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ORIGINAL PAPER

Development and application of a new index-overlay method to assess urban runoff vulnerability to contamination (evaluation in the Ardabil city, Iran)

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Abstract

Urban runoff is an effective alternative water resource, particularly in arid and semi-arid regions. Urban runoff exploitation permits cities to have a significant amount of water, but without assessing the runoff quality, harvesting of this resource is complicated and requires further investigations. Due to the lack of a specific method, in this study, a new index method (WLTR) was developed for assessing the urban runoff vulnerability to contamination. The WLTR index is based on rating different sub-factors of wastewater (W), land use (L), transportation (T), and rainfall runoff (R) factors. The efficiency of the WLTR index was investigated in 12 sub-catchments of the Ardabil city in Iran. The priority of sub-catchment vulnerability was determined via WLTR index value. The efficiency of the developed method was investigated using direct measurement of several water quality parameters (pH, EC, TDS, TSS, TH, and SO_4) in the sub-catchments outlet. A Water Quality Index (WQI) was calculated for each sub-catchment. The quality priority of sub-catchments was determined based on the WQI value. According to the measured data, an acceptable efficiency was observed for WLTR index. According to the results, the most vulnerable sub-catchments (Nos. 4, 11, and 12) had the lower runoff quality among studied sub-catchments, whereas the least vulnerable sub-catchments (Nos. 2, 9, and 8) had the higher runoff quality.

Keywords Urban runoff · Vulnerability assessment · Index-overlay method · WQI · Contamination

Introduction

Over the current century, the urban population has been raised rapidly. The urban population is expected to rise to 70% by 2050 (UN 2012). Water scarcity is one of the major challenges in urban areas, especially in arid and semi-arid regions of the world (Mays 2009; Taffere et al. 2016).

Due to the high potential of runoff generation, there is enormous potential in urban runoff harvesting and utilization (Zhu et al. 2004; Angrill et al. 2017; Zhou et al. 2017). Urban runoff harvesting could lead to a reduction in the flooding, decreasing cost of the urban water/wastewater infrastructures, and finally decreasing the pressure on the drinking water and other water resources such as groundwater (van Roon 2007; Fletcher et al. 2008; Antunes et al. 2016).

Accumulation of various pollutants on urban impervious surfaces increased due to population density, development of the different industrial, and commercial and recreational activities (Tsihrintzis and Hamid 1997). These pollutants are picked up by surface runoff during the storm events and negatively affect the runoff quality. Consequently, the runoff usability can be restricted and can induce deleterious effects on receiving water bodies and aquatic biota (Behera et al. 2006; Richardson and Tripp 2006; Chevre et al. 2007; Ghodsi et al. 2016a; Fan et al. 2017).

The quality management of the urban runoff is one of the most important steps for supplying sustainable water in urban areas (Jia et al. 2014; Shah Naqvi et al. 2015; Ghodsi et al. 2016b). Recognition of urban runoff quality is a prerequisite for determining optimal quality management strategies. The

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urban runoff vulnerability assessment can be an efficient and low-cost alternative to those analyses, especially in developing countries. Urban runoff quality was investigated in many studies (e.g., Chen and Adams 2007; Freni et al. 2010; Young et al. 2011; Liu et al. 2013; Nosrati 2017; Hur et al. 2018).

Various methods have been introduced to estimate water resource vulnerability to contamination. These methods are divided to three general categories: (1) process-based simulation models, (2) statistical methods, and (3) overlay and index method (National Research Council 1993; Eimers et al. 2000; Harbaugh et al. 2001; Saatsaz et al. 2011; Ghazavi and Ebrahimi 2015). The overlay and index method has more priority due to the need to few, accessible, and low-cost data. Despite that several prominent index-overlay methods were developed to estimate pollution vulnerability of surface water resources in a certain hydrogeological unit (e.g., WRASTIC index (NMED/DWB), USGS index (Eimers et al. 2000), methodology of the ECOMAN Project (Harum et al. 2004), and methodology of the Californian Department of Health Services (CDHS)), there is not an efficient method to estimate urban runoff vulnerability to contamination.

This study investigates two hypotheses: (1) the urban runoff vulnerability to contamination can assess based on rating different sub-factors of wastewater (W), land use (L), transportation (T), and rainfall runoff (R) factors. (2) WLTR is a suitable index for assessing the urban runoff vulnerability to contamination. Accordingly, the main aim of this study is to develop a new index-overlay method for assessing surface runoff vulnerability to contamination in urban hydrological sub-catchments. As the various factors can influence urban runoff vulnerability, the main limitation of this study should be factor selecting, sample size, and the sampling method. This sample might not be representative for other cities with the same conditions. The standards of urban runoff quality and the socio-cultural condition of the cities should also importantly investigate urban runoff vulnerability to contamination.

Methodology

Development of the vulnerability assessment method

The most important sources of urban runoff pollutants are automobiles, avenues, parking lots, gas stations, soil wash off and erosion, sewer and septic systems, commercial, and industrial areas (EPA 1999). Geographic characteristics of the region, traffic volume, maintenance practices, drainage system configuration, rainfall patterns, volume, intensity, and antecedent number of dry days should also affect urban runoff quality (Chui et al. 1982). These pollutant sources can be classified into four main categories of wastewater, land uses, transportation, and rainfall runoff.

In this study, based on the combination of the various factors which can influence urban runoff vulnerability, a new index-overlay method (WLTR) was developed to assess surface runoff vulnerability to contamination in urban hydrological sub-catchments. For this propose, four major pollutant sources including wastewater factor (W), land use factor (L), transportation factor (T), and rainfall-runoff factor (R) were determined as vulnerability affecting factors.

Then, each factor was encompassed to several major related sub-factors. The sub-factors were determined according to the pollutant sources mentioned above. These factors and their related sub-factors were assigned weights based on their relative importance on the urban runoff vulnerability using analytic hierarchy process (AHP) method (Table 1). The AHP method is one of the most widely used multi-criteria decision analysis models, which are used for the environmental management purpose (Pourghasemi et al. 2012; Chandio et al. 2013; Althuwaynee et al. 2014). This method was introduced by Thomas Saaty (1980) and was described in detail in Saaty (1980, 1986).

Each sub-factor was categorized over the range of its possible values that assigned a rating on a scale of 1 to 5 (1 reflects the lowest contribution to urban runoff vulnerability, whereas 5 reflects the most contribution).

Wastewater factor

One of the main environmental issues, especially in developing countries, is wastewater discharged into water bodies (Margaryan 2016). In undeveloped or developed cities, the absence of separate sewage network and septic tank leakage are the major factors that cause wastewater discharging to land surface and/or to urban runoff drainage system (Tsihrintzis and Hamid 1997; EPA 1999). Therefore, the percentage of the area without separate sewage system (WW) and the number of septic tanks per hectare (WS) were defined as the wastewater-related sub-factors. The high percentage of area without a separate sewage system and the large number of septic tanks per hectare increase the probability of sewage discharging and consequently urban runoff vulnerability. The weight, categories, and ratings of wastewater sub-factors are presented in Table 2.

