runoff (Faye et al., 2016). The SWMM model was used to simulate and calibrate storms observed in a large basin in Tallinn. The results showed that the SWMM model is sensitive to the percentage of impermeable areas, flow volume, and peak discharge (Maharjan et al., 2017). The SWMM model can estimate flood volume and peak discharge in urban sub-basins based on previous research studies. In recent years, new methods for flood control in urban watersheds have been studied by researchers.

One of the advantages of these new methods is being friendly to the environment. Green Infrastructure (GI), Best Management Practices (BMPs), and Low-Impact Development methods (LID) are among these methods (Eckart et al., 2012; Jia et al., 2015). However, to optimize LID and the costs allocated to these methods, appropriate optimization measurements should be used, especially when there are multiple decision-making criteria (Babaei et al., 2018). Recently, LID has been introduced as a completely reliable method in controlling urban runoff, surface water pollution in the urban basin, and urban ecosystem. (Teymouri et al., 2020; Kayhanian et al., 2012; Ahiablame et al., 2012; Randhir and Raposa, 2014). LIDs are a green approach to urban flood management. LIDs seek to assist in the hydrology of the urban basin, and this assistance is implemented on a small scale in the urban basin. (HUD, 2003). However, the use of these methods requires further experimental studies to determine the exact characteristics of these methods to make them more effective in controlling floods and peak discharges. The first goal of using LID in urban environments is to prevent floods by reducing possible runoff with a specified return period (Park et al., 2013). Mathematical models can determine the type of LID and its location, especially when there is a limited budget for urban flood management (Prez-Pedinin et al., 2005). These models can be more effective in clarification of LID use (Elliott and Trowsdale, 2007).

The main idea is to use the LID method to control runoff and reduce pollution on site. Different types of LIDs include bio-retention cells, rain gardens, green roofs, rain barrels, Infiltration trenches, permeable pavements, roof separation, and green swale (Hoang and Fenner, 2016). One of the complexities of using LID methods is optimizing the space allocated to them and their implementation costs (Martin-Mikle et al., 2015; Geng and Sharpley, 2019). The purpose of implementing the LID-BMPs is to flood reduction to create the natural hydrology of the urban basin as much as possible. However, the optimization of LIDs will be commensurate with their performance by considering criteria such as effectiveness in reducing the quantity of flood volume, improving the quality of urban runoff, physical constraints of the area, implementation costs, and even social factors. Therefore, prioritizing the implementation of proposed LID designs has certain complexities and requires multi-criteria selection methods to select the best design. However, the selection of LIDs using multi-criteria selection methods has been conducted almost rarely and in few studies (Chen et al., 2015; Zou et al., 2015; Efta and Chung, 2014). For example, safari et al. selected and prioritized the necessary water resources for irrigation of Buin Zahra urban green basin of Qazvin province in Iran using the AHP-PROMETHEE method (safari et al., 2020).

1-2) Multi-Criteria decision making

Water basin management is one of the essential tools for managing and controlling water resources in any region (Sriyana 2020). One of the most understandable systems designed for decision-making is AHP which can examine different forms of a problem. These processes involve various decision options, making it easy to analyze the sensitivity of criteria and sub-criteria in these methods. (Ahmadi et al., 2020). The AHP method is a structured method developed based on psychology and mathematics. AHP is used to design and interpret criteria that are generally contradictory. Thomas L. Saaty developed this method in the 1970s. AHP has been used in many studies since then. This method is widely used in studying various scientific disciplines worldwide because it covers a broad and diverse range of decision-making conditions (Thungngern et al., 2015). The basis of this method is a pairwise comparison between decision criteria. Controllability of decision operation compatibility is one of the advantages of the AHP method. This feature means that the calculation of the weight of equal matrices is done simply by normalizing each column's members, so the decision operation's incompatibility will be zero. However, in incompatible matrices, finding the weight of each criterion will be a challenge, and consequently, the degree of incompatibility must be calculated (Mutikanga et al., 2011). In the AHP method, the decision matrix is made to find the weights, and the diameter of this matrix will always be equal to 1 (Ghodsi pour 2012). In another study, the AHP method was used to select the most suitable place to store water for use in times of drought (Ahmad and Verma 2018).

The use of the AHP-PROMETHEE technique in water resources management studies has been seen in several studies. For example, in 2019, Karleusa et al. (2019) used the AHP-PROMETHEE technique to rank suitable neighborhoods in Slovakia for agricultural irrigation projects using three environmental, social, and economic criteria. Finally, they introduced five areas with good potential for implementing irrigation projects (Karleusa et al., 2019). Also, in a study conducted by Tschikner et al. in 2017, it was found that the AHP-PROMETHEE method compared to other multi-criteria decision-making methods, showed better results in selecting the location of wells in urban areas (Tscheikner Grath et al., 2017). However, the review of previous studies indicates that not much research has been done in the quantitative and qualitative management of urban floods using LID-BMPs to control and reduce urban floods. Latifi et al. (2019) used the game theory model to optimize urban flood management. They finally used the PROMETHEE method by identifying the Pareto front of optimal solutions to find the best-proposed options for LID methods. They concluded that this method allows decision-makers to make decisions with a more realistic approach to urban flood control (Latifi et al., 2019). Using SWMM and the PROMETHEE method, Babaei et al. prioritized urban sub-basins by considering the peak flood discharge (Babaei et al., 2018). Using the AHP method and considering different selection criteria in their research, Fuamba et al. and Young et al. sought to select the BMP methods by evaluating the performance in several ways. Sometimes consulting with experts to quantify the criteria for decision criteria can be complex (Fuamba et al., 2011; Young et al., 2010). To rank the performance of BMPs, Jia et al. provide a two-tier index that operates by calculating a cumulative number. However, how to weigh the criteria is not clearly stated (Jia et al., 2013). Martin et al. used a simple method to weight the requirements for the stakeholders but used the same weights in cases where the importance of policymakers was similar. They used ELECTRE III to select LID methods (Martin et al., 2007). Chitsaz and Banihabib used combined weight selection and ranking methods in their study (Chitsaz and Banihabib, 2015). They evaluated eight different multi-criteria ways to select the best technique for flood control.

In previous studies, the ranking has been done only by using LIDs individually; while considering the different performance of different LID methods, it can be suggested that combined LID methods can be more robust compared to individual LID methods. Therefore, studies on the performance of composite LIDs in flood control will be very critical. The core purpose of this study was first to model the drainage system of the study area under rainfall with a return period of 5 years in SWMM software. Then seven scenarios were defined, considering rain barrels, permeable pavement, and infiltration trench as LID techniques. Each scenario includes ten different plans. These 70 plans differ in terms of LID usage percentages and their combinations. Another purpose of this study is to investigate the performance of each plan in controlling flood volume and peak discharge in the study area. Implementation cost, hydraulic performance, environmental impact during implementation, and ease of implementation were considered decision-making criteria. Then, using the AHP method, the weight of these criteria was determined relative to each other and using the PROMETHEE method, all 70 proposed plans were ranked where the top five designs were introduced. Figure 1 is a flowchart of the whole process of the present study.

2) Materials And Methods

2 – 1) Study area

This study's area is part of Golestan town of Semnan city located in Semnan province in Iran. Semnan province is located in the south of the Alborz Mountains, which has caused a large part of this province to have a desert nature. Semnan province is between the longitude of 53° 23′ to 53°26′ east and the latitude of 35°33′ to 35°35′ north. The Golestan town is located northwest of Semnan city with an area of about 2.86 Km^2. The maximum and minimum elevations of the area are 1243.73 and 1175 meters, respectively. Figure 2 shows the geographical location of Golestan town.

2–2) SWMM

EPA-SWMM software is an open-source dynamic model for rainfall-runoff simulation and is used in urban flood management, planning, analysis, and design of surface water collection networks. This model was first introduced in 1971 by the US Environmental Protection Agency. This software has a simple working environment and high power in simulating quantitative and qualitative models. The equations used in SWMM are the mass conservation equation and the momentum equation, which are known as the Saint-Vanant equations (Equations (1) and (2)).

$$\frac{\partial Q}{\partial x} + \frac{\partial Q}{\partial t} = 0 \qquad (1)$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g\left(S_o - S_f\right) = 0 \qquad (2)$$

By solving these equations, this software simulates three methods of steady flow routing, kinematic wave routing, and dynamic wave routing. In the above relation, A (m^2) is the area of the cross section of the flow, Q (m^3/s) is the flow rate, y (m) is the water depth, Sf is the energy line slope, So is the slope of the conduit, g (m^2/s) is the acceleration of gravity, x (m) and t (min) are spatial and temporal variables, respectively. Steady flow routing is the simplest type of routing. This Approach assumes uniform and stable hydrograph flow, which transmits the input current to the output. This method of solving the Saint-Venant equations can not model waterway storage, water return effects, inlet and outlet losses, reverse flow, and pressure in conduits. Also, this method is not sensitive to time steps and is only suitable for initial analysis and long-term continuous flow simulation. In routing by the kinematic wave method, the mass conservation equation is solved along with the simple form of the momentum equation. In solving this equation, the slope of the water surface is considered equal to the slope of the conduit floor. Dynamic wave routing solves one-dimensional Saint-Venant equations completely without any simplification. Unlike the previous two methods, dynamic wave routing simulates the storage of waterways, the amount of water return, the energy losses at the inlet and outlet of the conduit, and the reverse flow. In this research, the dynamic wave method is simulated at 1-minute intervals.

SWMM needs three main categories of information for quantitative simulation of urban runoff: 1) Physical characteristics of sub-basins, 2) Information on rainfall events, and 3) Water infiltration information.

The physical characteristics of sub-basins include :

- Sub-basins.
- Percentage of impermeable areas of each sub-basin.
- The equivalent width of sub-basins.
- The medium slope of sub-basins.
- Surface storage of permeable and impervious areas.
- The roughness coefficient of porous and impervious surfaces.

Most information was based on the available maps of Golestan town. In this study, Horton's equation has been used to model water infiltration in soil. Horton's equation (Eq. 3) is expressed as follows:

$$F_t = F_c + \left(F_0 - F_c\right)e^{-kt} \quad (3)$$

In Eq. 3, F_t: penetration at time t in millimeters per hour, F_c: final penetration intensity in millimeters per hour, F_0: Initial penetration intensity in millimeters per hour, and k is Horton constant, which depends on land use and soil type

2-3) Low-Impact Development

Two critical issues in using these methods are determining the appropriate places for their construction and the area covered by them according to different criteria. The location of these techniques affects the peak flow rate and flow volume, and their structure in inappropriate sites can contribute to the poor performance of the existing flood collection system. Numerous studies have been conducted to develop standards for the optimal selection of LID-BMPs. For example, considering the slope of the area (Clean Water services, 2009), (UACDA, 2010), (County of Los Angeles, 2014), (County of Mendocino) have suggested that for slopes between 1 to 5 percent, different types of permeable pavement have shown good performance. Also, infiltration trenches are suitable in areas with less than 15% slope, while the area's pitch is ineffective in selecting rain barrels. By studying various LIDs, (Caraco & Claytor, 1997) has stated that the barrel of rain in cold and mountainous areas has very low effectiveness. It is also suggested that the distance of groundwater to the permeable pavement and infiltration trench should be more than 1 meter and between 2 to 4 feet, respectively. (California stormwater BMP Handbook Manual) and (Low impact development guidance manual, 2009) have suggested that using infiltration trenches and permeable pavement in soils with a minimum penetration intensity of 38.1 mm / h shows considerable effects. According to the studies conducted in this study, three types of LID with the names of rain barrel, permeable pavement, and infiltration trench have been used, the specifications of which are shown in Table 1 (Prince George's County Maryland (1999), ACCWP, 2001) And (EPA 2010,). Figures 3, 4, and 5 show examples of rain barrels, permeable pavement, and infiltration trench, respectively.

