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PAPER

Optimizing urban stormwater control strategies and assessing aquifer recharge through drywells in an urban watershed

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Abstract

A coupled simulation-optimization model (SOM) is developed in this work that links the US Environmental Protection Agency's Storm Water Management Model (SWMM) with a genetic algorithm. The SOM simulates rainfall-runoff processes in urban watersheds and optimizes the implementation of drywells (DWs), bio-retention cells (BCs), and permeable pavement (PP) for stormwater control and aquifer recharge in District 6 of Tehran Municipality, Iran. Feasible DWs are selected through site inspection and considering stormwater quality criteria to prevent aquifer contamination. This study compares the current rates of urban runoff and groundwater recharge (baseline scenario) with new stormwater management strategies, which were designed based on several levels of funding. Results show the highest rate of runoff reduction and infiltration, as well as the most cost-effective options, would be achieved when DWs are added to the combination of BCs and PP for stormwater management. The runoff reduction rate in the presence of DWs would rise by 11.7, 7.0, and 6.1% in comparison to their absence for 12-, 17-, and 22-million-dollar budget levels, respectively. Implementation of BCs and PP would cause infiltration of about 235, 274, and 279 thousand m^3 for the three cited budget levels, while combining DWs with BCs and PP would increase infiltration by 19, 15.6, and 14% for the three levels of investment, respectively. These results demonstrate the benefits of using local nonfunctional wells and qanats to reduce peak flows, replenish urban aquifers, and improve the economic efficiency of urban stormwater management projects.

Keywords Socio-economic aspects · Stormwater management model · Simulation-optimization · Genetic algorithm · Aquifer recharge

Introduction

Fast-growing urbanization and climate change have led to significant changes in hydrologic responses and extreme hydrologic patterns and frequencies (Dietz 2007; Ahiablame et al. 2012; Bell et al. 2016; Wang et al. 2016). An increased in impervious surfaces in cities and the rise in intensity and frequency of extreme precipitation events have disrupted the

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natural water cycle and impacted water resources (Pauleit et al. 2005; Hanak and Lund 2012; Saraswat et al. 2016). These changes have altered the natural surface runoff peaks and volumes, which have, in turn, caused degradation in water quality, environmental systems and ecosystems (Klöcking and Haberlandt 2002; Schoonover et al. 2006; Saraswat et al. 2016; Kong et al. 2017; Babaei et al. 2018).

Various stormwater management measures have been investigated and implemented to replicate the predevelopment hydrology of watersheds. Proposed approaches and adopted actions have often been named differently even though they serve similar functions, e.g., best management practices (BMPs) and low impact development (LID) practices in the USA (USEPA 2000), Water Sensitive Urban Design (WSUD) in Australia (Mouritz 1992), sustainable urban drainage systems (SUDS) in the United Kingdom, low impact urban design and development (LIUDD) in New Zealand (Fletcher et al. 2015), low-impact development (LID) stormwater control measures (SCMs) for flood control and water quality improvement in Los Angeles, California, USA (Loáiciga et al. 2016), and 'Sponge City' in China (Randall et al. 2019). The more generic term that covers all aforementioned terms used to describe sustainable urban runoff control measures is green stormwater infrastructure (GSIs). GSIs are implemented to decrease stress on conventional runoff control networks (Ahiablame et al. 2012, Liu Y et al. 2016, Sadeghi et al. 2019, Xu et al. 2019), and to improve the urban stream quality (Malinowski et al. 2018).

The main functionality of GSIs is to reduce peak flow, volume, and pollution load (Ahiablame et al. 2012; Liu et al. 2015; Eckart et al. 2017; Li et al. 2019), and various features such as land use, slope, soils, vegetative cover, and imperviousness influence the selection, combination, and placement of GSIs. Small-scale distributed GSIs such as permeable pavements, are categorized as LID practices for source control, while large-scale centralized GSIs, e.g., detention basins, are SCMs commonly deployed at the outlet of catchments. Analyzing all the possible combinations of possible GSIs for complex and large systems might lead to infeasible solutions (Elliott and Trowsdale 2007; Zahmatkesh et al. 2015; Wang et al. 2016). Therefore, the achievement of optimal or near-optimal solutions commonly relies on the application of hydrologic simulation models that are dynamically coupled with optimization solvers. Various simulation-optimization frameworks have been utilized to optimize the placement and selection of GSIs based on single- or multi-objective optimizations, where the goals are often minimization of peak flow and total runoff volume, improvement of stormwater quality, and/or minimization of the total cost expressed as a life cycle cost. A summary of investigations which applied simulation-optimization methods for controlling urban stormwater is listed in Table 1.

It is noteworthy that the idea of applying nonfunctional local infrastructures such as abandoned wells and qanats, as a potential GSI has not been addressed in the aforementioned studies. The qanat is a network of manmade wells and underground water channels, which were built centuries ago in the Middle East to collect water from recharge areas and transfer it to discharge areas. The studies listed in Table 1 (Li et al. 2019; Winston et al. 2020) establish that bio-retention cells and permeable pavements (selected GSIs in this study due to the specific features of the study area) mainly contribute to the reduction of runoff volume and peak flow by increasing the surface depression storage, evaporation, and infiltration, whereas the rainfall–runoff reduction process in drywells is mainly dominated by the expansion of storage and infiltration (Edwards et al. 2016; Sadeghi et al. 2019). Drywells can effectively replenish the groundwater aquifer by deep infiltration (Edwards et al. 2016; Dandy et al. 2019), and are more suitable for areas with low surface permeability but permeable subsurface. However, specific design criteria and pretreatment are achieved to prevent the risk of groundwater pollution caused by controlling the movement of infiltrated stormwater through the vadose zone (Edwards et al. 2016).

Stormwater quality (Hamilton et al. 2004), runoff control performance (Bouwer 2002; Gonzalez-Merchan et al. 2012), and groundwater recharge quantity and quality (Snyder et al. 1994; Beganskas and Fisher 2017) have been the focal point of drywell-related studies. Groundwater overdraft (see, e.g., Loáiciga 2017) has led to the persistent falling of the phreatic surface and consequent increase in the number of dried out wells over past decades (Aggarwal et al. 2013). The abandoned wells have been decommissioned and a few studies have explicitly focused on the investigation of the potential of dried out, inactive, or abandoned wells, and qanats. Two features drive the insight of assessing the application of nonfunctional wells as GSI in this study. First is the technical potential of nonfunctional wells and qanats and their similarities with drywells, and second is the high capital cost of stormwater management measures and the possibility of introducing new GSIs to cope with stormwater control (Li et al. 2019). In addition to the construction costs, sometimes land limitations put further financial pressure on these projects, e.g., payments to farmers to utilize their cropland for groundwater recharge (Gailey et al. 2019).

Nowadays, the focus of research is mainly on the operation optimization of the manmade structures such as reservoirs (Bozorg-Haddad et al. 2009; Shokri et al. 2013; Akbari-Alashti et al. 2014; Asgari et al. 2016) and water distribution networks (Soltanjalili et al. 2011) for improving water supply, whereas the potential of natural or existing structures such as GSIs, for water retention has received less attention. The economic feasibility of GSI implementation may be improved by existing structures that could be potentially transformed into GSIs, which has been neglected in previous studies. Several studies have focused solely on the cost-effectiveness of GSI design and stormwater control capacity. This study, on the other hand, offers a new modeling framework to analyze the

Table 1 Examples of simulation-optimization tools applied in urban stormwater control

Reference	Modeling method	Optimization method	GSI type	Objective function	Study area
(Luan et al. 2019)	SWMM	TOPSIS	DB, BC, GS, PP	Reduce runoff volume and peak flow, remove pollutant, minimize economic cost	Western New City in Zhuhai, China
(Macro et al. 2019)	SWMM	OSTRICH	RB	Optimize rain barrel location	Buffalo in New York, USA
(Eckart et al. 2018)	SWMM	Borg MOEA	RB, PP,BC,IT	Minimize peak flow, reduce total runoff, minimize cost	Windsor in Ontario, Canada
(Montaseri et al. 2015)	MUSIC	GA	RB, BC, VS, RP	Minimize cost	Canberra, Australia
(Ghodsi et al. 2019)	SWMM	GA	PP, BC, IT, VS	Reduce total runoff, peak flow, suspended substance (SS) pollutant, and LIDs cost	Velenjak in Tehran, Iran
(Alamdari and Sample 2019)	RSWMM	NSGA-II	BC, GR, PP,RP, DS	Minimize cost	Fairfax County in Virginia, USA
(Huang et al. 2018)	SWMM	SA	PP, BC, IT, RB, VS, GR	Optimize benefit/Cost ratio	Taipei, Taiwan
(Liu Y et al. 2016)	L-THIA LID	AMALGAM	DB, VS	Reduce runoff volume and pollutant loads	Northwest Indiana, USA
(Jing Wu et al. 2019)	SWMM	NSGA-II	BC, IT, PP	Reduce pollutant loads, minimize cost	San Francisco, USA
(Mani et al. 2019)	SWMM	MOALOA	BC, PP, VS, IT	Minimize runoff volume, minimize costs, minimize the service-performance reduction of LID.	Tehran, Iran

Acronynms: Model for Urban Stormwater Improvement Conceptualisation (MUSIC), autocalibration for SWMM using optimization in R (RSWMM), Long-Term Hydrologic Impact Assessment Low Impact Development (L-THIA LID), permeable pavements (PP), green roofs (GR), bio-retention cell (BC), grass swales (GS), detention basins (DB), rain barrel (RB), infiltration trenches (IT), vegetative swale (VS), dry swale (DS), retention pond (RP), SWMM (stormwater management model)

feasibility of utilizing nonfunctional wells and qanats as GSIs by assessing their economic value and performance. This paper's study site has been extensively investigated and inspected to identify feasible drywells and analyze their potential use as GSI. The proposed framework in this study is composed of a core stormwater modeling component (US Environmental Protection Agency's (EPA) Storm Water Management Model, SWMM) which is dynamically tied into an optimization solver (genetic algorithm, GA) to find the optimal selection and placement of GSIs in an urban watershed (the city of Tehran, Iran). A combination of appropriate GSIs for the study area, including bio-retention cells, permeable pavements, and drywells, is considered in this paper for the development of a unique stormwater management portfolio, which tends to maximize the runoff control capacity and aquifer recharge, while considering financial budget constraints.