Table 1 Assigned weights for factors

Factor	Symbol	Weight
Wastewater	W	0.52
Land use	L	0.27
Transportation	T	0.14
Rainfall runoff	R	0.07

Table 2 Weight, categories, and ratings of WLTR index sub-factors

Factor	Sub-factor	Symbol	Weight	Range	Rating
Wastewater (W)	Percentage of the area without a separate sewage system	WW	0.75	0	1
				< 0–25	2
				< 25–50	3
				< 50–75	4
				< 75–100	5
	Number of septic tanks per hectare	WS	0.25	0	1
				1–5	2
				6–10	3
				11–15	4
				< 15	5
Land use (L)	Area percentage of industrial land use	LI	0.57	0	1
	Area percentage of commercial land use	LC	0.24	< 0–5	2
	Area percentage of bare soil	LB	0.13	< 5–10	3
				< 10–15	4
				< 15	5
	Area percentage of green space	LG	0.06	0–5	5
				< 5–10	4
				< 10–15	3
				< 15–20	2
				< 20	1
Transportation (T)	Area percentage of main avenues	TA	0.54	0–5	1
				< 5–10	2
				< 10–15	3
				< 15–20	4
				< 20	5
	Area percentage of parking lots	TP	0.3	0	1
				< 0–2.5	2
				< 2.5–5	3
				< 5–7.5	4
				< 7.5	5
	Number of gas stations	TG	0.16	0	1
				1 and 2	2
				3 and 4	3
				5 and 6	4
				< 6	5
Rainfall runoff (R)	Average maximum number of days between two consecutive rainfall events	RD	0.59	≤ 50	1
				51–100	2
				101–150	3
				151–200	4
				≤ 201	5
	Area percentage of impervious surfaces	RI	0.23	0–60	1
				< 60–70	2
				< 70–80	3
				< 80–90	4
				< 90–100	5
	Land surface slope (%)	RS	0.12	0–2	1
				< 2–5	2
				< 5–10	3
				< 10–20	4

Table 2 (continued)

Factor	Sub-factor	Symbol	Weight	Range	Rating
				< 20	5
	Size of urban area (ha)	RA	0.06	Category #1	1
				Category #2	2
				Category #3	3
				Category #4	4
				Category #5	5

Land use factor

Land use is one of the most important factors affecting urban surface runoff quality. Land use represents the potential of the generation of non-point source contaminations (Tsihrintzis and Hamid 1997; Eimers et al. 2000). Industrial, commercial, bare soils, and green spaces are the most considerable urban land uses in association with urban runoff vulnerability (Boyd and Gardner 1990; EPA 1999). So, the percentage of the industrial area (LI), commercial area (LC), bare soil (LB), and green space (parks, gardens, squares, green belts, playing fields, and etc.) (LG) were determined as the land use-related sub-factors.

Industrial and commercial areas are major resources for different contaminant like organic materials, metals, pesticides, and herbicides, while bare soils are considerable sources for sediment, floatables, nitrogen, and phosphorus (EPA 1999). High percentage of bare soil, industrial, and commercial areas greatly increases contaminant, which consequently increases urban runoff vulnerability. Due to the runoff depuration capacity of urban green spaces (Zhang et al. 2012; McPhearson et al. 2014; Yang et al. 2015), the contribution of green spaces for runoff quality is considered positively. The more percentage of urban green space causes more runoff depuration and consequently decreases runoff vulnerability. The weights, categories, and ratings of land use sub-factors are presented in Table 2.

Transportation factor

Automotive fluids (fuel, coolants and antifreeze, oil, etc.), brake pads wear, tire wear, and vehicle exhaust are the most substantial sources of transportation pollutant (Lehner 1999). Once these pollutants are deposited on road, street, parking lots, and gas station surface, they are available for transport into the surface runoff (Lehner 1999; Chui et al. 1982). Accordingly, the percentage of the main avenue area (highway, road, street, etc. except alley) (TA), the percentage of the parking lot area (TP), and the number of gas stations (TG) were determined as transportation sub-factors. Weights, categories, and ratings of these sub-factors are presented in Table 2.

Rainfall runoff factor

The volume and velocity of urban runoff (which are related to rainfall and land surface properties) are the most important factors affecting contamination wash off into water bodies. The high volume and velocity of the runoff lead to more contaminant wash off (Chui et al. 1982; Zhou et al. 2015; Li et al. 2015).

Due to small size of the urban areas and limited numbers of rain gauge station in developing or less-developed areas, among rainfall properties, only the antecedent number of dry days was considered in this study.

The annual average of the maximum number of days between two consecutive rainfall events (RD), the percentage of the impervious surfaces area (RI), land surface slope (RS), and size of the urban sub-catchment (RA) were determined as the rainfall-runoff sub-factors which their weights, categories, and ratings are presented in Table 2.

Increase in the number of dry days between two consecutive rainfall events causes more pollutant accumulation on land surface and consequently more contaminated runoff generation. Moreover, steeper slopes, low permeability, and large size of urban sub-catchments are associated with large and rapid runoff that can pick up a large amount of deposited contaminants.

The rating scheme of RS was developed based on Eimers et al. (2000). For RA sub-factor, the urban sub-catchment size was divided into five categories with equal intervals. The rating 1 was assigned to the categories with the smallest size and the rating 5 to the categories with largest size.

Vulnerability determining

After determining the sub-factors rating in the studied area, the WLTR index value can be calculated by a linear combination of the weight and rating of factors according to Eq. (1). The sum of factor rating multiplied by weight ranges from 1 to 5.

$$WLTR\ Index = W_W W_R + L_W L_R + T_W T_R + R_W R_R \qquad (1)$$

where W_R, L_R, T_R, and R_R (rating of factors) can be calculated by linear combination of the weight and rating of their related sub-factors according to Eqs. (2), (3), (4), and (5), respectively.

$$W_R = WW_W WW_R + WD_W WD_R + WS_W WS_R \quad (2)$$

$$L_R = LI_W LI_R + LC_W LC_R + LH_W LH_R + LB_W LB_R + LG_W LG_R \quad (3)$$

$$T_R = TG_W TG_R + TA_W TA_R + TP_W TP_R + TC_W TC_R \quad (4)$$

$$R_R = RD_W RD_R + RL_W RL_R + RA_W RA_R + RI_W RI_R + RS_W RS_R + RP_W RP_R \quad (5)$$

where W and R subscripts refer to weight and rating of factors/sub-factors, respectively.