Table 1
LID specifications

LID type	LID features	Value
Rain Barrel	Barrel height (mm)	1000
	Flow coefficient	0.8
	Flow exponent	0.5
	Offset (mm)	6
	Drain daily (hrs)	6
Permeable pavement	Surface roughness	0.12
	Thickness (mm)	120
	Void ratio	0.6
	Flow coefficient	0.8
	Flow exponent	0.5
	Offset (mm)	15
	Soil conductivity (mm/hr)	120.4
	Soil thickness (mm)	150
	Storage thickness (mm)	250
Infiltration Trench	Surface slope (%)	1
	Storage thickness (mm)	1000
	Void Ratio	0.75
	Flow coefficient	0.8
	Offset (mm)	6

Different perspectives were examined to calculate the cost of implementing new structures. Estimating the cost of construction of these new structures was proposed considering the area, LID volume, and quality included in the model. Table 2 shows the cost of implementing the LIDs used in this study (CNT 2009; SEMCOG 2008; Strecker et al., 2010).

Table 2 - Cost range

LID type	Cost range (US Dollar)		Cost per unit
	Up limit	Low limit	
Rain barrel	380	100	One barrel
Preamble pavement	129.17	15.93	One m^2
Infiltration trench	2.196	1.92	One m^3

2-4) Intensity-Duration-Frequency (IDF) curve

Previous studies related to urban flood control with LID facilities show that the choice of storm event return period is essential in designing LID dimensions (Guo and Adams, 1998)(Baek et al., 2015). Based on the analysis, the IDF curve at Semnan Synoptic Station for design return periods of 2 to 100 years has been estimated by the Meteorological Organization of Semnan Province, which can be seen in Fig. 6 (HTTP://www.semnanweather.ir/). In this study, the return period for designing LIDs and reviewing the urban drainage system is five years (Baek et al., 2015).

Rainfall intensity for Semnan station with a return period of 5 years is 10.04 mm per hour. Figure 7 represents the cumulative rainfall over the 5-year return period and concentration time of the catchment. According to Fig. 7, this value is equal to 2.08 mm.

2–5) AHP

Thomas Saati stated the four principles of inversion, homogeneity, dependence, and expectations as the principles of AHP (Neshat and Pradhan 2015). Saati used numbers 1 to 9 to compare the pairs of criteria. The number 1 indicates the same importance of the criteria, and the number 9 indicates the importance of the criteria under consideration compared to other criteria. For each pairwise comparison matrix, an acceptable degree of incompatibility is defined as the inconsistency rate (Eq. 5). Saaty presented the number 0.1 as an acceptable limit and believed that if the degree of inconsistency (Eq. 4) is greater than 0.1, it is better to reconsider the judgments.

$$I.I. = \frac{\lambda_{max} - n}{n-1} \qquad (4)$$

Where λ_{max} is the maximum eigenvalues and n is the sum of the eigenvalues. The result of dividing the I.I. (Inconsistency Index) on R.I.I. (Random Inconsistency Index), the I.R. is Inconsistency Rate (Eq. 5).

$$I.R. = \frac{I.I.}{R.I.I} \qquad (5)$$

The evaluation criteria for ranking in the present study are implementation cost, hydraulic performance, environmental impact during implementation, and ease of implementation, which can be seen in Fig. 8.

At first, the opinions of ten hydraulic and water experts about decision-making criteria were collected using a questionnaire. The four final criteria were shown by involving ten experts in completing the pairwise comparison matrix of the criteria. The final weight of each criterion was calculated using EXPERT CHOICE (EC) software and the geometric mean (Equation 3). The geometric mean is defined as the nth root of the product of n numbers, i.e., for a set of numbers x_1, x_2, ..., x_n, the geometric mean is defined as:

$$\left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}} = \sqrt[n]{x_1 x_2 \dots x_n} \quad (3)$$

Table 3 shows the results obtained from the above operation. The final sensitivity analysis in the weighting process should be less than 0.1 to consider the weighting process correct. The sensitivity analysis of the final weights is equal to 0.07, which indicates the accuracy of the operation.

Table 3
Final weight of decision criteria

Criteria	Hydraulic performance	Implementation cost	Environmental impact during implementation	Ease of implementation
weight	0.66	0.17	0.05	0.12

2–6) PROMETHEE

The PROMETHEE method is one of the new ranking methods in multi-criteria analysis and was developed by Burns in 1982. Later versions were developed by Burns et al. in 1985 and 1994 (Brans et al., 2005). Each criterion is examined based on a separate function without relation to other criteria. Using different scales to measure criteria is a strength of this method. However, this technique does not provide a way to assign weights to criteria (Macharis et al., 2004), which eliminates this weakness with the AHP technique. Therefore, their combined use is a functional complement to overlap each other's weaknesses. Proponents of this approach have proposed six preference functions (Table 4) to decision-makers. The correct choice of these functions depends on decision makers' understanding of the relationship between criteria and options (Brans et al., 1998).

Table 4
PROMETHEE Functions

Type	Name of function	Function
1	Usual	$P(d) = \begin{cases} 0 \, if d \leq 0 \\ 1 \, if d > 0 \end{cases}$
2	Quasi	$P(d) = \begin{cases} 0 \, if d \leq q \\ 1 \, if d > q \end{cases}$
3	Linear	$P(d) = \begin{cases} 0 \, if d \leq 0 \\ \frac{d}{p} \, if 0 < d \leq p \\ 1 \, if d > p \end{cases}$
4	Level	$P(d) = \begin{cases} 0 \, if d \leq q \\ x \, if q < d \leq p \\ 1 \, if d > p \end{cases}$
5	Linear with indifference	$P(d) = \begin{cases} 0 \, if d \leq q \\ \frac{d-q}{p-q} \, if q < d \leq p \\ 1 \, if d > p \end{cases}$
6	Gaussian	$P(d) = \begin{cases} 0 \, if d \leq 0 \\ 1 - e^{-\frac{d^2}{2s^2}} \, if d > 0 \end{cases}$

After performing pairwise comparisons and selecting one of the appropriate functions for the function, the final ranking of the two options is obtained by adding the priority of all indicators, which is called the total value and is represented by Eq. 4.

$$\pi(a,b) = \sum_{j=1}^{k} w_j * p_j(a,b), \; \sum_{j=1}^{k} w_j = 1 \qquad (4)$$

In the above relation, w_j (j = 1, 2, 3, …, n) represents the normalized weights of each index. The value of π (a, b) varies between zero and one, and the higher this value, the higher the priority of option a over b will be. Finally, after calculating π (a, b) for each option a ∈ A and considering the other options x ∈ A, the following ranking process is obtained. In Eq. 5, the positive rating current or output current is calculated. In Eq. 6, the negative rating current or input current is calculated.

$$\Phi^{+}_{(a)} = \frac{1}{n-1}\sum_{x\in A}\pi(a, x) \quad (5)$$

$$\Phi^{-}_{(a)} = \frac{1}{n-1}\sum_{x\in A}\pi(a, x) \quad (6)$$

In equations 5 and 6, the value $\Phi^{+}_{(a)}$ indicates the strength of option a, and $\Phi^{-}_{(a)}$ indicates the weakness of option a. Each current can generate a complete ranking in A. The largest value of $\Phi^{+}_{(a)}$ represents the best a, and the largest value of $\Phi^{-}_{(a)}$ represents the worst a (Chitsaz and Banihabib, 2015). Finally, the best option can be determined by calculating the net current, which is obtained from Eq. 7 (Martin et al., 2007):

$$\Phi_{(a)} = \Phi^{+}_{(a)} - \Phi^{-}_{(a)} \quad (7)$$

Now, the options can be compared with each other and the best option can be selected.

3) Results And Discussion

3 – 1) Calibration and validation of SWMM

Since the information was not available for Golestan town, the model was calibrated and validated with the peak flow obtained from the SWMM, compared with the peak flow calculated from the logical relation (Formula 9) in each of the sub-catchment. This strategy was adopted from the land use and area of all sub-catchment of Golestan town. Considering that each sub-catchment was composed of different land uses, initially, the size of other parts of each sub-catchment was calculated using AutoCAD software. The results of these calculations can be seen in Table 5.

Table 5
Land use of each sub-catchments in Golestan town

Sub-catchment	Land use	Area (m^2)
1	Residential	4453
	Hospital	184404
	Public green area	43218
2	Residential	106402
	Educational	16585
	Public green area	43218
3	residential	299647
	Educationa	84423
4	Residential	120639
	Public green area	33104
	Mechanical installments	71718
5	Residential	308281
	Public green area	19035
6	Residential	195118
	educational	6128
	Public green area	13787
7	Residential	27871
	Health care centre	7137
	Educational	97115
	Mechanical installments	34950
8	Residential	137458
	Public green area	86592
9	Residential	205809
10	Resedential	104707
	Public green area	217605
11	Residential	182240
	Public green area	33700
12	Residential	156262
	Educational	14071

Sub-catchment	Land use	Area (m^2)
	Public green area	44507

The Table 6 shows the runoff coefficients of each sub-catchment according to the land use of that sub-catchment. By using relative weight averaging (Eq. 8), the runoff coefficient of each sub-catchment was calculated.

$$\bar{C} = \frac{\sum_{i=1}^{n} C_i A_i}{\sum_{i=1}^{n} A_i} \quad (8)$$

In the above relation C_i is the value of the runoff coefficient related to the area A_i of each sub-catchment. After calculating the value of $\bar{C}$ for each sub-catchment using the logical formula (Eq. 9), the peak flow rate in each sub-catchment was calculated:

$$Q = 0.278 * \bar{C} * i * A \quad (9)$$

Which Q stands for maximum peak discharge (m^3/s), $\bar{C}$ is the runoff coefficient, i is rainfall intensity (mm/hr), and A is the area of catchment (km^2).

Table 6
Runoff coefficient table in rational formula (Alizadeh, 2006)

Area	The type of catchment	Average Runoff Coefficient (C)
Residential	House	0.4
	Apartment	0.6
Industrial	Low density	0.65
	High density	0.75
Commercial	In the City	0.825
	Out of the City	0.6
Street	Asphalt	0.825
	Non-asphalt	0.6
Non-urban catchment	Gravel soil with low slop	0.05
	Gravel soil with high slop	0.125
	Gravel soil with very high slop	0.175
	Clay soil with low slop	0.15
	Clay soil with average soil	0.185
	Clay soil with high slop	0.25

To compare the peak discharge calculated from the logical formula with the peak discharge calculated by SWMM software, the coefficient of determination (R^2) (Eq. 10) (Karami et al., 2022) and Root Mean Square Error (RMSE) (Eq. 11) (Hu et al., 2021). The comparison results showed that R^2 = 0.8657 and RMSE = 0.01653(m^3/s). This result were indicated in the Fig. 9 which approves the validity of the SWMM software results for flood simulation in Golestan town.

$$R^2 = \left[\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y}) \Big/ \sqrt[2]{\sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2 \sum_{i=1}^{n} \left(y_i - \bar{y}\right)^2} \right]^2 \quad (10)$$

$$RMSE = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2 / N} \quad (11)$$

Which in the above relations x_i and $\bar{x}$ express the observational values and their averages; y_i and $\bar{y}$ also represent the predicted values and their mean.

3-2) LID scenarios

The seven scenarios include three individual scenarios, three pair scenarios, and one general scenario. Each one contains ten different plans. Table 7shows how to name the plans. The maximum flood volume and maximum runoff for the outfall point were considered as model outputs.

Table 7
-LID Scenarios

scenario	type	Number of plans	symbol
1	individual	10	RB-Usage percentage
2	individual	10	PP-Usage percentage
3	individual	10	IT-Usage percentage
4	Paired composition	10	IT-PP-Usage percentage
5	Paired composition	10	IT-RB-Usage percentage*
6	Paired composition	10	PP-RB-Usage percentage
7	Triple composition	10	IT-PP-RB-Usage percentage

* : IT-RB-15 means that The LIDs used are infiltration trench and rain barrel, and the percentage used of each of them is 15%.