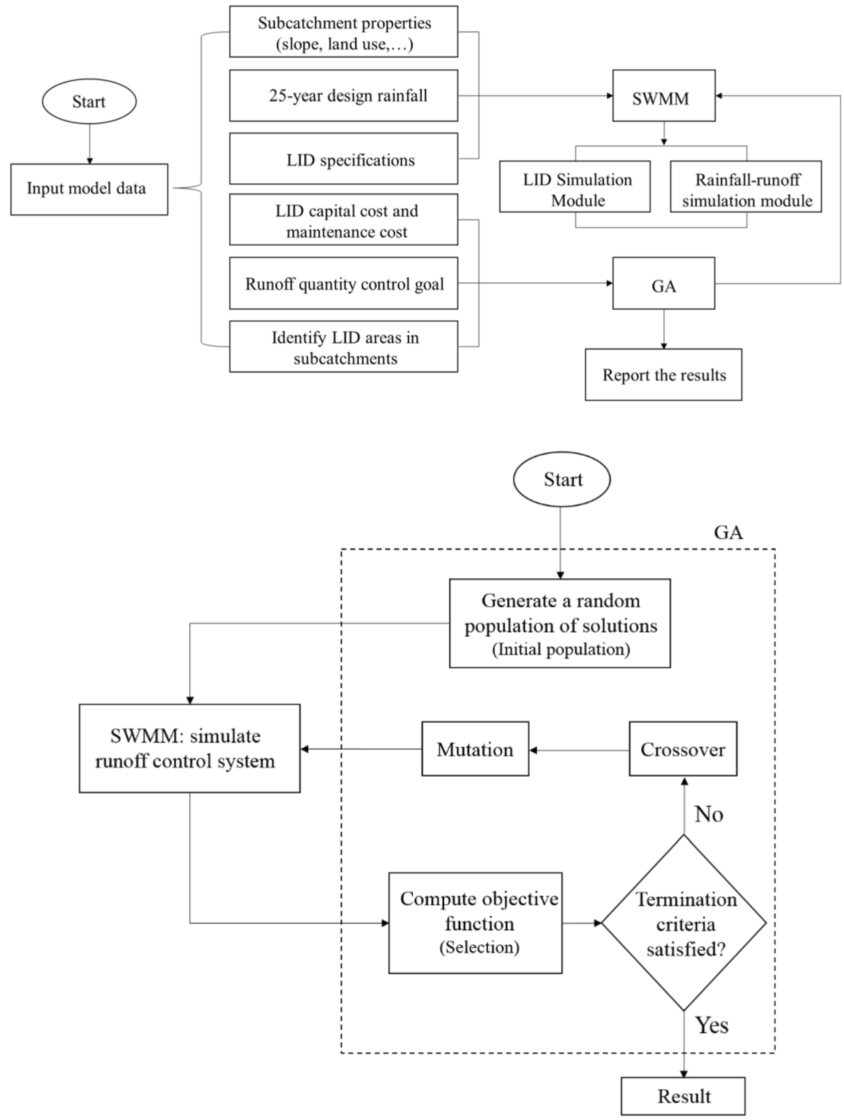
Materials and methods

This work develops an integrated simulation-optimization method (SOM) to minimize runoff volume while meeting budget constraints. The budget range is derived from previous studies (see, e.g., Bahrami et al. 2019). The SWMM is coupled with a GA module which identifies the best sets of GSIs and their placement in a catchment. The nonfunctional wells and qanats are generically herein called drywells, whose rehabilitation and use bypass the need for installing new drywells, and provide underground storage for stormwater retention. The type and (surface) area of bio-retention cells and permeable pavements are the decision variables in this paper's SOM. The impact of infiltration from GSIs on groundwater relies on a budgeting method to represent aquifer recharge. The proposed methodology's flowchart is displayed in Fig. 1. The following sections describe the study area, present the methodology, and summarize this paper's results consecutively. This paper also states the main assumptions and limitations of its SOM, and ponders future paths for pertinent research.

Study area

The proposed SOM (Fig. 1) was used to model urban runoff generation in District 6 of the Tehran municipality. District 6

Fig. 1 Flowchart of the applied methodology



is a densely populated residential area with predominantly impervious surfaces, which historically has been subjected to flooding during heavy rains. District 6 is representative of highly urbanized and populated residential areas in semiarid and arid regions subjected to frequent floods. The study region has an area of about 21.37 km^2, approximately 3.45% of Tehran's total area. The catchment was divided into 45 subcatchments (Fig. 2). The study area is located in downtown Tehran, where the impervious area is close to 100%, except for parks and open spaces making up less than 12% of the total study area. The preponderance of impervious area is why permeable pavements and bio-retention cells were chosen as suitable options over other types of GSIs. The slope and elevation of the terrain in the study area vary from 0.01 to 0.04 and from 1,460 m to 12,14 m above sea level, respectively. The temperature in this region fluctuates seasonally between 41 °C and − 40 °C, with an average temperature of 10 °C. Tehran is located in a semiarid part of the country with a long-term average annual precipitation of about 275 mm. The average number of rainfall days varies from 1 day in September to 10.9 days in March. The 25-year return period rainfall with a 6-h duration is chosen for the simulation of runoff by SWMM (Mahab and Pöyri 2010).

The study area is part of the Tehran Plain, an alluvial pediment region located south of the Alborz Range. Tehran has been experiencing increasing water consumption as a result of population growth over the last 40 years (Haghshenas Haghighi and Motagh 2019). Various infrastructure projects, such as building new dams, have been investigated and constructed since the 1960s. Nevertheless, the total surface-water resource budget is not sufficient to meet the growing water demand of the agricultural, domestic, and industrial sectors. Existing water supply sources will not be sufficient or reliable in the near future on account of the increasing trend of population growth and climate change patterns. Thus, groundwater has been depleted to close the gap between water demand and

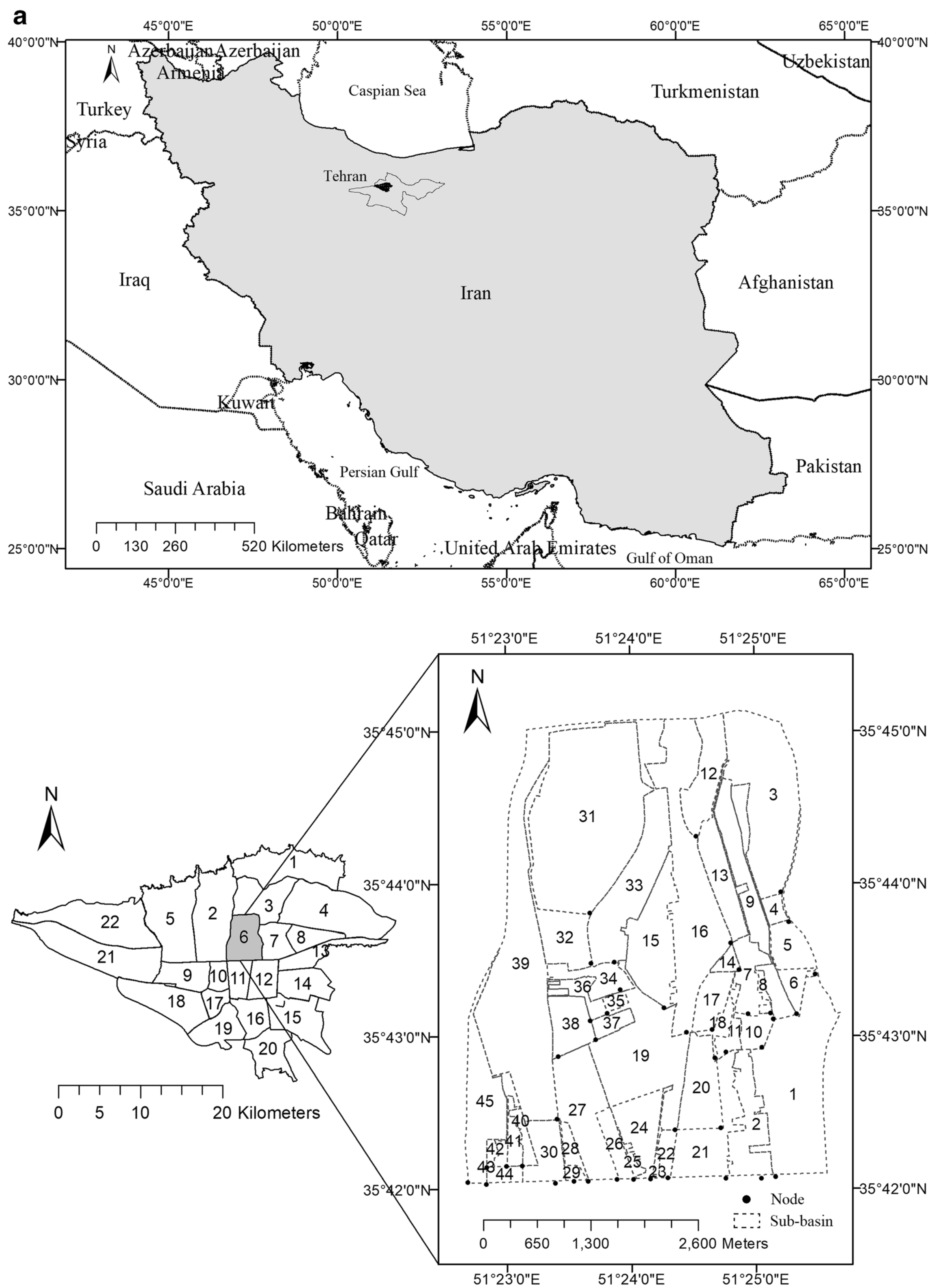


Fig. 2 Study area characteristics: **a** District 6 of Tehran Municipality, divided in 45 subcatchments; **b** Topographic map