Finally, the urban runoff vulnerability rank could be determined based on the calculated WLTR index using Table 3.

Model validation

Case study area

The proposed method (WLTR index) was applied in a high-intensity residential area in Ardabil city to assess surface runoff vulnerability. The studied area is located in the northwest of Iran and eastern slopes of Sabalan Mountain (38° 13′ to 38° 14′ N and 48°16′ to 48° 19′ E; Fig. 1). The studied area has a cold semi-arid climate. The average annual precipitation and temperature of the study area are 290 mm and 9 °C, respectively. The average elevation and slope of the studied area are 1357 m and 3.3%, respectively. The size of the studied area is about 570 ha that contains bare soils, pavements, parking lots, green spaces, residential, commercial, and industrial land uses. The separate sewer system is developing in the study area. But some of the gray water (from sinks, showers, dishwashers, and clothes washers) joint to surface runoff and flow as the surface runoff. The map of flow directions and the outlets of the urban runoff conveyance network in the studied area were prepared based on the field survey. Based on the runoff flow directions and outlet location, the studied area was divided into 12 hydrological sub-catchments (Fig. 1). The vulnerability of urban runoff to contamination related to each sub-catchment was estimated using the WLTR index-overlay method.

Table 3 WLTR index and vulnerability rank

WLTR index	Vulnerability rank
1–1.8	Very low
< 1.8–2.6	Low
< 2.6–3.4	Moderate
< 3.4–4.2	High
< 4.2–5	Very high

Methods

Data collection and sub-factor rating The location of urban septic tanks and separate sewage network map of the studied area was prepared from Water and Wastewater Company of Ardabil. The maps of the urban septic tank location and sewage network coverage were prepared using Arc Map 10.3. The rating of WW and WS sub-factors were determined for each sub-catchment using Table 2.

The detailed map of urban land uses was prepared from Central Municipal of Ardabil. The land use map was updated using satellite images (which was taken on 25 May 2018) in Google Earth software and direct survey. The percentage of the industrial and commercial land uses, bare soils, green spaces, transportation avenues, parking lots, and impervious surfaces in studied sub-catchments were calculated via Arc Map 10.3. The rating of LI, LC, LB, LG, TA, TP, and RI sub-factors was determined in each sub-catchment using Table 2.

The location map of gas stations was prepared using field survey and GPS information in Arc Map 10.3 and the rating of TG sub-factor was determined for each sub-catchment using Table 2.

The daily precipitation data (2000 to 2017) of the Ardabil synoptic station (the only effective meteorological station on the studied area) (Fig. 1) was prepared from Meteorological Organization of Ardabil. The number of average annual maximum consecutive days without rainfall was calculated for this station. The rating of RD sub-factor in the study area was determined using calculated average annual maximum consecutive days without rainfall (Table 2.

The slope map of the studied area was created in Arc Map 10.3 using Shuttle Radar Topography Mission (SRTM) digital elevation layer at 1 arc-second (~30 m) resolution (https://earthexplorer.usgs.gov/). Based on the average slope (in percent) and Table 2, the rating of RS sub-factor was determined in each sub-catchment.

The size of the studied sub-catchments was ranged from 20 to 100 ha. So, the urban area size categories and their rating in this study were composed according to Table 4. The rating of RA sub-factor was determined according to the size of the sub-catchments and Table 4.

Vulnerability assessment The rating of W, L, T, and R factors in each sub-catchment were calculated using Eqs. (2), (3), (4), and (5), respectively. The WLTR index and vulnerability class of studied sub-catchments were determined using Eq. (1) and Table 3, respectively. The vulnerability priority of the sub-catchments was determined in order of WLTR index decreasing. The first priority (1) was assigned to sub-catchment with

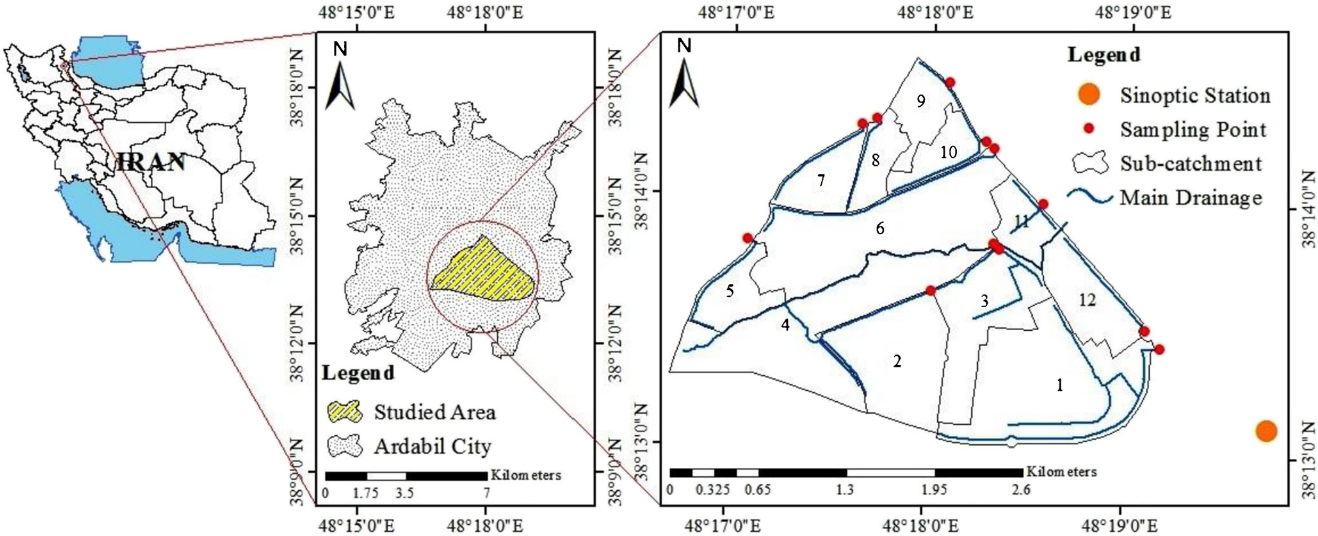

Fig. 1 Location of the studied urban area, sub-catchments, runoff sampling points, and meteorological station

the highest WLTR index value, and conversely, the last priority (12) was assigned to sub-catchment with the lowest WLTR index value.

Efficiency evaluation of the proposed method To evaluate the efficiency of the WLTR index method in urban runoff vulnerability assessment, the overall quality of runoff generated from studied sub-catchments in a rainfall runoff event was determined based on several quality parameters. Urban runoff samples were collected in the outlet of sub-catchments (Fig. 1) during a rainfall runoff event caused by a 5 mm/20 min rainfall on 20 January 2018 (a wet season of the study area). General low-cost water quality parameters (pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), total hardness (TH), and sulfate (SO_4)) of the samples were measured using routine methods in soil and water laboratory of Kashan University.