3-3) modeling the study area in the current conditions

Figure 10 is a schematic view of the runoff collection system in Golestan town. The initial modeling results indicate the phenomenon of flooding in one of the nodes.

The simulation results of the drainage system before using Low-Impact Development methods in the study area include the total volume of the flow of and Runoff peak. These results showed that the hydraulic outcomes in the outfall node (O1) are 3.446 liter (10^6) and 0.559 m^3/s for the total volume of the flow of and Runoff peak respectively, while the numbers in the flooded node (J18) are 1.281 litr (10^6) and 0.569 m^3/s. Based on the simulation of current drainage system, it was observed that node 18 was flooding with a maximum flow rate of 0.569 m^3/s and a volume of 12810000 liters. The flow output hydrograph in the existing system is also shown in Fig. 11.

3-4) Scenario 1: RB

A general rule for all scenarios is that each has ten different designs. This difference is in terms of the level of coverage that each LID occupies from each sub-basin. In the RB scenario, ten different plans are proposed. This scenario showed that the rain barrel had an excellent ability to reduce the volume of floods and peak discharges. Figure 12 shows how different rain barrel designs have successfully reduced flood volume and peak discharges. Figure 12 shows the reduction of peak discharge and flood volume at the outlet point in different cases of this scenario compared to the current situation. Figure 12 shows the overall performance of RB scenario designs in flood control. According to Fig. 12, it is clear that this scenario has high effectiveness in reducing flood volume and peak discharge. The hydraulic outputs of different designs of RB scenario are not much different while increasing the percentage of LID imposes financial pressure on the plans. The results showed that the RB-10 project was able to reduce peak discharge and flood volume by 74.5% and 79%, while the RB-100 project was able to reduce the peak discharge and volume of floods by 79.5% and 83%. This scenario showed a remarkable hydraulic effect, but the application of high costs will not be economically logical.

3-5) Scenario 2: PP

The area of sidewalks in Golestan town has been calculated by AutoCAD and has been 112,500 square meters. The required values for the Pavement section in SWMM software have been selected according to the research study of Teymouri et al. (Teymouri et al., 2020). Figure 13 shows that in the PP scenario, increasing the percentage of LID succeeded in gradually reducing the volume of floods. According to Fig. 13, despite increasing the percentage of LID, the plans have shown a similar performance in peak flow control. But the plans' performance in controlling the volume of floods increases. Figure 13 shows that an 80% increase in permeable pavement coverage has not effectively reduced peak flow.

3-6) Scenario 3: IT

According to figure 14, the IT scenario shows poorer performance than the PP and RB scenarios. As shown in Figure 14, the increase in the LID percentage after the IT-20 project did not make a difference in reducing the flood rate and peak discharge. But project costs are rising, indicating a waste of money after the IT-30 project. Figure 15 compares the output hydrograph in 100% and 10% LID cases in scenarios 1, 2, and 3. As shown in Figure 15, it makes sense that using 100% LID hydrographs has significantly reduced the output of the drainage system. However, to select the best design, it is necessary to review all procedures in terms of selection criteria. According to Figure 15, it can be concluded that the RB-100 and RB-10 plans performed better than the other plans. Also, according to the PP scenario hydrographs (PP-10 and PP-100), it can be concluded that a 90% increase in the area of permeable pavement will lead to an approximate decrease of 0.1 cubic meters per second in the output flow. However, comparing the results of the IT scenario with the RB and PP scenarios shows the poor performance of the IT in controlling floods and peak discharges in the region.

3-7) Scenario 4: IT-PP

The IT-PP scenario has shown an appropriate and acceptable performance in controlling runoff. The results from the hydraulic analysis shown in Figure 16 indicate this achievement. The total flood volume and maximum flow values for IT-PP-5 and IT-PP-50 designs are 2.674 million liters, 0.387 (m3/s), 1.011 million liters, and 0.062 (m3/s), respectively. The results of Figure 16 show a sharp decrease in peak discharge at the output point. Successful designs of this scenario (IT-PP-45 and IT-PP-50) have reduced the flood discharge by about 90% and the flood volume by 70%. This reduction indicates the effectiveness of this combination on urban runoff in the study area. The results from this scenario show that the combination of IT and PP can cover each other's problems and show better hydraulic performance than IT and PP scenarios.

3-8) scenario 5: IT-RB

Simultaneous use of RB and PP has had acceptable results in flood control in the study area. According to the results shown in Figure 17, increasing the percentage of these two LIDs has a significant effect on controlling urban runoff. Figure 17 also indicates increasing the coverage percentage after the IT-RB-15 reduction, the peak discharge and total flood volume decrease to 90% and 80%, respectively, which is a significant amount. However, considering the operating costs, it can be concluded that using more than 25% of these two methods simultaneously will not be economically logical because there is no significant positive change in hydraulic performance.

3-9) Scenario 6: PP-RB

This scenario consists of a combination of RB and PP. In this scenario, different percentages are used in 10 different plans. The results in Figure 18 show that this scenario's plans have shown the highest effectiveness in flood control and management. However, Figure 18 shows that increasing the coverage percentage of these methods may not be economically viable because the percentage reduction of peak discharge and flood volume in the designs of this scenario is almost high and in the same range. This means that this plan is suitable for flood control, but the cost factor in this section is the most effective in choosing the best plan. Figure 18 also shows that the percentage reduction for peak discharge and flood volume is between 80 and 98% for peak discharge and 70 to 90% for flood volume.

Figure 19 shows the comparison between hydrographs in the output node of the system with the lowest and highest LID coverage in each of the paired scenarios (IT-RB, IT-PP, PP-RB).

According to Figure 19, the PP-RB-50 hydrograph shows the highest effectiveness in flood control by recording a peak discharge close to zero. The PP-RB-5 plan performs well, with a peak discharge of 0.12 (m3/s). These results show that the plans of the PP-RB scenario manage the whole flood, and almost at the outfall node, we do not see any severe phenomenon in terms of discharge. According to the diagram, the IT-PP-5 and IT-RB-5 plans have the worst performance among the others by recording peak flow rates of 0.39 and 0.27 (m3/s), respectively.

3-10) Scenario 7: IT-PP-RB

This scenario examines the performance of using all three LIDs in different plans. The results show that this scenario effectively reduces the flood's volume and peak discharge. This effect increases with increasing the coverage percentage of each LID. Figure 20 shows the hydraulic performance of the plans for this scenario. According to Figure 20, this method performs well in reducing flood volume and discharge peak. But it is important to note that increasing the coverage percentage of LIDs and consequently increasing the costs does not significantly improve the hydraulic performance of the designs. Therefore, in this scenario, the implementation cost significantly impacts choosing the best plan.

According to Figure 21, increasing the percentage of LID coverage will significantly reduce the discharge point of the study area so that the IT-PP-RB-3.3 plan has a peak flow of 0.274 (m^3/s), this value for the IT-PP-RB-33.3 plan is equal to 0.042 (m^3/s), which shows a decrease of 7 times.

3-11) Average effects of scenarios

This section examines the effectiveness of each scenario in terms of cost of implementation, reduction of flood volume, and reduction of peak discharge. For this purpose, the arithmetic mean for the performance of the plans of each scenario is calculated. Figure 22-a shows the comparison mode between the seven scenarios in peak discharge. According to this figure, it is clear that the PP-RB scenario has recorded the lowest peak flow rate at the output point. The RB, the IT-RB, and the IT-PP-RB scenarios are in the following ranks in peak discharge, respectively. While the highest peak discharge at the output node is related to the IT scenario. Figure 22-b has the same explanation as Figure 22-a, except that this figure represents the total volume of the runoff. According to this figure, the PP-RB scenario has the best performance, and the IT scenario has the worst. Also, the IT-PP-RB and IT-RB scenarios and the IT-PP and RB scenarios have shown considerable performance in the total runoff volume. Figures 22-c and 22-d show the average percentage of peak discharge and flood volume reduction in seven scenarios, respectively. According to these two figures, the PP-RB scenario has shown the best hydraulic performance by recording an average 90% reduction in peak discharge and 80% in flood volume. At the same time, the weakest results are obtained in the IT scenario, with an average decrease of approximately 60% in peak discharge and 40% in flood volume. The results show the similar performance of the two scenarios, IT-PP-RB and IT-RB, in reducing the peak discharge by 80 percent. Also, the three scenarios of RB, PP, and IT-PP have shown similar results in reducing the peak flow rate (75%). Regarding cost criteria, the highest implementation cost is for the RB scenario, which is around $ 600,000.

3-12) selecting the 5 best plans using AHP-PROMETHEE

The AHP-PROMETHEE conducted the ranking process. After finding the weights from the AHP method, the plans were ranked by visual PROMETHEE according to the introduced criteria. Table 8 shows the required characteristics of each criterion to perform the ranking process. It should be noted that the implementation environmental criteria and ease of implementation are qualitative, and information about them is included using the five-point method in visual PROMETHEE software. Table 9also shows the statistical parameters of the analyzes performed.

Table 8
required properties to apply in visual PROMETHEE software

Criteria	**Implementation Cost**	**Hydraulic performance**	**Environmental impact during implementation**	**Ease of implementation**
unit	US Dollar	CMS*	5 point	5 point
Criteria type	Max	min	min	Max
weight	0.17	0.66	0.05	0.12
Function	linear	level	usual	usual
threshold	absolute	absolute	absolute	absolute
Q: Indifference	0 US $	0 CMS	-	-
P: Preference	408 US $	0.006 CMS	-	-

*CMS: Cubic meter per second

Table 9
Statistical characteristics of the output results of the analyzes

Criteria	Implementation Cost (US $)	Hydraulic performance	Environmental impact during implementation	Ease of implementation
Minimum	743	0.106	1	1
Maximum	1144600	0.533	5	5
Average	214608	0.439	2	2
Standard deviation	267224	0.077	2	2

Table 10 shows the top 5 rankings among the proposed designs. According to the results of this table, the IT-RB-5 plan has been able to reduce flood volume by 51% and reduce peak discharge by 49% and record a cost of $ 57,710, being the best option among all proposed projects.

Table 10
5 Top rankings

Plan	Rank	Flood reduction (%)	Peak discharge reduction (%)	Cost (US Dollar)
IT-RB-5	1	51.54	48.8	57710
PP-RB-25	2	81.3	93	293946
PP-RB-40	3	90.8	95.3	470314
PP-RB-35	4	88.4	95.2	411525
PP-RB-20	5	75.5	91.8	235157

Figure 23 shows the hydrographs of the top plans at the outfall node. According to Fig. 23 and Fig. 24; although the next top rankings have been able to reduce the flood volume and reduce the peak performance better than the top rank (IT-RB-5), considering the cost, these plans are more expensive than the top ranking.

4) Conclusion

The present study was conducted to investigate the drainage system of Golestan town of Semnan city with and without applying Low-impact development methods. In this study, after selecting three low development methods of rain barrel, permeable pavement, and infiltration trench, 70 different plans under seven scenarios were introduced. These scenarios include three individual scenarios, three paired scenarios, and a triple scenario. The results of SWMM showed that among these seven scenarios, the PP-RB scenario showed the best results in terms of flood volume reduction and peak discharge reduction. The PP-RB scenario recorded an average of 80% reduction in flood volume and a 90% reduction in peak discharge compared to the current system. Unlike the PP-RB scenario, the IT scenario showed the weakest performance among the seven scenarios, with an average 60% reduction in peak discharge and a 40% reduction in total flood volume. Four decision criteria, namely implementation cost, hydraulic performance, implementation environmental effects, and ease of implementation, were identified to select the best-proposed plan. Then, using a questionnaire and asking for experts' opinions, the weights of decision criteria were determined using the AHP method, which was equal to

0.17, 0.66, 0.05, and 0.12 for the performance cost, hydraulic performance, implementation environmental impact, and ease of implementation, respectively. Sensitivity analysis was performed using EXPERT CHOICE software. The sensitivity analysis result was equal to 0.07, indicating the calculated weights' reliability. Then, using the PROMETHEE method and specifying the preference functions for each criterion, the degree of preference, and the degree of indifference in the ranking process, the selection of the best plan were conducted. The results show the superiority of the IT-RB-5 plan for 57,710 $, the reduction of flood volume by 51.54 percent, peak discharge by 48.8 percent, the appropriate environmental impact during implementation, and the relatively simple performance.