surface-water supply, which has led to drilling new wells, from as many as 3,906 in 1968 to 32,518 in 2012 (TRWC, TRC 2012). Therefore, increased overdraft and decreased net recharge of aquifers have resulted in the continuous depletion of Tehran's aquifers. The average groundwater level in Tehran fell about 11.65 m between 1984 and 2012. The

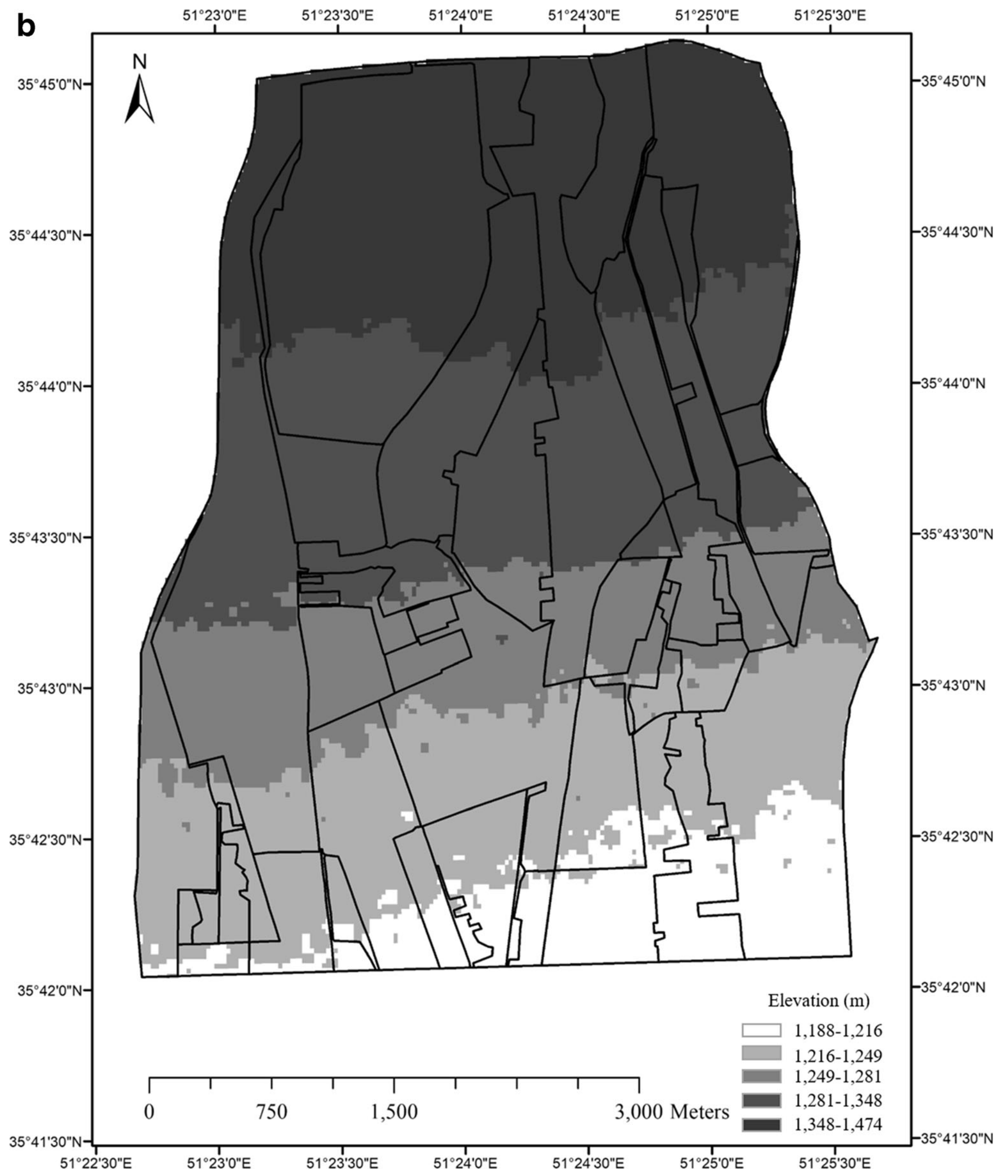


Fig. 2 (continued)

decline of the water table has dried wells and qanat galleries. In particular, the total number of active qanats has decreased from 522 to 167 between 1970 and 2012 (Mahmoudpour et al. 2016). Data reported by Tehran Water Organization in 2019 shows that District 6 of the Tehran municipality contains 20 inactive wells, 15 active wells used for landscape irrigation, and 80 inactive qanats. These authors' site inspections assessed the possibility of using these nonfunctional wells and qanats as drywells after undergoing minor changes. The criteria for drywell selection were the pollution load in stormwater and topographic constraints. Table 2 summarizes the storage volume of observed feasible drywells, and Fig. 3 depicts their locations. More details of wells and qanats in the study area can be found in the electronic supplementary material (ESM).

Rainfall–runoff simulation

This study evaluated 19 common hydrologic models following the work by Bosley and Kern (2008), and concluded that the SWMM was the most suitable open-source tool for modeling hydrological systems in urban settings of the type considered in this paper (York et al. 2015; Zhang and Chui 2018). The application of the SWMM for simulating GSIs is well documented (Rossman 2010; Niazi et al. 2017; Huang et al. 2018). This paper adopted theUS EPA's SWMM version 5.1 to simulate surface runoff for dynamic single-event conditions. The SWMM develops a moisture balance during simulation for tracking how much water moves between and is stored within the GSI layers.

The SOM inputs include catchment maps, containing land use features, nonfunctional well and qanat locations, catchment slopes, Manning's roughness, impervious area percentage, design hyetograph for a 25-year return period, and specification layers of the GSIs. Values of the aforementioned parameters for 45 subcatchments are listed in Table 3. Dynamic wave flow routing and Horton's method for infiltration calculations are applied by the SWMM. The routing time step was set to 30 s in this work. It is noteworthy that the calibrated model for the study watershed was developed by Mani et al. (2019) and Bahrami et al. (2019), which was used in this study.

Design rainfall

This study applies a 25-year return period rainfall event with 6-h duration. The reason behind this selection was the concentration time for the City of Tehran and the technical advice of Mahab and Pöyri (2010) for LID design in Tehran. The concentration time for the entire City of Tehran is about 3 h (Mahab and Pöyri 2010); therefore, the duration of the design rainfall for rainfall-runoff assessment exceeds 3 h. Liu A et al. (2016) indicated that using a hydrologic design based on relatively light rain and frequent rainfall events is more appropriate for water treatment purposes. Larger rainfall design events are cost-effective in this instance. Therefore, a 6-h duration rainfall event was selected. It is noteworthy that the concentration time (3 h) is shorter than the duration of the design rainfall duration (6 h).

Gibb (1975) developed the intensity-duration-frequency (IDF) curve for the short-term rainfall in Tehran Plain. The extracted empirical equation, representing the typical IDF curves for short-duration rainfall of Tehran, is as follows:

$$I = C_{\mathrm{AltPR}} \times D^{-0.645} \tag{1}$$

where I, D, and C_{AltPR} denote, respectively, the rainfall intensity (mm/h), the rainfall event duration (minutes), and a coefficient related to the return period of the rainfall event and the average elevation of the study area. The value of C_{AltPR} was estimated as 237, corresponding to an average elevation of the study area equal to 1,300 m for a 25-year return period rainfall.

The rainfall intensity for the 10-min time intervals was calculated with Eq. (1). The rainfall depth was calculated by multiplying the rainfall duration (h) by the intensity (mm/h). The distribution of the precipitation depth was calculated as follows: the maximum rainfall block falls in the middle of the hyetograph, the second largest block is positioned to the right of the maximum block, the third-largest block is positioned to the left of the maximum block, and so on. The subsequent hyetograph for the design rainfall with a 6-h duration is depicted in Fig. 4. More details of hyetograph calculations can be found in the ESM.