To determine the overall quality of samples and relative comparison of runoff quality of sub-catchments, a Water Quality Index (WQI) based on pH, EC, TDS, TSS, TH, and SO4 was calculated in four steps for each sub-catchment based on the measured quality parameters and method developed by Brown et al. (1970). The WQI is defined as a rating reflecting the composite influence of different water quality parameters on the overall quality of water (Batabyal and Chakraborty 2015). Unlike other WQI methods, the main advantage of this method is its insensitivity to the number of used water quality parameters.

In the first step, each of the six water quality parameters was assigned a weight (w_i) according to its relative importance in the overall quality of water.

In the second step, the relative weight (W_i) of each parameter was computed using Eq. (6).

$$W_i = {}^{w_i}\!/_{\sum_{i=1}^{n} w_i} \tag{6}$$

where W_i is the relative weight, w_i is the weight of each parameter, and n is the number of parameters (Batabyal and Chakraborty 2015).

In the third step, a quality rating (q_i) was calculated for each parameter using Eq. (7).

$$q_i = \left[{}^{(C_i - S_{io})}\!\Big/_{(S_i - S_{io})} \right] \times 100 \tag{7}$$

where q_i is the quality rating, C_i is the concentration of each parameter in samples, S_{io} is the ideal value of the parameter in pure water, and S_i is the standard permissible value for each parameter. The S_{io} value is equal 0 for all other parameters except pH and dissolved oxygen (7.0 and 14.6 mg/L, respectively) (Batabyal and Chakraborty 2015; Yogendra and Puttaiah 2007).

In this study, the standard permissible value (S_i) of measured parameters was extracted from standards of drinking water quality recommended by the World Health Organization (WHO 2006, 2011).

The relative weight (W_i) and standard values (S_i) of measured water quality parameters are presented in Table 5.

In the fourth step, the WQI value was calculated for each sub-catchment by linear aggregating of the water quality rating with the relative weight using Eq. (8). The

Table 4 Urban area (sub-catchment) size categories and ratings

Urban area size (ha)	Rating
< 20	1
20–< 40	2
40–< 60	3
60–< 80	4
> 80	5

overall water quality class was determined based on the calculated WQI and Table 6.

$$WQI = \sum_{i=1}^{n} q_i W_i \quad (8)$$

The runoff quality priority of sub-catchments was delineated in order of WQI decreasing. The first priority (1) was assigned to sub-catchment with the highest WQI index value, and conversely, the last priority (12) was assigned to sub-catchment with the lowest WQI index value.

Sensitivity analysis of the proposed method The sensitivity analysis of WLTR index sub-factors was done to identify the most and the least effective sub-factors. In this study, the single component sensitivity analysis method was used and the relative sensitivity of the sub-factors in each sub-catchment was calculated using Eq. 9.

$$S = \left({W_t \times R}/{WI} \right) \times 100 \quad (9)$$

where S is the sensitivity of sub-factor, W_t is the theoretical weight of sub-factor, R is the rating of sub-factor, and WI is the value of WLTR index in each sub-catchment. The theatrical weight of each sub-factor is sub-factor weight multiplied by the weight of related factors.

Results and discussion

WLTR index

The location of septic tanks, urban sewage network, areas lacking sewage network, and gas stations in the studied area are shown in Fig. 2a. Figure 2b shows the prepared land use map of the studied area.

The size of the areas with no sewage system (WW), industrial (LI) and commercial (LC) land uses, bare soils (LB), green spaces (LG), main avenues (TA), parking lots (TP), impervious surfaces (RI), and urban sub-catchments (RA), the number (#) of septic tanks (WS), gas stations (TG) and days between rainfall events (RD), and the average land slope (RS) in the studied sub-catchments (SC) are shown in Table 7.

Table 5 Standard values (S_i) and relative weight (W_i) of measured water quality parameters

Quality parameter	Unit	Standard value	Relative weight
pH	-	6.5–8.5	0.115
Electrical conductivity	µS/cm	1500	0.165
Total dissolved solids	mg/L	1000	0.165
Total suspended solids	mg/L	500	0.275
Total hardness	mg/L	500	0.225
Sulfate	mg/L	250	0.055

Table 6 WQI categories and water quality classes (Chatterji and Raziuddin 2002)

WQI value	Water quality class
< 25	Excellent
25–< 50	Good
50–< 75	Poor
75–< 100	Very poor
> 100	Unsuitable

According to the values of sub-factors in Table 7, information of Table 2 and Eqs. 2, 3, 4, and 5, the rating of WLTR index sub-factors and factors in studied sub-catchments were determined according to Table 8.

Due to the large size of the areas with no sewage system (about 76% and 100% of total area in sub-catchment Nos. 11 and 12, respectively), the relative highest rating of W factor (4.25) is related to sub-catchment Nos. 11 and 12. In these sub-catchments, a considerable amount of household sewage (gray water from sinks, showers, dishwashers, and clothes washers), roofs runoff, and also sewage from industrial and commercial areas discharge to urban surface runoff conveyance network.

The two relatively higher ratings of L factor (3.32 and 2.75) are related to sub-catchment Nos. 11 and 12 (respectively), where 12% and 6% of their total area are covered by industrial land use, respectively. These industrial areas are mostly in relation with repairing and maintenance of automobiles and urban buses.

The existence of one gas station caused the relative highest rating of T factor (3.08) to be assigned to sub-catchment No. 11. Due to the traditional discharging of fuel tankers and using low developed pump nozzles, there is a high potential for fuel leakage in this gas station.

As a result of the combined effect of large area and portion of impervious surfaces, the highest relative rating of R factor (2.21) was assigned to sub-catchment No. 2. Also, the sub-catchment Nos. 5, 9, and 12 with rating of 2.1 for R factor were placed in second rank.

Also, due to the existence of only one affective meteorological station, the maximum average rainfall distance was constant in studied area, and consequently, the same ratings were assigned for RD sub-factor in sub-catchments.

The results of WLTR index value, runoff vulnerability rank, and also vulnerability priority in order of WLTR index decreasing in the studied sub-catchments are shown in Table 9.