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Conflicts of interest

The authors declare no conflict of interest.

Author’s contribution statement

YD, HK, SM: Conceptualization; YD, HK, SA: Data curation; YD, HK, SM: Formal analysis; YA: Investigation; YD: Methodology; YD, HK, SM: Project administration; YD, HK: Resources; YD, HK, SM: Software; YD: Supervision; HK, SM: Validation; YD, HK, SM: Visualization; YD, HK: Roles/Writing – original draft; YD, HK, SM: Writing – review & editing.

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Figures

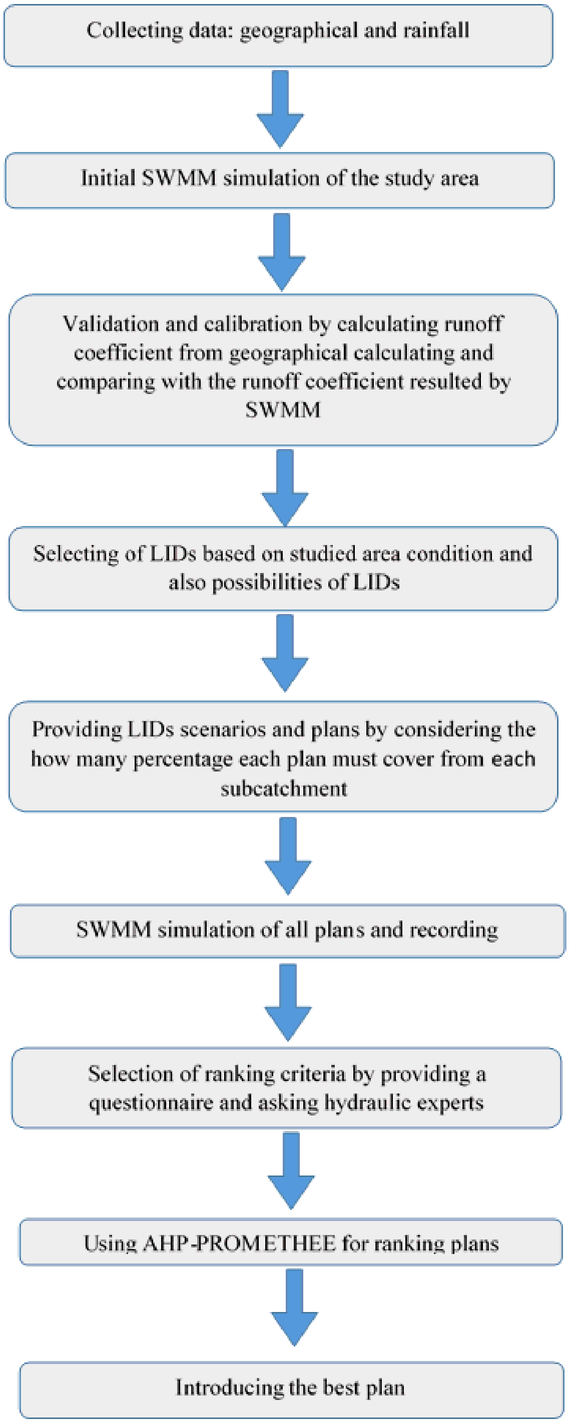

Figure 1

the flowchart of the study

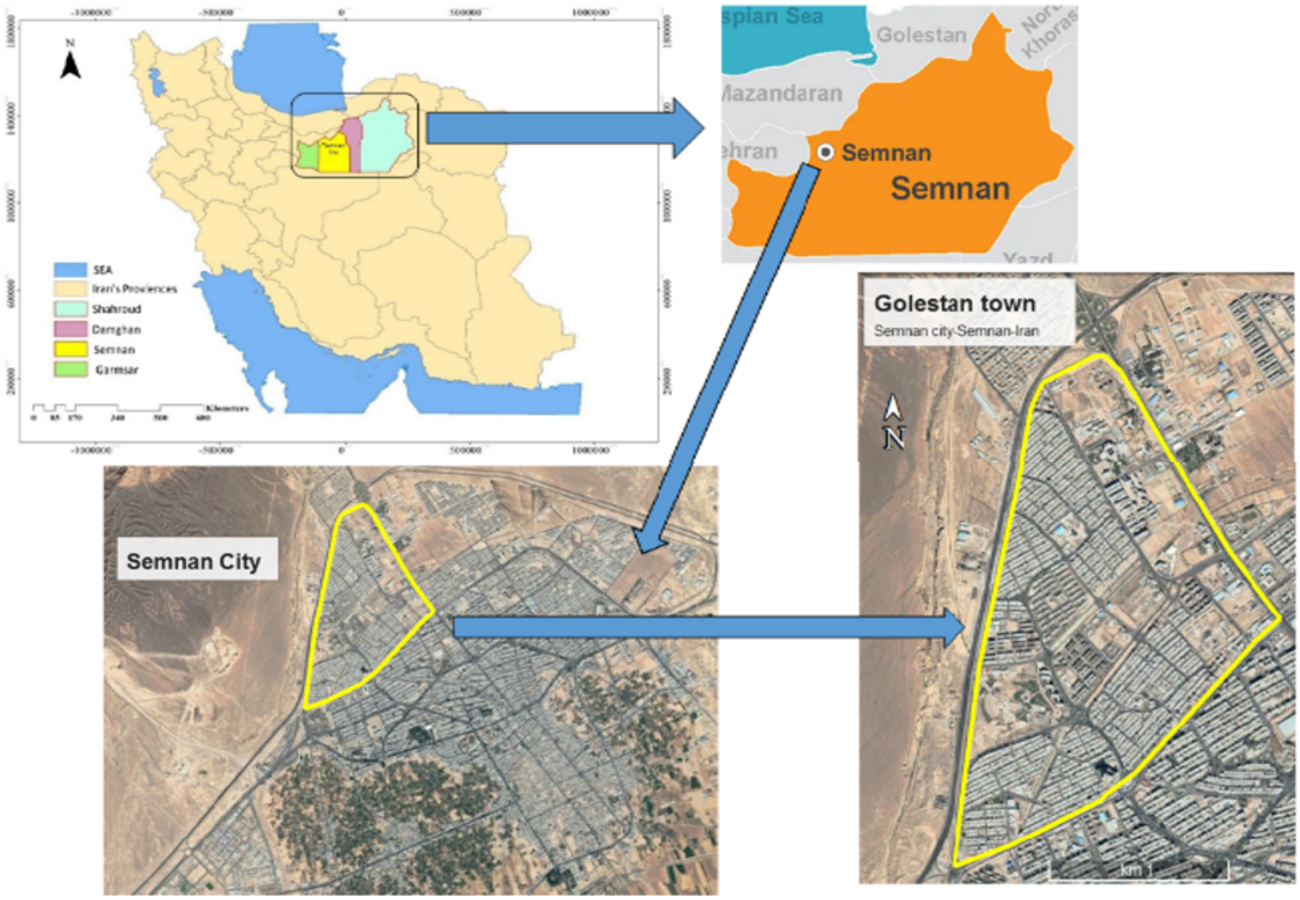

Figure 2

study area

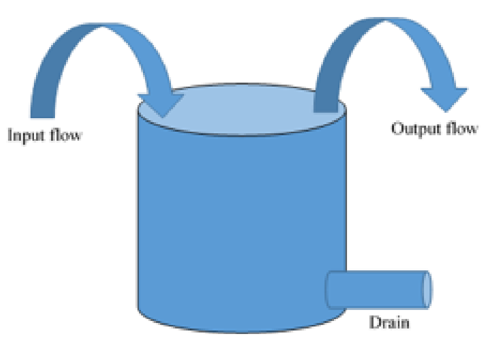

Figure 3

Rain barrel