Urban runoff management

Minimizing the runoff with a limited available budget in the study area is achieved with drywells, bio-retention cells, and permeable pavements as the chosen GSI controls based on the characteristics of the subcatchments in the study area. Bio-retention cells and permeable pavements were selected considering the study area's features and the available budget for implementation over green roofs and rain barrels, and because of their capacity to control extreme rainfalls such as the selected design rainfall, compared to infiltration trenches and

Table 2 The feasible drywell volumes in the subcatchments

Subcatchment	Drywell storage volume (m^3)		
	Ineffective qanat	Landscape irrigation wells	Abandoned wells
1	1,272.7	0.0	25.4
2	172.1	47.7	0.0
3	2,591.8	34.1	3.0
5	0.0	0.0	35.0
6	254.2	0.0	0.0
7	179.6	0.0	0.0
9	223.5	41.4	0.0
12	1,340.9	0.0	0.0
13	0.0	0.0	12.7
15	1,231.1	63.6	0.0
16	2,346.3	31.8	38.2
19	1,078.4	19.5	5.1
20	0.0	3.5	0.0
21	79.0	0.0	30.1
26	0.0	8.0	0.0
27	27.9	0.0	0.0
31	7,239.6	38.2	81.3
32	970.4	0.0	0.0
33	3,611.0	55.3	47.7
34	420.0	0.0	0.0
35	525.5	0.0	0.0
36	64.0	0.0	12.7
37	250.5	10.2	0.0
38	930.5	36.3	0.0
39	3,406.2	0.0	12.7
40	424.2	0.0	0.0
41	208.9	0.0	0.0
42	171.3	0.0	0.0
44	188.5	0.0	48.1
45	1,250.1	0.0	0.0

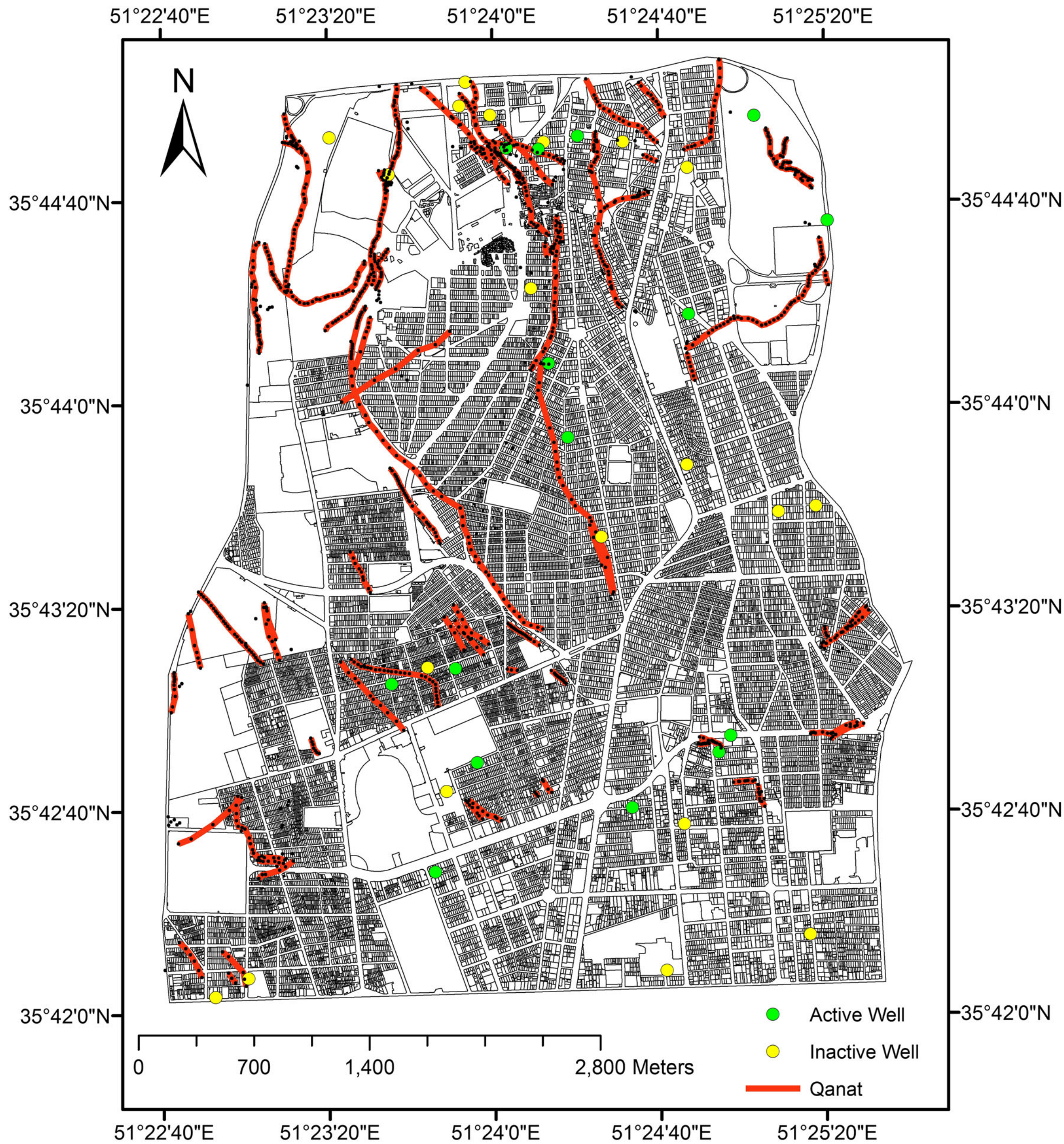


Fig. 3 Feasible drywells in the study area

vegetative swale. The budget limits were derived from the results of Bahrami et al. (2019).

Drywells

Drywells are useful GSIs for stormwater control and groundwater recharge; however, they may induce subsurface contamination and clogging (see, e.g., Pyne 2005). Various studies have recognized that the pollutants that are usually found in drywells are similar to those detected in stormwater runoff (EPA 1999; Hamilton et al. 2004). Results from previous studies indicate that after about 1.5 m of water travel through gravel with silt and sand, and before reaching the water table, concentrations of the majority of the nonmetal pollutants, copper, lead, benzo(a)pyrene, pentachlorophenol, and diethyl hexyl-phthalate fall below detection limits (Edwards et al. 2016). Therefore, groundwater contamination is avoidable if drywells are correctly designed, implemented in suitable locations, and are regularly maintained. It is recommended that to protect against groundwater pollution and to decrease the clogging risk, pretreatment be applied to the water before recharging the drywells (e.g. sedimentation chamber, filter, vegetative cover) or to limit inflow to stormwater with low pollution levels, such as roof runoff (Pitt and Talebi 2012). Moreover, deicing salts in the snowmelt increase the sodium adsorption ratio (SAR) and decrease the infiltration rates; thus, stormwater gathered from roofs is more desirable than walkway or driveway runoff for drywell recharge (Pitt

Table 3 Input data for SWMM model in the study area

Subcatchment number	Area (ha)	Slope (%)	Impervious ratio (%)	Horton infiltration rate (mm/h)	
				Min	Max
1	160	1.3	94.7	8.1	47.3
2	49.6	1.2	100	0	0
3	139	2.9	33.1	103.6	601.9
4	8.1	2.1	100	0	0
5	27.8	1.5	97.4	4	23.4
6	25.5	2.9	98.4	2.3	13.8
7	31.9	1.8	98	2.9	17.2
8	4.7	1.4	100	0	0
9	58.8	2.7	100	0	0
10	15.3	1.4	98.3	2.5	15
11	11.2	1.4	100	0	0
12	45.1	3.3	99.5	0.7	4.2
13	39.8	2.9	65.2	53.9	313
14	6.64	2.1	100	0	0
15	71.6	2.5	100	0	0
16	155	3.3	96.9	4.7	27.7
17	24	1.7	100	0	0
18	9.7	1.4	98.7	1.9	11.5
19	118	1.9	100	0	0
20	47.4	1.4	97.5	3.8	22.3
21	58.5	1.1	100	0	0
22	10.5	0.9	100	0	0
23	3.37	1	100	0	0
24	38.8	1	100	0	0
25	4.45	0.8	100	0	0
26	16.2	0.9	100	0	0
27	72.5	1	47.3	81.5	473.6
28	8.7	0.9	100	0	0
29	4.8	0.9	100	0	0
30	29.7	0.9	100	0	0
31	258	4.1	96.1	5.9	34.6
32	48.4	2.6	96.7	4.9	28.9
33	109	3.2	93.7	9.7	56.5
34	24.3	2.3	99.4	0.8	5.16
35	4.83	2.2	100	0	0
36	13.8	2.3	97.5	3.8	22.3
37	10.7	2	100	0	0
38	34.5	2.3	100	0	0
39	225	2.3	82.1	27.7	160.9
40	13.2	1.2	100	0	0
41	10.9	1	100	0	0
42	5	1	100	0	0
43	3.9	0.8	100	0	0
44	8.3	0.8	100	0	0
45	65.9	1.5	100	0	0

and Talebi 2012). The transfer of stormwater to drywells without consuming electrical energy can be achieved by gravity conveyance in many instances. The pollution load of runoff can be reduced by means of nonfunctional wells and qanats as drywells, which can also collect roof runoff. Drywell maintenance is costly; installing litter and trash filters in the roof gutters and downspouts prevents the entrance of debris into drywells and is essential for acceptable long-term performance (Pitt and Talebi 2012). The cost of drainpipe, filter, and sedimentation-chamber installation is considered as the capital cost for drywells. Gonzalez-Merchan et al. (2012) have shown that the presence of vegetation diminishes the concentration of pollutants in stormwater and can reduce the clogging ratio in drywells. The selection of appropriate wells with regard to the discussed characteristics was made during the authors' site inspections, in which stormwater inflow towards wells by gravity was taken into account. The installation of pretreatment equipment and careful selection of feasible drywells decreases the clogging and damage risk, yet, annual inspection and proper maintenance is essential to keep the drywells functional.