According to the results, the sub-catchment Nos. 11 and 12 had a high vulnerability, and based on the vulnerability

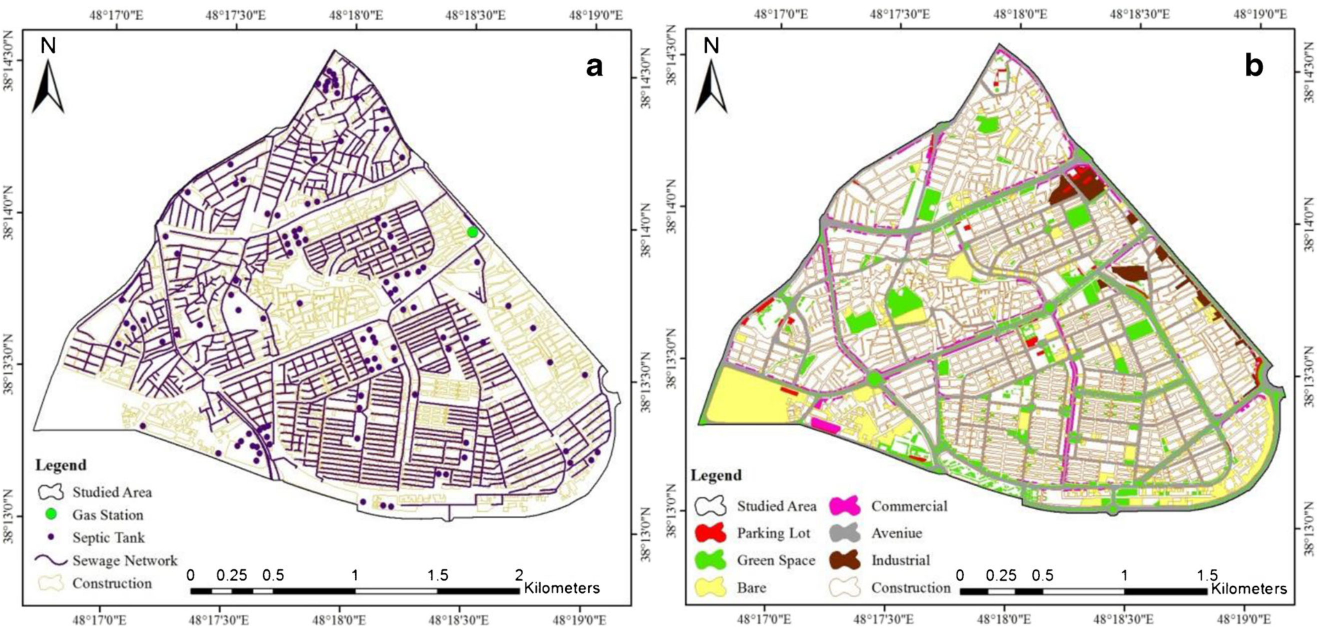

Fig. 2 **a** Septic tanks, sewer network, gas stations, carwashes, **b** transportation avenues, and different land-uses in the studied area

priority, are the most vulnerable sub-catchments between studied sub-catchments.

Because of high similarity in the investigated characteristics of studied sub-catchments, some of the sub-factors especially WS, LC, TG, RD, and RS were assigned the same rating. Despite that these sub-factors have no effect on range of WLTR index value in studied sub-catchments, but due to the high importance of septic tanks (McDowell et al. 2005; Mallin 2013; schaider et al. 2016), commercial land uses (Kang et al. 2010; Paule et al. 2014; Maharjan et al. 2017), gas stations (Hilpert et al. 2015;), as well as land slope (Lee and Bang 2000; Li et al. 2015) on urban runoff quality, and also considering the transferability of WLTR method, the contribution of these sub-factors was not refused. The considerable variation of these sub-factors will make a considerable variation in WLTR index value and vulnerability rank in other case studies. The sub-catchment Nos. 2, 8, and 9 are the three least vulnerable sub-catchments that have very low vulnerability with vulnerability priority of 10, 11, and 12, respectively.

Sensitivity analysis

The results of the sensitivity of WLTR index sub-factors in studied sub-catchments are shown in Table 10. The main affecting sub-factor on the vulnerability index for WLTR

Table 7 The value of WLTR index sub-factors in studied sub-catchments

SC No.	Sub-factors											
	WW (ha)	WS (#)	LI (ha)	LC (ha)	LB (ha)	LG (ha)	TA (ha)	TP (ha)	TG (#)	RD (#)	RI (ha)	RS (%)	RA (ha)
1	16.94	11	0.00	0.82	9.86	6.40	20.27	0.03	0	39	87.73	3.88	103.99
2	0.00	8	0.00	0.61	1.10	4.19	8.99	0.00	0	39	55.93	3.02	61.21
3	0.00	17	0.20	0.86	2.28	5.33	8.18	0.41	0	39	46.17	3.67	53.78
4	44.09	14	0.00	2.46	20.84	4.42	10.95	0.46	0	39	69.67	3.69	94.92
5	0.00	5	0.00	0.17	0.38	0.76	4.36	0.56	0	39	21.58	4.47	22.72
6	15.34	24	3.99	1.35	4.69	8.31	13.89	0.63	0	39	84.79	3.08	98.08
7	0.00	4	0.00	0.46	0.33	0.52	3.12	0.11	0	39	21.32	2.47	24.10
8	0.00	3	0.00	0.28	0.53	1.78	1.92	0.00	0	39	15.70	2.56	18.01
9	0.00	12	0.00	0.29	0.75	1.14	1.92	0.13	0	39	19.70	2.41	21.59
10	1.05	4	0.00	0.47	0.58	0.41	1.87	0.02	0	39	16.88	2.52	18.84
11	14.54	1	2.23	0.41	0.23	0.56	3.42	0.12	1	39	18.52	2.21	19.31
12	34.39	4	1.96	0.07	1.50	0.64	5.19	0.23	0	39	32.33	2.49	34.47

Table 8 The rating of WLTR index sub-factors and factors in studied sub-catchments

SC No.	Rating																
	Sub-factors													Factors			
	WW	WS	LI	LC	LB	LG	TA	TP	TG	RD	RI	RS	RA	W	L	T	R
1	2	2	1	2	3	4	4	2	1	1	4	2	5	2	1.68	2.92	2.05
2	1	2	1	2	2	4	3	1	1	1	5	2	4	1.25	1.55	2.08	2.22
3	1	2	2	2	2	4	4	2	1	1	4	2	3	1.25	2.12	2.92	1.93
4	3	2	1	2	5	5	3	2	1	1	3	2	5	2.75	2	2.38	1.82
5	1	2	1	2	2	5	4	2	1	1	5	2	2	1.25	1.61	2.92	2.1
6	2	2	2	2	2	4	3	2	1	1	4	2	5	2	2.12	2.38	2.05
7	1	2	1	2	2	5	3	2	1	1	4	2	2	1.25	1.61	2.38	1.87
8	1	2	1	2	2	4	3	1	1	1	4	2	1	1.25	1.55	2.08	1.81
9	1	2	1	2	2	4	2	2	1	1	5	2	2	1.25	1.55	1.84	2.1
10	2	2	1	2	2	5	2	2	1	1	4	2	1	2	1.61	1.84	1.81
11	5	2	4	2	2	5	4	2	2	1	5	2	1	4.25	3.32	3.08	2.04
12	5	2	3	2	2	5	4	2	1	1	5	2	2	4.25	2.75	2.92	2.1

method in all studied sub-catchments was the percentage of area without a separate sewage system (WW). The number of septic tanks per hectare (WS), the area percentage of the industrial land use (LI), the size of urban sub-catchment (RA), and the land surface slope (RS) sub-factors are the other sensitive sub-factors of WLTR index method, respectively.