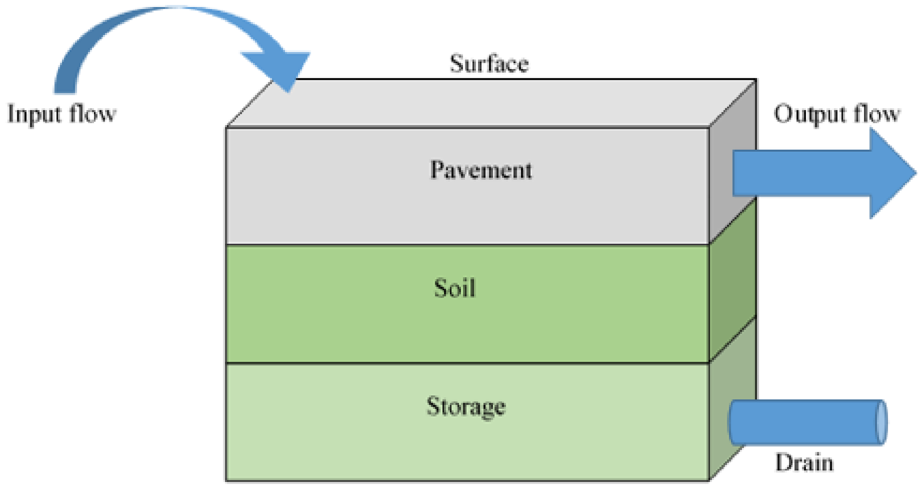

Figure 4

Preamble Pavement

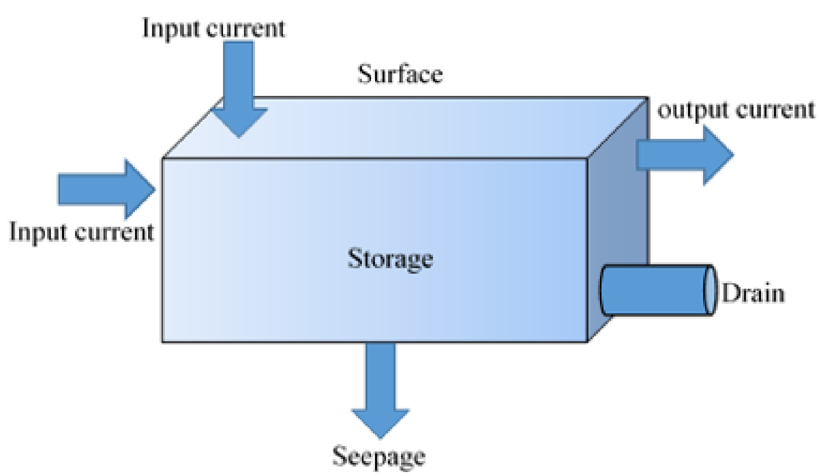

Figure 5

Infiltration trench

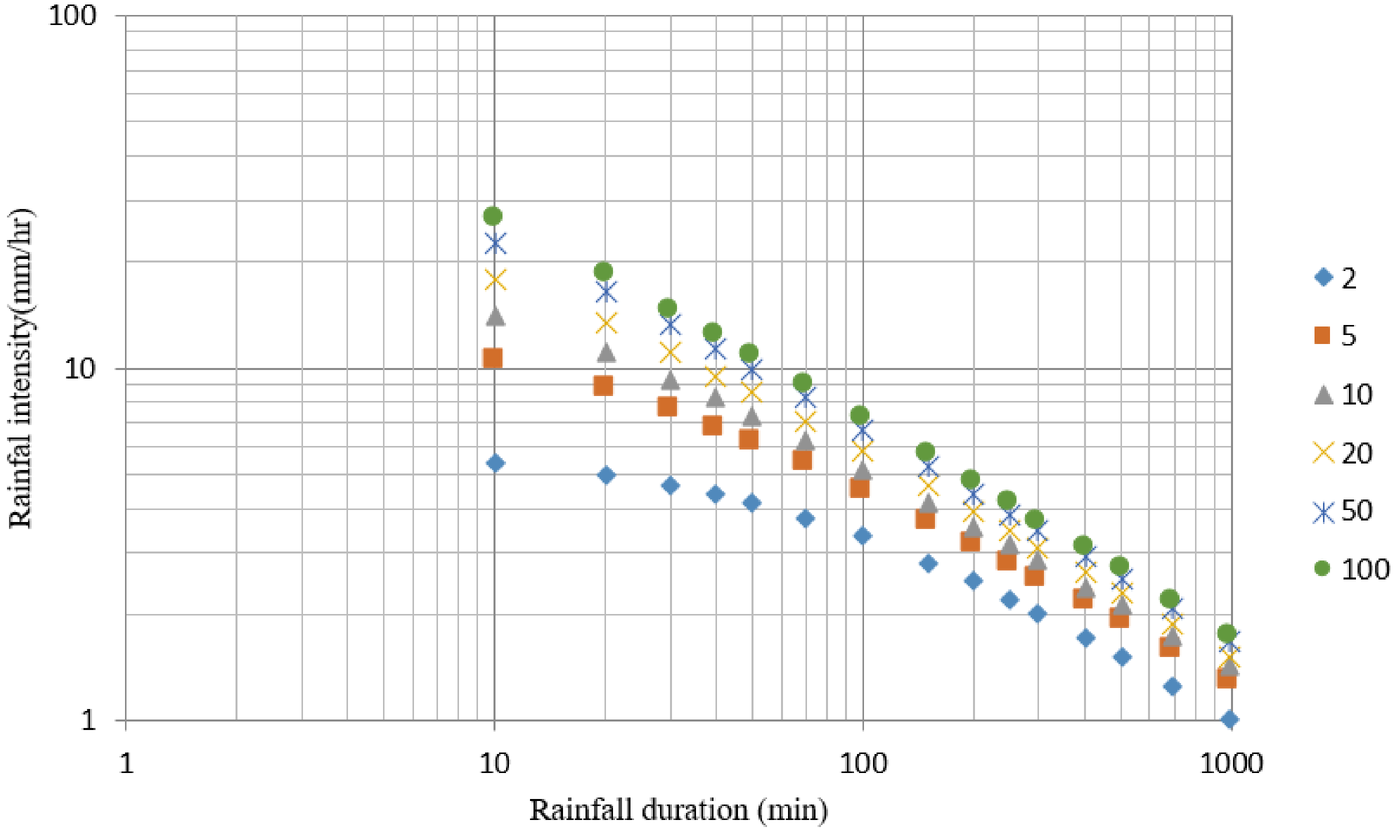

Figure 6

IDF curve of Semnan synoptic station

Figure 7

Cumulative precipitation for a 5-year return period

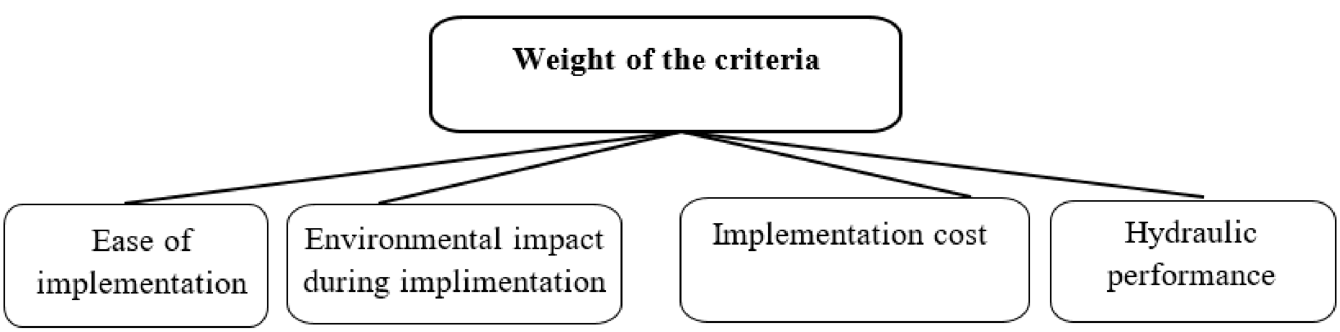

Figure 8

Criteria tree diagram

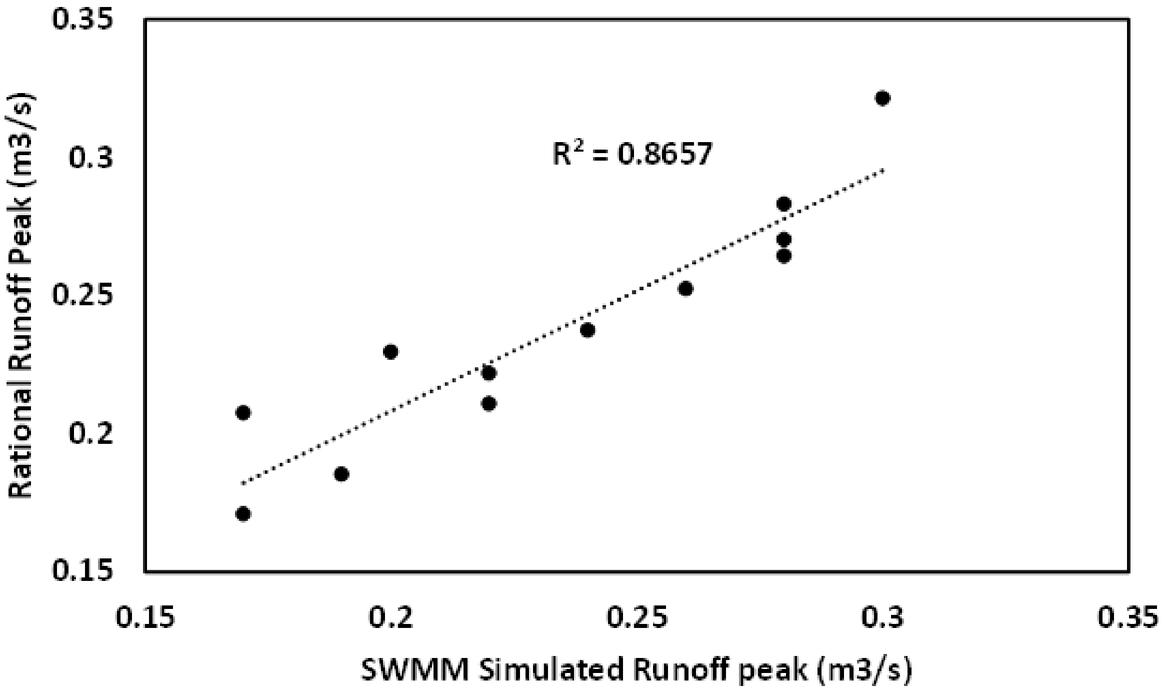

Figure 9

Peak discharge obtained from the logical equation and peak runoff calculated by SWMM

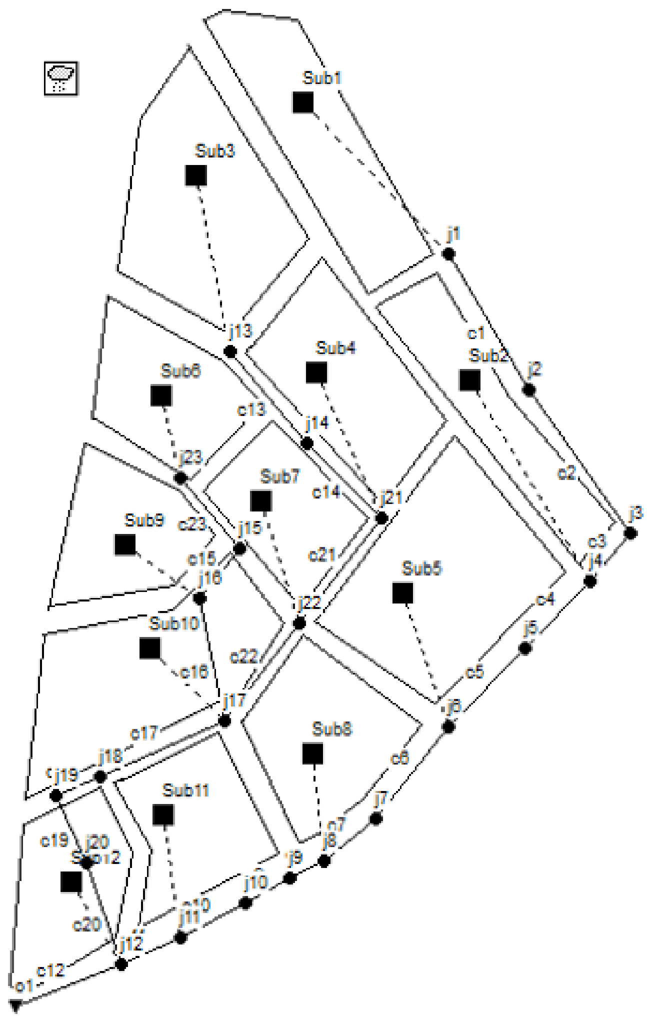

Figure 10

Schematic of runoff collection system

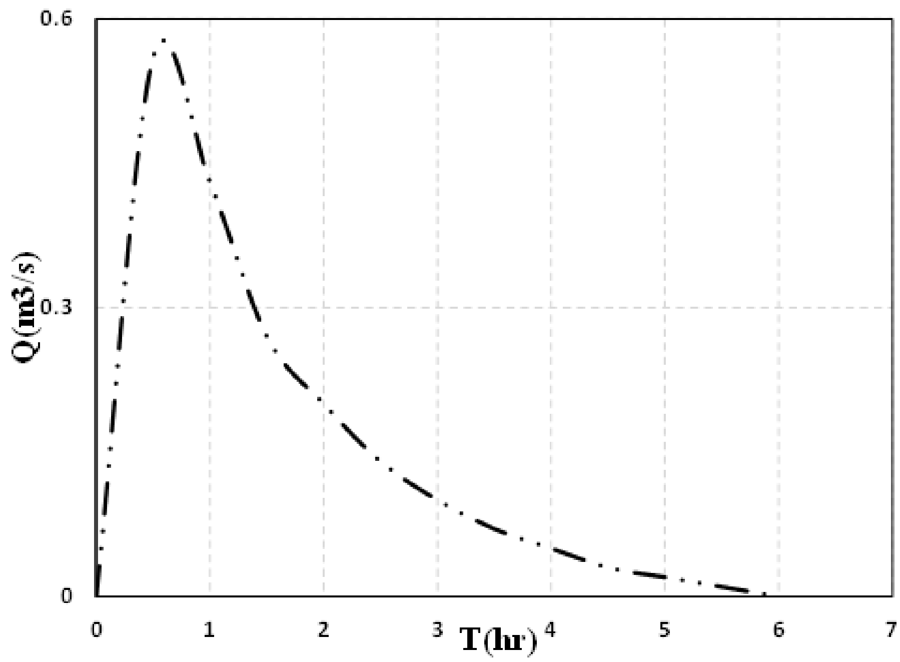

Figure 11

Output node hydrograph in the current system

Figure 12

RB scenario, percentage reduction of peak discharge and percentage reduction of flood volume