Another critical factor for the implementation of drywells is the subsurface soil's ability to allow stormwater infiltration. Soils are classified into four groups based on their runoff potential: groups A, B, C, and D. In this classification, A has the largest infiltration and smallest runoff potential when thoroughly wet, while D has the smallest infiltration and largest runoff potential (NRCS 2009). It is noteworthy that the infiltration rate of soil groups A and B is appropriate for implementing drywells (Pitt and Talebi 2012). Tehran's subsurface soil is classified as hydrologic soil group B (Mahab and Pöyri 2010). The historical discharge data of the selected drywells confirm their capacity to be fully drained in less than 3 days (Blick et al. 2004; Edwards et al. 2016).

Additionally, the decision to use active wells as drywells, which were utilized for landscape irrigation, was motivated by capture and reuse projects in managed aquifer recharge (MAR) operations. Using active irrigation wells for aquifer recharge is common in MAR programs. It is noteworthy that MAR programs specify criteria on water quality to prevent aquifer contamination. The stormwater quality is not assessed in this study via simulation-optimization, but water quality considerations are taken into account and constrain the number of selected feasible drywells as explained previously. A similar measure considered was crop irrigation by stormwater, as practiced in California (Dillon et al. 2006; Dahlke et al. 2019). Using irrigation wells as GSIs in public areas provides the following benefits: backwash clogging layers due to regular pumping of stored water (Dahlke et al. 2019), and economic benefits associated with meeting water demand close to the place where stormwater is stored (Dandy et al. 2019; Torres et al. 2020). The general design concept of drywells in this study (including perforated concrete or PVC casing with an average diameter of 1.2 m (m), and depth of 0.6–26 m) is shown in Fig. 5.

Bio-retention cells

Bio-retention cells are depression storages whose designs include layers of vegetation, filter media, storage, and an optional underdrain (Ahiablame et al. 2012; Liu et al. 2015). Their main use is for stormwater treatment and peak flow and volume reduction provided by storage, infiltration, and evaporation of surface runoff. Generally, bio-retention cells performed effectively in the (1) first flush of runoff caused by rainfall after a prolonged dry period, and (2) runoff volume reduction; however, their performance concerning peak flow reduction varied with storm characteristics (Eckart et al. 2018; Yang and

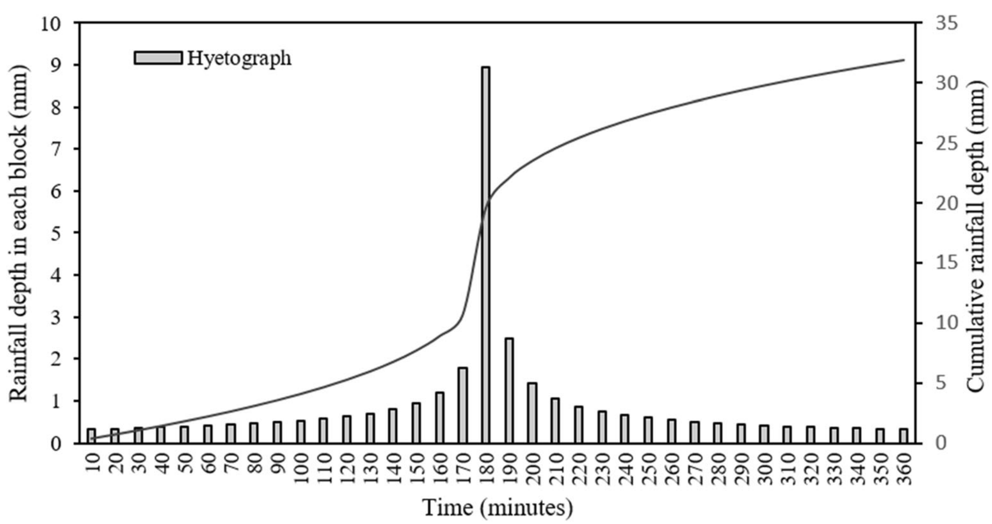


Fig. 4 Hyetograph and cumulative depth of the 25-year design rainfall in study area

Chui 2018). Sun et al. (2019) showed that bio-retention cells had better performance during longer rainfall events with lower intensity, which delayed the generation of runoff. The features of the GSIs are listed in Table 4, except those of drywells.

Permeable pavement

Permeable pavement (PP) materials typically include a durable permeable paving surface, a storage space, and an optional underdrain system (Li et al. 2019). Infiltration, void space storage, and evaporation are the three steps of stormwater runoff mitigation processes in permeable pavement. Drake et al. 2013), after investigations in Vaughan, Ontario, Canada, revealed that permeable pavement captured a significant part of rainfall for events with less than 7 mm depth. Permeable pavement efficiently reduced the outflow volume (Luan et al. 2019), which confirmed that in combination with other GSIs permeable pavement could potentially reduce total runoff by 30% (Li et al. 2019).

Optimization model

Traditional optimization algorithms are effective for solving relatively simple problems with a limited number of variables, whereas evolutionary and metaheuristic algorithms are more suitable for solving highly nonlinear and complex problems with large numbers of decision variables (Bozorg-Haddad et al. 2013). Evolutionary algorithms (EAs) are independent of problem type and have gained popularity due to their accuracy and speed without the limitations of classical methods (Bozorg-Haddad and Mariño 2011).

Esat and Hall (1994) showed that the required computer time and memory required to solve water-resources optimization problems with classic methods increased exponentially for increasingly complex problems, whereas they increased linearly when solved with the genetic algorithm (GA). Also, the GA was less sensitive to problem type and has been widely used in water-resource management problems.

The GA starts the optimization search with the random generation of populations of tentative solutions, and via selection, crossover, and mutation, an offspring population of improved solutions is generated (Fig. 1). The members of the offspring population are evaluated based on their objective function values, or fitness function values if constraints are present. Successive improved populations of solutions are generated until predefined stopping criteria are met (Bahrami et al. 2019).

The GA is applied in this work to determine the best combination of GSIs regarding their types and the area in each subcatchment. This implies the need for a capable optimization technique that can differentiate between suitable and unsuitable surfaces upstream of the flooding nodes, and choose the appropriate GSIs and their respective area to mitigate the impacts of rainfall at those nodes. To achieve this goal the study area has been modeled by SWMM for the baseline condition (before implementing GSIs) and the flooding nodes in the study are identified (section "Optimizing implementation of the GSIs in the study watershed"). Based on the initial results reported by SWMM the optimization model has been defined by Eq. (2), which minimizes the volume of the total runoff at the four identified flooding nodes and in turn minimizes the runoff volume in all nodes in the study area, separately. Guided by this objective function, the GA finds decision variables that can mitigate the effects of flooding in the mentioned nodes. The constraints on costs lead to an economical set of decision variables.

The GA was herein coupled with the SWMM open-source code in MATLAB 8.6 to form the simulation-optimization method (SOM). The GA found the optimal possible solution for the decision variables meeting all the constraints and given the objective function. This work's objective function consists of the minimization of the total runoff volume (V) at flooding nodes of the study area under three certain budget levels. Furthermore, the design variable consists of determining the total area of each GSI in the appropriate subcatchment. Equations (2)–(4) define the objective function and its constraints:

Runoff volume minimization:

$$\begin{array}{l} \mathrm{Min} V_{\mathrm{Total}} = \sum_{i=1}^{m} V_i \\ i = 1, \ldots, m \end{array} \tag{2}$$

Constraints on GSIs area sizes:

$$\begin{array}{l} 0 \le A_{kj} \le A_{\mathrm{M}_{kj}} \\ j = 1, \ldots, n \\ k = 1, \ldots, p \end{array} \tag{3}$$

Constraint on financial resources:

$$\begin{array}{l} C_{\mathrm{Total}} \le C_{\mathrm{Level}} \\ C_{\mathrm{Level}} = \begin{cases} \$12\mathrm{million} & \mathrm{Low} \\ \$17\,\mathrm{million} & \mathrm{Medium} \\ \$22\,\mathrm{million} & \mathrm{High} \end{cases} \end{array} \tag{4}$$

in which V_{Total} represents the cumulative runoff volume at flooded nodes (m^3); V_i is the flood volume at flooding node i (m^3); m denotes the total number of flooding nodes; n is the total number of subcatchments (n = 45); p equals the total number of GSI types (p = 2; bio-retention cells and permeable pavement); A_{kj} denotes the area of GSI type k in subcatchment j (the decision variables); $A_{\mathrm{M}ki}$ denotes the maximum available area for the kth LID in subcatchment j; C_{Level} and C_{Total} denote respectively the maximum limit of allowed cumulative lifecycle costs of total GSIs in the study area in millions of dollars and the cumulative lifecycle cost of all GSIs in the