Water Quality Index

Table 11 indicates the quality rating of measured parameters(q_i), WQI value, runoff quality rank, and quality priority in the studied sub-catchments. EC and TDS concentration considered to indicate the cumulative effect of different water anions and cations.

Table 9 WLTR index and vulnerability rank and priority in studied sub-catchments

SC No.	WLTR index	Vulnerability rank	Vulnerability priority
1	2.05	Low	5
2	1.52	Very low	10
3	1.77	Very low	7
4	2.43	Low	3
5	1.64	Very low	8
6	2.09	Low	4
7	1.55	Very low	9
8	1.49	Very low	11
9	1.47	Very low	12
10	1.86	Low	6
11	3.68	High	1
12	3.51	High	2

According to the results, the sub-catchment Nos. 11 and 12 with WQI value of 170.92 and 217.45 and quality priority of 2 and 1, respectively, have the lowest runoff quality among studied sub-catchments. These sub-catchments were determined as the two most vulnerable among studied sub-catchments.

High concentration of EC, TDS, TSS, TH, and SO_4 cases is higher WQI in sub-catchment Nos. 11 and 12. These parameter concentrations were 1540 μs/cm, 1186, 1720, 660, and 229.82 mg/L in sub-catchment No. 11 and 1631 μs/cm, 1256, 2560, 670, and 241.11 mg/L in sub-catchment No. 12, respectively. The major reasons for low quality of urban runoff in these sub-catchments are the considerable discharging of domestic, commercial, and industrial wastewaters in urban runoff network (Taebi and Droste 2004; Ding et al. 2015), high percentage of industrial land use, and high traffic volume (Bartlett 2016).

The sub-catchment Nos. 2, 8, and 9, with WQI of 68.02, 74.05, and 73.8, and runoff quality priority of 12, 10, and 11, respectively, are the three sub-catchments with relative higher runoff quality among studied sub-catchments. These sub-catchments were determined as the three least vulnerable sub-catchments among studied sub-catchments.

Comparison of the priorities of vulnerability (WLTR) and runoff quality (WQI) in studied sub-catchments demonstrated the acceptable efficiency of WLTR index method in vulnerability assessment of the urban sub-catchment runoff. The sub-catchment Nos. 4, 11, and 12 that determined as the three most vulnerable sub-catchments had also least water quality, whereas the sub-catchment Nos. 2, 8, and 9 that determined as the three least vulnerable sub-catchments had highest water quality among studied sub-catchments.

Table 10 The sensitivity of WLTR index sub-factors in studied sub-catchment

Sub-factor	Theoretical weight (%)	SC No.											
		1	2	3	4	5	6	7	8	9	10	11	12
WW	39.00	38.13	25.74	22.08	48.14	23.77	37.34	25.18	26.24	26.47	41.96	52.98	55.58
WS	13.00	12.71	17.16	14.72	10.70	15.85	12.45	16.79	17.49	17.65	13.99	7.06	7.41
LI	15.39	7.52	10.16	17.43	6.33	9.38	14.73	9.94	10.35	10.45	8.28	16.73	13.16
LC	6.48	6.33	8.55	7.34	5.33	7.90	6.20	8.37	8.72	8.80	6.97	3.52	3.69
LB	3.51	5.15	4.63	3.97	7.22	4.28	3.36	4.53	4.72	4.77	3.78	1.91	2.00
LG	1.62	3.17	4.28	3.67	3.33	4.94	3.10	5.23	4.36	4.40	4.36	2.20	2.31
TG	2.24	1.09	1.48	1.27	0.92	1.37	1.07	1.45	1.51	1.52	1.20	1.22	0.64
TA	7.56	14.78	14.97	17.12	9.33	18.43	10.86	14.64	15.26	10.26	8.13	8.22	8.62
TP	4.20	4.11	2.77	4.76	3.46	5.12	4.02	5.42	2.83	5.70	4.52	2.28	2.39
RD	4.13	2.02	2.73	2.34	1.70	2.52	1.98	2.67	2.78	2.80	2.22	1.12	1.18
RI	1.61	3.15	5.31	3.65	1.99	4.91	3.08	4.16	4.33	5.46	3.46	2.19	2.29
RS	0.84	0.82	1.11	0.95	0.69	1.02	0.80	1.08	1.13	1.14	0.90	0.46	0.48
RA	0.42	1.03	1.11	0.71	0.86	0.51	1.01	0.54	0.28	0.57	0.23	0.11	0.24

To evaluate WLTR index method efficiency, six water quality parameters (pH, EC, TDS, TSS, TH, and SO_4) were analyzed. Despite that the used WQI method has the advantage of applicability with any number of water quality parameters (Chatterjee and Raziuddin 2002; Yogendra and Puttaiah 2007; Batabyal and Chakraborty 2015), but it is offered that more number of water quality factors should be analyzed to assess the efficiency of WLTR index method in other case studies whit different land and climate characteristics.

Determining the vulnerability of surface runoff in urban sub-catchments using WLTR index method could be a large contributor in the prioritization of different sub-catchments for implementation of practical applications and environmental disciplines (e.g., pre-treatment, storage and/or dispose of urban runoff, implementation of low impact development techniques (LIDs), and urban maintaining infrastructures) toward sustainable water resource management and environment conservation.

Conclusions

In this study, for the first time, an index overlay method (WLTR index) was developed to assess urban runoff vulnerability to contamination. The urban runoff vulnerability was determined based on rating different sub-factors of wastewater (W), land use (L), transportation (T), and rainfall runoff (R) factors.