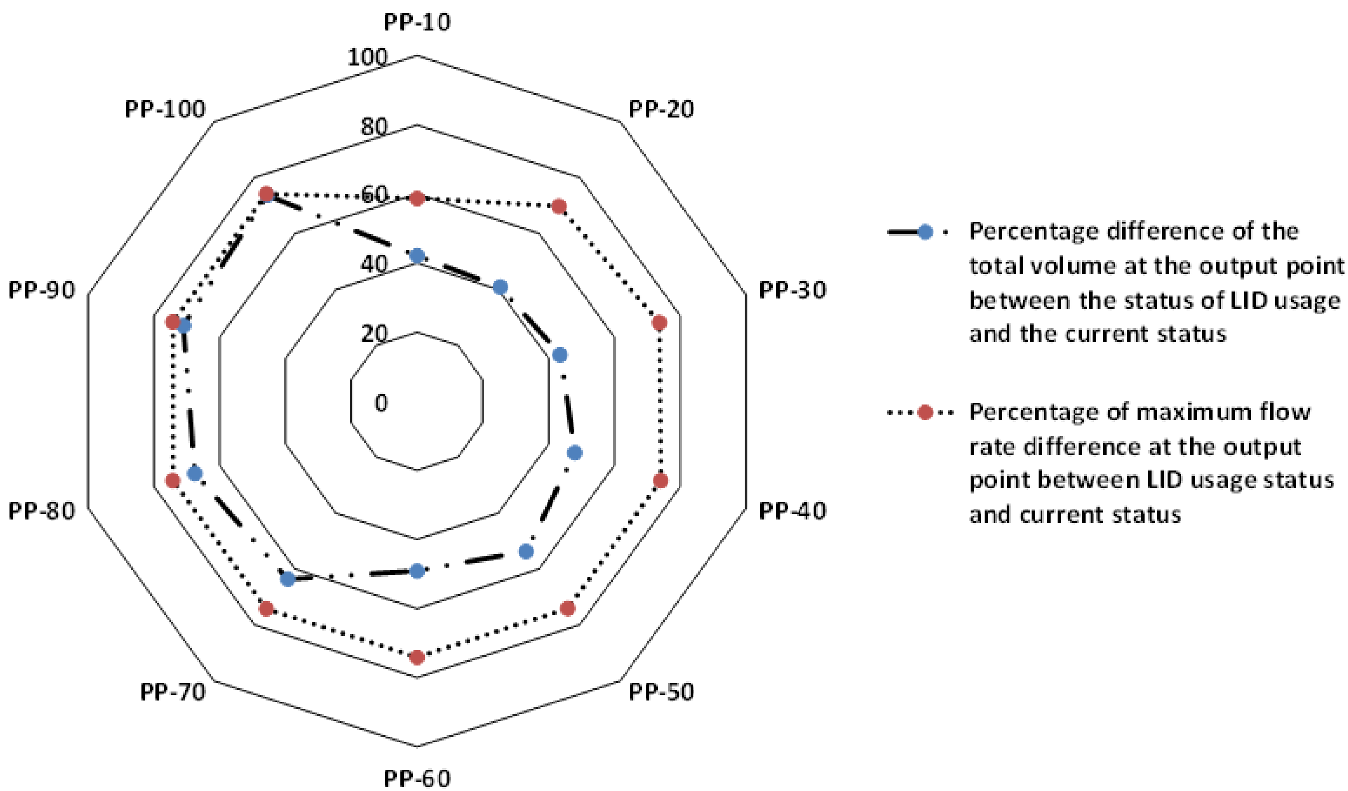

Figure 13

PP scenario, percentage reduction of peak discharge and percentage reduction of flood volume

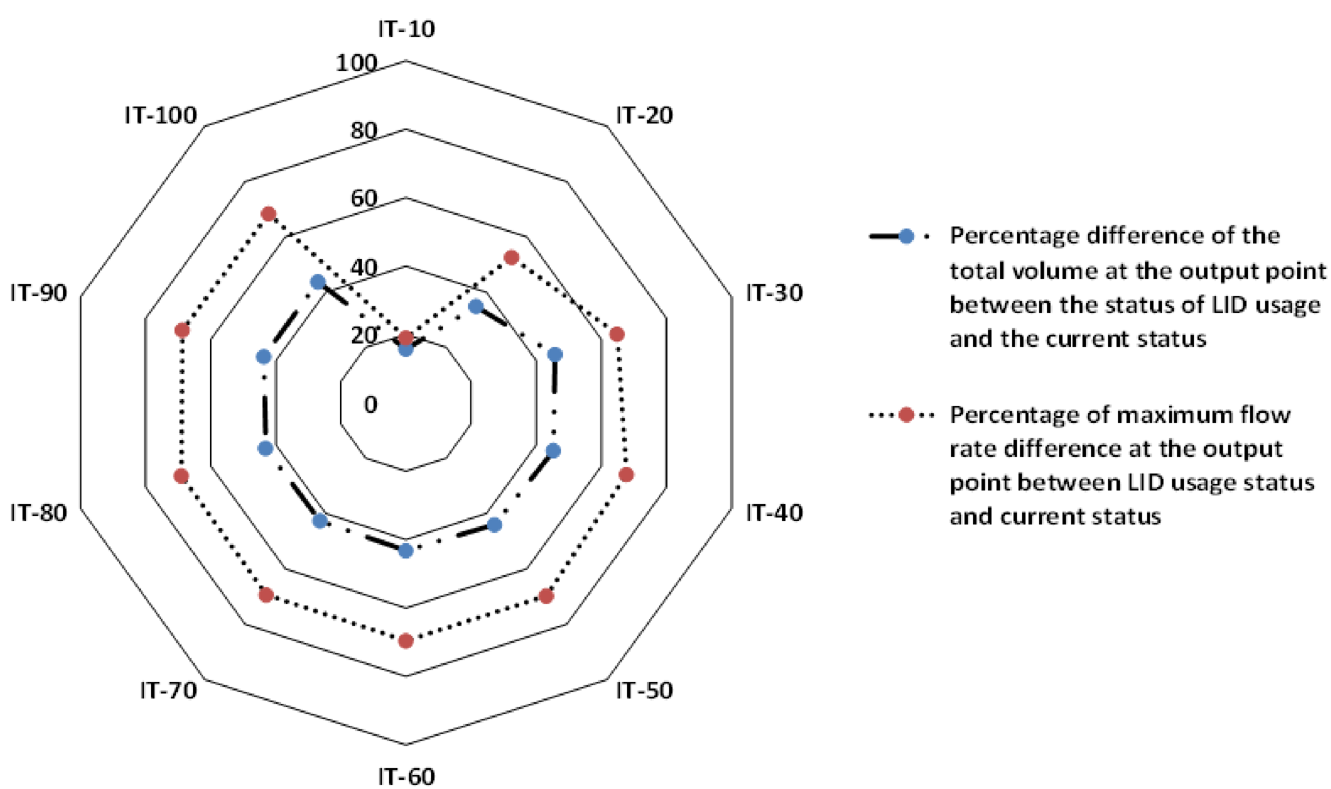

Figure 14

IT scenario, percentage reduction of peak discharge and percentage reduction of flood volume

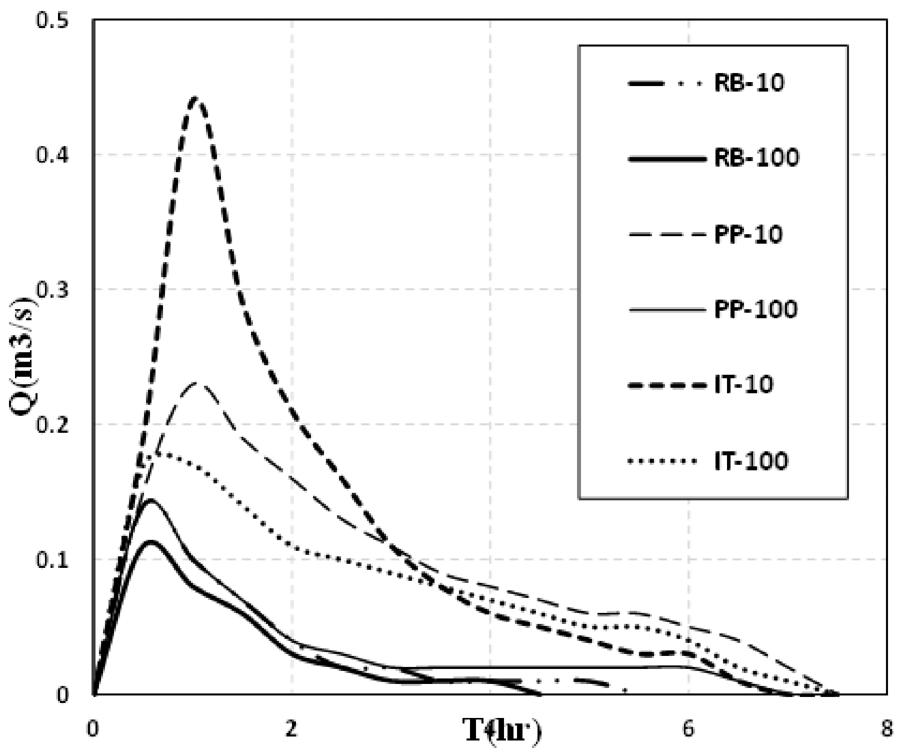

Figure 15

Comparison of output hydrographs in the lowest and highest coverage percentages of individual scenarios

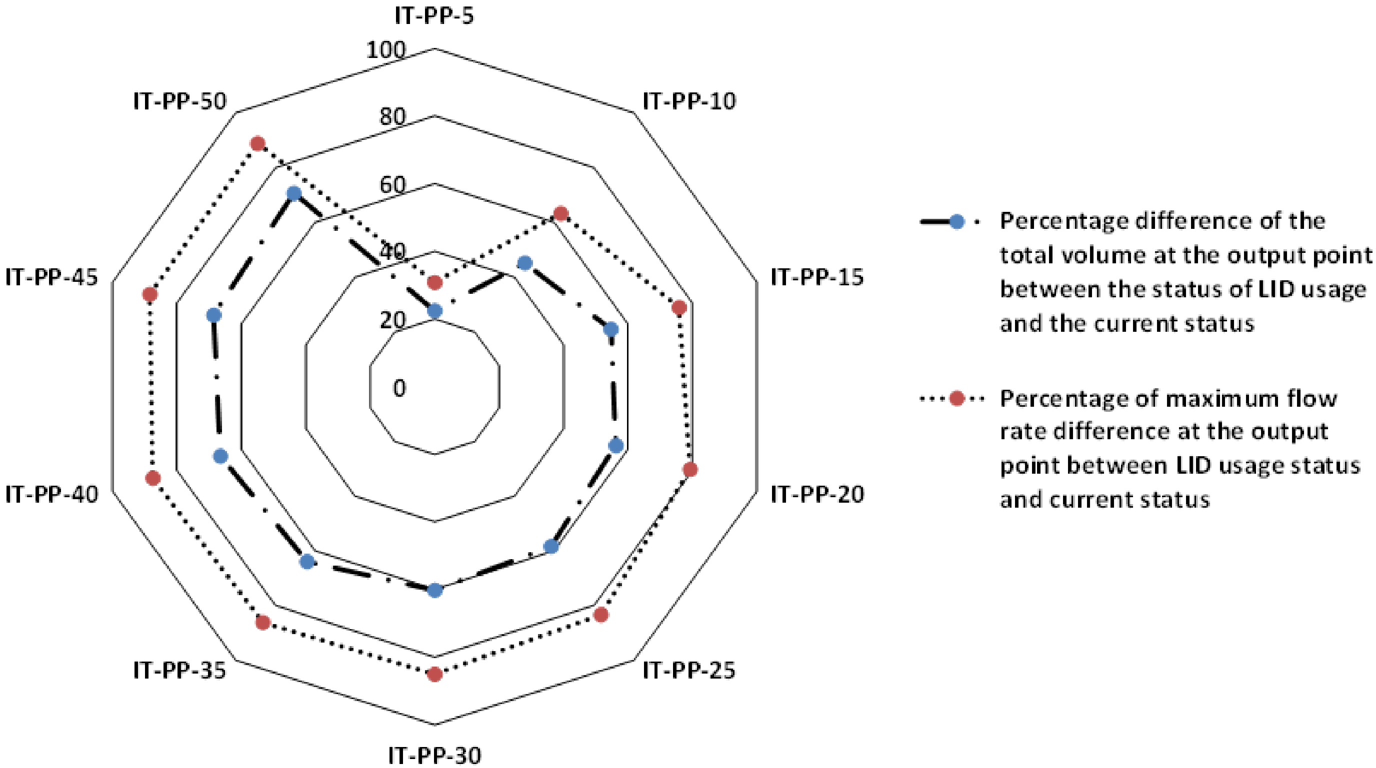

Figure 16

IT-PP scenario, percentage reduction of peak discharge and percentage reduction of flood volume