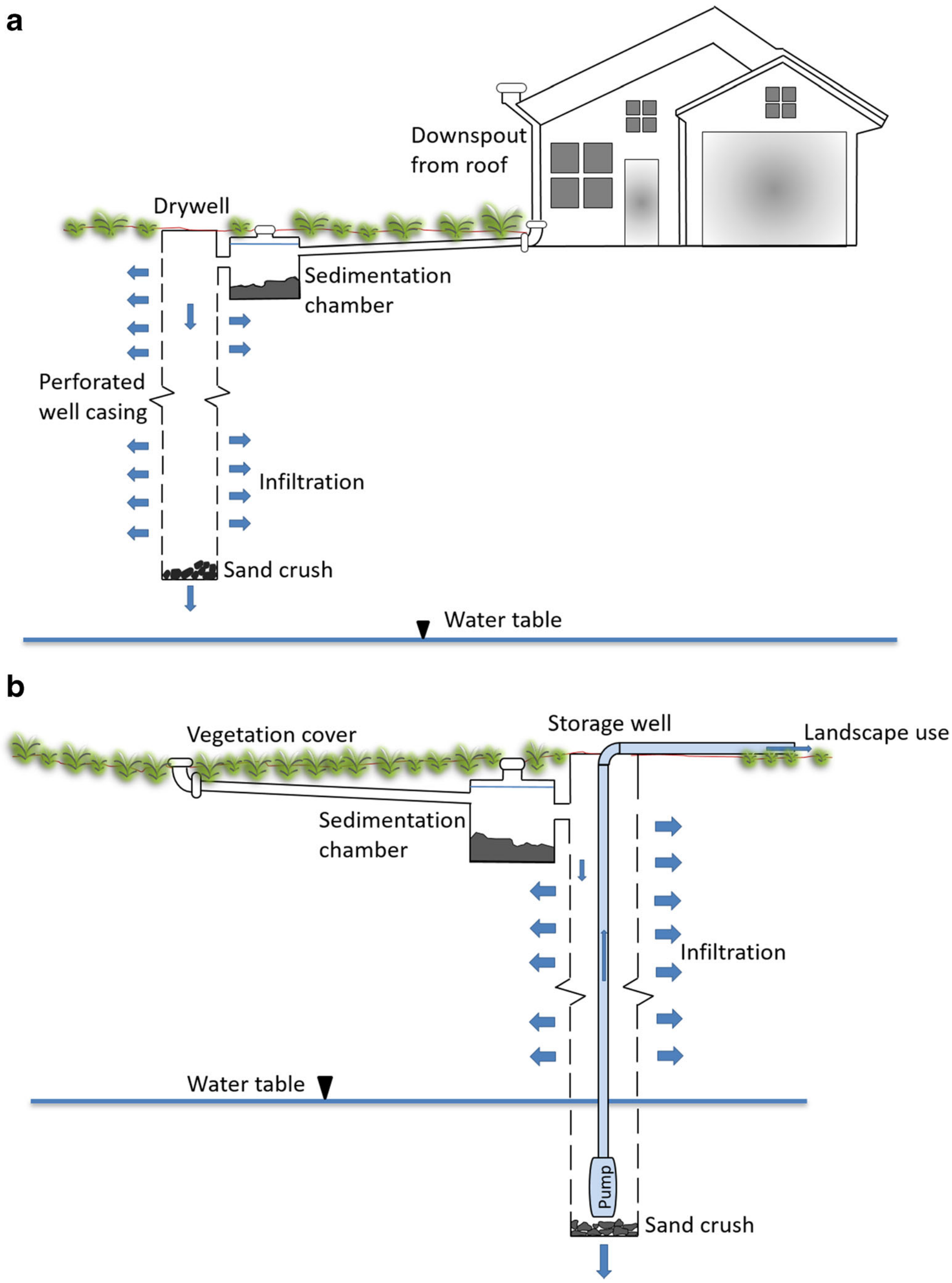


Fig. 5 The general design of a **a** drywell and **b** storage well

study area, which is calculated as follows (following Bahrami et al. 2019):

$$
\begin{aligned}
C_{\mathrm{Total}} &= \sum_{j=1}^{n}\sum_{k=1}^{p} C_{kj} \\
C_{kj} &= C_{k0j} + \sum_{t=1}^{T} \frac{C_{kjt}}{(1+r)^t} \\
C_{k0j} &= A_{kj} \times C_{\mathrm{unit}k}
\end{aligned}
\tag{5}
$$

in which C_{kj} represents the lifecycle cost of GSI type k in subcatchment j; C_{k0j} denotes the construction cost for LID type k in subcatchment j (\$/m^2); C_{kjt} represents the lifetime maintenance cost for LID type k, subcatchment j, in year t (\$/m^2); $C_{\mathrm{unit}k}$ represents the unit construction cost for GSI type k (Table 5); T is the service lifetime of the system of GSIs; r denotes the annual discount rate.

The unit costs of GSIs used in this study are listed in Table 5. The total cost of bio-retention cells and permeable pavement equals the sum of the construction and maintenance costs during the system lifetime. The total cost for drywells consists of the modification cost to prepare abandoned wells, qanats, and irrigation wells, i.e. the costs of drainpipe and sedimentation chamber installation for each well, as well as

Table 4 GSI specifications implemented in this study

Layer	Parameter	GSI	
		Bio-retention cell	Permeable pavement
Surface	Berm height (mm)	200	4
	Vegetation volume fraction	0.1	0
	Manning's *n*	0.03	0.012
	Surface Slope (%)	0	Related to subcatchment
Pavement	Void ratio	–	0.15
	Permeability (mm/h)	–	500
	Thickness (mm)	–	100
Soil	Porosity	0.4	–
	Conductivity (mm/h)	250	–
	Thickness (mm)	900	–
Storage	Void ratio	0.7	0.5
	Conductivity (mm/h)	44	44
	Thickness (mm)	350	300

maintenance cost during its lifetime. More details of optimized variables and economic analysis can be found in the ESM.

Groundwater recharge

Several estimation methods, and in situ or simulation modeling, have been applied in previous studies, including HYDRUS-2D, in situ drainage method, the Darcy method, and the water budget method have been used to estimate groundwater recharge. This work applies a water-budget method to estimate the average annual recharge via drywells. The water-budget method assumes the following:

1. Stormwater from rooftops and upstream greenspaces are first routed to the drywells in each subcatchment before reaching other GSIs (bio-retention cells and permeable pavement).
2. All the runoff routed to drywells may infiltrate into the aquifer in less than 72 h, which was the threshold of the standard drywells' design (Blick et al. 2004; Edwards et al. 2016).
3. The available runoff volume routed through drywells equals the total precipitation falling on different surfaces (i.e., residential rooftops and impervious surfaces in public land) minus the detention-storage losses in those surfaces calculated by the SWMM.
4. The ratio of the long-term average annual rainfall depth to the cumulative depth of the design rainfall was assumed to be equal to the ratio of the annual infiltration to infiltration resulting from the design rainfall. The infiltration in the drywells becomes groundwater recharge.

The volume of infiltration in each rainfall event, I_V, is calculated with Eq. (6):

$$I_V = P - R - ET - \Delta S \tag{6}$$

where *P*, *R*, ET, and ΔS denote respectively the volume of precipitation (m^3), the volume of runoff flowing into the basin (m^3), the volume of evapotranspiration (m^3), and the net change in volume stored in the basin (m^3).

The variables on the right-hand side of Eq. (6) are calculated by the SWMM, which allows calculation of the infiltration volume. The SWMM results are reported for every GSI in each subcatchment separately, which permits the calculation of infiltration through drywells, bio-retention cells, and permeable pavement for the design rainfall event. It was assumed that in addition to direct infiltration, the stored water in bio-retention cells and associated with permeable pavement infiltrates toward associated aquifers, thus becoming groundwater recharge. The cost-efficiency of GSI is calculated by dividing the total volume infiltration by the total cost, which yields the most cost-effective option for recharge.

Table 5 The total unit costs of GSI implementation in 2019 in Tehran

GSI type	Unit	Total cost (US $)
Bio-retention cell	Square meter	18.1
Permeable pavement	Square meter	9.6
Drywell	Per well	17.1

Table 6 Impact of GSI optimization on runoff volume at flooded nodes

Scenario name	Total cost (10^6\$)	Flood volume in nodes (m^3)					Total flood volume (m^3)	Reduction percentage (%)	GSI occupied area ratio (%)
		n6	n10	n16	n31	n40			
Baseline	0	67	10,193	78,441	42,400	5,W154	136,255	–	–
A	12	–	4,555	47,384	34,392	–	86,331	36.6	4.45
	17	–	3,522	44,382	18,833	–	66,737	51.0	6.33
	22	–	1,318	41,606	16,758	–	59,682	56.2	8.46
B	12	–	2,726	40,156	27,787	–	70,669	48.1	4.66
	17	–	2,571	40,802	13,787	–	57,160	58.0	6.44
	22	–	871	39,251	11,272	–	51,394	62.3	8.45

Results and discussion

Design rainfall and runoff simulation

The hyetograph of design rainfall was generated using the method described in section 'Design rainfall' (Fig. 4). The hyetographs generated for the corresponding design storm were used as the inputs to the SWMM under the baseline scenario. This rainfall led to a flooding volume of runoff equal to 136,255 m^3 at five nodes (n6, n10, n16, n31, and n40), over 12.33 h. The flooded nodes' features are summarized in Tables 6 and 7, and their locations in the study area are depicted in Fig. 6. Two management scenarios (described in section "Optimizing implementation of the GSIs in the study watershed") were created to reduce the flood volume at flooded nodes, and their performance was evaluated under three different budget levels. The effects of implemented control measures on runoff are discussed in the next section.