Table 11 Quality rating of parameters, WQI, and quality rank and priority of urban runoff in studied sub-catchments

SC No.	Concentrations						WQI	Quality	
	pH	EC	TDS	TSS	TH	SO_4		Rank	Priority
1	24.67	101.53	117.30	108.00	90.00	25.33	90.29	Very poor	7
2	32.00	49.73	57.40	112.00	68.00	10.19	68.02	Poor	12
3	100.00	71.13	82.20	132.00	114.00	12.97	99.46	Very poor	5
4	4.00	99.27	114.70	184.00	122.00	84.98	118.49	Unusable	3
5	38.00	32.60	37.70	192.00	74.00	11.58	86.06	Very poor	8
6	16.00	87.33	100.90	196.00	124.00	25.03	116.08	Unusable	4
7	28.00	43.73	50.50	172.00	54.00	9.15	78.72	Very poor	9
8	50.67	30.73	35.50	152.00	60.00	36.24	74.05	Poor	10
9	44.00	28.47	32.90	160.00	60.00	20.26	73.80	Poor	11
10	24.67	59.87	69.10	156.00	122.00	85.92	99.19	Very poor	6
11	44.00	102.67	118.60	344.00	132.00	91.93	170.92	Unusable	2
12	22.00	108.73	125.60	512.00	134.00	96.44	217.45	Unusable	1

In the dry seasons, there is no rainfall runoff or its amount is insignificant. Reducing the amount of rainfall and runoff causes increase of pollutants at road surface or in the effluents. In this case, the first rains after dry season should contain a large amount of pollutant. The effect of dry season at WLTR model is applied in the form of RD sub-factor (average maximum distance between two annual rainfalls), and due to its importance, the highest weight is assigned to dry season factor (RD). The weight of RD sub-factor is equal to 6.

It should be noted that WLTR model provides an estimate of the overall pollution potential status of urban watersheds (annual pollution potential). The maximum distance between rainfall events (RD) and the average annual rainfall (RP) were used in the rainfall runoff factor section. But, WLTR model can be improved separately for wet and dry seasons in different regions via changing the ranges, weights, and scores of the two sub-factors RD and RP.

The efficiency of this method in assessing urban runoff vulnerability was investigated via direct measurement of the runoff quality in a WQI framework in several urban sub-catchments of Ardabil city. The comparison of vulnerability priority with the quality priority of urban runoff in the studied sub-catchments showed an acceptable efficiency for WLTR index method.

Determining urban runoff vulnerability using WLTR index could be a useful tool in determining the priority of different urban sub-catchments for quality/quantity management of urban runoff especially in the semi-arid regions of developing countries. In this study, WQI was developed for investigating urban surface runoff vulnerability to contamination for urban runoff management programs such as runoff collection, but, the results of WQI should also use to investigate the suitability of an urban area to inject its runoff to the aquifer for groundwater recharge.

References

Althuwaynee OF, Pradhan B, Park HJ, Lee JH (2014) A novel ensemble bivariate statistical evidential belief function with knowledge-based analytical hierarchy process and multivariate statistical logistic regression for landslide susceptibility mapping. Catena 114:21–36

Angrill S, Petit-Boix A, Morales-Pinzon T, Josa A, Rieradevall J, Gabarrell X (2017) Urban rainwater runoff quantity and quality - a potential endogenous resource in cities. J Environ Manag 189:14–21

Antunes LN, Thives LP, Ghisi E (2016) Potential for potable water savings in buildings by using stormwater harvested from porous pavements. Water 8(4):1–18

Bartlett, J. H. (2016). Impacts of transportation infrastructure on storme water and surface waters in Chittenden County, Vermont, USA. Thesis for Master of Science, Faculty of the Graduate College, University of Vermont

Batabyal AK, Chakraborty S (2015) Hydrogeochemistry and water quality index in the assessment of groundwater quality for drinking uses. *water Environ. Res.* 87(7):607–617

Behera PK, Adams BJ, Li JY (2006) Runoff quality analysis of urban catchments with analytical probabilistic models. J Water Resour Plan Manag 132(1):4–14

Boyd G, Gardner N (1990) Urban stormwater: an overview for municipalities. Public Works, December, 39–42

Brown RM, Mcclelland NI, Deininger RA, Tozer RG (1970) A water quality index: do we dare? Water Sewage Works 117:339–343

Chandio IA, Matori ANB, WanYusof KB, Talpur MAH, Balogun AL, Lawal DU (2013) GIS-based analytic hierarchy process as a multicriteria decision analysis instrument: a review. Arab J Geosci 6(8):3059–3066

Chatterjee C, Raziuddin M (2002) Determination of water qualti index (WQI) of a degraded river in Asanol Industrial area, Raniganj, Burdwan, West Bengal. Nature Environ and Pollution Technol 1(2):181–189

Chen J, Adams BJ (2007) Development of analytical models for estimation of urban stormwater runoff. J Hydrol 336:458–469

Chevre N, Vallotton N, Rossi L (2007) Risk assessment of urban runoff pollution in rivers: how to deal with time-varying concentrations? NOVATECH 2007 - Sixth International Conference on Sustainable Techniques and Strategies in Urban Water Management, Lyon

Chui TW, Mar BW, Hornet RR (1982) A pollutant loading model for highway runoff. J Environ Engi 108(6):1193–1210

Ding J, Jiang Y, Fu L, Liu Q, Peng Q, Kang M (2015) Impacts of land use on surface water quality in a subtropical river basin: a case study of the Dongjiang river basin, southeastern China. Water 7:4427–4445

Eimers JL, Weaver JC, Terziotti S, Midgette RVW (2000) Methods of rating unsaturated zone and watershed characteristics of public water supplies in north carolina, U.S. Geological Survey Water-Resources Investigations Report 99–4283

EPA (1999) Preliminary Data Summary of Urban Stormwater Best Management Practices, U.S.

Fan R, Tong STY, Lee JG (2017) Determining the optimal BMP arrangement under current and future climate regimes: case study. J Water Resour Plan Manag 143 (9):1–16

Fletcher TD, Deletic A, Mitchell VG, Hatt BE (2008) Reuse of urban runoff in Australia: a review of recent advances and remaining challenges. J Environ Qual 37(5):116–127

Freni G, Mannina G, Viviani G (2010) Urban storm-water quality management: centralized versus source control. J Water Resour Plan Manag 136:268–278

Ghazavi R, Ebrahimi Z (2015) Assessing groundwater vulnerability to contamination in an arid environment using DRASTIC and GOD models. Int J Environ Sci Technol 12:2909–2918

Ghodsi SH, Kerachian R, Zahmatkesh Z (2016a) A multi-stakeholder framework for urban runoff quality management: application of social choice and bargaining techniques. Sci Total Environ 550:574–585

Ghodsi SH, Kerachian R, Malakpour Estalaki S, Nikoo MR, Zahmatkesh Z (2016b) Developing a stochastic conflict resolution model for urban runoff quality management: application of info-gap and bargaining theories. J Hydrol 533:200–212

Harbaugh AW, Banta ER, Hill MC, Mcdonald MG (2001) MODFLOW-2000, the US Geological Survey modular ground-water model users guide to modularization concepts and the groundwater flow process, U.S. Geological Survey open-file report 00–92

Harum T, Saccon P, Calasans N, Ruch C h (2004) Water resources, vulnerability assessment and quality of water in Cachoeira Catchment. ECOMAN Newsletter 3:1–8