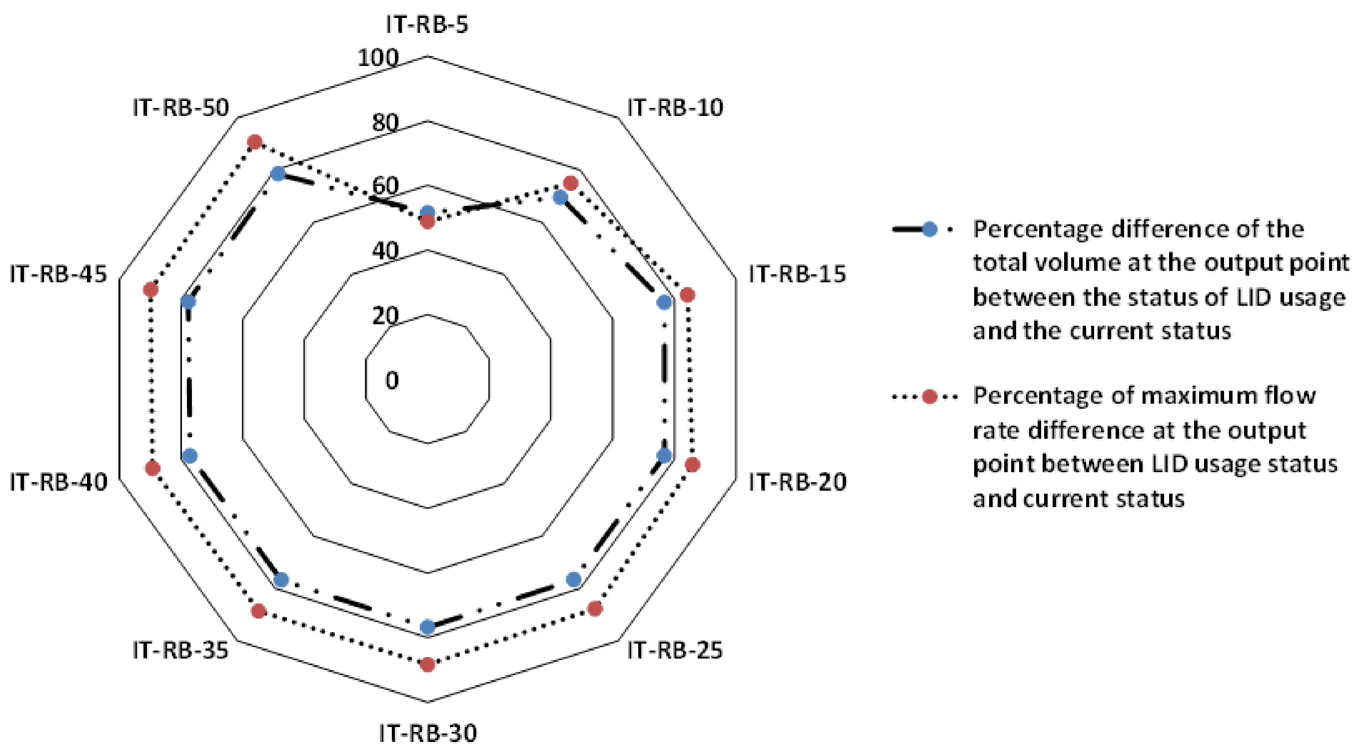

Figure 17

IT-RB scenario, percentage reduction of peak discharge and percentage reduction of flood volume

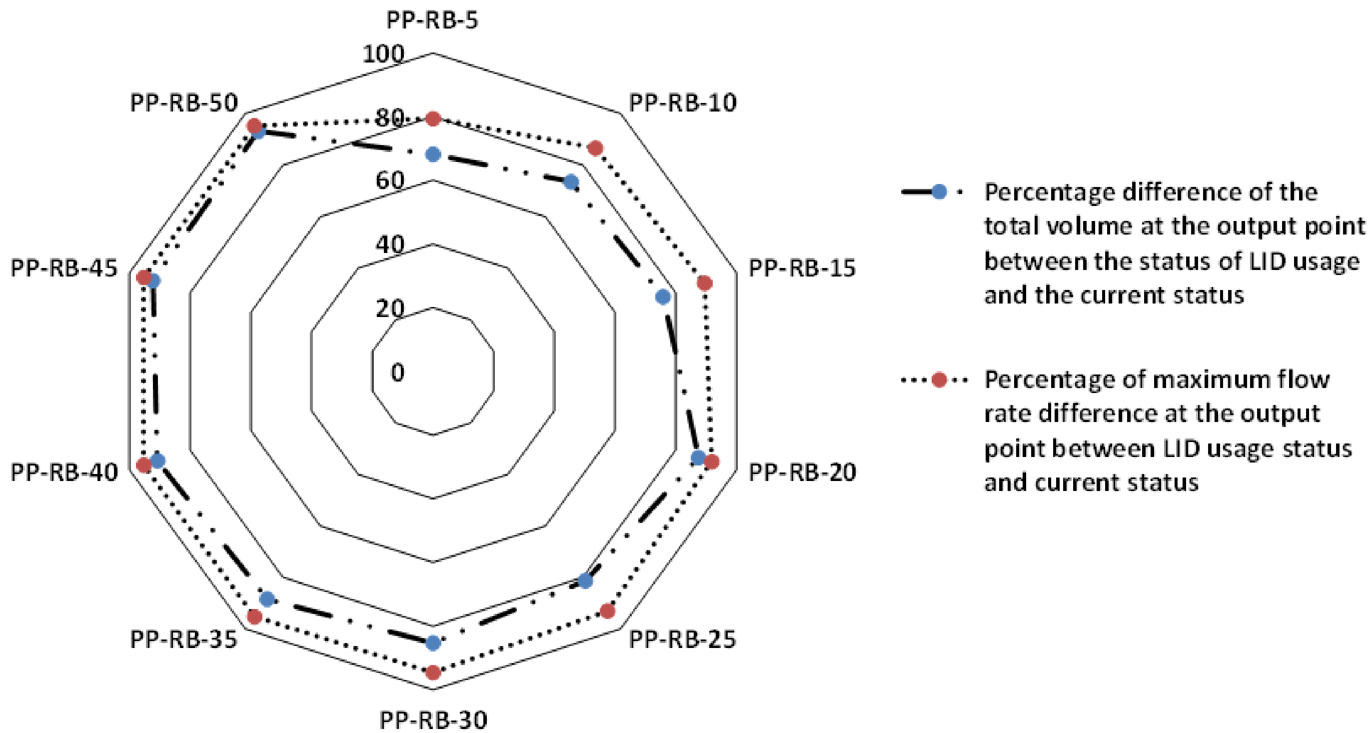

Figure 18

PP-RB scenario, percentage reduction of peak discharge and percentage reduction of flood volume

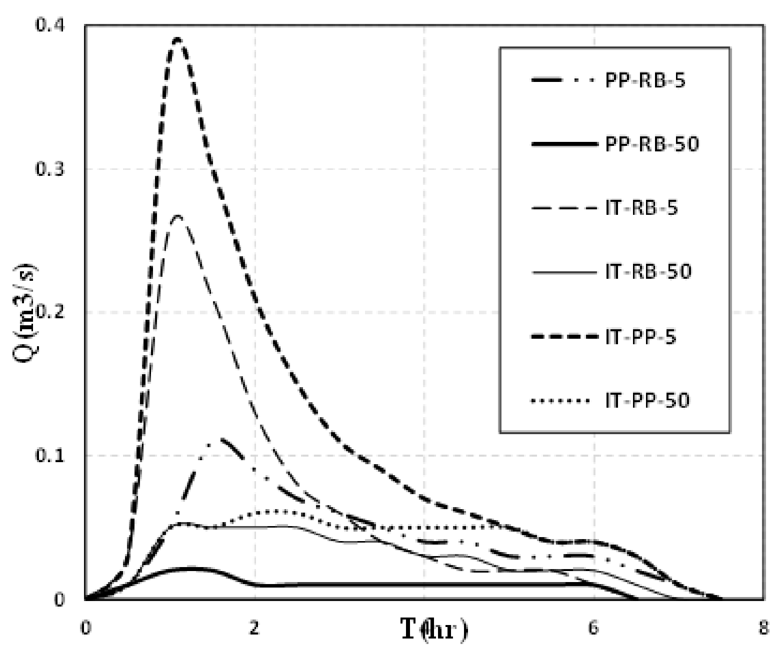

Figure 19

Comparison of output hydrographs in the lowest and highest coverage percentages of Pair scenarios

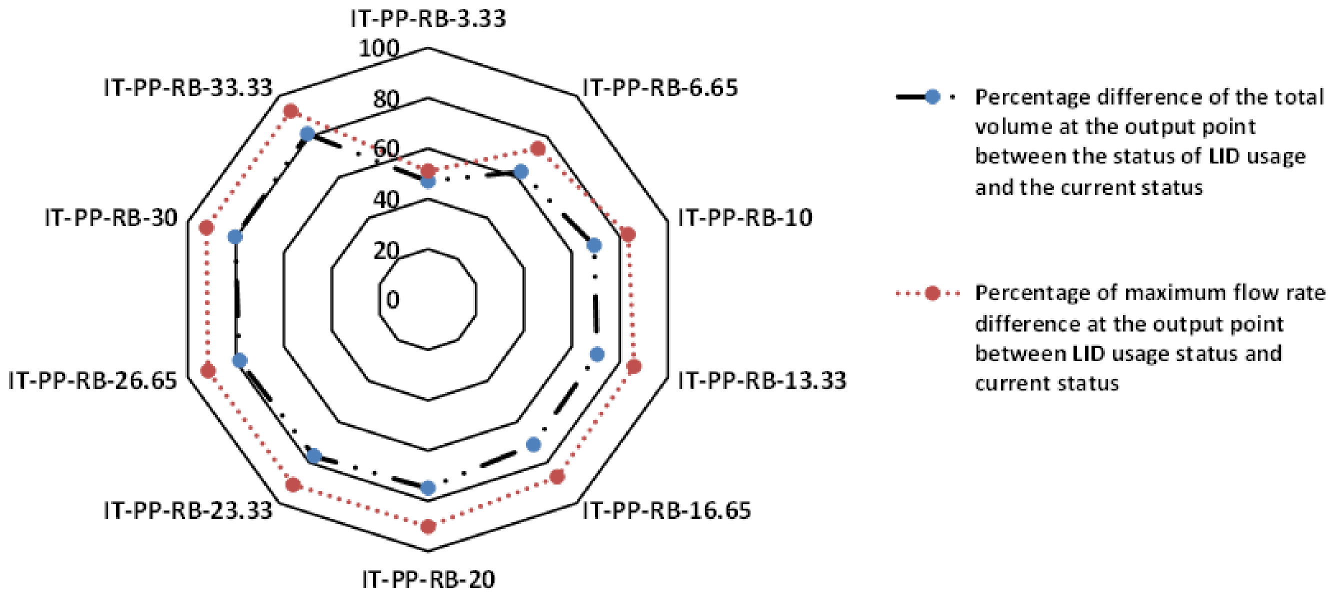

Figure 20

IT-PP-RB scenario, percentage reduction of peak discharge and percentage reduction of flood volume