Optimizing implementation of the GSIs in the study watershed

Considering 45 potential subcatchments and two different types of GSIs (i.e., bio-retention cells (BCs) and permeable pavement (PP) produces 90 decision variables in the optimization problem, representing the area and type of GSIs in the subcatchments. The variables designation scheme is such that decision variables X_1, X_2 denote the occupied area of BCs and PP in subcatchment 1, respectively, and the corresponding areas of BCs and PP are denoted by X_{89} and X_{90} in the 45th subcatchment, with analogous notation applied to all intervening variables. The decision variables vary between zero and a defined upper bound, which is determined based on the subcatchments' land use and area. The simulation-optimization method (SOM) herein developed applies the SWMM model with the design rainfall and considered three budget levels under two scenarios: (1) without feasible drywells (scenario A), and (2) with feasible drywells (scenario B). The values of uncontrolled runoff volume and duration at selected nodes are reported in Tables 6 and 7.

The results in Table 6 indicate that nodes n6 and n40, which historically flooded, would not flood anymore under scenarios A or B. Nodes n10, n16, and n31 still flood but with diminished severity, varying from 19% in node n31 to 91% in node n10 relative to baseline flooding conditions (i.e., without optimized GSIs). As the budget level increased, the GA favored the option of increasing the GSI area in subcatchments upstream of nodes n10 and n31 compared to n16 to reduce flooding. This is due to the land use constraints for implementing GSIs in some subcatchments, which could

Table 7 Impact of GSI optimization on flooding duration at flooded nodes

Scenario name	Total cost (10^6\$)	Flood duration at node (hr.)					Total time (h)	Reduction percentage (%)
		n6	n10	n16	n31	n40		
Baseline	0	0.06	0.85	7.72	3.26	0.5	12.33	–
A	12	–	0.61	7.51	2.81	–	10.93	11.3
	17	–	0.56	7.51	1.63	–	9.7	21.3
	22	–	0.34	7.51	1.53	–	9.38	23.9
B	12	–	0.47	7.38	2.69	–	10.54	14.5
	17	–	0.43	7.37	1.55	–	9.35	24.2
	22	–	0.3	7.37	1.49	–	9.16	25.7

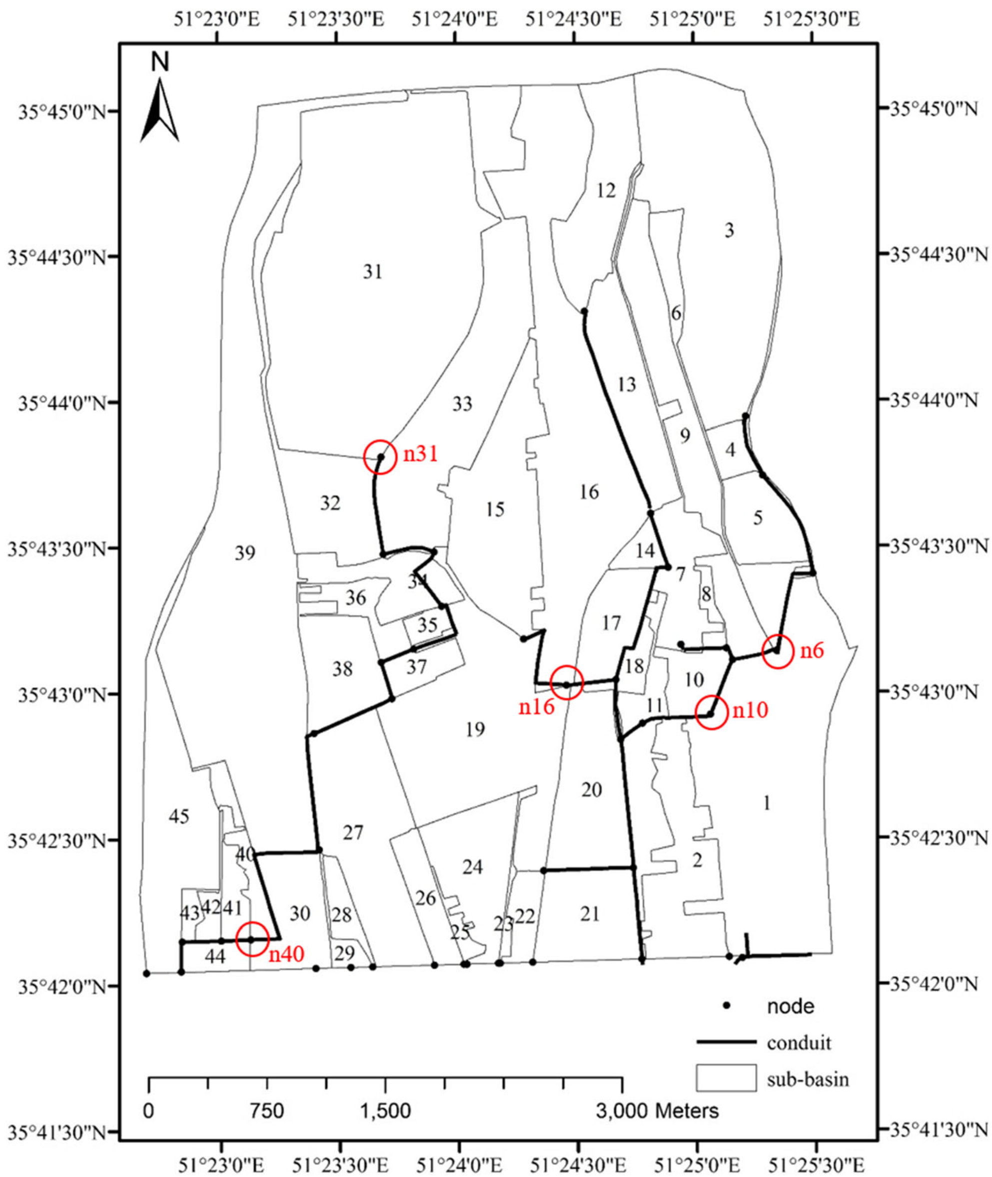


Fig. 6 Locations of flooded nodes in the study area, determined by red circles

cause the process to become more expensive. The total area occupied by GSIs varied from 4.45 to 8.46% for the whole District 6 area, which seemed reasonable for the proposed scenarios. Generally, an increase in the budget level for GSI

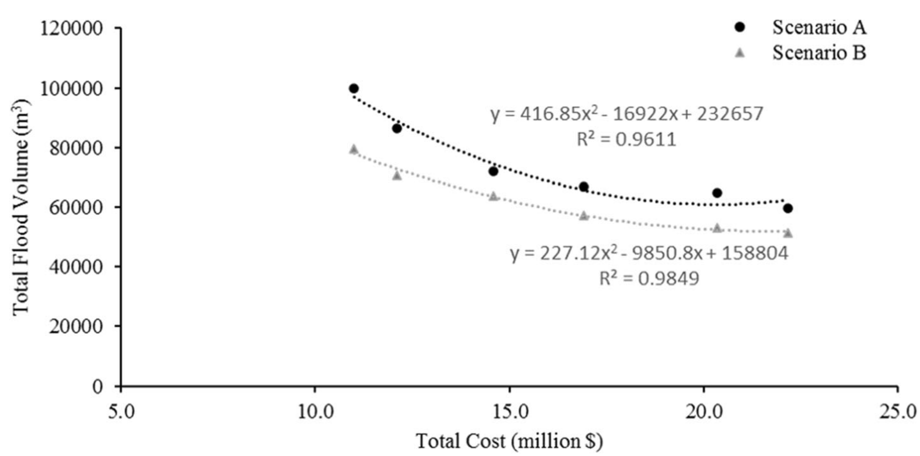


Fig. 7 Changes in flood volume reduction for various budget levels (y = total flood volume; x = total cost)

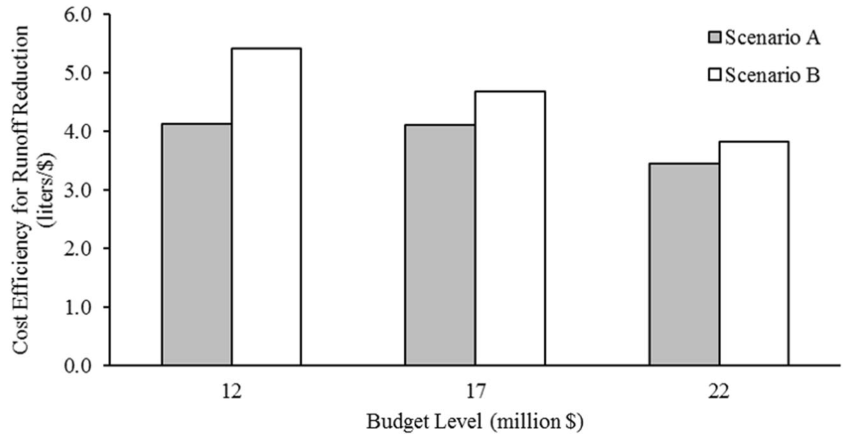


Fig. 8 The cost-effectiveness of scenarios A and B in runoff reduction under various budget levels

implementation led to a reduction in total runoff volume. This had a nonlinear behavior, as shown in Fig. 7. The SOM was implemented for other budget levels (11, 14.5, and 20 million dollars), seeking to develop a relation between increase in budget level and reduction in flood volume. The results presented in Table 6 and Fig. 7 reveal that flood reduction would be more effective in the early investment stages; thus, the flood reduction rate would be larger for the first 5 million dollars of investment than for the second 5-million-dollar-investment increment under scenarios A and B (see Table 5). This pattern reveals that the SOM detects the most cost-effective GSIs in function of the level of investment. Trend line formulas (Fig. 7) confirm that the pattern of association between reduced runoff and the capital cost was weaker for scenario B than for A when the number of GSIs increased.