Hilpert M, Mora BA, Ni J, Rule AM, Nachman KE (2015) Hydrocarbon release during fuel storage and transfer at gas stations: environmental and health effects. Current Environ. Health Rep 2(4):412–422

Hur S, Nam K, Kim J, Kwak C (2018) Development of urban runoff model FFC-QUAL for first-flush water-quality analysis in urban drainage basins. J. Environ, Manage. 205:73–84

Jia H, Ma H, Sun Z, Yu S, Ding Y, Liang Y (2014) A closed urban scenic river system using stormwater treated with LID-BMP technology in a revitalized historical district in China. Ecological Engin 71:448–457

Kang J, Lee SW, Cho KH, Ki SJ, Cha SM, Kim JH (2010) Linking land-use type and stream water quality using spatial data of fecal indicator bacteria and heavy metals in the Yeongsan riverbasin. Water Res 44: 4143–4157

Lee JH, Bang KW (2000) Characterization of urban stormwater runoff. Water Res 34(6):1773–1780

Lehner P H, Aponte Clarke GP, Cameron DM, Frank AG (1999) Stormwater strategies: community responses to runoff pollution. Natural Resources Defense Council, New York, p 269

Li D, Wan J, Ma Y, Wang Y, Huang M, Chen Y (2015) Storm water runoff pollutant loading distributions and their correlation with rainfall and catchment characteristics in a rapidly industrialized city. PLoS One 10(3):e0118776

Liu A, Egodawatta P, Guan Y, Goonetilleke A (2013) Influence of rainfall and catchment characteristics on urban stormwater quality. Sci Total Environ 444:255–262

Maharjan B, Pachel K, Loigu E (2017) Modelling stormwater runoff, quality, and pollutant loads in a large urban catchment. Proceedings of the Estonian Academy of Sci 66(3):225–242

Mallin MA (2013) Septic systems in the coastal environment: multiple water quality problems in many areas. Monitoring Water Quality 2013:81–102

Margaryan L (2016) Impact of domestic wastewater on surface water quality of selected residential settlements in Armenia. European Water 53:5–12

Mays L (2009) Integrated urban water management: arid and semi-arid regions. UNESCOIHP, CRC Press, Taylor & Francis Group, Boca Raton, London, New York

McDowell W, Brick Ch, Clifford M, Frode-Hutchins M, Harvala J, Knudsen K (2005) Septic system impact on surface waters: a review for the inland northwest. Tri-State Water Quality Council

McPhearson T, Hamstead ZA, Kremer P (2014) Urban ecosystem services for resilience planning and management in New York City. AMBIO 43(4):502–515

National Research Council (1993) Ground water vulnerability assessment, predicting relative contamination potential under conditions of uncertainty. National academy press, washington

Nosrati K (2017) Identification of a water quality indicator for urban roof runoff. Sustain. Water Quality Ecology 9-10:78–87

Paule MA, Memon SA, Lee BY, Umer SR, Lee CH (2014) Stormwater runoff quality in correlation to land use and land cover development in Yongin, South Korea. Water Sci Technol 70(2):218–225

Pourghasemi HR, Moradi HR, Fatemi Aghdam SM, Gokceoglu C, Pradhan B (2012) GIS-based landslide susceptibility mapping with probabilistic likelihood ratio and spatial multi criteria evaluation models (north of Tehran, Iran). Arab J Geosci 7(5):1857–1878

Richardson CP, Tripp GA (2006) Investigation of boundary shear stress and pollutant detachment from impervious surface during simulated urban storm runoff. J Environ Eng 132(1):85–92

Saatsaz M, Sulaiman WNA, Eslamian S (2011) GIS DRASTIC model for groundwater vulnerability estimation of Astaneh-Kouchesfahan Plain, Northern Iran. Int J Water 6(1/2):1–14

Saaty TL (1980) The analytical hierarchy process, pinning priority, resource allocation. RWS, U.S

Saaty TL (1986) Axiomatic Foundation of Analytical Hierarchy Process. Manag Sci 31(7):841–855

Schaider LA, Ackerman JM, Rudel RA (2016) Septic systems as sources of organic wastewater compounds in domestic drinking water wells in a shallow sand and gravel aquifer. Sci Tot Environ 547:470–481

Shah Naqvi SAA, Sultan A, Eslamian S (2015) Water Quality Issues in Urban Water, in Urban Water Reuse Handbook, Ch. 8, Ed. By Eslamian, S., CRC, U.S.

Taebi A, Droste RL (2004) Pollution loads in urban runoff and sanitary wastewater. Sci. of the Tot. Environ. 1(3):175–184

Taffere GR, Beyene A, Vuai SAH, Gasana J, Seleshi Y (2016) Reliability analysis of roof rainwater harvesting systems in a semi-arid region of sub-Saharan Africa: case study of Mekelle, Ethiopia. Hydrol Sci J 61(6):1135–1140

Tsihrintzis VA, Hamid R (1997) Modeling and management of urban stormwater runoff quality: a review. Water Resour Manag 11:137–164

UN (United Nations) (2012) World Urbanization Prospects: the 2012 Revision. New York

Van Roon M (2007) Water localisation and reclamation: steps towards low impact urban design and development. J Environ Manag 83: 437–447

WHO (World Health Organization) (2006) Guidelines for drinking-water quality, 3rd ed.

Yang J, Wang ZH, Chen F, Miao S, Tewari M, Voogt J, Myint S (2015) Enhancing hydrologic modelling in the coupled Weather Research and Forecasting–urban modelling system. Bound-Layer Meteorol 155: 87–109

Yogendra K, Puttaiah ET (2007) Determination of water quality index and suitability of an urban waterbody in Shimoga Town, Karnataka. the 12th world lake conference 2007, ILCE, Jaipur, 342–346

Young KD, Dymond RL, Kibler DF (2011) Development of an improved approach for selecting storm-water best management practices. J Water Resour Plan Manag 137:268–275

Zhang B, Xie GD, Zhang CQ, Zhang J (2012) The economic benefits of rain water-runoff reduction by urban green spaces:A casestudy in Beijing,China. J Environ Manage 100:65–71

Zhou J, He Z, Yang Y, Deng Y, Tringe SG, Alvarez-Cohen L (2015) High-throughput metagenomic technologies for complex microbial community analysis: open and closed formats. mBio 6(1). https://doi.org/10.1128/mBio.02288-14

Zhou Q, Blohm A, Liu B (2017) Planning framework for mesolevel optimization of urban runoff control schemes. J Water Resour Plan Manag 143(4):1–11

Zhu K, Zhang L, Hart W, Liu M, Chen H (2004) Quality issues in harvested rainwater in arid and semi-arid Loess Plateau of northern China. J Arid Environ 57:487–505