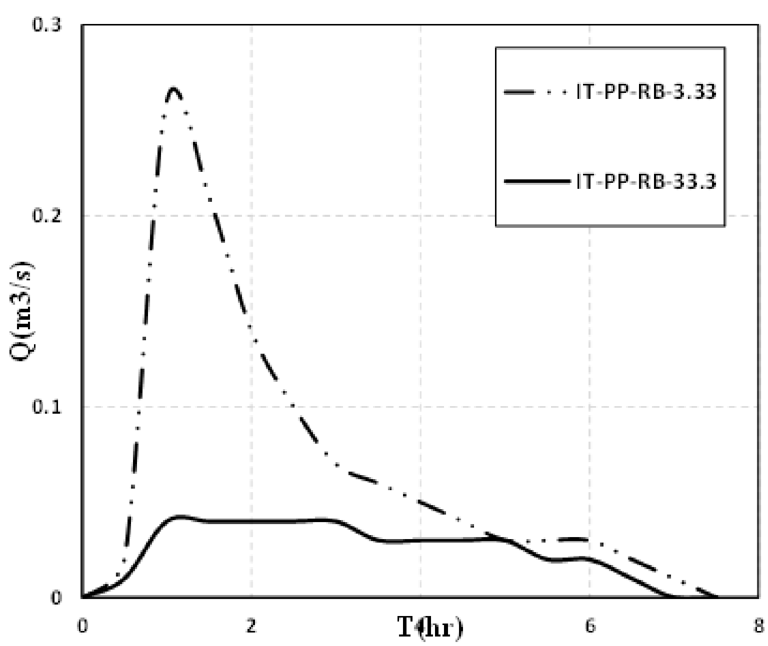

Figure 21

Comparative hydrograph in both 33.3% and 33.3% combinations of all three LIDs

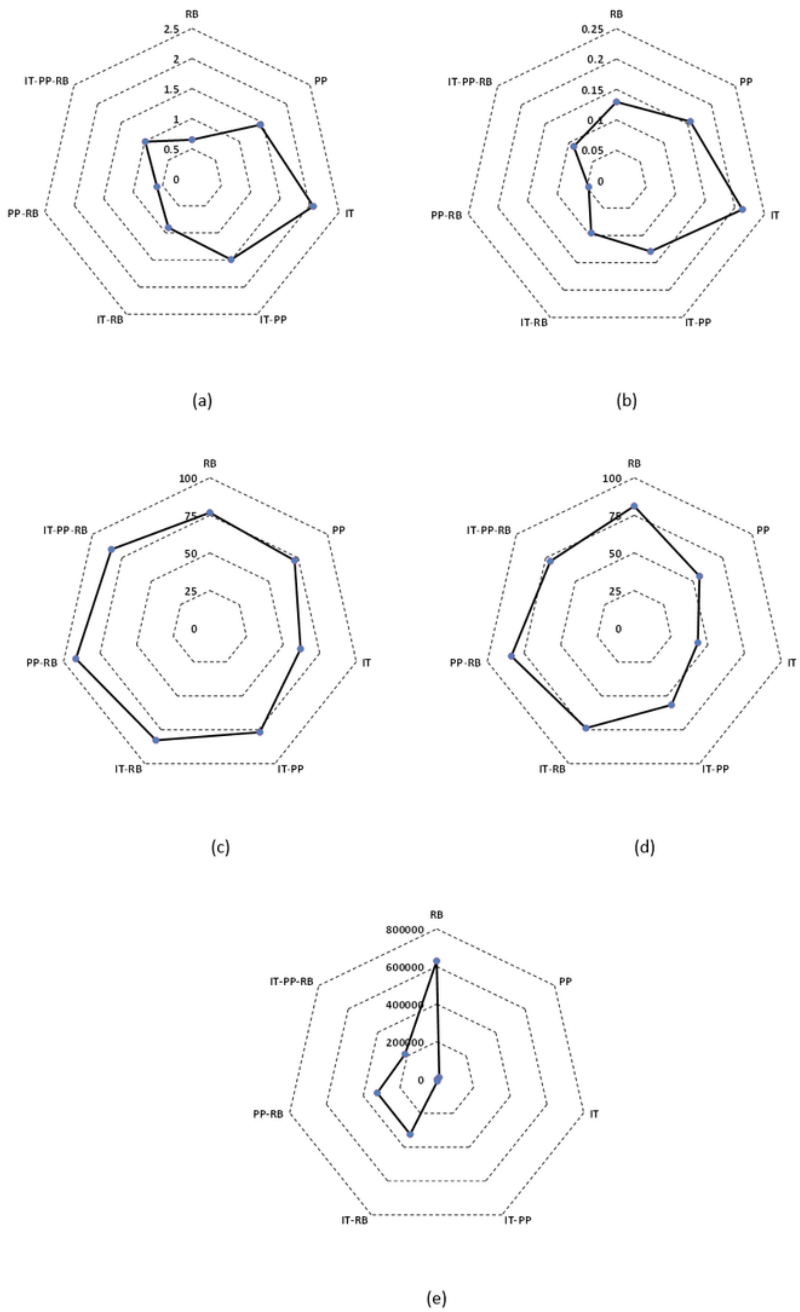

Figure 22

Comparison of the average performance of 7 scenarios (a maximum flow, b) Flood volume, c) percentage of peak discharge reduction, d) percent reduction in flood volume, e) implementation cost

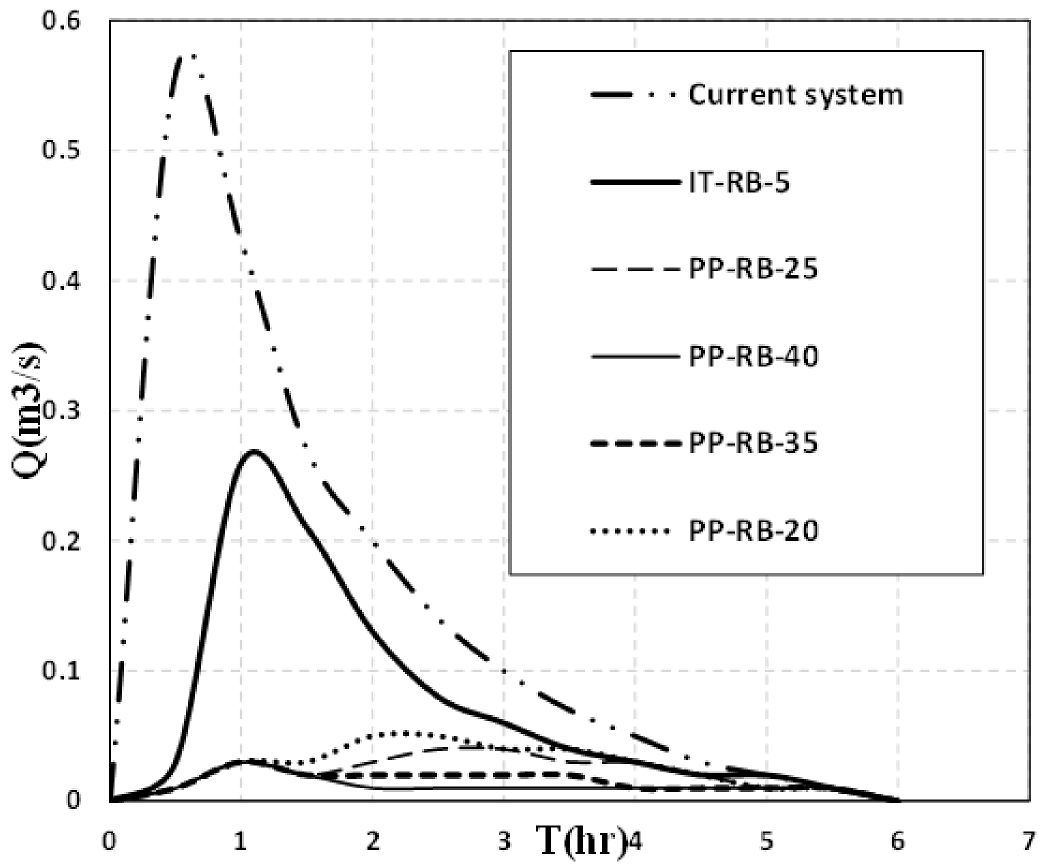

Figure 23

Hydrograph of the best plans

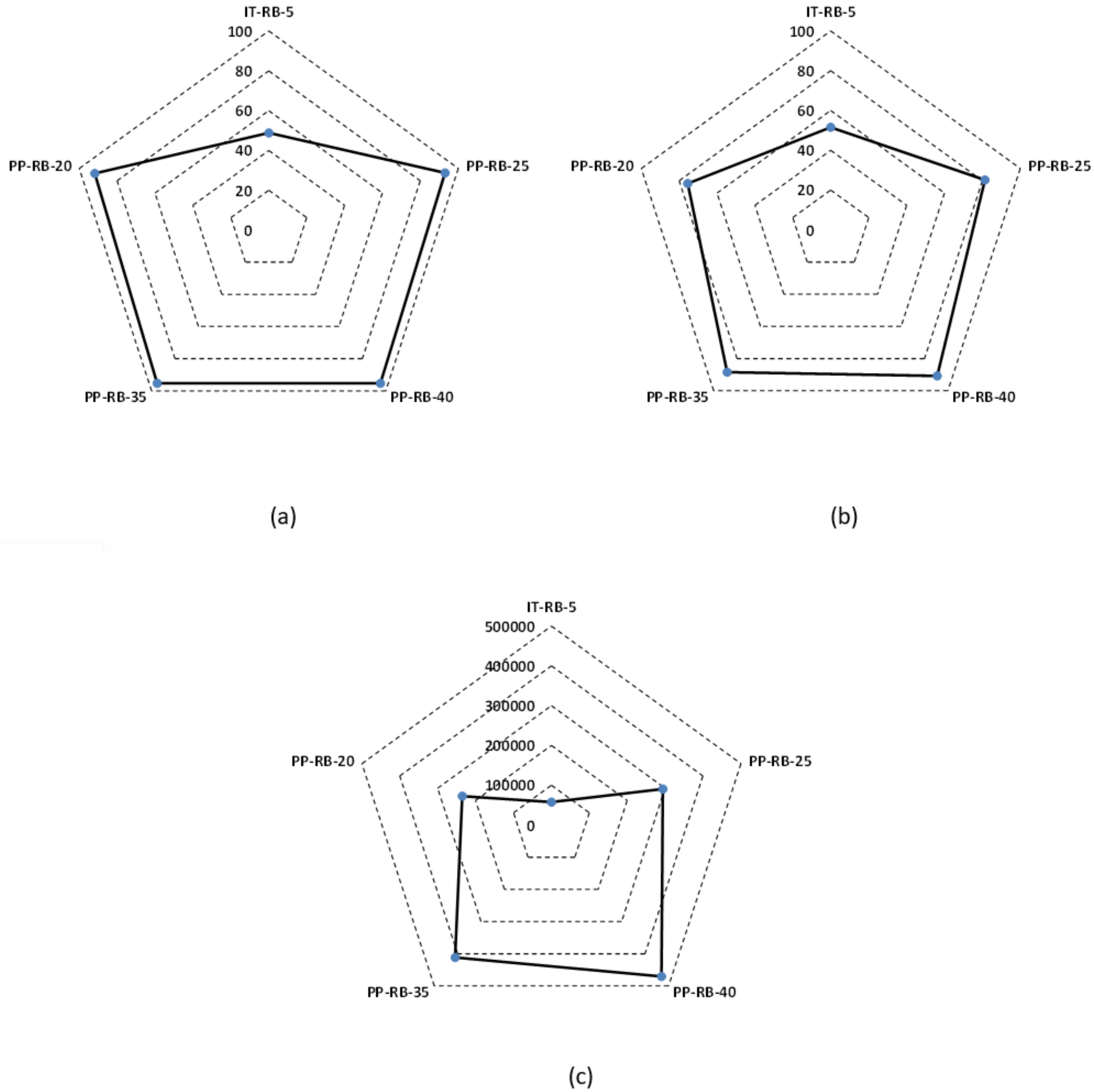

Figure 24

Comparison of the top 5 rankings. a) Percentage reduction of peak discharge, b) Pain reduction of flood volume, c) implementation cost