A key finding from Tables 6 and 7 is that the drywells would have a significant role in flood reduction and produced a lower cost. Comparison between scenarios A and B show that drywells captured 15,662, 9,577, and 8,288 m^3 more stormwater than without them at the 12-, 17-, and 22-million-dollar budget levels, respectively. Tapping nonfunctional wells and qanats as drywells would save money and effort in the building of stormwater control measures. For instance, decreasing the total runoff volume by 56.2% using bio-retention cells and permeable pavement (scenario A) would cost 22 million dollars. However, feasible drywells (scenario B) would produce a larger reduction in the runoff volume (58%) with much lower investment, about 5 million dollars.

The aforementioned explanations are also valid from the flood duration standpoint. Table 7 shows that the flooding time under scenario B would be on average 2.6% shorter than under scenario A. Under both scenarios the flood duration would be shortened significantly when the budget level increased from 12 to 17 million dollars in comparison to the investment increase from 17 to 22 million dollars.

The economic efficiency of scenarios A and B regarding their runoff reduction is depicted in Fig. 8. The relative cost was calculated by dividing the total volume of runoff reduction for each option by its total cost. The SOM results establish that scenario B would be more cost-effective than scenario A mainly because a significant part of the stormwater runoff was transferred and collected by drywells, while drywells construction costs would be low compared to the GSIs' implementation expenses. Another noteworthy feature emerging from Fig. 8 is that the cost-efficiency exhibits an inverse relation with the budget level, i.e., 12 million dollars investment in GSI implementation was more cost-effective than dedicating 17 and 22 million dollars to runoff control. However, it is noteworthy that in this study potential financial losses resulting from floods and other hazard damages were

Table 8 The ratio of total infiltration to total precipitation in the study area

Scenario name	Total cost (10^6\$)	Infiltration percentage of precipitation		
		Permeable pavement	Bio-retention cell	Drywell
A	12	16.8	14.1	–
	17	22.9	13.1	–
	22	23.0	13.7	–
B	12	12.5	14.5	6.4
	17	20.6	13.6	6.4
	22	24.7	14.3	6.4

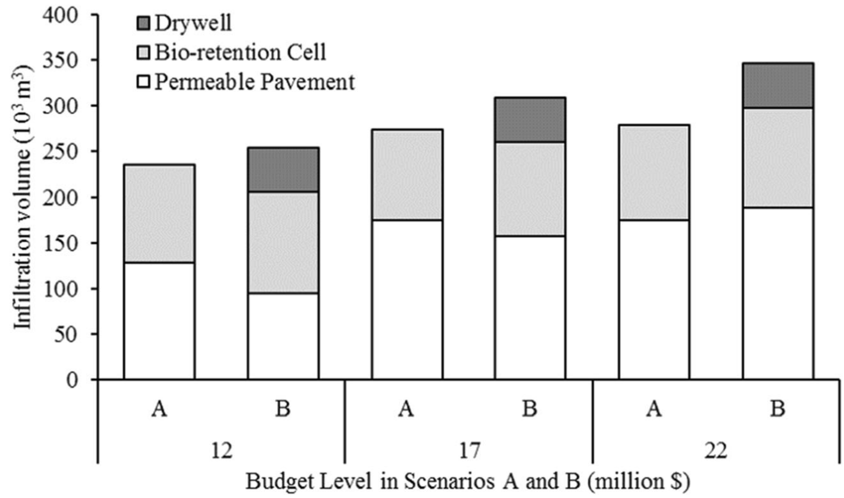


Fig. 9 Infiltrated volume of runoff produced by the design rainfall

overlooked. These should be included in future and more detailed feasibility studies.

Groundwater recharge

The continuous depletion of the Tehran aquifer was is a key underlying motive of this work. This work searched for ways to replenish the aquifer and evaluate the impacts of proposed GSIs on the groundwater system. The infiltration in bio-retention cells, permeable pavement, and proposed drywells was calculated with Eq. (6). The permeable pavement had the highest fraction of infiltrated rainfall followed by bio-retention cells and drywells respectively (Table 7). The feasibility of implementing permeable pavement on a large scale can be considered a more efficient method for increasing the groundwater recharge. Permeable pavement overrides bio-retention cells when budget limitations are not stringent because the land-use limitations for bio-retention cells are more restrictive than those for permeable pavement. In terms of drywells, although their share of the investment cost was lower than for the other two GSI types, they proved valuable because of their economic efficiency (which rises because the drilling cost is omitted). The infiltration rate for drywells was assumed constant since the drywells' volume did not vary with budget level and soil hydraulic conductivity is constant (Table 8).

Figure 9 demonstrates the comparison between the infiltrated volume of GSIs under the two scenarios and three budget levels. For all investment levels, as expected, the volume of infiltrated stormwater under scenario B would be larger than in scenario A, which confirms the role of drywells in increasing infiltration. The water infiltrated by permeable pavement and bio-retention cells changed randomly after adding drywells to the simulation model. The irregular fluctuations of permeable pavement and bio-retention cell infiltration are presumed to be due to changes in their optimal locations, which were determined by the optimization model. The volume of infiltrated water would vary from 235,000 m^3 to more than 346,000 m^3, and the share of feasible drywells from total runoff generated by the design rainfall events would be about 48,560 m^3. According to the assumptions in section 'Groundwater recharge' the average total infiltration volume over a year varies from 2.03 to 2.98 million cubic meters for the lowest investment level under scenario A to the highest investment level under scenario B, which is between 1.7 and

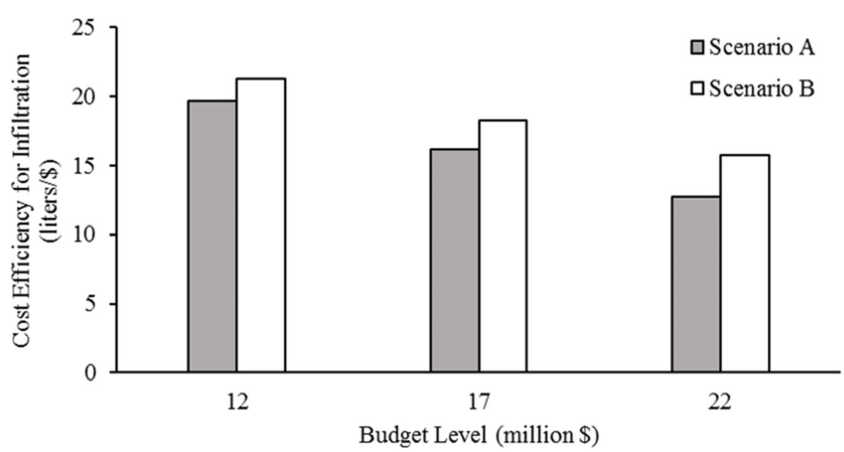


Fig. 10 The cost-effectiveness of scenarios A and B for runoff reduction under various budget levels

2.5% of the annual water consumption by the industrial sector in Tehran province. It is noteworthy that GSI implementation in 3.45% of Tehran's area could provide up to 2.5% of the industrial water demand, while expanding the area of proposed GSIs throughout the entire city would meet a significant share of the industrial demand via infiltrated runoff.

Figure 10 compares the cost-effectiveness of scenarios A and B, and it is evident that scenario B is more cost-effective than scenario A, due to the reliance on drywells and thus higher infiltration rates. It is evident in Fig. 10 that the cost effectiveness declined moderately with increased investment levels.

Conclusions

The present study applied a simulation-optimization method to determine the most cost-effective combination of bio-retention cells and permeable pavement with feasible drywells. The simulation-optimization method coupled the SWMM with the GA using a MATLAB interface. This work evaluated the merits of using abandoned or dried out wells and qanats as drywells after minor alterations to aid reducing the cost of green stormwater control strategies. Results revealed a noticeably improved performance after applying GSIs for stormwater management compared to conventional gray systems. Implementing the GSIs would reduce runoff from 36.6 to 62.3% from the baseline runoff conditions, depending on the GSI combinations and investment levels. The largest amounts of flood reduction and infiltration volume would occur in the presence of drywells at the 22 million dollars' investment level with an area of GSIs equal to 8.45% of the drainage area.

Employing feasible drywells improves the cost-effectiveness of stormwater reduction measures and aquifer recharge in District 6 of Tehran under three investment levels. Two scenarios, with (scenario A) and without (scenario B) drywells, would be most cost-effective under a 12-million-dollar-budget; yet, at this level of investment in GSIs, the associated flood damage would be higher than those associated with larger budgets dedicated to GSIs. Benefits from aquifer recharge and the cost of refurbishing damaged qanats and the clogging of wells must be considered in making a final economic evaluation of the best level of investment in GSI with flood control and water conservation perspectives. Some of the results obtained in this study depend on area-specific conditions such as land use distribution and hydrologic properties; thus, conclusions and results may vary from those that would arise in other regions. However, the proposed framework, underlying steps, and concepts herein presented are of general applicability.

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Declarations

Conflict of interest None.

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